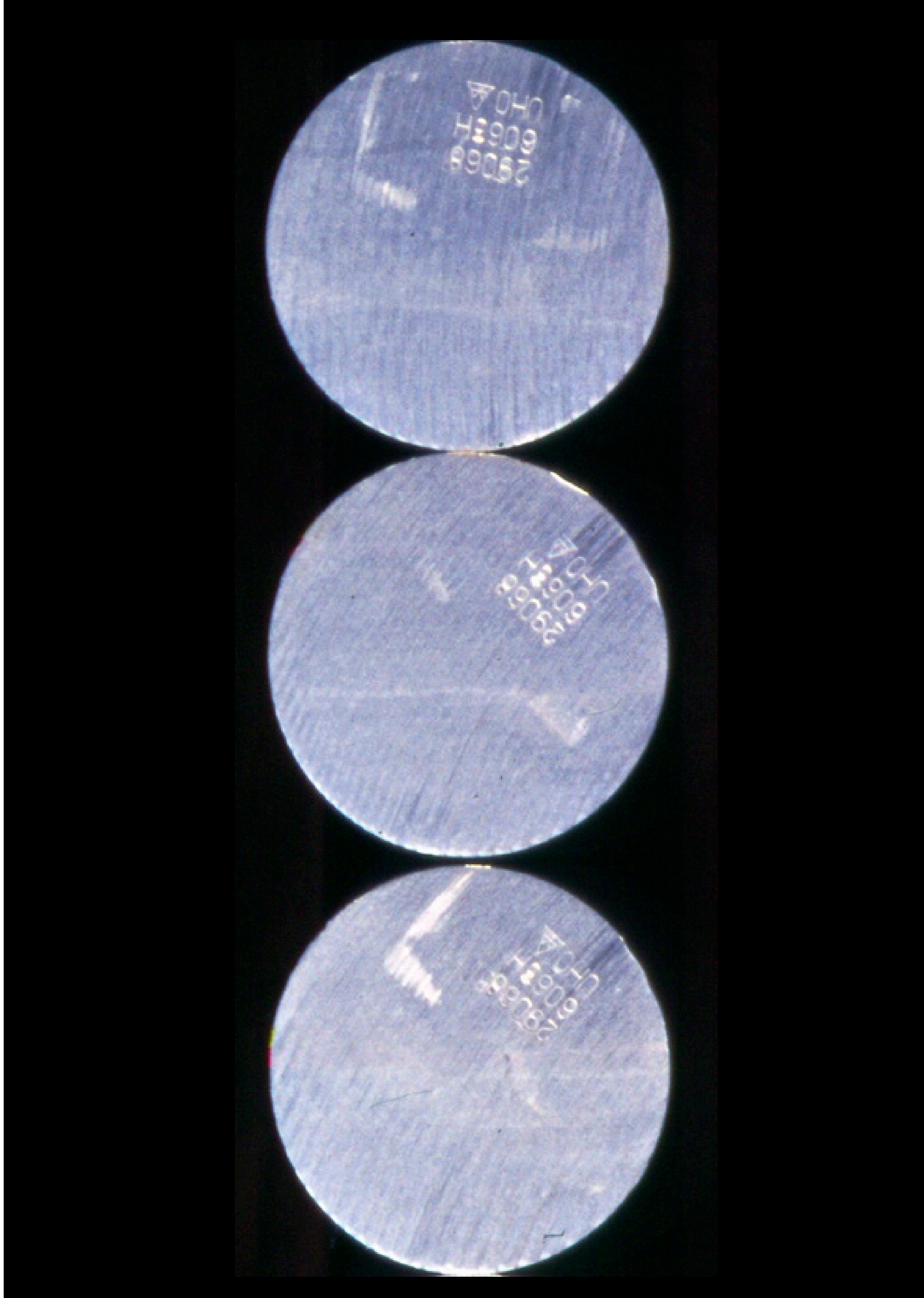
Aluminium: Flexible and Light

Towards Sustainable Cities

Michael Stacey



WORLD ALUMINIUM

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Nottingham + Llundain

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Michael Stacey Architects

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introduction

Introduction

Aluminium: Flexible and Light is the fourth report resulting from the Towards Sustainable Cities research programme, following on from *Aluminium and Durability, Aluminium Recyclability and Recycling, and Aluminium and Life Cycle Thinking*. The objective of the Towards Sustainable Cities (TSC) research, funded by the International Aluminium Institute (IAI), is to quantify the in-use benefits of aluminium in architecture and the built environment. The programme was initiated by Chris Bayliss, Deputy Secretary General of IAI, and Michael Stacey of Michael Stacey Architects in the spring of 2012. Research collaborators include the Architecture and Tectonics Research Group [ATRG] of The University of Nottingham, and KieranTimberlake of Philadelphia, Pennsylvania, USA.

Within this text, when a word or phrase is in bold, it is defined in the Glossary; this occurs on the first entry only.

To many geologists the present time period should in geological terms be defined as the **Anthropocene**, an epoch where humankind has altered the environment and ecology of Earth to the extent that it is being recorded in the Earth's crust, in the very rocks of planet Earth. Robert Macfarlane suggests: 'The idea of the Anthropocene asks hard questions of us. Temporally, it requires that we image ourselves inhabitants not just of a human lifetime or generation, also of "deep time" – the dizzyingly profound eras of Earth history that extend behind and ahead if the present.'[1]

The roots of the Anthropocene has it's origin in the industrial and urban revolution of the Nineteenth Century when humankind harnessed the means of production so successfully it made work at vast scales possible, without the enormous workforce seen in ancient Egypt or Rome. The term Anthropocene was coined in 1999 by Paul J. Cruzten, a Noble Prize winning atmospheric chemist, who believed the term **Holocene** was no longer accurate.[2] The Holocene epoch began about 11,700 years before 2000AD, and simply means *entirely recent,* in ancient Greek. Based on the record of greenhouse gases such as $CO_{2,}$ Paul J. Cruzten and his colleagues propose that the Anthropocene started in 1782 the year James Watt patented, in the United Kingdom, his efficient steam engine, a key invention of the Industrial Revolution. It should be noted that Anthropocene is not yet an officially recognised epoch of geological time, by either the International Commission on Stratigraphy or the International Union of Geological Sciences, and other start dates have been proposed. The Anthropocene Working Group proposes to make an announcement during 2016, whether it should be ratified as a geological epoch.

Whilst reviewing the role of aluminium in the construction of the built environment and how it can be marshalled as an on-going resource for humankind, it is important to use a clear and effective definition of sustainability, as discussed in TSC Report Two *Aluminium Recyclability and Recycling*.[3] For architecture and the built environment, sustainability is a balancing of economic, ecological, political and cultural objectives within a spatial project.[4] Thus, sustainable development 'seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future', stated Gro Harlem Brundtland in 1987.[5]

On Saturday 12 December 2015 the COP 21 meeting in Paris announced a global agreement on climate change, the United Nation had spent 23 years seeking a collective agreement to tackle this issue of global significance. The full text of the UN *Framework Convention on Climate Change* can be downloaded via *unfccc.int*.[6]

This convention on climate change has 29 articles; the key principles can be summaries as:

- Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change, (part of Article 2).[7]
- In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country, (part of Article 4).[8]
- Article 8 (1) states: Parties recognize the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change, including extreme weather events and slow onset events, and the role of sustainable development in reducing the risk of loss and damage.[9]
- Article 14 (1) calls for a global stocktake every five years: The Conference of the Parties serving as the meeting of the Parties to the Paris Agreement shall undertake its first global stocktake in 2023 and every five years thereafter unless otherwise decided by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement.[10]

Agreed actions prior to 2020 in the convention include:

> Urging all Parties to participate in the existing measurement, reporting and verification processes under the Cancun Agreements, in a timely manner, with a view to demonstrating progress made in the implementation of their mitigation pledges.[11]

However the *Framework Convention on Climate Change* does not include the financial target of $100bn (£66bn) a year to tackle climate change – this was restricted to the discussion text accompanying the convention, largely to a swage US political concerns. Arguably the key funding required to tackle climate change has not been included in the *Convention*.[12]

Clearly there is a need for investment in research and development into renewable energy technology and low carbon architecture to achieve the ambitious goal of keeping the global climate temperature increase to 1.5°C above pre-industrial levels. Furthermore, well-informed design by skilful design teams has an immense role to play in the success of low carbon architecture and infrastructure, as demonstrated by many of the case studies included in this report. For example the overcladding of Guy's Hospital with folded anodised aluminium panels and new double glazed curtain walling design by Penoyre & Prasad Architects with Arup Façades has a carbon payback period of only 12.5 years, combined with a durability from the cladding of over 80 years, as detailed in Chapter Four.

In Chapter 8, *Aluminium: Servant of Sustainability includes the* Sino-Italian Ecological & Energy Efficient Building in Beijing, designed by Mario Cucinella Architects, Italian architects who specialise in low carbon architecture. Mario Cucinella attributes 17 per cent of the carbon savings to technology and 36 per cent to the design of the architecture.[13]

Aluminium

Aluminium is a silvery, soft, ductile, light metal. The chemical symbol for aluminium is Al, and it has an atomic number of 13. Alloyed with other metals, such as copper, it has become the first-choice material for many contemporary uses. Aluminium is the third most abundant material in the Earth's crust and the most abundant metal. Aluminium is eight per cent of the Earth by mass, typically found in the form of bauxite. The chemical composition of the fired clay in a common brick wall typically contains 10–20kg of aluminium per square metre. One square metre of aluminium sheet for wall cladding weighs less than two kg.[14]

Fig 1.1 A common brick wall contains 10–20kg of aluminium per square metre

Fig 1.2 The 3mm polyester powder coated aluminium of the Soho Galaxy Prototype Zaha Hadid Architects fabricated by Permasteelisa

Aluminium can be cast, extruded, press-moulded and roll-formed, among other processes. Many of the forming processes exploit the inherent ductility of aluminium. It can be readily cast and recycled as its melting point is only just above 660°C. The flexibility of aluminium to form affordable components is discussed further in Chapter Two *Flexible: Fabrication Processes*. The recyclability of aluminium benefits from the retention of all of its material qualities after recycling, combined with the monetary and societal value of this metal, as analysed in TSC Report Two.[15]

The reason aluminium smelting requires a lot of energy is the strong bond between aluminium and oxygen in alumina molecules (Al_2O_3). However, this reactivity is the chemical property that also gives the metal many of its valuable physical qualities, which makes it the material of choice in many applications.[16]

Aluminium has seven primary qualities that make it ideal for use in applications within architecture and the built environment, it is:

- durable;
- recyclable;
- flexible;
- light and strong;
- efficient or powerful;
- economical;
- sympathetic.

These qualities are explored in detail on *The Future Builds with Aluminium* website (http://greenbuilding.world-aluminium.org).

Jules Verne, writing in 1865, in his novel *From the Earth to the Moon* is clearly aware of the properties of aluminium. He cites the large-scale chemical production of aluminium by the French chemist Henri Étienne Sainte-Clair Deville in 1854. But this is before a cost effective process for the production of aluminium from alumina had been developed. In 1886, the Hall-Héroult process was simultaneous invented in the USA and France, named after the two inventors Charles Martin Hall and Paul Héroult.[17]

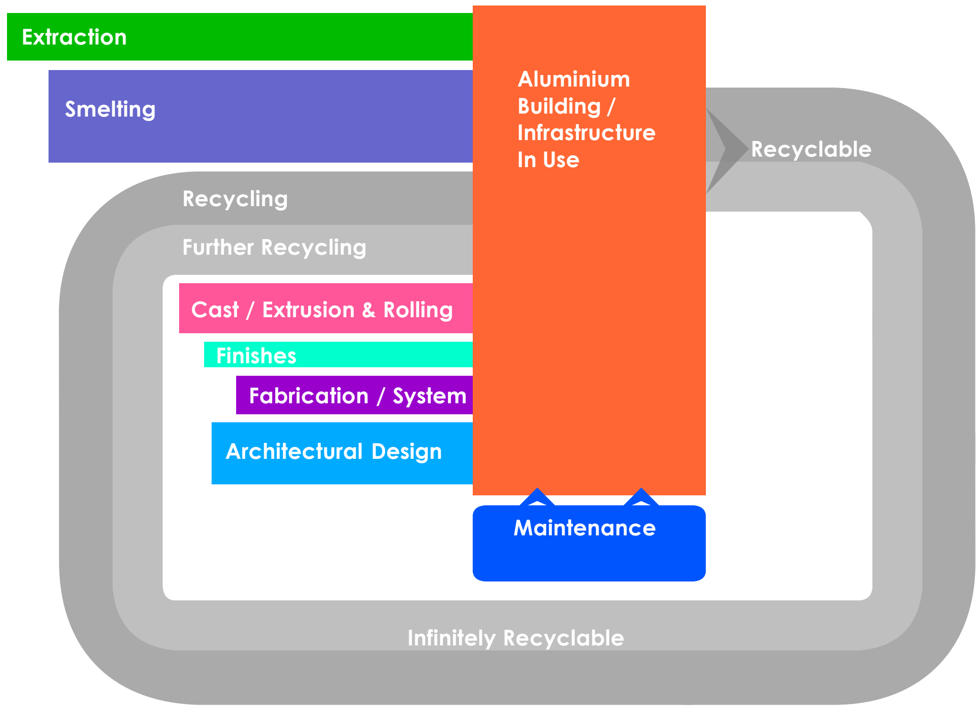
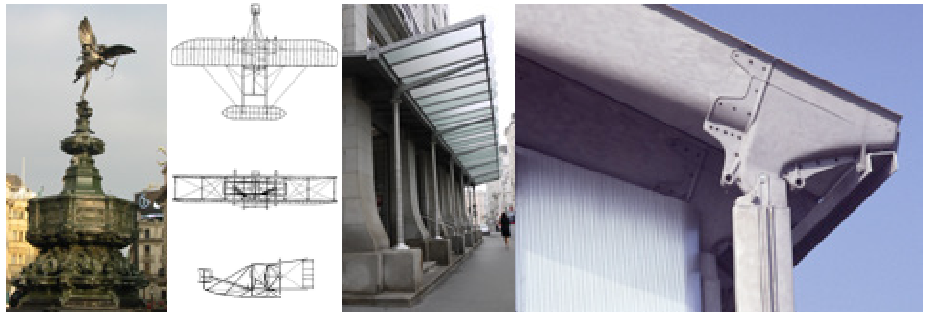


Fig 1.3 All participants add value to aluminium

Jules Verne presciently describes the benefits of aluminium to produce the capsule that was to be fired (or launched) to reach the moon.

> This valuable metal possesses the whiteness of silver, the indestructibility of gold, the tenacity of iron, the fusibility of copper, the lightness of glass. It is easily wrought, is very widely distributed, forming the base of most of the rocks, is three times lighter than iron, and seems to have been created for the express purpose of furnishing us with the material for our projectile.[18]

Timeline of Aluminium up to the Jet Age



1800 – 1960

- **1808** Aluminium is discovered by Sir Humphry Davy as constituent of alum, in England
- **1821** Pierre Berthier discovers bauxite ore in Les Baux-de-Provence, in southern France
- **1825** H. C. Ørsted produces significant quantities of aluminium, in Denmark
- **1827** Friedrich Wöhler isolates aluminium, in Germany
- **1854** Henri Étienne Sainte-Claire Deville enhances Wöhler's method of isolating aluminium and chemical production of aluminium commences in France
- **1855** Aluminium spoons and forks used by visiting dignitaries at the Court of Napoléon III, in France
- **1858–60** Aluminium casting of Diane de Gabies by Paul Morin et Cie, in France
- **1884** Cast aluminium pyramid cap to the Washington Monument, in USA
- **1886** Hall-Héroult process – affordable volume production of aluminium invented by Charles Martin Hall and Paul Héroult
- **1887** Bauxite refining, the Bayer process is invented & patented by Austrian scientist Karl Josef Bayer
- **1888** Pittsburgh Reduction Company founded to develop the Hall-Héroult process
- **1890** First use of aluminium for overhead electric power cables
- **1891** First aluminium boat fabricated in Switzerland
- **1892** Cast aluminium sculpture of Eros at Piccadilly Circus, London
- **1895** Aluminium ceiling installed at Church of St Edmund, King & Martyr, Derbyshire, Fenny Bentley
- **1897** Aluminium sheet cladding of the cupola of the church of San Gioacchino, Rome
- **1902** Aluminium is the key material in the interior of St Mary the Virgin, Great Warley, Essex
- **1903** First powered flight by Wright brothers, Kill Devil Hills, USA, using a cast aluminium engine
- **1903** Alfred Wilm invents Duraluminium in Germany
- **1906** Otto Wagner's Postsparkasse, Vienna – cast and sheet aluminium
- **1920s** Development of anodising and aluminium extrusion processes
- **1931** Empire State Building, New York, USA, by William F. Lamb: cast aluminium spandrel panels
- **1934** Anodised aluminium windows installed at University of Cambridge Library, architect Sir Giles Gilbert Scott
- **1940** Anodised aluminium windows installed at New Bodleian Library, architect Sir Giles Gilbert Scott
- **1949** Unitised aluminium curtain walling by Jean Prouvé for Fédération du Batiment Office, Paris
- **1950s** Pioneering of aluminium curtain walling in USA
- **1950** UN Secretariat Building, New York, clad in aluminium curtain walling, executive architects Harrison & Abramovitz
- **1953** Alcoa Building 'The worlds first aluminum skyscraper', Pittsburgh, by Harrison & Abramovitz
- **1954** Jean Prouvé's Aluminium Centenary Pavilion is built to celebrate the 100th anniversary of the industrial production of aluminium in France
- **1957** Jean Prouvé designs extruded aluminium curtain walling for CIMT

Fig 1.4 Timeline of the history of aluminium up to the Jet Age

Fig 1.5 Large format aluminium alloy extrusions in Constellium's plant, Singen, Germany

Flexible

One of the primary reasons for the wide spread adoption of aluminium to make the components of human life – from Apple laptops to curtain walling, is its inherent flexibility, not necessarily its physical flexibility. In some applications its stiffness, provided by a high strength to weight ratio, is of vital importance. In many applications it is the flexibility of designing with aluminium that is key. Aluminium extrusions can adopt complex forms without additional costs, as discussed in Chapter 2, details can be built in that facilitate fabrication process – such a screw groove that ensures fixing remain correctly placed or screw ports that enable aluminium sections to be fixed together. Aluminium can be cast, extruded, press-moulded and roll-formed. It can be readily drilled, machined, laser cut, waterjet cut and bonded or welded. It accepts finishes well, offering long term durability, as reviewed in TSC Report 2: *Aluminium and Durability*.[19]

Fig 1.6 The Millennium Dome (O2) designed by Richard Rogers + Partners and completed in 1999 may at first sight only use aluminium louvres to clad the services pods, however the PTFE is secured in maintainable segments by about 24 kilometres of large aluminium extrusions

Today, Jaguar Land Rover (JLR) primarily uses aluminium to produce lightweight yet robust cars. In 1948, Sir William Lyons, the founder and chief designer of Jaguar cars, decided that despite post-Second World War austerity the world needed an all new open-topped sports car, which he inteded to exhibit at that summer's London Motor Show. The new model used sheet aluminium for the body of the car, primarily for the speed of production. A colleague, Bob Knight, describes Sir William Lyons 'could not draw to save his life; he could only style in metal ... Lyons would walk down to the styling shop and start waving his hands in the air to show what he envisaged. A sheet metal worker would be with him, watching all this, and would set about trying to create what he thought was wanted. It might have been unconventional but it was brilliant and very successful.'[20] In 1948, Jaguar produced the XK120; Bob Knight states that 'Lyons did the XK120 in no time: it took only six weeks to design and build the aluminium prototype.'[21] The XK120 was so successful Jaguar invested in tooling to press the body components from steel. Of the surviving XK120 cars the most valuable vehicles are the original production run in aluminium.

Fig 1.7 Jaguar XK120 (courtesy of Classic & Sports Car)

The XK120 was produced in an era of Aluminium Pioneers, as discussed in TSC Report 1. An early English example not covered by that report from 1959 is the aluminium cladding of the Turbine House of Bowater-Scott Paper Mill, Northfleet, England, architect Farmer & Dark. Whereas the Climatron, Missouri Botanical Garden, St Louis, USA, designed by Richard Buckminster Fuller and completed in 1960, is discussed in the first TSC Report *Aluminium and Durability*.[22]

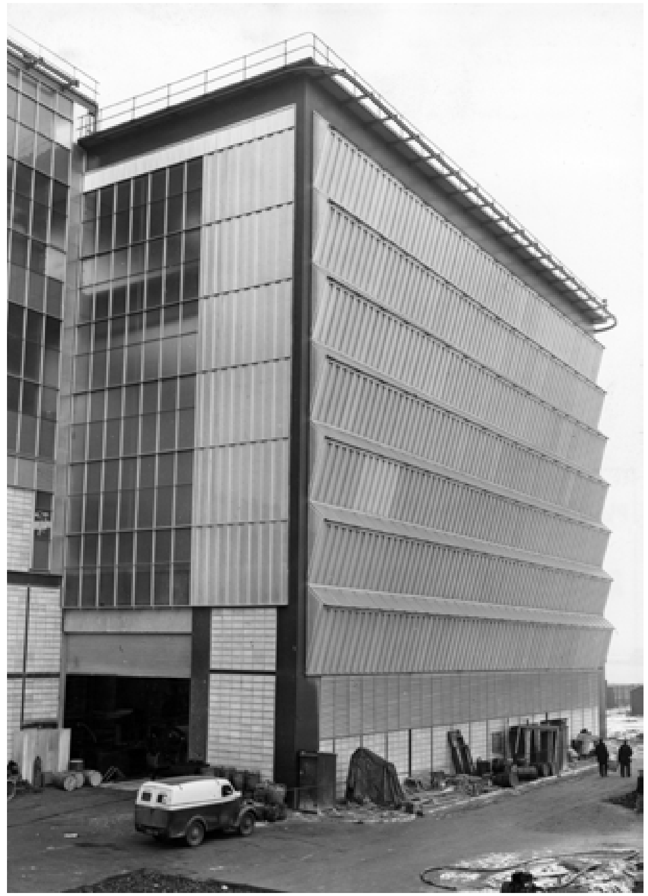


Fig 1.8 Aluminium cladding of the Turbine House of Bowater-Scott Paper Mill, Northfleet, England, Architect Farmer & Dark, 1959

Design flexibility can be experienced in the new top floor of the OXO Tower Wharf, London, completed in 1996, in the form of an unusual combination of solar shading and adaptive architecture, designed by Alex Lifschutz of Lifschutz Davidson Sandilands Architects. The building dates back to the late nineteenth century, becoming the Oxo Tower in 1929, when rebuilt to Art Deco designs by Albert Moore. It is now an exemplar of a mix use refurbishment of an existing Thameside building, with five floors of housing for Coin Street Community Housing Co-op. The lower floors are design studios and specialist retail outlets. The Oxo Tower is topped by a 500-seat restaurant that affords spectacular views of London. The atmosphere in this restaurant is transformed by a soffit of motorised extruded aluminium louvres that appear white in the daytime and midnight blue after dusk. The daytime shading of the generous glazed riverside façade is provided by a further bank of similarly profiled extruded aluminium louvres.

The increasing use of three-dimensional digital design by architects has resulted in an increased use of double curvature in contemporary architecture, which has led manufacturers to develop more flexible means of production, beyond the linear constraints of roll forming, for example. In 2005, Kalzip introduced a variable geometry version of its aluminium standing seam roof sheet, which quite literally leaves the roll forming line to complete its fabrication. The geometric variation per sheet is quite small but the soon builds up in a modular system. Kalzip XT was first used for the aluminium standing seam roof of Spencer Street Station in Melbourne, Australia, architect Grimshaw in 2006.

Fig 1.10 The adaptive aluminium ceiling and solar shading of the restaurant on the top floor of the Oxo Tower Wharf, architect, Lifschutz Davidson Sandilands, 1996

Fig 1.9 The Oxo Tower Wharf, architect Lifschutz Davidson Sandlilands, 1996

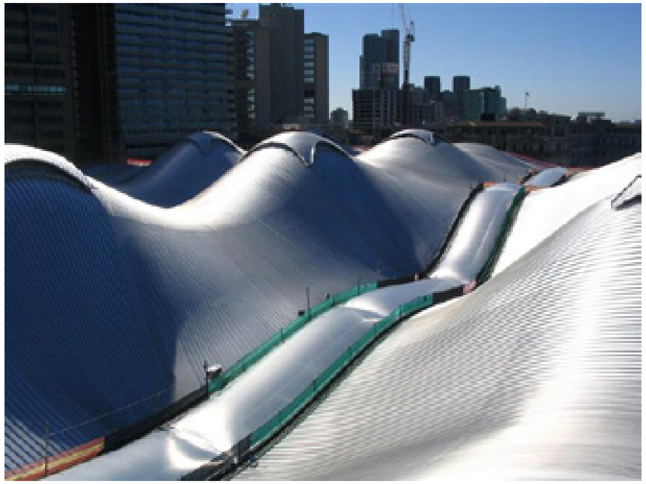


Fig 1.11 Aluminium standing seam roof of Spencer Street Station in Melbourne, Australia, architect Grimshaw, 2006

Chapter 5 *Light and Strong* includes a brief history of the use of aluminium in the assembly of road, rail and pedestrian footbridges. Although this parallels the use of aluminium in architecture, uptake is later and arguably more variable. However there are many more aluminium bridges than suggested by numerous contemporary commentators and academics, as demonstrated in this chapter. The first aluminium bridge deck was installed on Smithfield Street Bridge in Pittsburgh, USA in 1933, almost 40 years later the first use of aluminium in architecture – the ceiling of Church of St Edmund, King and Martyr, Fenny Bentley, Ashbourne, Derbyshire, England in 1895. The earliest extant all-aluminium bridge is the Arvida road bridge, 1950, spanning the Saguenay River at Saguenay–Lac-Saint-Jean in Québec with primary arch spanning 88.4m. Chapter 5 *Light and Strong* includes many examples of more recent and contemporary applications of aluminium alloys in the assembly of bridges from the elegance of the Bridge of Aspiration by WilkinsonEyre, 2003, to the design and fabrication of a rapidly deployable bridge for the Canadian Army by MAADI Group in 2016. The first decades of the twenty-first century reveals a renaissance in all-aluminium

Fig 1.12 Arvida Bridge spanning the Saguenay River at Saguenay–Lac-Saint-Jean in Québec, 1950

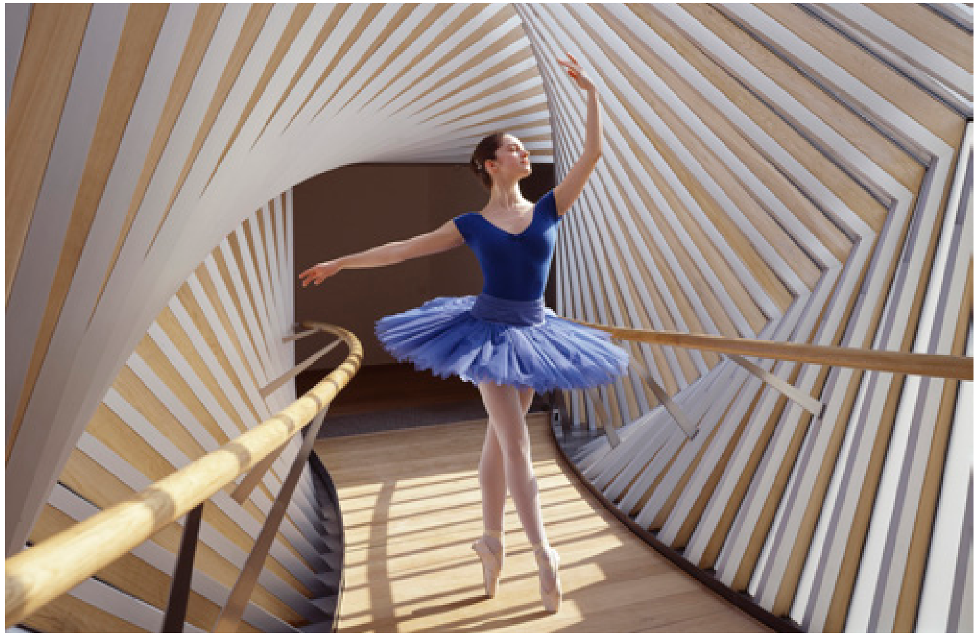


Fig 1.13 Bridge of Aspiration, Covent Garden, London, England, architect WilkinsonEyre, 2003

Fig 1.14 Deployable Military Bridge, Canada, designed and fabricated by MAADI Group, 2016

bridges, and in particular all-aluminium pedestrian bridges, where speed of erection combined with long-life durability, requiring almost no maintenance, is making aluminium the first choice in the specification of this infrastructure. This combination of qualities is also resulting in the specification of aluminium for highly prefabricated buildings such as the Lord's Media Centre by Future Systems, 1996, this and other prefabricated architecture case studies concludes this chapter.

Fig 1.15 Lord's Media Centre by Future Systems, 1999

Chapter 5 *Light and Strong* also features long span roof structures assembled from aluminium alloy sections and in particular de Havilland Comet Test Flight Hangar, Hatfield, England, designed by architect James M. Monro & Son and completed in 1953, with a clear span of over 66m and the 67m clear span all-aluminium roof structure of Ghent Velodrome, Belgium, architect M.J. Tréfois, completed in 1964. The 53m-span aluminium structure of the Climatron, designed by Richard Buckminster Fuller and completed in 1960, also reveals the potential of long span aluminium roof structures, where the high strength to weight ratio of aluminium alloys is particularly important, as the weight of a roof structure first has to sustain the load of its self-weight and the loads of substructure, cladding and waterproofing, combined with the imposed loads of wind and snow.

Fig 1.16 de Havilland Comet Test Flight Hangar, Hatfield, England, architect James M. Monro & Son, 1953

Fig 1.17 Aluminium structure of the Climatron, Missouri Botanical Garden, St Louis, USA, designed by Richard Buckminster Fuller, 1960

Fig 1.18 Ghent Velodrome, Belgium, architect M.J. Tréfois, 1964, under construction

Noting the success of aluminium standing seam roofing discussed in TSC Report 1 *Aluminium and Durability* and in Chapter 9 of this report, which can be supported by substrate of aluminium decking, it is surprising that there are not more all-aluminium roof structures in medium to long span applications, although Chapter 5 does provide some other examples. T. Höglund, P. Tindall and Haig Gulvanessian the authors of *Designers' Guide to Eurocode 9: Design of Aluminium Structures: EN 1999-1-1 and -1-4 observe:* 'Aluminium is not as widely used for structural applications as it could be, partly as a result of misconceptions about material strength and durability but largely because engineers and designers have not been taught how to use it - additional specific design checks are needed.[23] Alexandre de Chevrotière, CEO of the MAADI Group, observes that 'the Aluminum Association regularly updates and maintains the *Aluminum Design Manual*.'[24] There is a very strong potential for affordable, durable and elegant all-aluminium roof structures, decking and cladding in the twenty-first century, in parallel to the growing uptake of all-aluminium bridges.

Design Space

Common to all the case studies in *Aluminium: Flexible and Light* is the commitment to design excellence, demonstrated by highly skillful multidisciplinary design teams. Chris Wilkinson, founding partner of WilkinsonEyre believes that 'good design comes from a combination of technical expertise, a high level of visual awareness and creative skills combined with confidence'.[25] To create well-designed architecture there are three prerequisites: the opportunity, time to develop the ideas and the freedom or space to develop ideas, in essence design space. Charles Eames' diagram of the process of designing emphasise the social role of design, which was first exhibited in 1969, it shows the area which represents the interests of the design office and a much more free-form shape representing the genuine interests of the client.[26] A wider field forms the 'concerns of society as a whole', concluding that the central zone is the 'area of overlapping interest and concern that designers can work with conviction and enthusiasm'. Thus, Eames clearly articulates the responsibility of an architect to his or her client and to society in general. Perceptively Eames goes on to note that 'putting more than one client in the model builds the relationship – in a positive and constructive way.'[27]

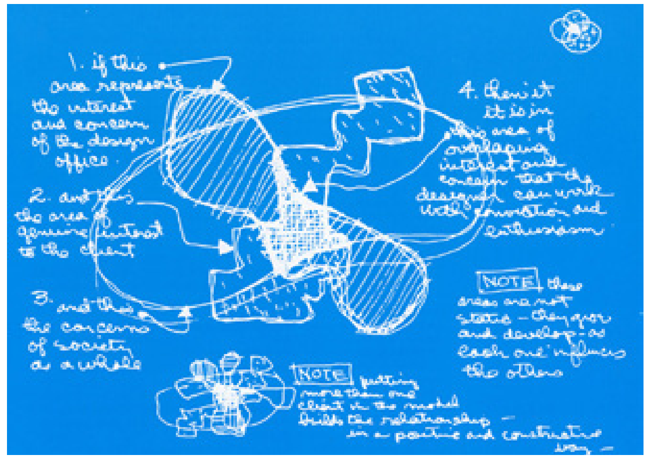


Fig 1.19 The design process as described by Charles Eames in 1969

Beyond recognising the social role of architecture and design – a purposefulness, all the case studies in this report demonstrate that integrated design is where a wide range of factors are synthesised to form a significant work, including the informed selection of materials. A holistic approach to the design and realisation of architecture and infrastructure is illustrated in many of the case studies, from Renzo Piano's High Museum Expansion in Atlanta to Soho Galaxy in Beijing, designed by Zaha Hadid Architects.

Fig 1.20 Solar shading prototype for the High Museum Expansion, designed by Renzo Piano Building Workshop in collaboration with Arup

Even in post digital design practice, the prototype remains a vital means of collaboration and design development.[28]

Many of the case studies also demonstrate collaboration within the design team between diverse experts, often, but not always led by architects, and now increasingly facilitated by the use of three dimensional digital **building information models** [BIM]. The collaborative process extends into the realisation of architecture and infrastructure via collaboration with industry, manufacturers and main contractors.

Fig 1.21 The Loblolly House Prototype being assembled at Prototyping Architecture, Nottingham

Light

In the title of this report light is primarily used with two meanings, firstly the literal quality of lightness, providing high performance components, such as windows or curtain walling that are light in weight. The second meaning is visually light and slender. Today aluminium alloy 6061 is often used in the extrusion of sections for windows or curtain walling because it is readily extrudable and offers a good strength to weight ratio. A cubic centimetre, about the size of a sugar cube, of 6061 aluminium alloy weighs just 2.7grams (lighter than the weight a typical white sugar cube of 4grams) and this alloy has a Young's Modulus of between 70–80kN/mm². Other aluminium alloys including the 7000s alloys offer even greater stiffness, an even better strength to weight ratio.

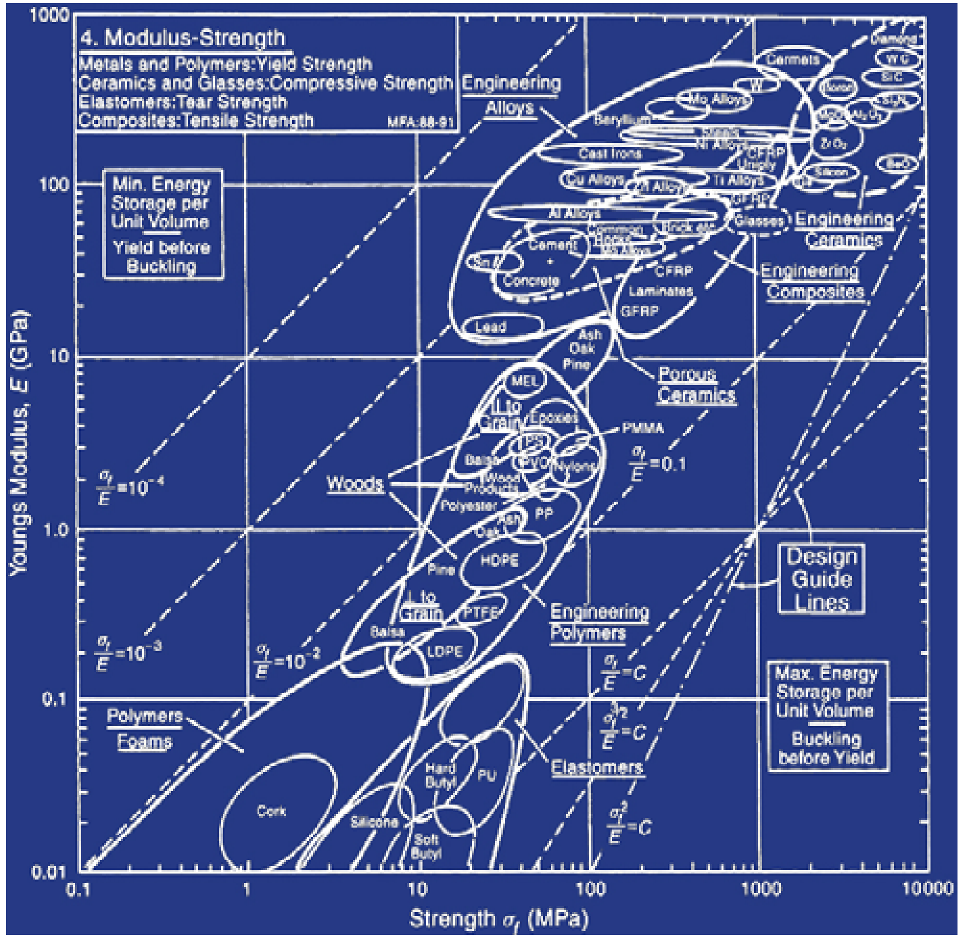


Fig 1.22 Young's Modulus plotted against strength for a wide range of materials (chart courtesy of M.F. Ashby from Materials Selection and Mechanical Design, 1987)

The high strength to weight ratio of aluminium alloys produces building components that use less energy to transport, less energy to install and less energy to disassemble. Producing components that can safely be handled by people following contemporary health and safety guidance, as discussed in Chapter 5 *Light and Strong*.[29]

The second way in which light is used in the report is the role of aluminium in forming window, glazing and curtain walling sections that are slender and strong. When combined with contemporary glazing technology it is possible to fabricate very large windows, offering excellent daylight and the amenity of views and visual links. The careful use of daylight can result in major energy and carbon savings, once the building envelope is well insulated and combined with a low air infiltration rate. This is explored in Chapter 3 *Solar Shading,* for example in the design of the Yale Sculpture Building and Gallery by KieranTimberlake. The performance of window and glazing sections is reviewed in Chapter 6 *Light and Slender* with key case studies, the Dun Laoghaire Lexicon Library and Cultural Centre, designed by Carr Cotter & Naessens Architects and the Eden Project by Grimshaw Architects.

The qualities of lightness and slenderness are often combined in architecture, where lightness can be interpreted in a literal sense - achieving the best possible result with as little material as possible. As in 'how much does your building weigh Mr Foster?' It can also describe the lightness of an interior the lightness of the framing and structural elements and the bathing of an interior with soft and gentle light. Combined in the hand of a skilful architect, lightness

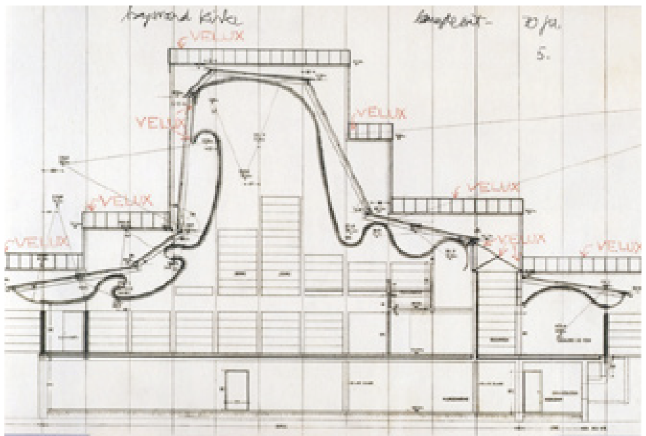


Fig 1.23 Jørn Utzon's sectional drawing of Bagsværd Church

Fig 1.24 Bagsværd Church, designed by Jørn Utzon, 1976

becomes transformative and gains a metaphorical quality – a central aspiration of Modernist architects including Alvar Aalto, Jørn Utzon and Ludwig Mies van der Rohe.

Wim Hafkamp, contributing an essay in *Lightness,* edited by Adriaan Beukers and Ed van Hinte, observes: 'Lightness is not a word that appears in economic literature.'[30] He cites the American economist Herman Daly in 'doing more (function fulfilment) with less (physical material), or in the terminology of Daly: the added value rises, while that to which material value added decreases.'[31] Hafkamp draws 'a distinction between services-in-the-product (design, communication, function fulfilment), services-pertaining-to the product (product/service combinations) and services without products (business/personal services). Light structures are a perfect example of the first category, services-in-the-product: both in the design and the production of new high-value materials and the design of the structure itself. A lot of added value to not many kilos.' [32]

As demonstrated throughout this report, from the products of Dieter Rams to bridges of WilkinsonEyre lightweight materials are a vital part of sustainability. Hafkamp writes 'looking at it from the angle of sustainable economic development, lightweight materials and structures are of incredible importance.'[33] In the words of Dieter Rams 'Less, but better – because it concentrates on the essential aspects, and the products are not burdened with non-essentials. Back to purity, back to simplicity!' [34]

Lightweighting

Although not the most elegant of English words, lightweighting is of vital importance in the design and realisation of trains, planes and automobiles and key to enabling spacecraft to escape the gravitational pull of planet Earth. In automobile design, the relationship between the saving of one kg of mass and the resultant saving in CO_2 is well understood, even if the mathematical models are complex. Modelling by IAI reveals that 'one kg of aluminium replacing heavier materials in a car or light truck can save a net 20 kg of CO_2 over the life of the vehicle or up to 80 kg of CO_2 in trains.'[35] Furthermore 'the use of aluminium in car structures allows for greater material thickness and rigidity, improving overall safety performance, and ensuring efficient crash energy absorption without adding weight. Lighter vehicles also have reduced braking distances and lower crash forces.'[36]

Fig 1.25 Devinci Cycles, Quebec based manufacturers of aluminium framed city bikes

Architecture and the Built Environment can learn from the significant Research and Development investment in other industries, for example Jaguar Land Rover spend over £900,000,000 annually on R&D, (2011-2012).[37] In particular, the realms of science, digital technology, transportation and aerospace. One limitation experienced in architecture is that it remains fundamentally linked to the human scale of spatial enclosure. Architects and engineers can learn from other industries - it is obsolete to think of technology as being specific to a particular industry. The essence of technological development is not high or low technology. Technological development is characterised by the layering of technologies. One technology informing another, for example Perspex or Plexiglas is manufactured on acid etched glass. An iPhone or smart phone can incorporate up to 10,000 patented items.[38]

The all-aluminium alloy body shell of the Range Rover 2013 is an excellent example of focused Research and Development expertise and teamwork. Jaguar Land Rover (JLR) has built on its own past experience of developing all-aluminium body structures, including the XJ Jaguar, the first volume-production car to use an all-aluminium alloy monocoque chassis, in 2003. The Range Rover 2013 has been designed and fabricated with an all-aluminium alloy body. This is JLR's third generation of lightweight body architecture.

Fig 1.26 A Nottingham NET Citadis 302 tram built by Alstrom in 2014, with an all aluminium body

Fig 1.27 XJ Jaguar, the first volume-production car to use an all aluminium monocoque chassis

Designed and engineered in Britain, the Range Rover 2013 is the world's first SUV with a lightweight all-aluminium alloy body. It was launched by JLR in September 2012 and exhibited in Nottingham, as part of *Prototyping Architecture* Exhibition, from October of that year. The all-new Range Rover achieves a weight saving of 420kg when compared with the previous model, which is the equivalent to the weight of five average adults. This third generation of JLR's lightweight vehicle architecture, combined with improved aerodynamics, results in an increase in fuel efficiency of over 20 per cent, significantly reducing the carbon footprint of owning a SUV. The development of the new Range Rover required significant R&D investment by JLR. The use of virtual testing reduced the R&D carbon footprint by 320kg of CO_2 by saving 750 miles of testing, however, over 300 physical prototypes were produced in the development of the new Range Rover.[39]

There is a competitive EU road map for carbon reduction in the European car industry, Mark White observes 'in Europe there is now an agreed [car] industry roadmap to reduce emissions by 3% per year over the next 20 years'.[40] This is undertaken collaboratively with outcomes being shared by the major car manufacturers but is competitive since the methods used to generate the achieved

Fig 1.28 The Range Rover 2013 – a mimetic design that is 420kg lighter than the previous model

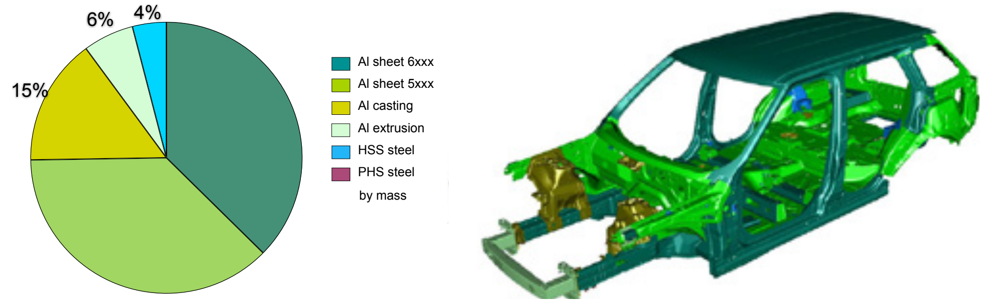


Fig 1.29 The composition of the aluminium alloy body shell of the Range Rover 2013

Fig 1.30 A prototype all aluminium alloy body shell of the Range Rover 2013 at Rover 2012 Prototyping Architecture, Nottingham

savings remain specific to each manufacturer. Perhaps this is a better model for the construction industry rather than the narrow prescriptions of Code for Sustainable Homes or Passivhaus standards.[41] Thus the construction industry has the potential to learn from the processes and products of other industries.

For many people in the automotive and aluminium industry, the key step change was the production of the all-aluminium alloy bodied 2015 Ford F-150 Pick-up, which began production in November 2014 at its Dearborn Truck Plant.[42] The F-150 is the first mass market all-aluminium vehicle, as well as being an iconic pick-up truck. During the first 11 months of 2015, Ford sold 695,143 F-150 Pick-ups in North America, the best seller in its truck division.[43] The body is primarily formed of 5000s aluminium alloy, which American marketers insist on calling military grade aluminium, when the same series is used to make drink cans!

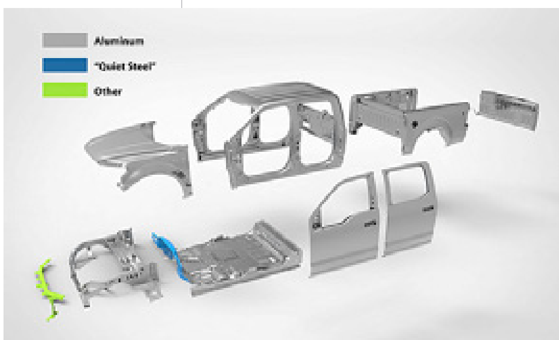


Fig 1.31 The composition of the aluminium alloy body of the 2015 Ford F-150

The most dramatic demonstration of lightweighting using aluminium is arguably the design of the Gossamer Condor in the 1970s, with the aim of achieving human powered flight and winning the Kremer Prize.

Gossamer Condor and the Kremer Prize

The Kremer Prize for the first successful human powered flight around a measured figure of eight course, with turning points at least one-half mile apart, was established by Henry Kremer and the Royal Aeronautical Society in November 1959.[44] Kremer was a talented engineer and entrepreneur who held patents for the plywood manufacturing processes used in the assembly of the de Havilland Mosquito fighter-bomber (1941).

In the summer of 1976, inspired by the Wright Brothers, soaring birds and the relatively new invention of hang gliders, Paul MacCready (a champion glider pilot with a PhD in aeronautics from Cal Tech) decided to attempt human-powered flight with the aim of winning the £50,000 Kremer Prize. By the end of August he had made two balsa wood models of his design for the Gossamer Condor, which were not very stable in flight. He sought advice from Dr Peter Lissaman, another aeronautical graduate of Cal Tech who had worked at the Bristol Aeroplane Company (producers of AIROH, aluminium prefabricated houses).[45] Based on Lissaman's input a larger canard was fitted to the second model and it flew successfully. This was beginning of the Gossamer Condor expert team of volunteers.

The first prototype took 10 days to assemble, in a hangar at Mojave Airport in early September 1976. [46] The Gossamer Condor was designed, built and tested by team of volunteers who brought a diverse range of skills to the project. Paul MacCready literally got 'a little help from his friends', to quote Paul McCartney and John Lennon, many with experience of making and flying model aircraft, even making and flying full-scale hand gliders. Although assembled in 1976, the Gossamer Condor truly deserves the term air-*craft*, with the making skills evident in the iterative process of design, making, testing, failing, crashing, re-design, making, reassembly and further testing. Throughout this process, Gossamer Condor remained an experimental prototype and Morton Grosser observed that this human powered aircraft 'even looked like a strange sort of giant model'.[47]

Paul MacCready considered **polymer composites** for the structure of Gossamer Condor and sought advice from Hans Neubert, who, to his surprise, recommended aluminium alloy tubing, chemically milled to reduce its weight.[48] Paul MacCready 'quickly agreed that aluminium had some convincing advantages, including well-known mechanical properties, ready availability, and relatively low cost.'[49]

The first version of Gossamer Condor, assembled at Mojave Airport, had a wing-span of 29.26m (96'), swept back at 9°, with a wing cord of 2.921m (9'7") and it weighed just 38.1kg (84lb). The components of Gossamer Condor were lofted, drawn at full size on the hangar floor, a design process that dates back millennia in shipbuilding. Paul MacCready believed that any moderately skilled craftsman could build a Gossamer Condor, 'with an outlay of about $6oo for materials'.[50]

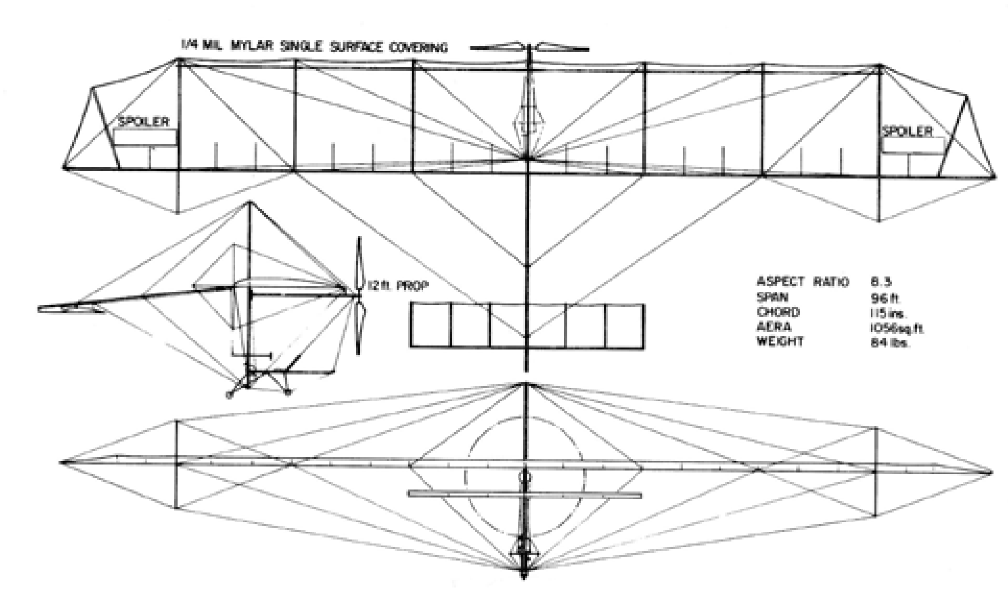


Fig 1.32 Plan and elevations of the first Gossamer Condor, as assembled and flown at Mojave Airport

Wing spars were assembled from eight lengths of 6061-T6 heat-treated 50.8mm (½″) aluminium alloy tubing in 3.66m lengths (12′), with an original wall thickness of 0.89mm. After chemical milling, the spars had a section thickness of 0.5mm (0.020″) at the centre to 0.38mm (0.015″) at the wing tips. Morton Grosser thought the following to be evocative analogy for this component: 'A 29.26m-(95′)-long aluminium beer can would be a close approximation of the size, shape, strength, and weight of the complete spar. It could be squashed between your thumb and index finger and it was, more than once.'[51] Other frame components were milled to 0.5mm (0.02″) and ranged in diameter from 6.35 mm (¼″) to 50.8mm (2″), each wing has seven tubular ribs. The aluminium tubing is primarily joined by aluminium sheet gussets, and the structure is stabilised by steel piano wire that ranges from 0.56mm (0.022″) to 0.89mm (¼″) in diameter. The aircraft is skinned in Mylar film supplied by DuPont.[52]

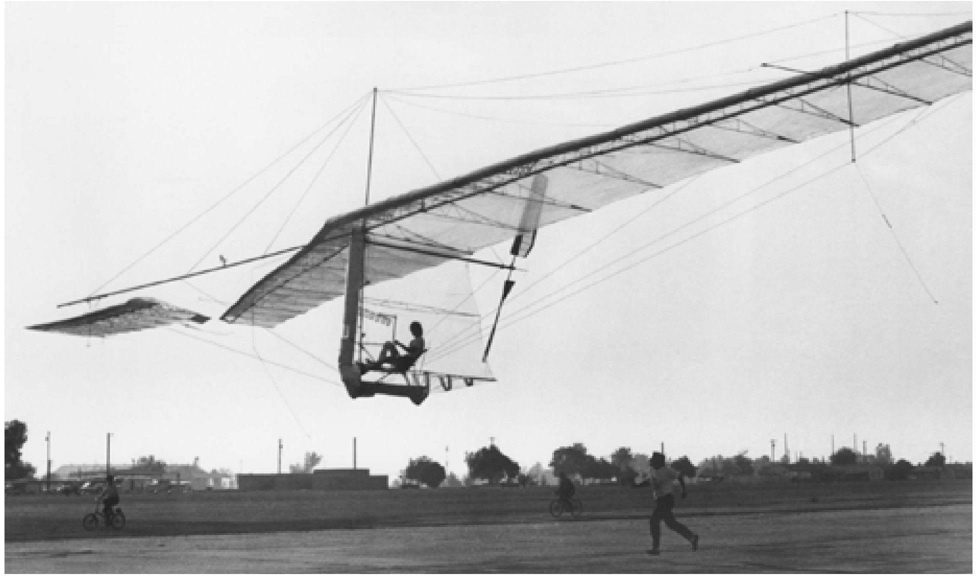


Fig 1.33 A test flight of the Gossamer Condor

Morton Grosser observed the design of Gossamer Condor is: 'Like any object that must conform to the laws of nature, an airplane is a set of interlocking compromises.'[53] This is an essential quality of design, including architecture and infrastructure, the need to balance a range of factors, yet produce a design that achieves the overall goals of the design team with purpose and clarity.

Paul MacCready thought that the design assembly and testing of Gossamer Condor would take six weeks, it actually took a year.[54] In early 1977, due to frustration with the weather and especially relatively high wind speeds at Mojave Airport, the team relocated to the calmer environment of Shafter Airport, which is north west of Los Angeles in the San Joaquin Valley.[55]

This move coincided with the decision to totally rebuild the aircraft, although a significant step change, this was part of evolutionary and iterative processes of design, assembly and testing. From the first prototype to the prize-winning aeroplane 'there were 12 more or less discernable "marks"', recorded by Morton Grosser.[56] A key to the success of Gossamer Condor was this experimental process, facilitated by robust and accessible technology that could be readily assembled repaired and reassembled. On the 6 March 1977 the longest human flight in history was achieved by Gossamer Condor – 5 minutes and 5 seconds.[57] The process of trial and assessment would continue until late August of that year. At 7.30 AM on Tuesday 23 August 1977, on the measured figure of eight course, with a total flying time of 7 minutes and 27.5 seconds and covering a distance of 1.35 miles, the Gossamer Condor won the Kremer Prize for the first human powered flight.[58]

Fig 1.34 The design development of the Gossamer Condor was a process of iterative experiments, flight testing and further improvements

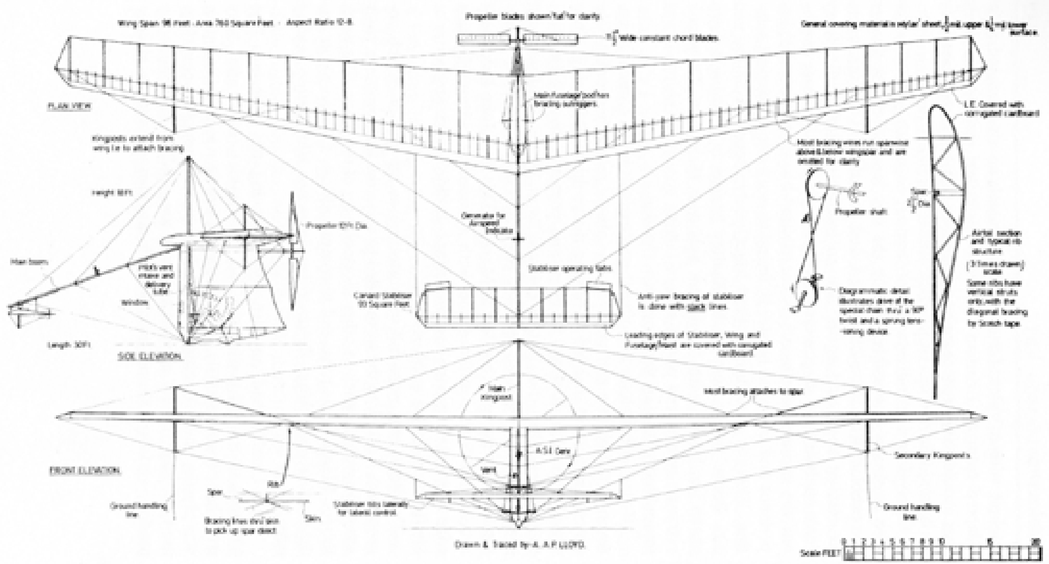


Fig 1.35 Plan and elevations of the final design of the Gossamer Condor, as assembled and flown at Shafter Airport

Fig 1.36 The flight of the Gossamer Condor was witnessed by an official observer for the Kremer Prize, with increasing numbers of well wishers as news got out of the remarkable achievements of this team of volunteers

Vitally important to the success of this project was its situation, in terms of the social and technological potential of California. Although famous for Hollywood, it is one the centres of high technology industries in the United States of America. For example the team could readily have aluminium tubing chemically milled – chemically reduced in thickness. Aerochem of Orange, California undertook this work. This broad technological potential was made accessible by the pool of highly qualified talented people working in the region.

In London, on Wednesday 30 November 1977, Prince Charles presented Paul MacCready and representatives of his team with the Kremer Prize and a cheque for £50,000. Prince Charles observed: 'For hundreds of years, if not thousands, the idea of manpowered flight has inspired countless brave men to design strange contraptions with which to rival birds.'[59] He continued: 'Long may such dedicated enthusiast and craftsmen continue to inspire us and fire our imaginations!'[60]

The prize-winning aeroplane was purchased by the Smithsonian Institute for the National Air and Space Museum in Washington DC, where it is still on exhibition. It was transported from California in a truck and trailer that weighed 11.5 tonnes, with the part dissembled Gossamer Condor suspended in the trailer weighing only 31.8 kg. [61]

Paul MacCready and his team went on to successfully cross the English Channel, or la Manche, on 12 June 1979 with a human powered aircraft, the Gossamer Albatross, which in essence was a refined and even lighter version of the final version of Gossamer Condor.[62]

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Flexible: Fabrication Processes

Introduction

Aluminium is a light and highly **corrosion** resistant metal and is, in itself, unchanged since it was identified by Sir Humphry Davy in 1808, as a constituent of alumina.[1] Aluminium was first produced in significant qualities by Hans Christian Ørsted in 1825, and in purer form by Friedrich Wöhler in 1827. The chemical symbol for aluminium is Al, and it has an atomic number of 13. Aluminium, however, is primarily used to form **alloys**, with small quantities of other metals or elements. The alloys for many architectural applications utilise the addition of magnesium and silicon to improve the mechanical properties of the aluminium. The commonly available alloys are classified in BS EN 485 and BS EN 755 and have very well defined performance characteristics. The internationally recognised 4-figure code used to describe aluminium alloys defines the content of the alloy. The application of aluminium in construction, and even the material itself, continues to be developed as new technical discoveries are made and exploited. The development of new alloys can offer increased performance and workability.

The Aluminum Association advise that the process 'from registering a new alloy to assigning a new designation, takes between 60 to 90 days. When the current system was originally developed in 1954, the list included 75 unique chemical compositions. Today, there are more than 530 registered active compositions and that number continues to grow. That underscores how versatile and ubiquitous aluminum has become in our modern world.'[2]

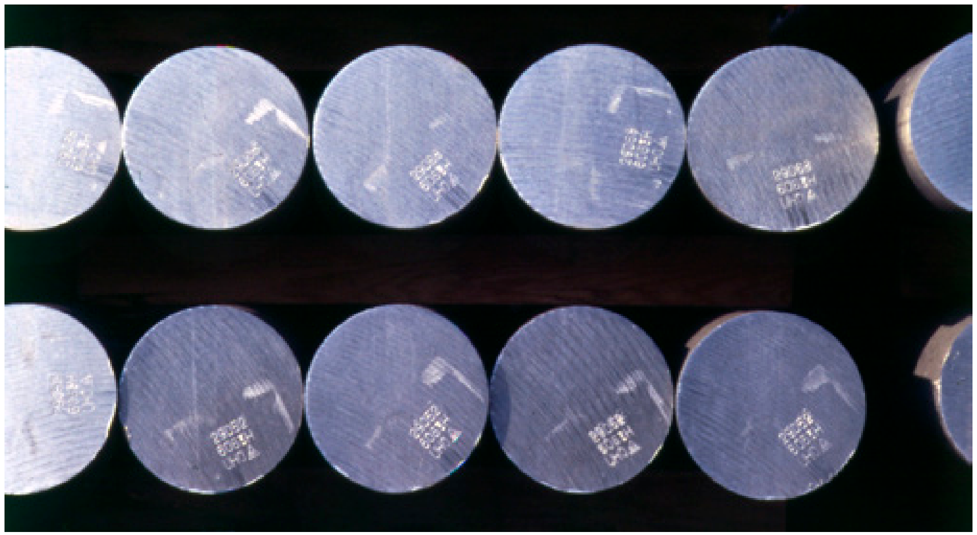


Fig 2.1 Billets of 6063H aluminium alloy

Aluminium Alloys

The internationally agreed definition of an 'aluminium alloy is aluminium which contains alloying elements, where aluminium predominates by mass over each of the other elements and where the aluminium content is not greater than 99%.'[3] When alloying other elements, the aluminium must be liquid and thoroughly mixed. A good introduction to the wide range of specifiable alloys and their properties can be found in, *Properties of Aluminium and its Alloys* (2014), which is available from the Aluminium Federation.[4] It is the proportion of other metals and elements, such as copper, magnesium and silicon, which modify the performance of the resulting alloy. A useful online resource is provided by Aluminum Association via www.aluminum.org. [5]

The global aluminium industry has harmonised the terminology used, with the exception that the North American aluminium industry use its vernacular English noun for this metal – aluminum. Aluminium alloys are set out in *International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys*[1] issued by the Aluminum Association of the USA. This is a four-digit system in which the first digit, from 1-9, indicates the principal alloying element. This system is used in British and European Standards for example BS EN 575:1996, *Aluminium and aluminium alloys.*

1000 series alloys are 99 per cent aluminium or higher purity. Common applications include electrical power lines, food packaging and foils. 1350 alloy is often used for electrical applications and 1100 alloy for food packaging trays and foils for vapour check layers and vapour barriers. Aluminium foils were first produced in Kreuzlingen, Switzerland in 1910.[6]

Fig 2.2 1100 aluminium alloy food tray, having been washed prior to recycling

Fig 2.3 The Boeing 247D is regarded as the first 2000 series aluminium alloy semi-monocoque airliner, 1933

Copper is the primary element added to 2000 series alloys, but typically not more than 5 per cent. 2000 series alloys can be strengthened by heat-treating, which is discussed below. This alloy series provides toughness and high strength, however the presence of copper limits its corrosion resistance and therefore components should either be protected by a coating system or cladding with a high purity aluminium alloy. 2024 alloy with 3.8–4.9 per cent copper is often used in aircraft assemblies. The first aircraft built from this series of aluminium alloys was the Boeing 247D, introduced in 1933.[7]

Manganese is the primary element added to 3000 series alloys, with typically between 0.3 and 1.5 per cent, and magnesium is also used between 0.2 to 8 per cent, depending on the specific alloy. 3000 series alloys offer reasonable strength and are readily worked. The body of an aluminium drinks can is typically formed from 3004 alloy and the ends are made from 5182 alloy. Incidentally, Coca-Cola was first produced in 1886, the same year that Hall–Héroult process was effectively simultaneously invented in the USA by Charles Martin Hall and in France by Paul Héroult.

Silicon is the primary element added In 4000 series alloys, which lowers the melting point of the aluminium. In 4043 alloy, between 4.5 and 6 per cent silicone is used. Typically produced as a wire 4043 is used for welding 6000 series components in automotive and structural applications.

Fig 2.4 An aluminium Coke can, with 3004 aluminium alloy deep drawn body and 5182 alloy cap

Fig 2.5 Audi's welded aluminium space frame of the Audi A8

Fig 2.6 Welded aluminium pedestrian bridge by MAADI Group

In 5000 series alloys, the primary element added is magnesium. Between 4 and 4.9 per cent magnesium is used in 5083 alloy. The Aluminum Association advise that 5000 series alloys offer 'moderate to high strength characteristics, as well as good weldability and resistance to corrosion in the marine environment.'[8] 5000 series alloys are often used for sheet products. 5005 anodises well and is used in architectural applications, 5083 in marine environments and as noted above, 5182 is used to make drink can lids.

In 6000 series alloys, the primary elements added are magnesium and silicon, which combine to form magnesium-silicide within the alloy. This series is very versatile offering excellent corrosion resistance, good strength, are **heat treatable**, highly formable and weldable. 6000 series alloys are readily extruded and are often used in structural applications, as shown in the bridge case studies in Chapter 5, and for relatively complex the sections used to fabricate windows and curtain walling. 6063 anodises well and is the most commonly used alloy. 6082 has two-thirds the tensile strength of steel, however, this alloy has variable grain structure, which can be visible on the surface of the components after anodising. If appearance is critical, it may be necessary to brighten the section by manual or electrolytic polishing before anodising. Sapa has developed a new 6000s alloy for high strength applications in automobile design. It has been researched and developed as an alternative to 7000s alloys, which are more difficult to extrude and relatively more expensive. The Sapa's test shows that the new alloy has a yield strength above 350 MPa and 10 per cent elongation. This alloy will be available to automotive producers in 2017.[9]

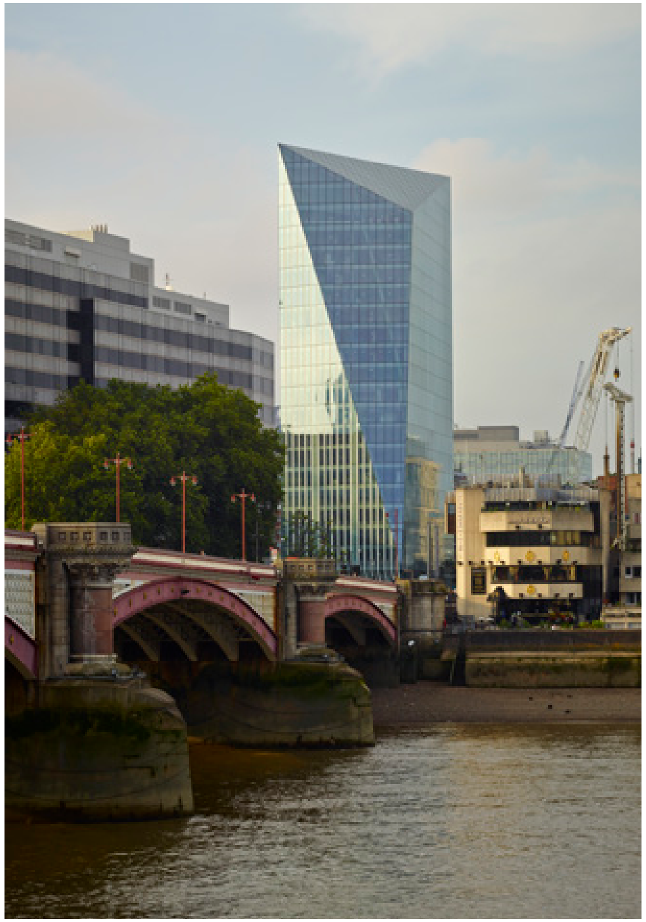


Fig 2.7 Silicone bonded aluminium framed curtain walling of 240 Blackfriars, designed by architect Allford Hall Monaghan Morris

Fig 2.8 [above] Schüco FWS 35 PD, tripple glazed curtain walling using 6000 alloys

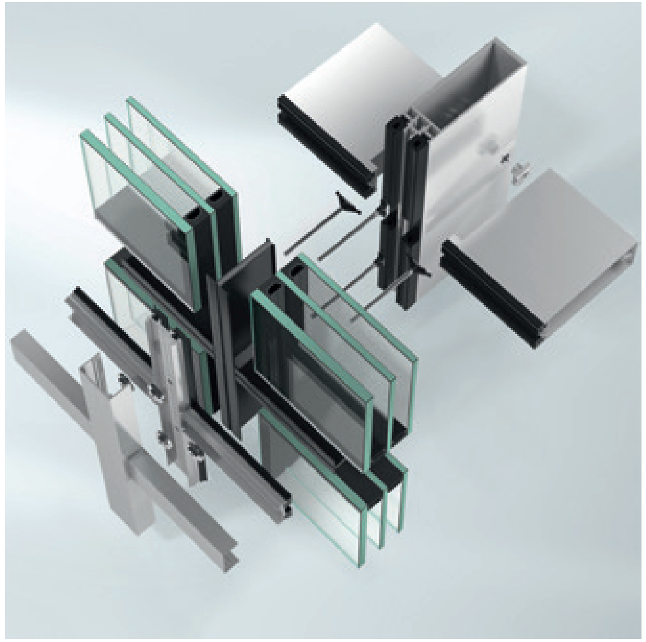


Fig 2.9 [right] Components of the Schüco FWS 35 PD

Fig 2.10 The case of Apple's iPhone 6s is made from a new aluminium alloy in the 7000 series

7000 series alloys utilise zinc, often in combination with magnesium, copper and chromium, these alloys are heat treatable and offer high strength. 7050 alloy comprises 5.1 to 6.4 per cent zinc, with 2.1 to 2.9 per cent magnesium, 1.2 to 2.0 per cent copper and 0.1 to 0.25 per cent chromium. Manganese, silicon, iron and nickel are also present in this alloy.[10] 7050 and 7075 alloys are widely used by aircraft industries 7000 series were often known as aerospace grades. 7000 alloys are increasingly being used in bicycle manufacture, and the exclusive association with aerospace is diminishing, as other relevant lightweight applications are found, which includes Apple iPhones. Apple describes the case of its iPhone 6s as a new aluminium alloy in the 7000 series.[11] 7005 alloy is used to extrude the weldable sections of lightweight yet stiff mountain bikes.

Fig 2.11 The author's twenty year old Marin mountain bike with a welded 7005 aluminium alloy frame and new British leather saddle

8000 series aluminium alloys use a diversity of principal alloying elements. For example in 8001 alloy the principal alloying element is nickel. It is zinc for 8007 alloy, iron-vanadium for 8009 and 8022 alloys, cerium for 8019 alloy, tin for 8081 and 8280 alloys, and lithium for 8024 alloy. For 8011 alloy iron-silicon is the principal alloying elements. Typical uses of 8000 series alloys include:

- 8001 alloy is used for corrosion resistance;
- 8081 and 8280 alloys are used to make bearings;
- 8024 alloy is typically used in aerospace applications; and
- 8011 alloy is used to make heat exchangers.

9000 series is being held in reserve for future alloys of aluminium.

Fig 2.12 Advanced aluminium alloys are used in the wings of Airbus A380 jetliner, Paris Air Show, 2015

Aluminium alloys can be placed in two groups, heat-treatable alloys and non heat-treatable alloys. The heat-treatable alloys are:

- 2000 series;
- 6000 series; and
- 7000 series.

Non heat-treatable alloys are:

- 3000 series;
- 4000 series; and
- 5000 series.

The Aluminum Association describe the process of heat-treating alloys as 'strengthened by solution heat-treating, where the solid, alloyed metal is heated to a specific point. Next the alloy elements (solute) are homogenously distributed, forming a solid solution. The metal is subsequently quenched, or rapidly cooled, freezing the solute atoms in place. These atoms consequently combine at room temperature (natural aging), or in a low-temperature furnace (artificial aging) creating a finely-distributed precipitate,' and thus an aluminium meeting the required performance.[12] Whereas non heat-treatable alloys are strengthened through **cold working**, which occurs during rolling or forging building, up dislocations and vacancies in the structure, inhibiting movement of atoms relative to each other increases the strength of the alloy.

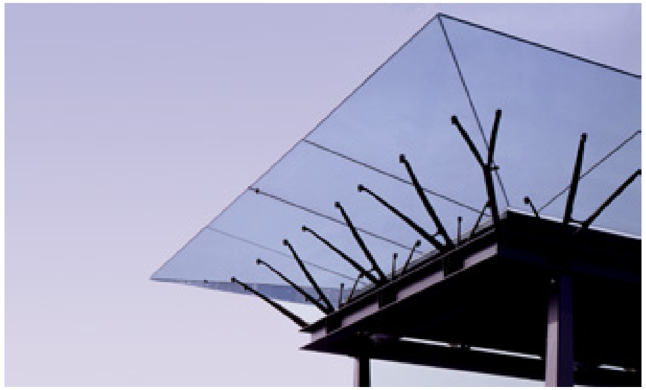


Fig 2.13 Aluminium Bronze castings supporting the toughened glass canopy of the Stoa of Enschede Transport Interchange, designed by Brookes Stacey Randal with IAA Architecten

Casting alloys are designated by the prefix LM in BS EN 1706:2010, for example LM2 is an alloy of aluminium, silicon and copper. Alloys for casting can have a high level of silicon. These will have a tendency to turn dark grey or black when anodised, which may cause some difficulties if a constant colour match between extruded and cast sections is required, in such cases polyester powder coating may prove a good option. The chapter on Cast Aluminium Components in TSC Report 2: *Aluminium Recycling and Recyclability* showed that there is a much wider uptake of cast aluminium components in architecture than many commentators expected. Therefore if you are interested in specifying a cast aluminium component please refer to this earlier report.[13]

Fig 2.14 The disassembled Aluminium Centenary Pavilion components being stored at Marquette-lez Lille

Fig 2.15 The Ljubljana Television Centre, Slovenia, used horizontally cast aluminium cladding panels in 1974, architect France Rihtar in collaboration with Branko Kraševac

Fig 2.16 Die cast aluminium brise soleil of the curtain walling of the Hongkong and Shanghai Bank Headquarters, Foster Associates, 1986

Fig 2.17 Cast aluminium shells of the solar shading at the Nasher Sculpture Center, designed by Renzo Piano Building Workshop, 2003

Fig 2.18 Heelis, The National Trust Headquarters, designed by Feilden Clegg Bradley Studios, 2005

Welding of aluminium is now commonly used as a means of jointing sections and can be successfully carried out on site, although the controlled conditions of a factory are often preferable to achieve good quality control. For further information on welding aluminium see pages 152 to 155. Where finishing is critical, the specification of the filler metal and the process of welding should be adjusted to accommodate the finishing method. Great care should be taken in the use of welding of components that are going to be anodised. The filler metal used for welding should match the alloy of the parent metal and the component should not contain silicon, if it is to be anodised.

Fig 2.19 Precise yet visible welding of the frame of a Marin mountain bike

The Temper of Aluminium Alloys

A temper is a stable level of mechanical properties produced in a metal or alloy by mechanical or thermal treatment(s). Following the four-digit code of wrought or cast aluminium alloy, a letter followed by numbers designates its temper. F is as fabricated, cold working is H, for example H1 is strain hardened only to obtain the desired strength without supplementary heat treatment. Heat Treatment is designated by T and the basic heat treatments are designated T1 to T9. For example Oil Rig Pedestrian Bridge, designed and fabricated by MAADI Group, a case study in Chapter 5, see pages 372-373, is in part fabricated from 6061-T6 aluminium alloy extrusions. This is a specific 6000 series alloy that has a temper of T6, meaning it was solution heat-treated and then artificially aged. For a complete description of temper designation see *Properties of Aluminium and its Alloys,* (2014).[14]

Table 2.1 Basic cold working designations

Symbol	Description
O	Annealed, soft
F	As fabricated
H12	Strain-hardened, quater hard
H14	Strain-hardened, half hard
H16	Strain-hardened, three quarter hard
H18	Strain-hardened, fully hard
H19	Strain-hardened, extra hard
H22	Strain-hardened, partially annealed, quater hard
H24	Strain-hardened, partially annealed, half hard
H26	Strain-hardened, partially annealed, three quarter hard
H28	Strain-hardened, partially annealed, fully hard
H32	Strain-hardened, and stabilised, quarter hard
H34	Strain-hardened, and stabilised, half hard
H36	Strain-hardened, and stabilised, three quarter hard
H38	Strain-hardened, and stabilised, fully hard

Heat Treatment	
T1	Cooled from an elevated temperature, shaping process and naturally aged to a substantially stable condition
T2	Cooled from an elevated temperature shaping process, cold worked and naturally aged to a substantially stable condition
T3*	Solution heat-treated, cold worked and naturally aged to a substantially stable condition
T4*	Solution heat-treated and naturally aged to a substantially stable condition.
T5	Cooled from an elevated temperature shaping process and then artificially aged.
T6*	Solution heat-treated and then artificially aged. Applies to products which are not cold worked after solution heat-treatment
T7*	Solution heat-treated and then artificially aged. Applies to products which are artificially aged after solution heat-treatment
T8*	Solution heat-treated, cold worked and then artificially aged
T9*	Solution heat-treated, artificially aged and then cold worked

*Some 6000 or 7000 series alloys attain the same specified mechanical properties whether furnace solution heat-treated or cooled from an elevated temperature shaping process at a rate rapid enough to hold constituents in solution.

Table 2.2 Basic heat treatment designations

Duraluminium

One of the key pioneers of aluminium alloys was Alfred Wilm, a German metallurgist. In 1903, he was experimenting with an aluminium alloy with 4 per cent copper seeking an alloy that was as strong as mild steel. Wilm, whilst experimenting with alloying aluminium and having become frustrated that **quenching** the alloy had no effect on its strength and it was still easily bent, left for a river cruise – according to Mark Miodownik. On Wilm's return, days later, the aluminium had become stronger, he had accidentally discovered **age hardening**.[15] By 1909, he had developed and patented Duraluminium, an age hardened aluminium alloy with copper, magnesium and manganese. Its properties are close to mild steel but one-third the weight. J. Dwight observed 'it was the start of what we now term the 2000 series alloy group.'[16] Noting that: 'A scientific explanation of age-hardening did not appear until 1920, soon after which a second kind of age-hardening alloy emerged, namely the Al-MgSi [aluminium, silicon and magnesium] type. This alloy group (the present day 6000 series) has a tensile strength in its strongest version of some 300 N/mm^2, and is thus generally weaker than the 2000 series. But it has other features that have since led it to become the 'mild steel' of aluminium.'[17] Thus, age hardening is like many discoveries; experimentation and tactile knowledge preceded scientific theory. Dwight observes: 'By 1939 all of today's main alloys had thus arrived except one, namely the weldable kind of 7000 series alloy. This was actively developed after the [Second World] War.'[18] Yoshio Baba cites the first development of 7075 alloy, which has strength characteristics comparable to steel, was in Japan during the Second World War by Sumitomo Metal, in 1943.[19]

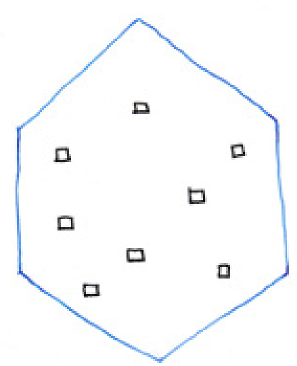


Fig 2.20 The crystalline structure of Duraluminium (after Mark Miodownik)

Forming Sheet Aluminium

Although metals have a crystalline structure, the bonds between crystals and crystalline layers are relatively weak. Thus, metals are mutable and thus forgeable and formable. The starting point for forming sheet aluminium is a cast slab ingot of a chosen alloy. This is machined to remove surface roughness resulting from the cooling of the aluminium during vertical casting and then heated to about 360°. It is then hot rolled to create a homogenous metallic structure. This slab, about 300mm thick, is fed into a rolling mill that

Fig 2.21 Post consumer aluminium scrap from the United Kingdom being loaded into the furnace of Hydro's cast house, Holmestrand, Norway

Fig 2.22 A 7 tonne cast aluminium ingot of 1200 alloy outside Hydro's hot rolling line, Holmestrand, Norway

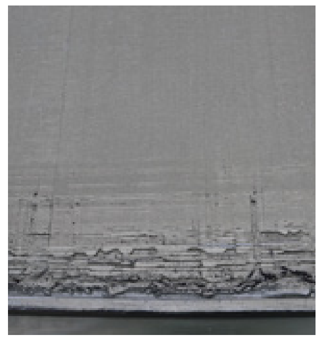
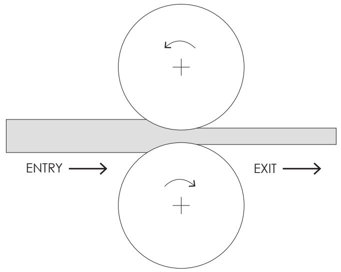
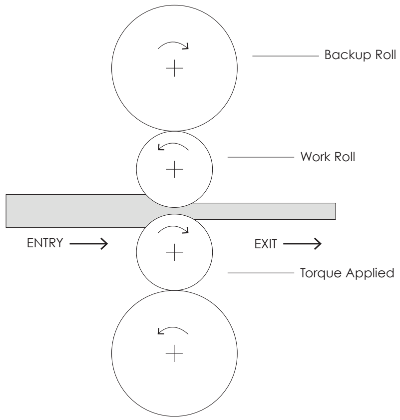


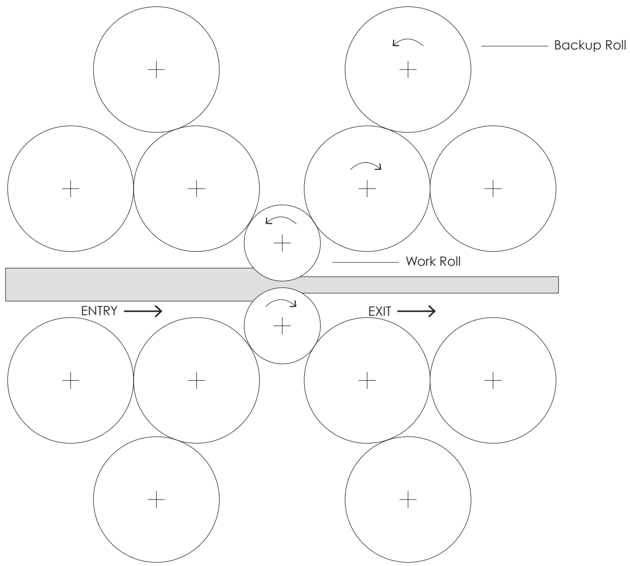
Fig 2.23 The surface roughness of the cast aluminium ingot is removed by milling before roll forming



2-High mill



4-High mill



Cluster mill

in its most basic form is two high precision steel rollers, know as work rollers. The rollers reduce the aluminium to a specified thickness; typically this is the first stage in achieving a final specified gauge for sheet or foil. A number of passes through the rolls may be required, or a second stage mill will be used.

During the rolling process finish, flatness and edge quality is also controlled. The steel rollers need to be manufactured to very fine tolerances, as fine as 0.006mm. The force required is dependent on whether the aluminium is hot or cold worked. Deflection of the roller is therefore an issue and thus the primary rollers are backed up by other rollers, these are known as four-high rolling mills. When multiple back up rollers are used, this arrangement is described as a cluster rolling mill.[20] Typically aluminium sheet is produced using four-high rolling mills. Roll stiffness is critical in forming flat sheet. The surface finish of the aluminium sheet is dependent on relative roughness of the work roll and this can range form matt mill finish to mirror smooth. Although mills are now computer numeric controlled (CNC) with specification parameters displayed in real time during the process, the metal structure under goes quantum effects and the craft skills of the operatives remain of vital importance in achieving the specified product.

Fig 2.24 [left] Configurations of rolling mills

Fig 2.25 The work rolls of a hot rolling mill, the first stage of Hydro's hot rolling line, Holmestrand, Norway

The hot rolling and cold rolling are two stages of a common process, where a 7tonne slab about 6000 × 300mm will become a coil 3mm thick and 1500m long or at 0.2mm, the gauge for say a food carton, the coil will be about 40km. The extent of the cold rolling is primarily a question of the metallic structure required following the reduction in material thickness as the metal is deformed. Cold rolling is undertaken at a temperature low enough for strain hardening to occur, typically a hot rolled coil is allowed to cool to ambient temperature before cold rolling. It can also provide a smoother finish than hot rolling. In hot rolling, the aluminium is at a high enough temperature to avoid strain-hardening occurring. The atomic structure of solid aluminium is a crystalline lattice forming a regular patter of distinct layers.

Fig 2.27 A 7 tonne coil of hot rolled aluminium

Fig 2.26 Work rolls from Hydro's hot rolling line, Holmestrand, Norway

Fig 2.28 Coils of hot rolled aluminium cooling next to Hydro's hot rolling line, Holmestrand, Norway

Cold rolling breaks and offsets the lattice layers, thus blocking slippages and making the aluminium stronger. The Aluminum Association advise that strain hardening by cold working 'is applied to the degree required by the product specifications, which involves a trade-off between maximum strength and maximum ductility.'[21] The heating and gradual cooling of **annealing** releases the dislocations and the crystalline layers are largely restored, thus the aluminium becomes more ductile at the expense of strength.

Fig 2.29 A cold rolling mill at Hydro, made in England in 1972

Hot rolling, as well as avoiding strain-hardening, closes the voids left by the casting process and it breaks up alloyed elements such as silicone that may have formed at the grain boundaries. In 7000 series alloys the amount of reduction per pass and the direction of rolling is important for the performance characteristic of these high strength alloys.

Fig 2.30 Aluminium alloy coils being loaded onto a truck destined for Hydro's automated paint line, which is co-located in Holmestrand

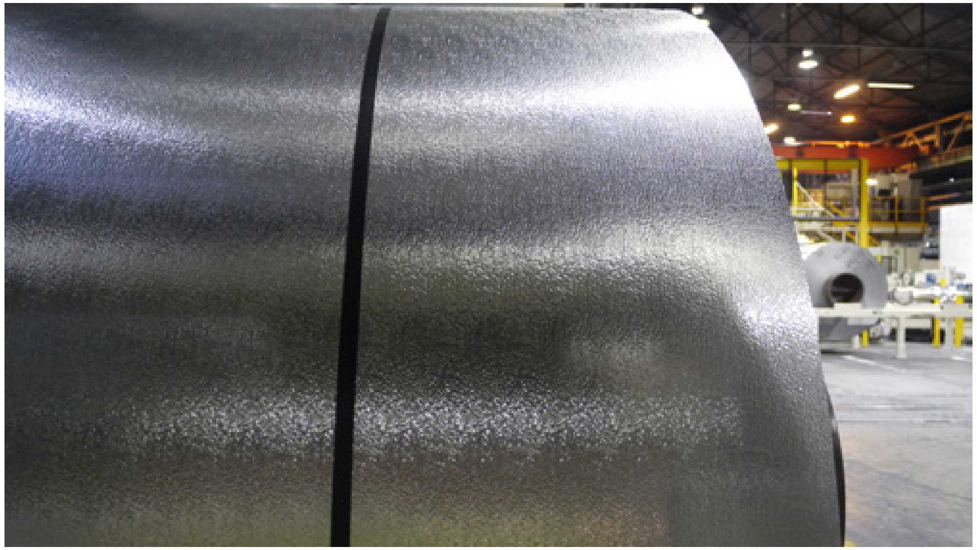


Fig 2.31 An embossed 3000 series aluminium alloy coil that will become standing seam roof sheet

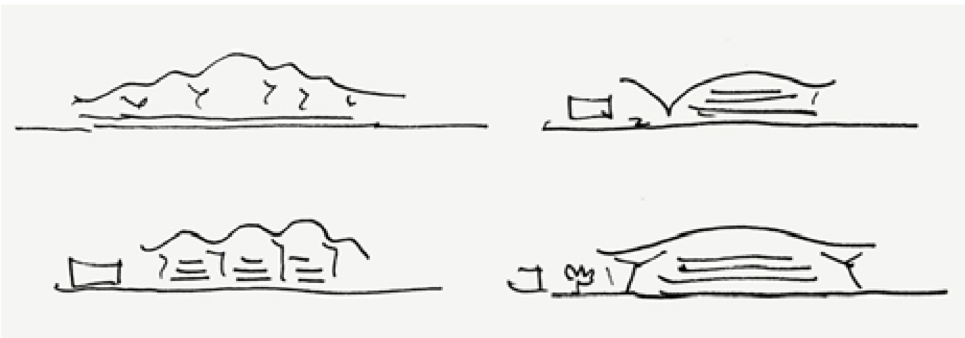


Fig 2.32 Richard Roger's sketches of the overall roof for Heathrow Terminal Five, England

Fig 2.33 The continuous single sheet aluminium standing seam roof of Heathrow Terminal Five, architect Rogers Stirk Harbour + Partners, 1988–2008

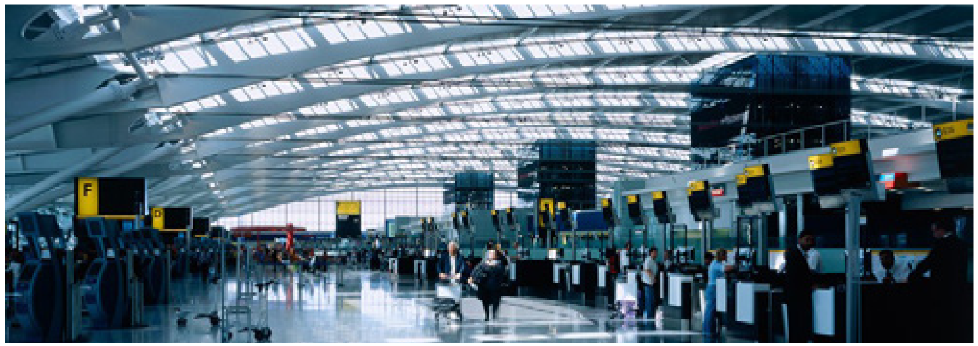
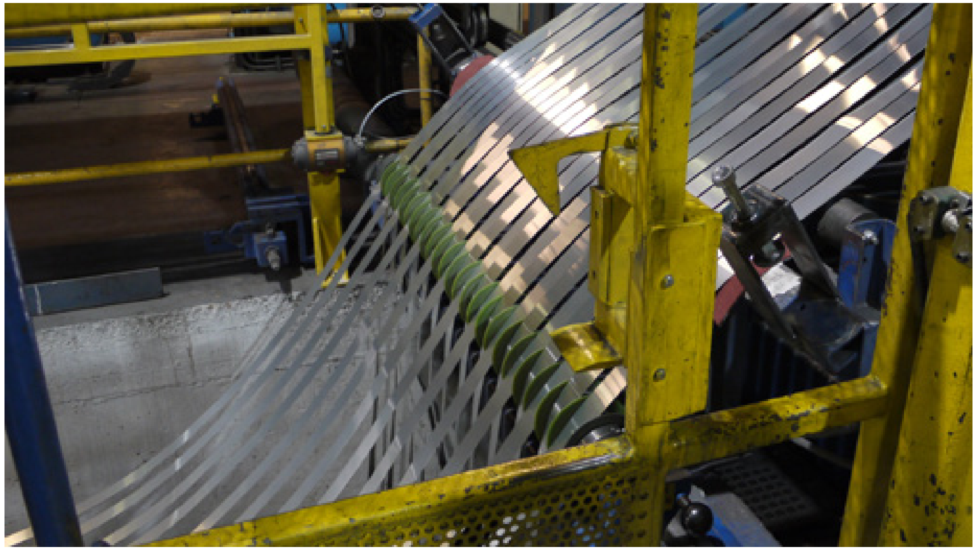


Fig 2.34 British Airways check-in zone at Heathrow Terminal Five



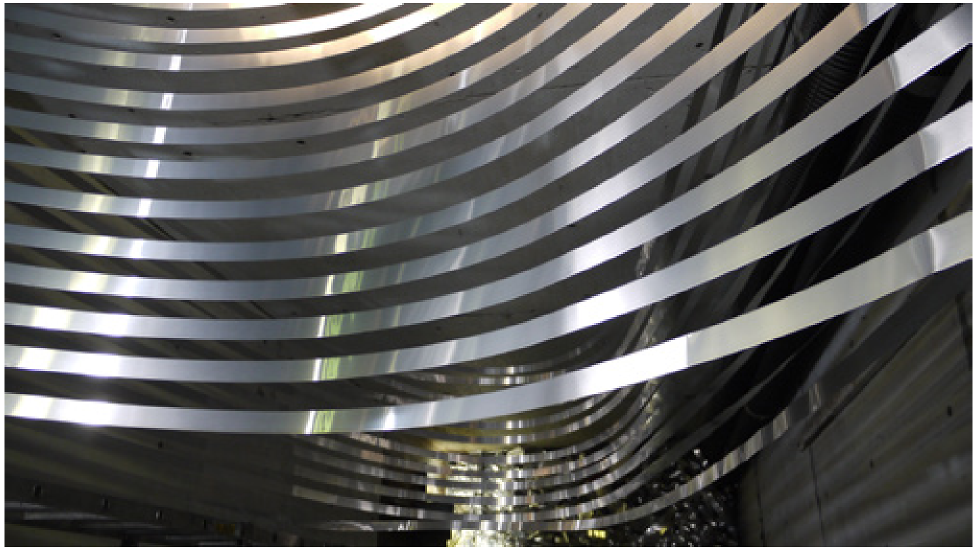


Fig 2.35 Hydro aluminium sheet slit cutter, the pit allows for the different lengths of the edges compared to the middle of the sheet

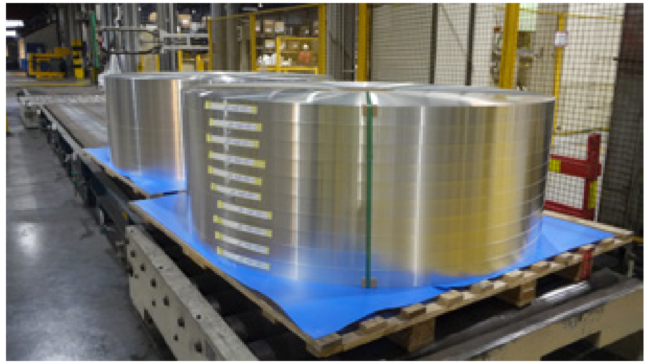


Fig 2.36 The slit sections reunited as a coil for delivery to a fabricator – possibly of tea lights

Fig 2.37 The rivet aluminium sheeting of Slipstream at Heathrow Terminal Two, sculptor Richard Wilson with Price and Myers Engineers, is reminiscent of a 1930s aeroplane translated through digital space

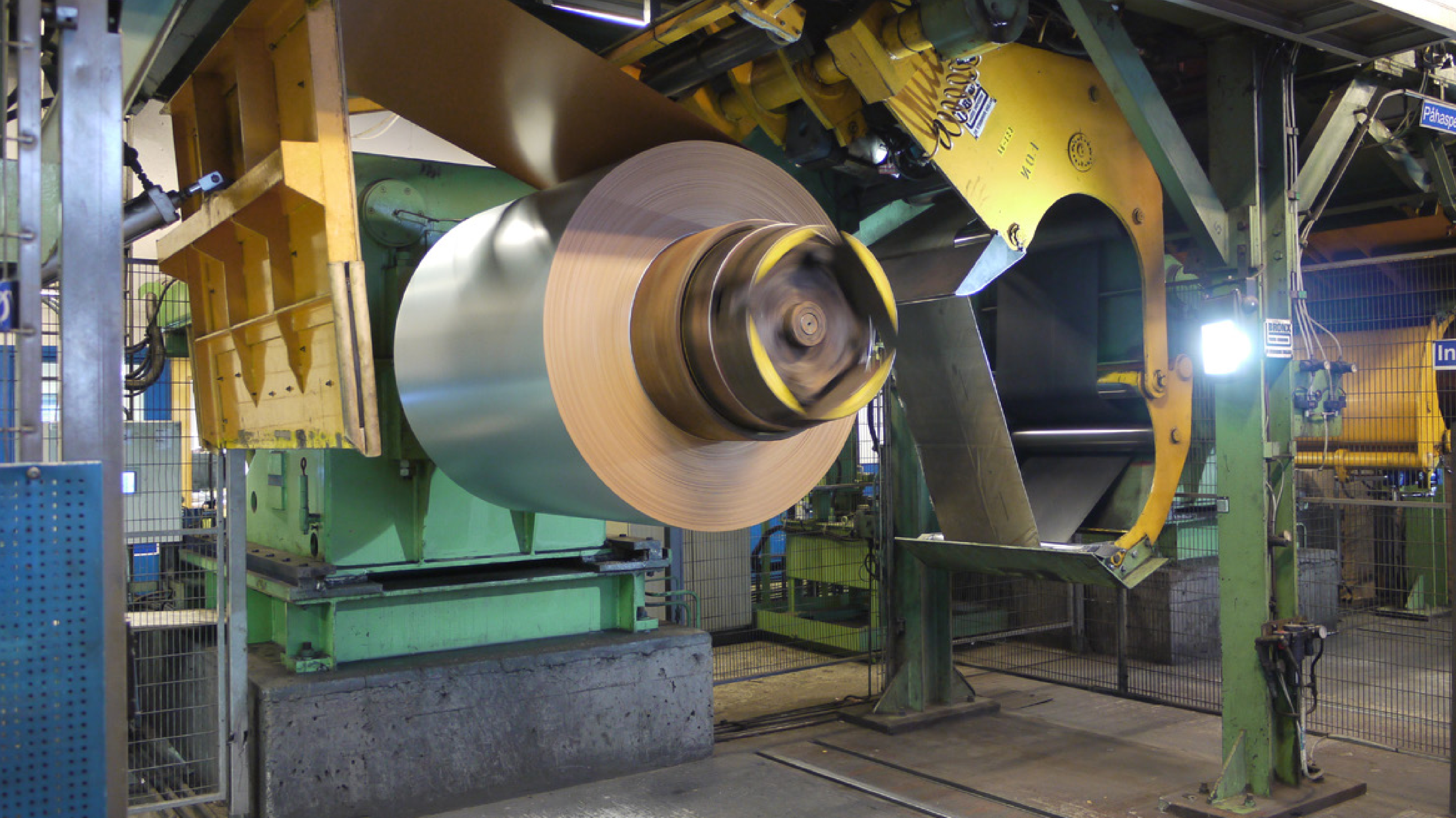


Fig 2.38 A primed coil of aluminium entering Hydro's automated coil coating line in Holmestrand

The hard oxide coating of **anodising** can reveal the gain structure of a rolled product, or the quality of a **die** and weld zones in extrusions. Anodising, introduced in 1920s, is now a closely controlled process; therefore the colour should be sufficiently consistent not to require a maximum and minimum colour sample. Silver anodising is popular with many architects as it offers the best possible durability, with a service life of over 80 years, and reveals the inherent quality of the aluminium components. However, if coloured anodising is specified a set of range samples should be agreed, especially if a dark colour is to be used, see for example the purplely-blue anodising of Vertical Shell, pages 322–328. Variation in colour is particularly noticeable in large uninterrupted expanses of flat panels, where even the grain of an aluminium sheet can become apparent. Foster + Partners specified silver anodised aluminium for the cladding and curtain walling of the Commerzbank. On this project, the architects avoids the potential pit fall of colour variation by the control of the alloy quality, which is critical, as is the orientation of the grain of the sheet aluminium, which is a rolled product. The plan form of this building and the articulation of the facades combined with the careful placement of the anodised components all helped to achieve a consistent appearance. This was achieved by close cooperation between the architects and the curtain-walling suppliers, Gartners.

Anodising is a batch process and the maximum sizes of aluminium components that can be anodised are governed by the chemical bath sizes a particular anodiser has invested in. United Anodisers, one of the United Kingdoms leading anodisers, offer the following maximum sizes: 7000 × 2000 × 450mm, (L) × (W) × (D).

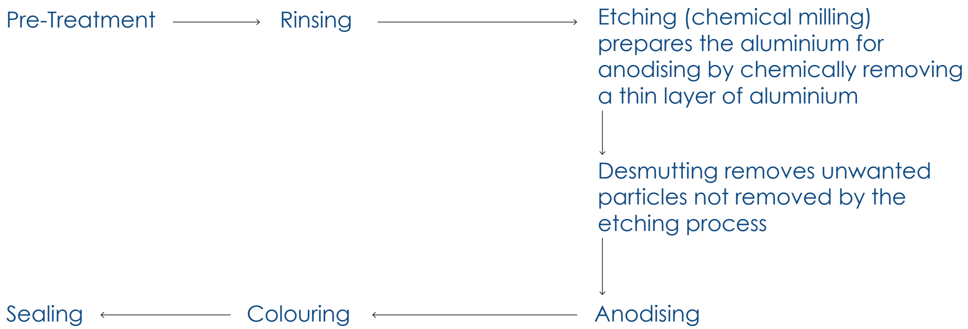


Fig 2.39 Anodising process

Fig 2.40 Anodised aluminium cladding of the Commerzbank in Frankfurt by Foster + Partners

Forming Sheet Metal Components

'When a metal component is being intelligently designed many factors are taken into account: the cost of the finished article, its strength, reliability in service and appearance. Often the facilities and skills of the manufacturer cause one or other process to be selected', observe William Alexander and Arthur Street in *Metal in the Service of Man*.[22]

All the processes for forming sheet metal are dependent on the ductility of the chosen metal or its alloy. If a metal is pre-finished with a polymeric coating, for example, the capability of the finish to withstand the forming process also needs to be considered. There are five basic methods of forming sheet metal into components:

- roll forming;
- hand forming;
- press brake;
- spinning;
  and
- pressing or stamping

Property	Value
Density	2720 Kg/m^3
Young's modulus	70 kN/mm^2
Thermal conductivity	237 W/m°C
Co-efficient of thermal expansion	2.3 × 10^{-5} per °C
Corrosion resistance	Excellent
Melting point	660°C
Recyclability	Excellent*

* Requires only 5% of the energy when compared to primary production

Table 2.3 Material properties of aluminium (pure)

Roll Forming

Profiled sheet cladding or roofing are very familiar linear building components. However, the process and its constraints remain unfamiliar to many architects. Most roll formers purchase the sheet metal in coil or pre-cut blanks. This may be mill finished, embossed or coil coated aluminium. Roll forming is applicable to a wide range of metals of appropriate **hardness**, including steel and copper. The aim of roll forming is to produce a rigid component from a thin sheet metal by developing a cross section of sufficient depth for the required span. The profile is formed by the progressive development of the shape by roll form tools, see Figure 2.41. It is essential that the final form is developed progressively in stages. A tool to develop an apparently simple square edge will have eight stages. If a desired form is produced in too few stages, too abruptly, the form will lack precision. All roll forming is subject to flaring where the ends of the sheet, say a panel skin, will be wider at the two ends than the middle. This is the result of tension being released at the end of the profile. If a sheet is not fed through square to the tool, residual stress will result in the sheet not being flat, which unacceptable in the face of a cladding panel for example. This is known by the literal metaphor: crabbing.

One constraint on roll-formed sheet components is the availability and size of sheet material, a roll of 1.6mm thick aluminium sheet is typically 430meters long. The constraint is primarily the width; typical maximum is 1250mm depending on the metal substrate and additional process required, although 1500mm wide sheet is available in some metals. It is important to remember the width of the final product is a result of the developed form. Essentially any stretching of the metal is minor and can be negated; the width is a resultant of the surface length of the profile.

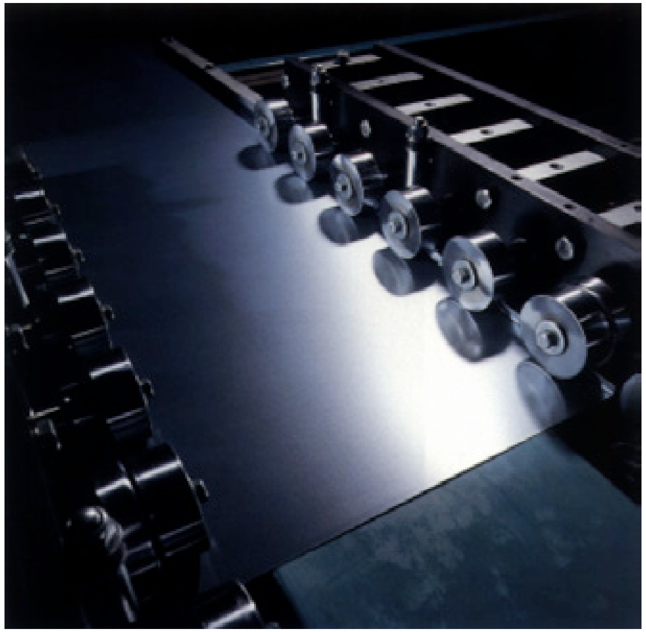


Fig 2.41 Roll forming the edges of a metal sheet to form the face of a metal composite panel

Aluminium Standing Seam Roofs

A Kalzip standing seam aluminium roof was first used in Europe to complete the Nuremberg Congress Hall in 1968. This and two other early Kalzip projects have been subject to long term testing by the German Federal Institute for Materials Research and Testing [BAM], as discussed in TSC Report One: *Aluminium and Durability*.[23] Kalzip have developed a robust and reliable technology of roll-formed sheet, about 300mm wide, that interlock and form a waterproof room with an upstanding seam, typically 65mm high. Offering this aluminium roof system in a range of width from 333 to 500mm. Other roll formers also fabricate aluminium alloy standing seam roof systems.

Kalzip aluminium roofing is assembled from roll-formed aluminium sheet, which has an additional top layer or plating layer, of approximately 5 per cent thick AlZn1 (aluminium zinc alloy).[24] Eighty per cent of projects completed by Kalzip in 2014 were mill finished as this specification offers lower maintenance and higher durability than post coated sheet.

An aluminium standing seam roof sheet can be formed to a 30–40m radius on site without distortion and the need for pre-curving. The minimum radius is dependent on the gauge specified. Kalzip can produce curved sheet to a radius as tight as 1.5m without crimping.

Kalzip has also been able to produce tapered sheets since the early 1990s, thus avoiding cutting and welding sheets or large hip flashings. BDP, for the replacement roof of Number One Court at Wimbledon, conceived as a 'grid shell' clad in a tapered and curved sheet to form a smooth toroidal roof. During 1996, Kalzip invested £250,000 in machinery and development to achieve this combination of tapering and curving. The roof of Number One Court was successfully completed and the equipment has since been extensively reused on other projects, providing a positive return for Kalzip's investment. Kalzip can produce tapered sheets with maximum dimension of 600mm tapering to 110mm.

Aluminium alloy standing seam systems offer architects and building owners rapid assembled roofs that are affordable, reliable and durable, as evidence by the case studies in Chapter Nine *Economic*.

Fig 2.42 The smooth torodial roof of Wimbledon Number One Court, formed from tapered aluminium standing seam sheeting, architect BDP, 1996

Fig 2.43 Greenwich Gateway Pavilions, Marks Barfield Architects, 2014, gold finished aluminium standing system roof installed by Lakemere, using both tapered and Kalzip XT sheets, delivered by the collaborative use of a Building information model (BIM). The gold finish is produced by and electrolytic passivation process

Press Brake

One way to avoid flaring in forming a sheet component, such as a metal tray, is to use a press brake. The metal is formed by the action of the upper press tool into the bed or lower tool of the press. The pressure necessary is dependant on the gauge, or thickness of the metal. As the force is applied as a uniformly distributed load over the length of the section, an even fold results, thus avoiding flaring. For a square section it is a one-stage process. One constraint of a press brake is the length of the press – typically 3 to 4m. Presses up to 12m can be found in Europe. It is possible to use two press brakes together with staggered tools. Sheet metal up to 10mm thick can be pressed braked, however the associated tolerances typically increase with thickness. Press brakes are inherently flexible with interchangeable top and bottom tools. Tool selection is based on the angle and radius required in the pressing.

The minimum radius at the corner of a 90° uncoated press-braked section is a function of the thickness of the metal, where internal radius equals the thickness of the metal. For a pre-coated metal

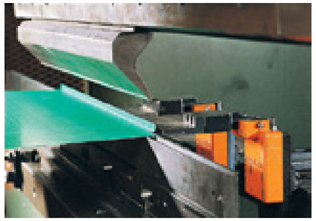
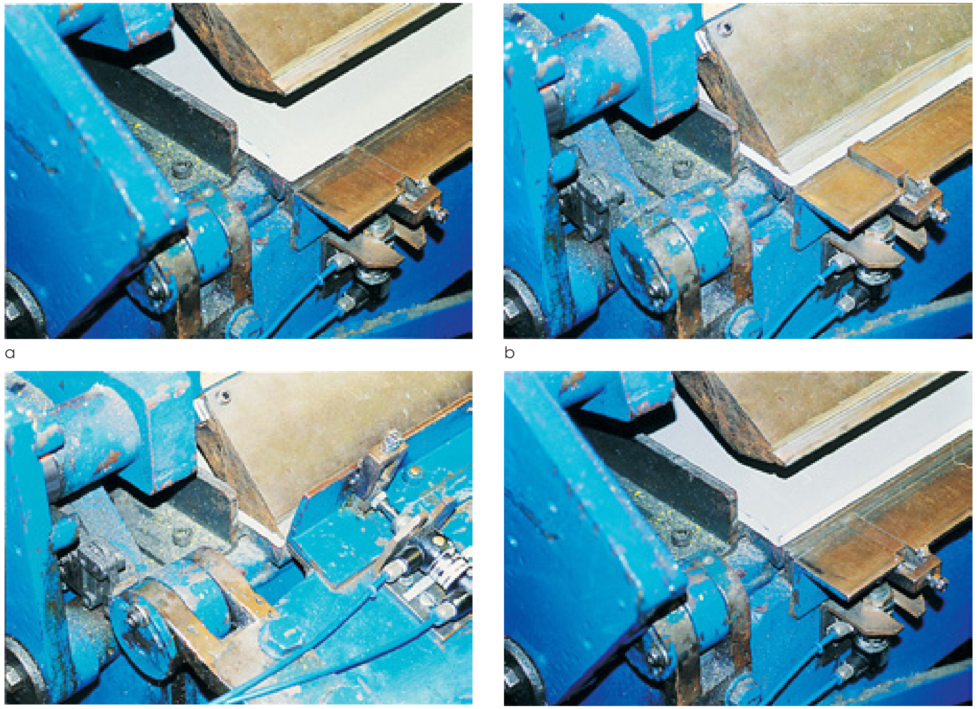


Fig 2.44 Press Braking a 90° edge, a second 90° is about to be formed (photograph courtesy of ame)



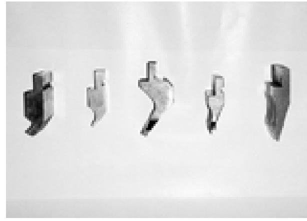
a

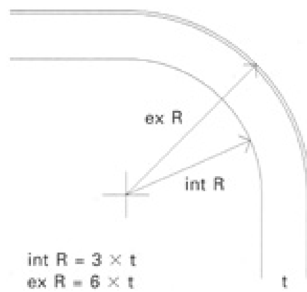
b

c

d

Fig 2.45 A-H, the eight stages of forming two 90° returns on a metal sheet cladding 'skin' or panel face



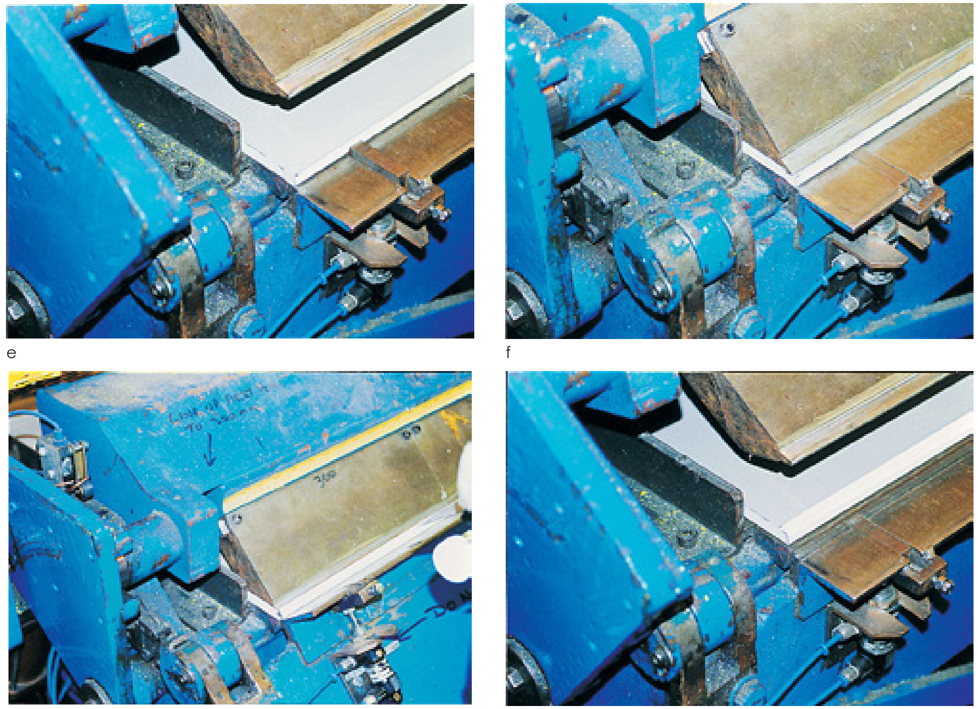


the radius should not exceed the stretchability of the coating (see Figure 2.47). When press braking aluminium, it is essential that the alloy and work hardening of the sheet are carefully controlled. If an inappropriate alloy is used, the final component will not be stiff enough or stretch cracking and/or brittle failure will occur, thus a component will either not function correctly, look unsightly, or premature failure will result.

In designing a press-braked component, it is essential that there is sufficient room for the tool to be withdrawn. This has lead to the development of swan-neck tools, which allow deep channel sections to be formed. If a narrow channel section is required,

Fig 2.46 [top left] A range of top tools removed from a press brake demonstrating the flexibility of this method of forming sheet metal

Fig 2.47 [left] Recommended minimum radius for press braking a coil coated metal – PVF[2]



e

f

g

h

it may be necessary to make the vertical side asymmetrical in height, to enable the component to be removed from the tool (see Figure 2.48). It is possible to press-brake smooth curved sections, as demonstrated by the press-braked and then anodised aluminium gutter of East Croydon Station, architect Brookes Stacey Randall Fursdon, produced by Majors of Croydon. The details of the restored roof of John Nash's Royal Pavilion at Brighton (1815-1822) used the same production method. The constructional aesthetic is governed by design and not the technology.

In producing a smooth curve it is essential that the section is pressed in small increments, otherwise telegraphed steps will show. This process can be aided by the use of a computer numeric controlled press-brake. The presence of telegraphed lines can also be a function of thickness. Curved column casings with folded fixing flanges are an example of components that can only be press braked, as it would be impossible to design a roll-forming tool through which such formed sheets could travel. Roll forming and press braking produce linear components. If a rotated geometry in metal is desired, or required, a spinning should be considered.

Fig 2.48 It is essential to design for removal from the press tool

Fig 2.49 Aluminium gutter of East Croydon Station being press braked by Majors of Croydon

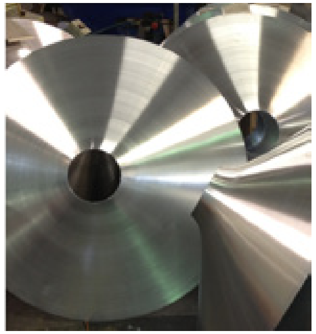


Fig 2.50 Aluminium spinnings

Spinning

Components produced by the spinning process are probably familiar to many readers in the form of aluminium light fittings. The spinning process starts with a flat sheet of the chosen metal, which is rotated at speed and formed over a hardwood or steel tool. It is also possible to form thin walled rotated forms using spun castings. In many applications aluminium is the first choice material to form spun components.

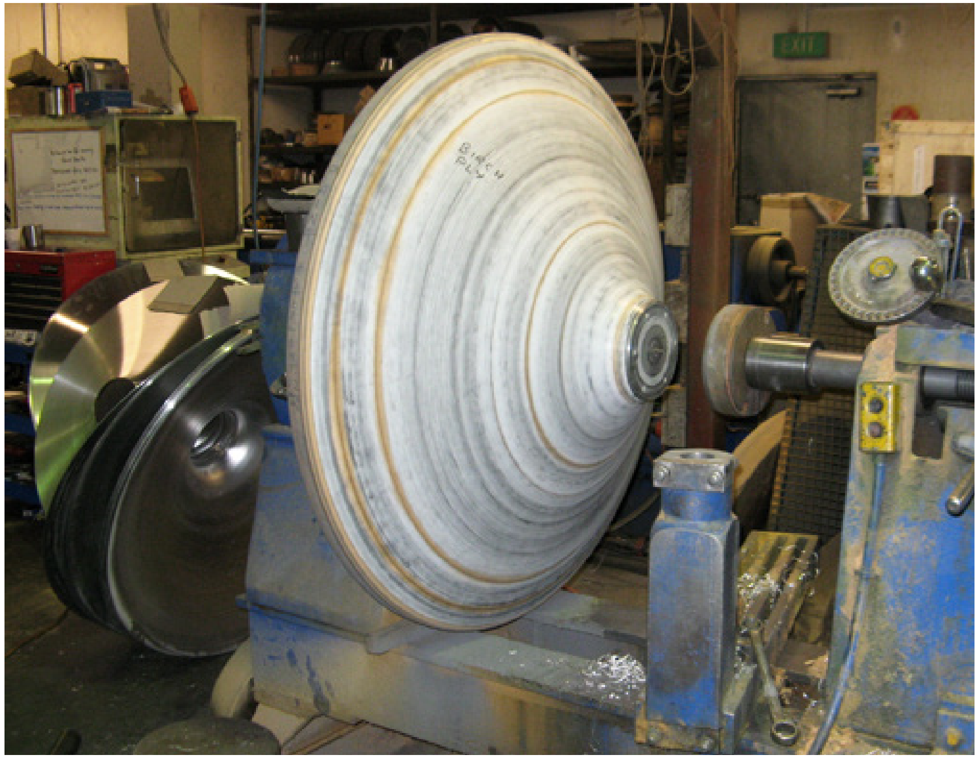


Fig 2.51 A metal spinning tool

Selfridges Department Store, Birmingham, England: Architect Future Systems, 1999

The client for the new Selfridges department store in Birmingham, its Managing Director Vittorio Radice, 'wanted to reintroduce a sense of spectacle into retail' records Deyan Sudjic.[25] Returning to the routes of the company and its commissioning of American architect Daniel Burnham to design its new Oxford Street palazzo-like store, which opened in 1909. Selfridges Birmingham Department Store is part of a larger development in the centre of Birmingham, near New Street Station and adjacent to the Bull Ring. Vittorio Radice, however, insisted in an autonomous architecture rather than the typical fit out of a store in a late twentieth century city centre shopping mall. This led to the commissioning of Future System Radice had been impressed by the Lords Media Centre (1996).

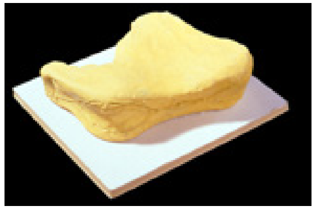


Fig 2.52 Future Systems' plasticine model of Selfridges Department Store

Models and prototyping were vital in the design development of Selfridges. The design accepts the paradigm of the blind retail box of maximum floor area, yet this is relieved by the daylight of two atria and the aluminium disc clad doubly curved skin. In Birmingham, Deyan Sudjic writes, 'Future Systems has built a giant blue bubble, studded with hundreds of anodised aluminium discs, that belongs to a family of objects relating to the work of such artists as Claes Oldenburg and Anish Kapor'.[26]

The store has a steel frame, spayed concrete building fabric that was then coated in 80mm of Sto insulated render. Each of the 15,000 aluminium spinnings is fixed back to the concrete by a single bolt, which is capable of carrying the weight of a person (to deal with unofficial climbers). The building fabric takes inspiration from and expresses the world of fashion within. The Sto render is finished in Yves Klein blue and the aluminium spinnings were inspired by a dress designed by Paco Rabanne (circa 1967–8), with linked-polished aluminium panels.

Fig 2.53 Paco Rabanne dress, with linked-polished aluminium, circa 1967–68

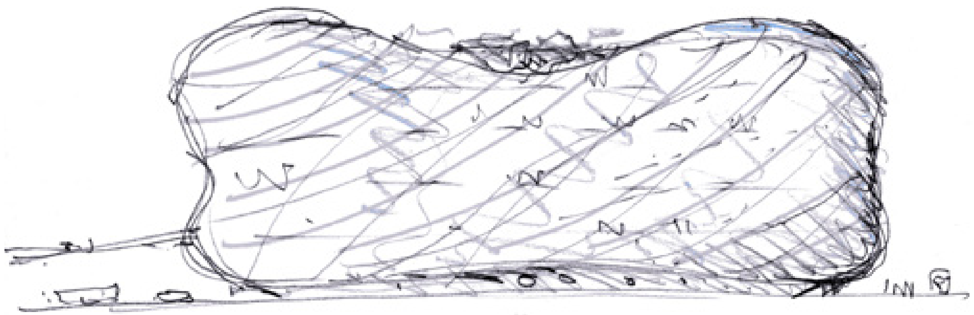


Fig 2.54 Jan Kaplicky's early sketch of Selfridges Department Store

Fig 2.55 Selfridges Department Store, with St Mary's Church and the Bull Ring in the background

3mm thick 660mm diameter aluminium spinning were organised by James and Taylor, specialists in façade engineering and procurement. The aluminium spinnings of Selfridges are silver anodised with 25μm in accordance with BS 3987:1991. Deyan Sudjic believes that this project has become part of the identity of the city, 'Selfridges' discs have become shorthand for the store and thus a new Birmingham, busy trying to shrug off its bleak post-war image.'[27]

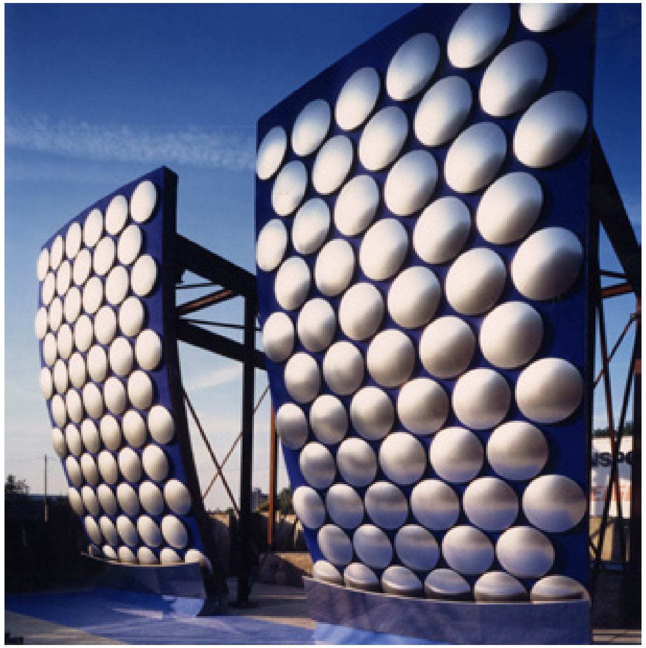


Fig 2.56 Selfridges Department Store façade prototypes

Fig 2.57 Yves Klein blue Sto render of Selfridges Department Store, photographed 2008

Fig 2.58 Typical wall build up, Selfrdiges, Birmingham, shown at 1:10:

1 660mm dia. feature dome
2 Support ring
3 Quarter turn security fastener
4 Outer sealing components
5 Inner sealing components
6 Cast-in socket
7 Render
8 80mm Insulation and weatherproof liquid membranes
9 Sprayed concrete substrate

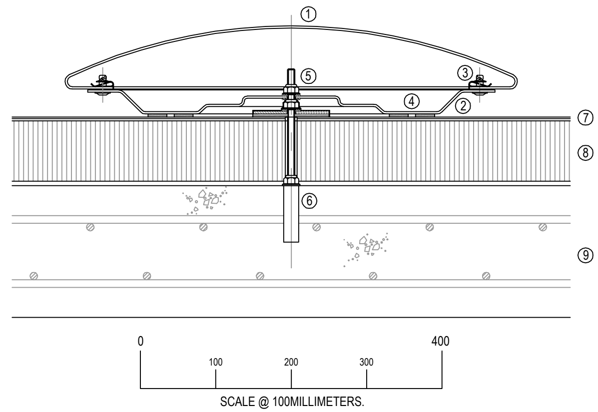


Fig 2.59 15,000 aluminium alloy spinnings form the façade of Selfridges Department Store, photographed 2008

FabPod, RMIT University, Melbourne, Australia: Architect and Researchers, SIAL @ RMIT, 2011

FabPod combines research into the sound diffusing properties of hyperbolic surfaces, the problem of semi-enclosed meeting areas within open plan settings and the use of digital modelling and bespoke CNC prototyping. The first iteration of this research was developed in 2011 for the Responsive Acoustic Surfacing (RAS) Cluster at the Smartgeometry workshops held in CITA, Copenhagen. It was initiated in response to anecdotal evidence from musicians that the newly completed interior of Gaudí's Sagrada Família Bassilica has a surprisingly diffuse acoustic. While techniques for evaluating reverberation and absorption of sound are well developed, the diffusion of sound is a more emergent area of research.[28]

Fig 2.60 SIAL's digital model of the FabPod meeting space

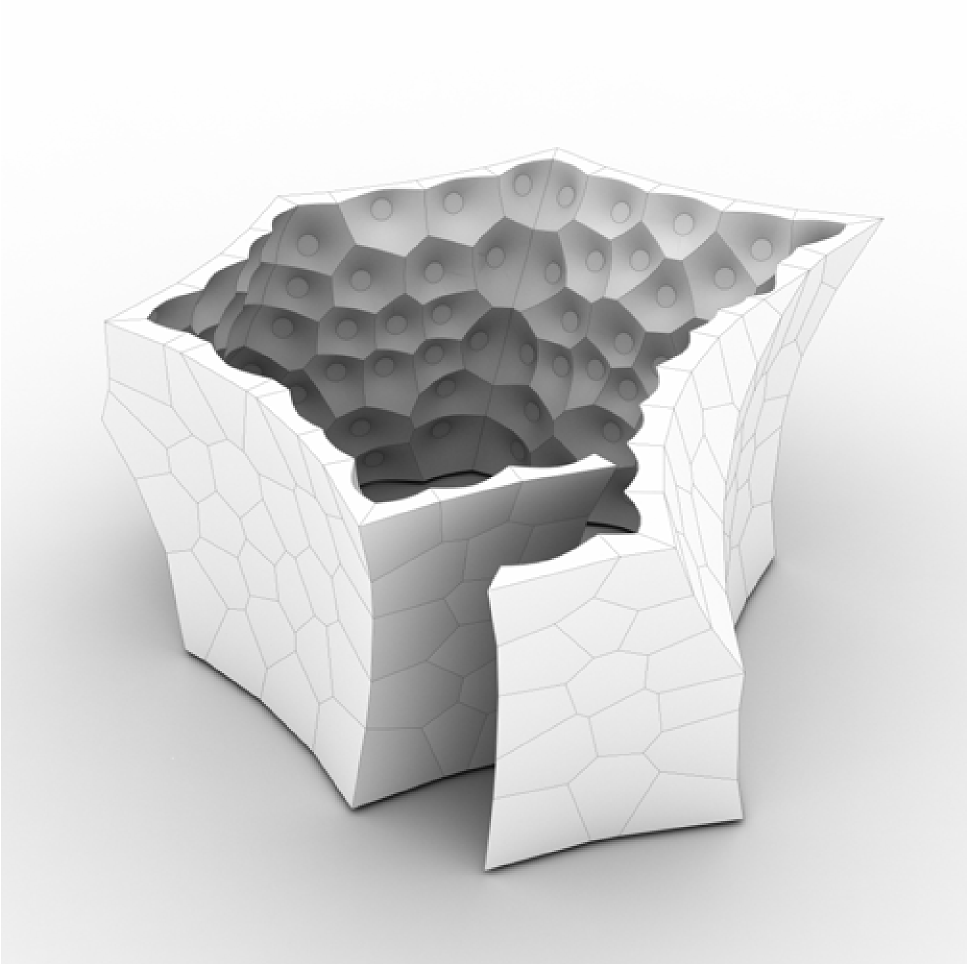


Fig 2.61 Screen shot of the workflow in the parametric design model of FabPod

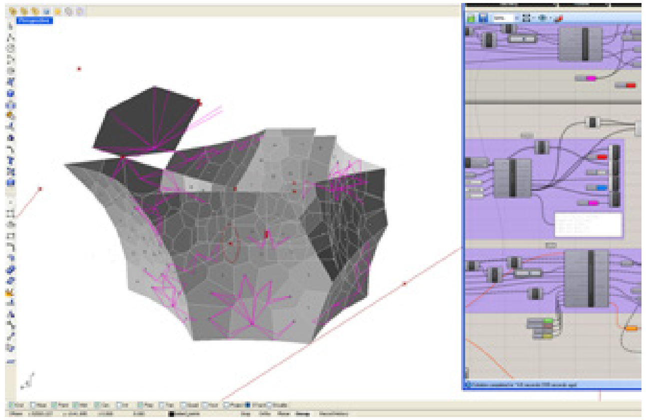


Fig 2.62 MDF frames awaiting facing panels and final finish

Initial research outputs from the design and testing of surfaces have been extended in this more complex brief. Based on a series of geometric and fabrication constraints, a digital workflow has been developed to allow for the quick proposal of form, geometric articulation and material distribution. These design proposals can be digitally simulated to understand acoustic performance and easily fed back into further design iterations. Acoustic performance acts as a design driver. This process was applied to the construction of full-scale proposals to rigorously test the flexibility and sophistication of the digital systems as well as the fidelity of the fabrication techniques. Importantly, this allowed for further layers of feedback from the physical to the digital, demanding that the digital model best abstract the behaviour of the physical and meaningfully enhance the design process.[29] The prototypes of FabPod were exhibited in Nottingham, London and Cambridge Ontario during 2012-13, as an integral part of Prototyping Architecture.

Fig 2.63 CNC machining of MDF components

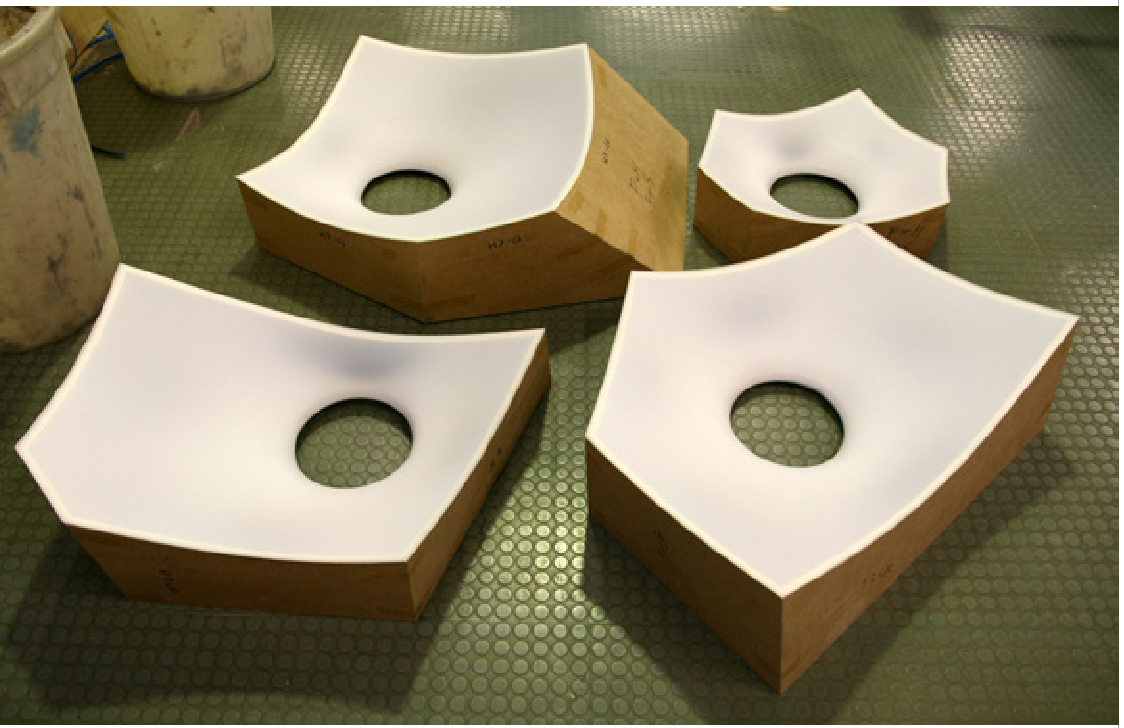


Fig 2.64 Part assembled FabPod cells

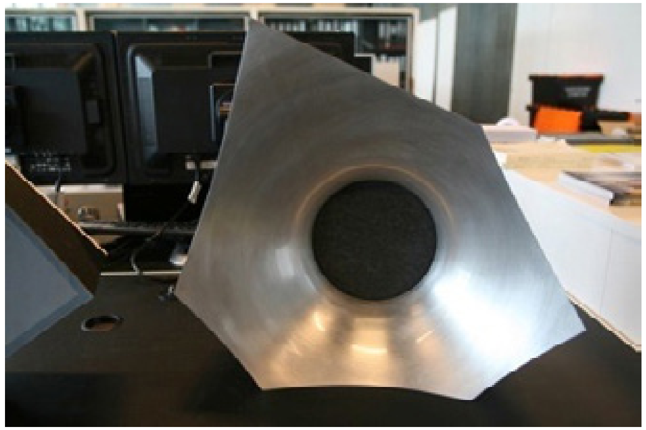


Fig 2.65 Aluminium spinning

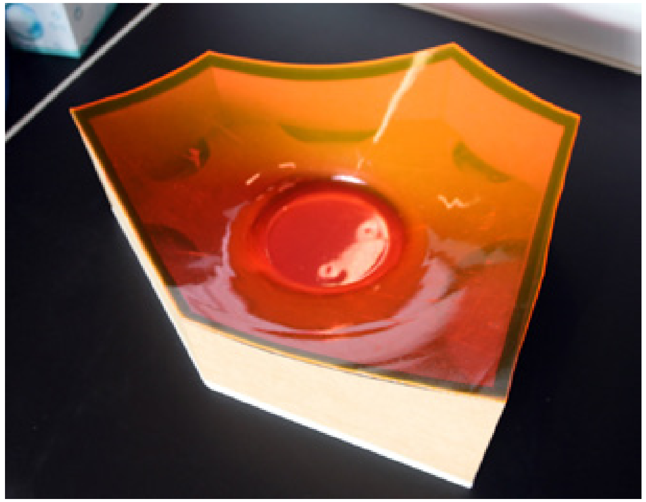


Fig 2.66 Vacuum formed acrylic layer

Fig 2.67 A completed FabPod cell

Although the inspiration for FabPod comes from the Sagrada Família Bassilica, the brief was to create an acoustically discrete meeting room for up to eight people in a new large open plan 'knowledge' space at RIMT University, Melbourne. Nicholas Williams and colleagues observed the 'enclosure was to provide an internal acoustic suitable for such small meetings and externally to improve the acoustic' of the larger space.[30]

The cells of FabPod are fabricated from: spun aluminium hyperboloid panels, formed from 1.5mm thick sheet blanks on a tool that was fabricated CNC fabricated from stacked 35mm MDF panels. The cells have a framing comprising 12mm CNC cut MDF and are complete by vacuum formed white translucent acrylic sheet and PET based absorbent material. Being hyperboloid in form, FabPod is a less obvious application of the spinning process in comparison to Selfridges, Birmingham, by Future Systems.

Fig 2.68 Walls of the FabPod prototype meeting space

Fig 2.69 The interior of the FabPod meeting space

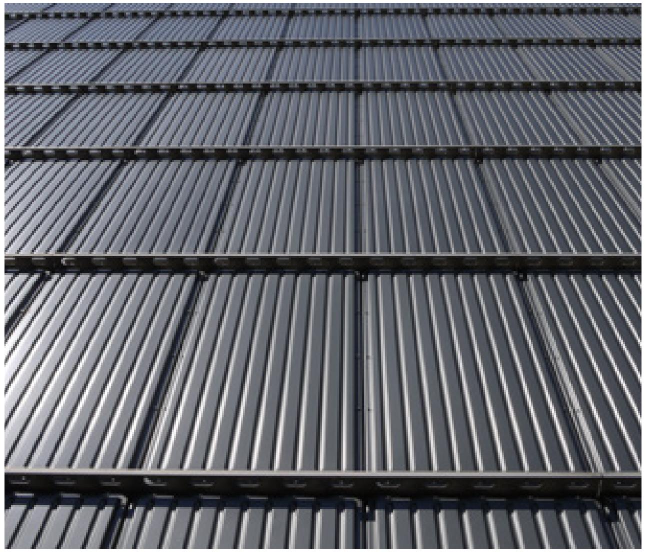
Fig 2.70 FabPod in open plan 'knowledge' spaces at RMIT University, Melbourne

Pressed Aluminium Cladding

The interchangeable system cladding, windows and doors of Herman Miller Distribution Centre, Chippenham, designed by Nicholas Grimshaw & Partners and completed in 1983 is an excellent example of the use of pressed aluminium cladding panels, finished with polyester powder coating. The project was inspected, reviewed and the powder coating tested in an earlier stage of this report, see TSC Report 1: *Aluminium and Durability*. The aluminium panels were pressed at Kinain Workshops. Whereas for the interchange panels of the Financial Times Printworks, designed by Nicholas Grimshaw & Partners and completed in 1988 chose to use superplastic aluminium panels finished with PVDF. When inspected in 2012 the cladding of this project had retained its original appearance.[31]

Fig 2.71 [below left] The PVDF coated superplastic aluminium panels of the Financial Times Printworks, designed Nicholas Grimshaw & Partners and completed in 1988

Fig 2.72 [below right] Curved corner panels and cladding rails of the Financial Times Printworks, London



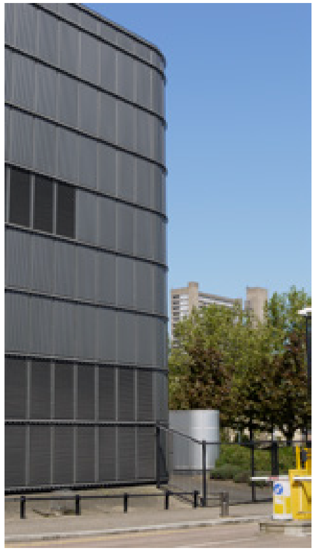
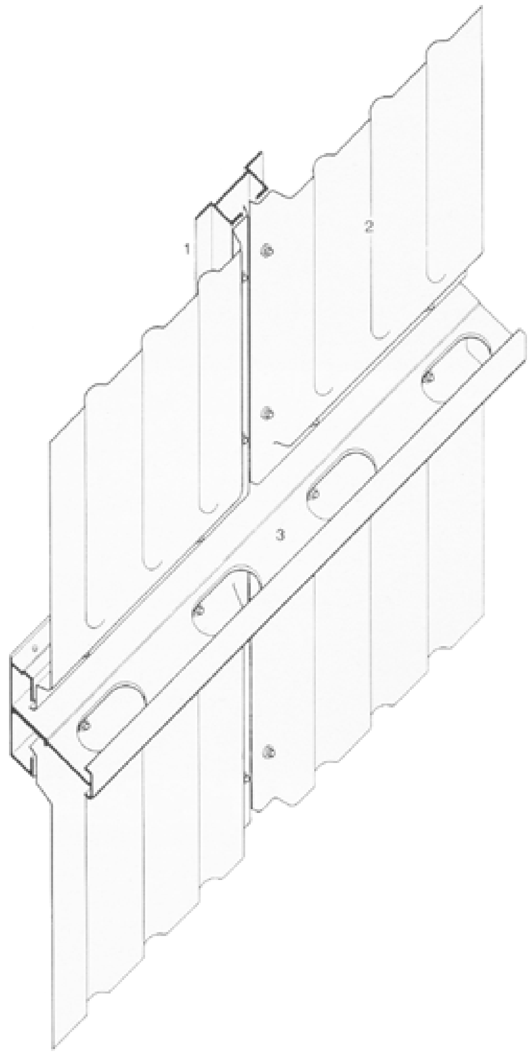


Fig 2.73 Cut-away axonometric of cladding assembly of the Financial Times Printworks:

1 vertical extruded aluminium cladding rail;
2 vacuum-formed aluminium panels;
3 horizontal extruded aluminium channel with projecting cladding rail



Superplastic Alloys

The limitation of cold forming metals under pressure is their ductility and thus the dangers of either brittle failure or wrinkling. This can be overcome by the use of superplastic alloys, which are capable of elongation of up to 1000 per cent, this compares to an elongation of 30 to 40 per cent for typical steel or aluminium alloys.

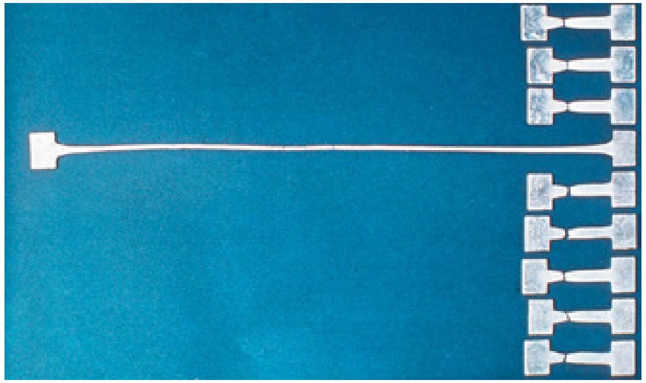


Fig 2.74 A comparative elongation test of superplastic aluminium and other aluminium alloys

Superplastic aluminium is now extensively used to form automotive, aerospace and architectural components. The superplastic quality of an alloy is the product of a fine and stabilised grain structure resulting in high ductility. Superplastic aluminium is appropriate when a doubly curved element or a component with a complex surface is required. The aim could be to create stiffness in an otherwise flat component, such as a cladding panel or to interface with the geometry of other components as in an aero-engine air intake.

The range of superplastic aluminium alloys available includes: 100 and 150 (2004) Supral 5000 (5251) 5083S PF, 7475 SPF and 8090 SPF. Alloys are selected on the basis of required stiffness and forming method.

The four primary methods of superplastic forming are:

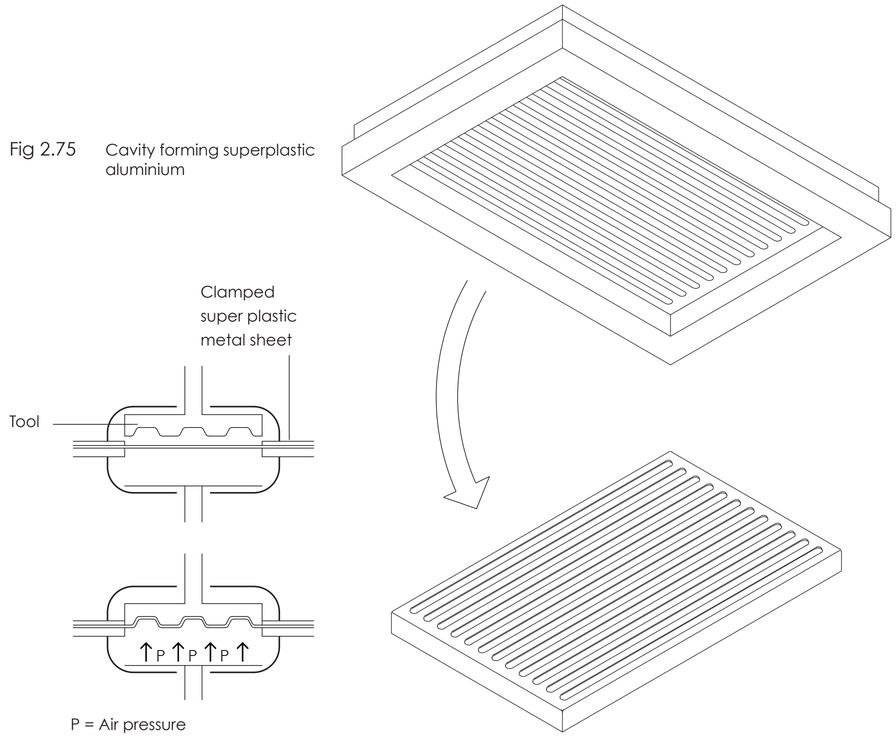
- Cavity forming – conventional and drape;
- Diaphragm forming;
- Bubble forming;
  and
- Back pressure forming.

Each process is set out on the following pages.

Cavity Forming

Figure 2.75 illustrates the cavity forming process; a sheet is preheated and clamped into the press. It is then forced into a cavity moulded by air pressure. The profiled cladding panels of Sainsbury Supermarket, Camden, London by Nicholas Grimshaw & Partners, were produced by cavity forming. Designers should note that the thickness of the sheet reduces in the 'deepest' parts of the mould. Thickness can be controlled by varying the cycle and speed at which air is blown. A minimum thickness should be specified and the metal deployed, if possible, where it is needed within the component.

Fig 2.75 Cavity forming superplastic aluminium



Drape Cavity Forming

Here the preheated sheet is placed above the negative tool. Thus the sheet is thickest at the top of the tool surface. Therefore the choice between conventional cavity forming and drape forming is dependent on where the greater thickness is required in a component.

Diaphragm Forming

This process enables the forming of non-superplastic aluminium alloys. This is achieved by clamping a sheet of superplastic aluminium above the sheet to be formed. The diaphragm sheet limits the tendency of the component to buckle. The advantage of this process is a constant material thickness is achieved. It is a relatively expensive process and has primarily found applications in the production of aerospace and defence components. However, the perforated acoustic ceiling panels in the subway of Stratford Jubilee Line Station, by WilkinsonEyre, were produced by diaphragm forming.

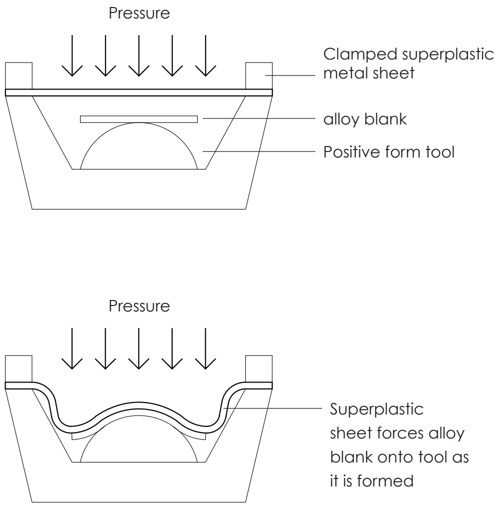


Fig 2.76 Diaphragm forming superplastic aluminium

Bubble Forming

As shown in Figure 2.77, in bubble forming the preheated sheet is clamped between a bubble plate and a tool plate. Pressure is applied from below and the superplastic aluminium forms a bubble. The tool is then pressed into this bubble. The air pressure is reversed, forcing the sheet or bubble into the detail of the tool. The advantage of this process is that a relatively consistent thickness is achieved. The doubly curved air intakes for the British Aerospace Hawk training aircraft, which is flown by the Red Arrows Display Team, are produced by this method.

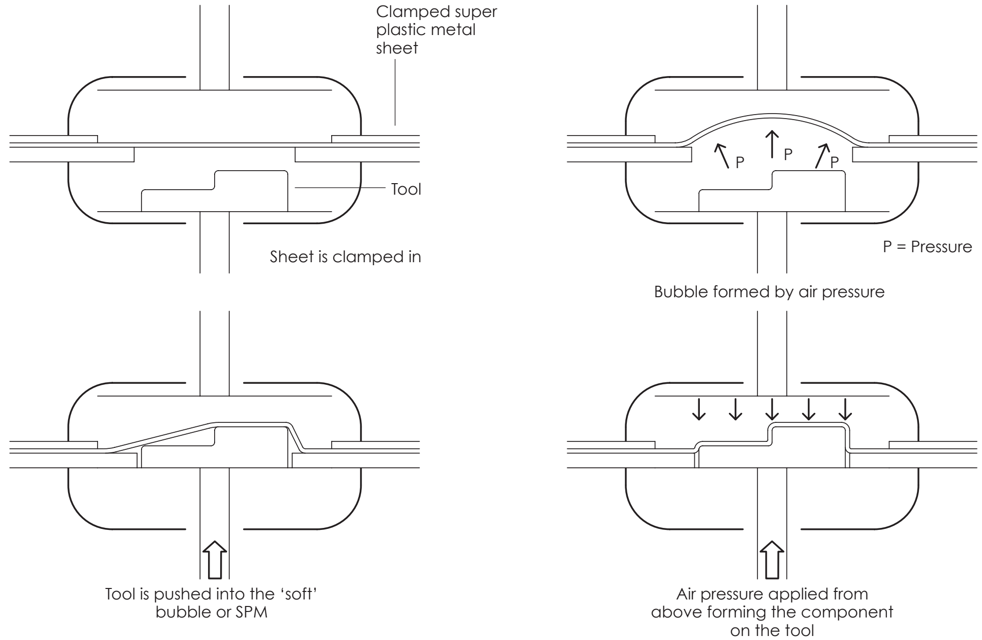


Fig 2.77 Bubble forming superplastic aluminium

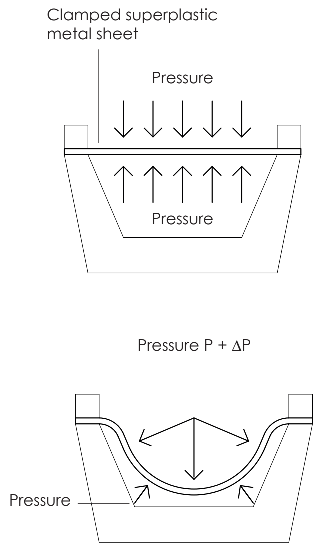


Fig 2.78 Back pressure forming superplastic aluminium

Back Pressure Forming

Most alloys develop microporosity, or 'tiny voids', during the superplastic forming process. This is also known as cavitation and it reduces the fatigue characteristics of the alloy. This needs to be avoided in structural applications, such as a Class One or safety critical aircraft component. This can be achieved by forming the component in a chamber at approximately 600psi (42 kg/cm^2). The pressure is applied to both surfaces of the sheet. Although this process is expensive and is only used for high strength alloys, including 7475 and 8090, it enables parts to be made that are deeper and more intricate. Examples of Class One aerospace components are air intakes or a pressurised cabin door. The tool used is dependent on the alloy, for Supral alloys with a forming temperature of below 500°C aluminium tools are used. The tool is produced by either machining a 'block' of aluminium or by sourcing a sand casting. For 5083, 7475 and 8090 alloys, which are all formed above 500°C, ferrous tools are required. To ensure that the sheet does not 'weld' itself to the tool, a graphite-based lubricant is used that enables relatively friction-free movement to occur.

It is critical to note that the tool side is dimensionally accurate and the 'air side' should be the exposed or visually significant surface.

Size Limitation and design guidance

Overall size is dependent on tooling and available sheet. Taking an architectural example, Superform's maximum size for a formed panel is 3000 x 2000mm, with a depth of 600mm. Figure 2.79 gives guidance in radii and aspect ratios for ribbed sections; note this is guidance and particular requirements should be discussed with the forming company. Superplastic aluminium sheet can be combined with other aluminium technologies. It can be more economical to form a panel with a flat edge and clamp it into a pressure plate curtain walling system as at Gatwick North Piers, architects YRM, or weld an edge to the panel as at the Financial Times Printworks, architects Nicholas Grimshaw & Partners. The original superplastic aluminium panels of the Sainsbury Centre for Visual Arts at the University of East Anglia, designed by Foster Associates and completed in 1978, are illustrated in TSC Report 1 *Aluminium and Durability*.[32]

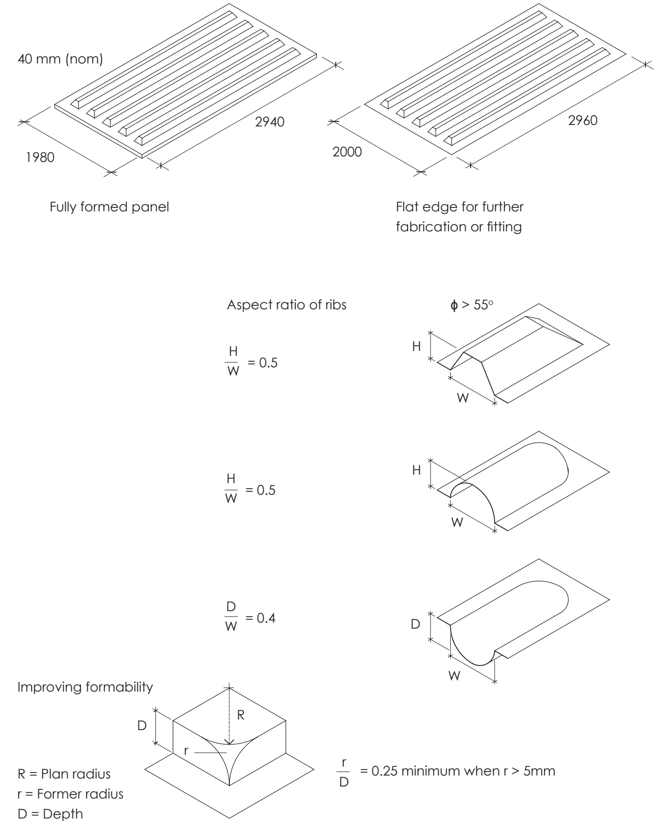


Fig 2.79 Indicative design guidance for superplastic

Advantages of Superplastic Aluminium

Cost savings can be achieved in comparison with fabricated or assembled parts. A single superplastic component will offer weight savings, structural and visual continuity. When formed in aluminium, the component retains all the advantages of 'conventional' aluminium alloys, including the range of finishes and a good strength-to-weight ratio. In comparison to die-casting, the tooling costs are significantly lower. Superplastic components have the benefit of offering form and grain to a product or building. Ron Arad's B.O.O.P table, see Figure 2.80, ably demonstrates the three-dimensional potential of superplastic aluminium. An alterative method for the forming or contouring aluminium cladding panels is explosion forming, as undertaken by 3D-Metal Forming BV of the Netherlands, which was founded as a spin off company form TNO in 1998.[33]

Fig 2.80 B.O.O.P low table by Ron Arad produced using cavity-formed superplastic aluminium

Milling, Machining and Cutting

The bedrock of aluminium fabrication processes are milling, machining and cutting. Most aluminium alloys are relatively soft and this aids all of these processes, especially in comparison to mild and stainless steels. Apart from the use of computer numeric control systems, these processes would be familiar to the workers in a nineteenth century workshop.

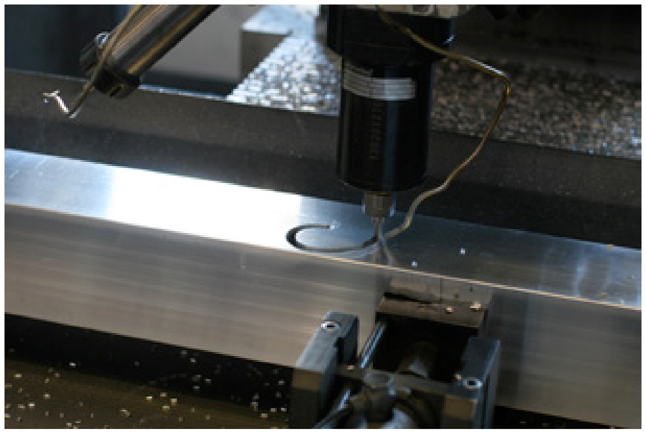


Fig 2.81 Machining a circular port in a square extruded aluminium section during the fabrication of Vague Formation

Fig 2.82 CNC machining centre at Unterfurtner, during the fabrication of Vague Formation: mobile music pavilion designed by soma

The general practice is for the system houses to sell the CNC control cutting centre as well as the curtain walling and window systems. Interestingly Schüco place a strong emphasis on improving the workflow and certainty of fabrication processes for its clients, the fabricators. This is embodied in Fabrication Data Centres that bring the Building Information Model (BIM) and all of Schüco systems, also in 3D into the fabricators workshop in the form of a robust touch screen.

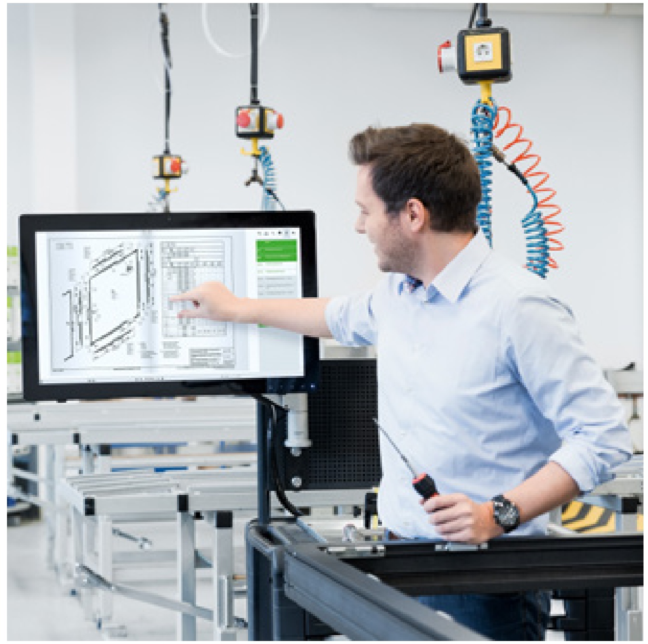


Fig 2.83 A Schüco fabrication data centre

Fig 2.84 A CNC cutting centre – courtesy of Schüco

Laser Cutting

A laser is computer numeric controlled (CNC) to cut sheet materials. Laser cutters come in three types: moving material, flying optics and hybrid systems. In the first type, as the name suggests, the laser optics are fixed and the material with the supporting bed move. The second type, the table is stationary and the cutting head moves – hence flying optics. This technique includes five-axis machines, thus sophisticated angled cutting is practical. In hybrid laser cutting, the bed moves in one direction, say the X-axis and the cutting head along the Y-axis.

Fig 2.85 A flying optics 4kw laser cutter at Metaveld BV

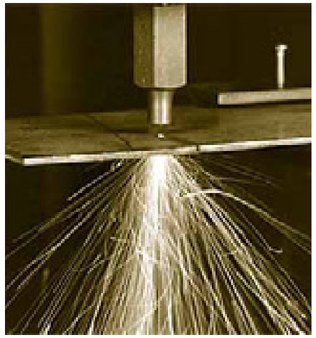


Fig 2.86 The first oxygen assisted laser cutting of 1mm thick steel sheet in May 1967

Laser processing of materials is a well-developed technology. Peter Houldcroft (Deputy Director of The Welding Institute, Cambridge, England) is credited as the first person to use laser cutting to cut metal, when in 1967 he cut 1mm thick steel sheet with an oxygen assisted focused CO_2 laser beam.[34] The first laser was produced in the USA by Ted Maiman in 1960.[35]

Typically aluminium sheet up to 8mm thick can be cut by a laser, with aluminium alloys more readily cut than pure aluminium. AGA advise that 'anodised aluminium is easier to cut due to the enhanced laser light absorption in the thick surface layer of aluminium oxide.'[36]

Fig 2.87 The two axis flying optics laser cutter, 1975, courtesy of Laser-Work AG

Town Hall Hotel, Bethnal Green, London, England: Architect, RARE Architecture, 2010

The laser cut aluminium solar shading of the new extension of Town Hall Hotel was designed by Nathalie Rozencwajg and Michel da Costa Goncalves of RARE Architecture using parametric techniques and full scale prototyping. It is designed to stand in contrast to the restored Edwardian Bethnal Green Town Hall and forms a key element of this new hotel and conference centre. The Town Hall, which is Grade II listed, was designed by architects Percy Robinson and W. Alban Jones and completed in 1910. The partners at RARE Architecture, Nathalie Rozencwajg and Michel da Costa Goncalves say of their practice:

> RARE Architecture directs its work towards the experience of phenomenon where one-to-one testing - the making of 'chef-d'oeuvre' - exists as a learning tool to refine our works based on contextual and phenomenological perception, which escapes codified representation and traditional simulation. The synergy of method and form not only brings us innovation, but permits us to produce effect.
>
> In the course of enhancing standard building materials by new modes of production, the perception of the finished product becomes entirely reformed. Our Town Hall Hotel project challenges the dichotomy between scale and complexity. An inverted approach was proposed, where the detail, the material and the perceptive, were guided by an overall coherent design informing the conversion of the 9,000m^2 Grade II listed structure into a hotel and serviced apartments, conference facilities and a fine dining restaurant and bar.[37]

The digitally sculpted new extension responds to the listed building, the context and rights to light. The geometry was studied by RARE via physical and digital models. The new aluminium architecture is crystalline in form yet clearly formed from folded aluminium skins.

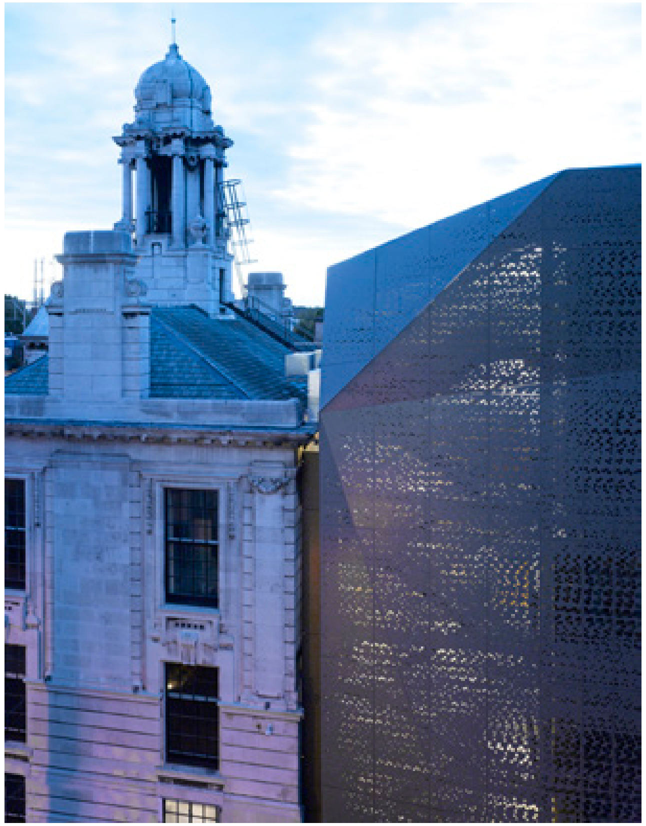


Fig 2.88 The laser cut aluminium façade of Town Hall Hotel, designed by RARE Architecture (2010), in contrast to the Town Hall designed by Percy Robinson and W. Alban Jones (1910)

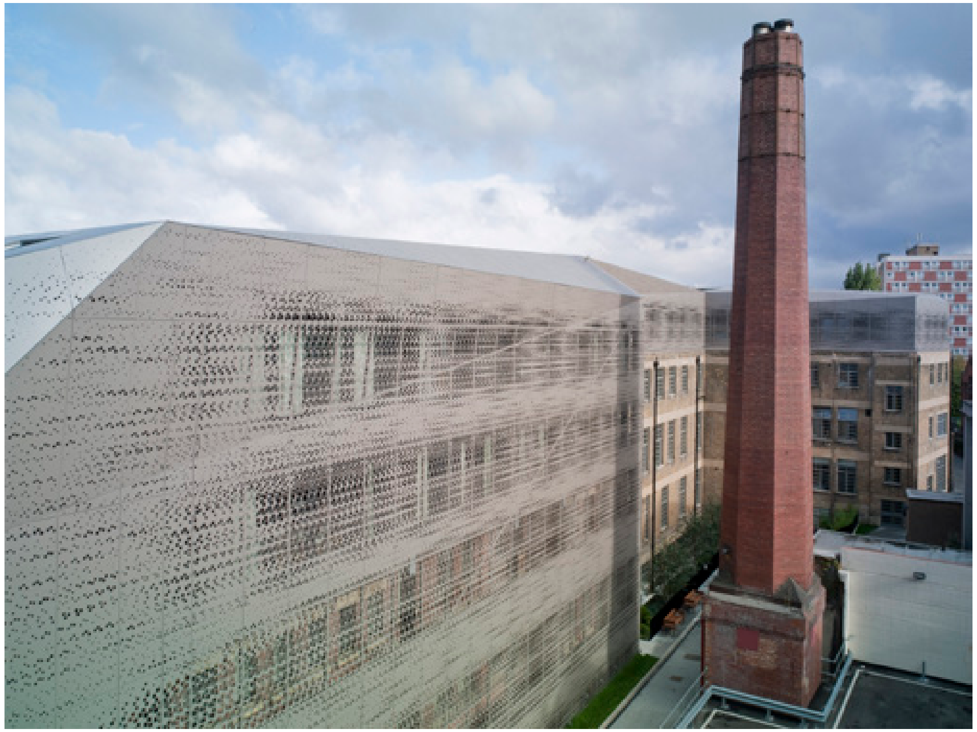


Fig 2.89 The perforated and folded aluminium skin of Town Hall Hotel

The solar shading was designed by compositional studies of existing façades, which RARE deconstructed 'to generate a new ornamental vocabulary'.[38] The patterns for the new performative aluminium skin, the solar shading and veiling of the hotel were studied both aesthetically and upon how well each option functioned. This design development depended on parametric modelling and digital fabrication, primarily laser cutting. The practice studied the cost of the options 'as cost is a direct factor of machining time – the scale and design of the cuts, scores and milling is inherently correlated to the cost of production.'[39]

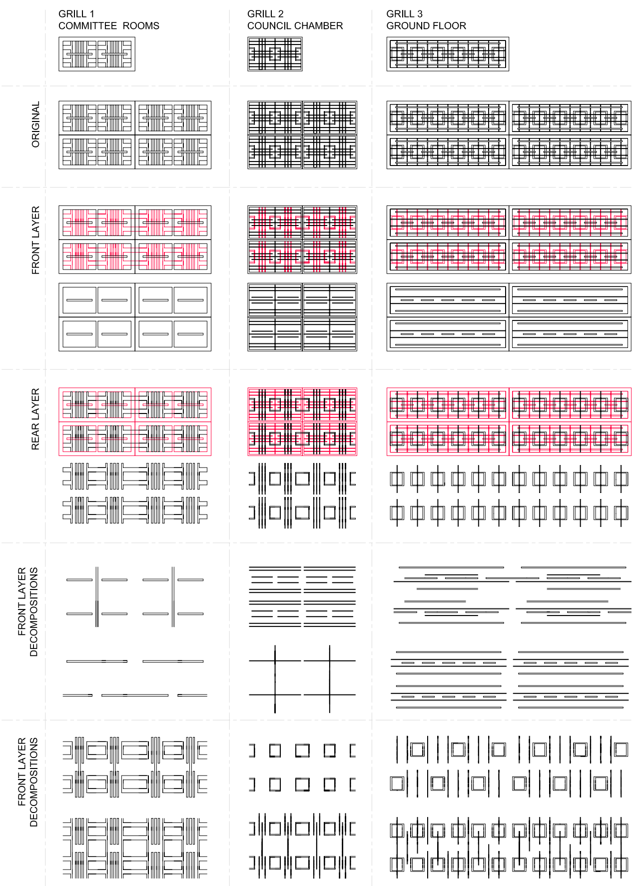


Fig 2.90 RARE Architecture's evolution of the façade elements

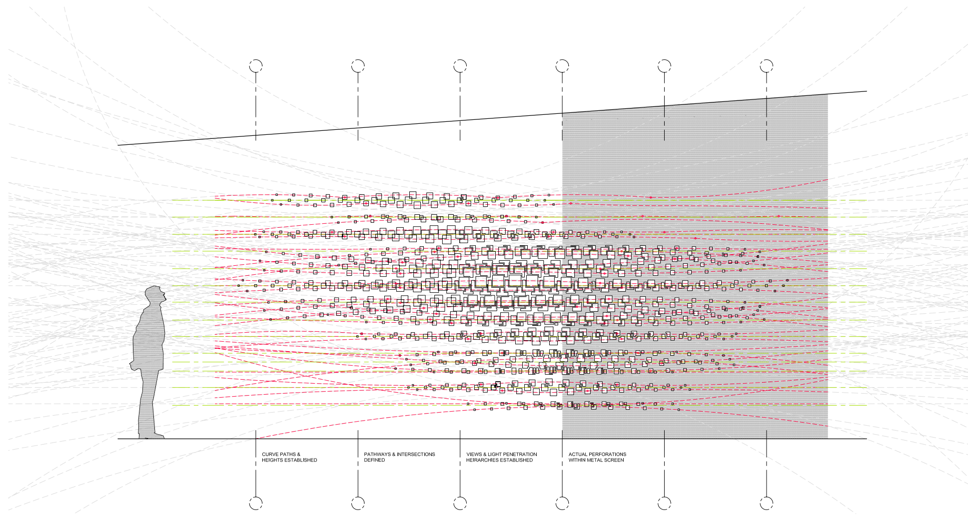


Fig 2.91 RARE Architecture's conceptual and digital approach to the façade composition

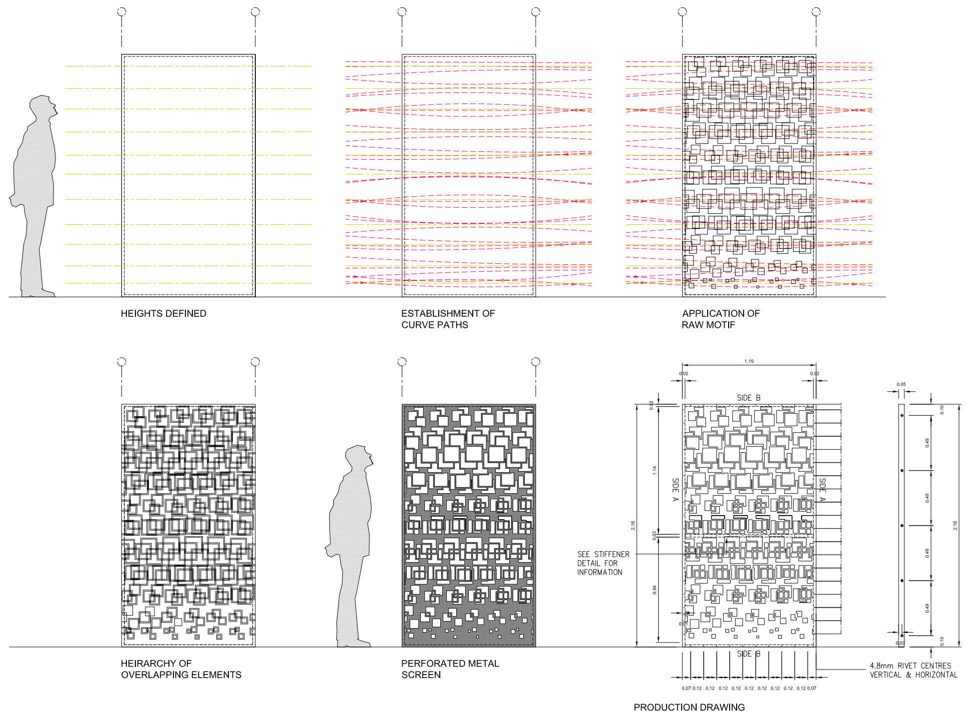


Fig 2.92 RARE Architecture's studies of the elements of the façade composition

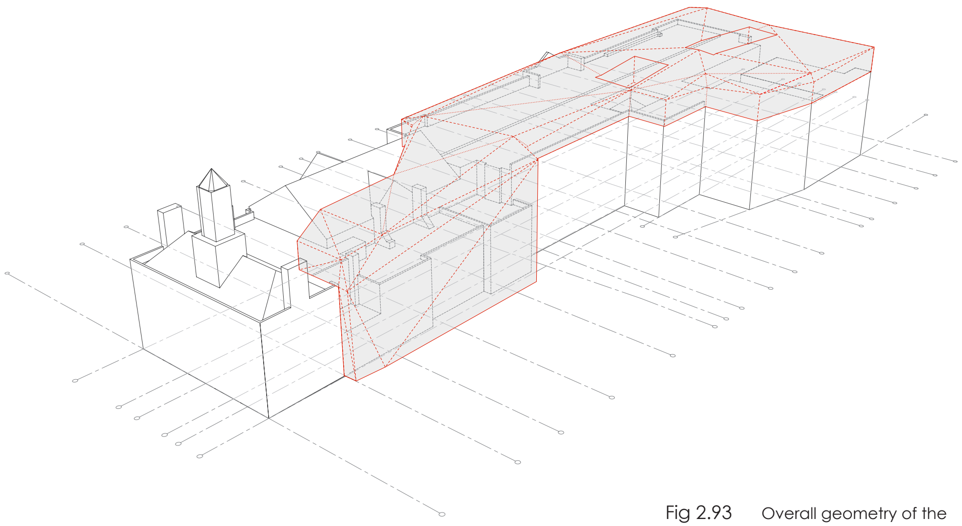


Fig 2.93 Overall geometry of the Town Hall Hotel extension

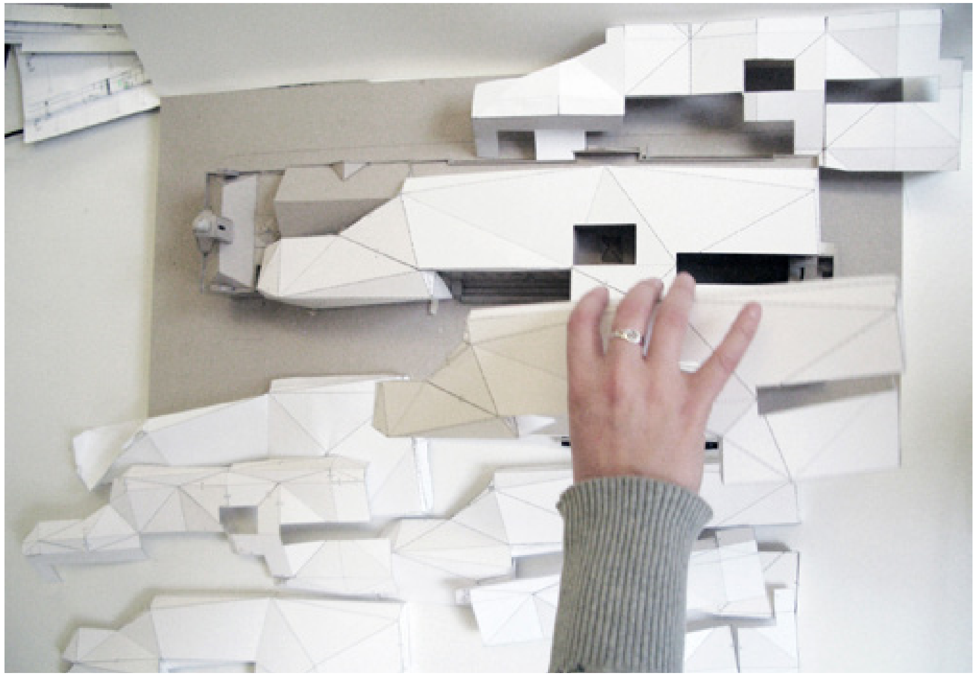


Fig 2.94 Iterative laser cut models fabricated in-house by RARE Architecture

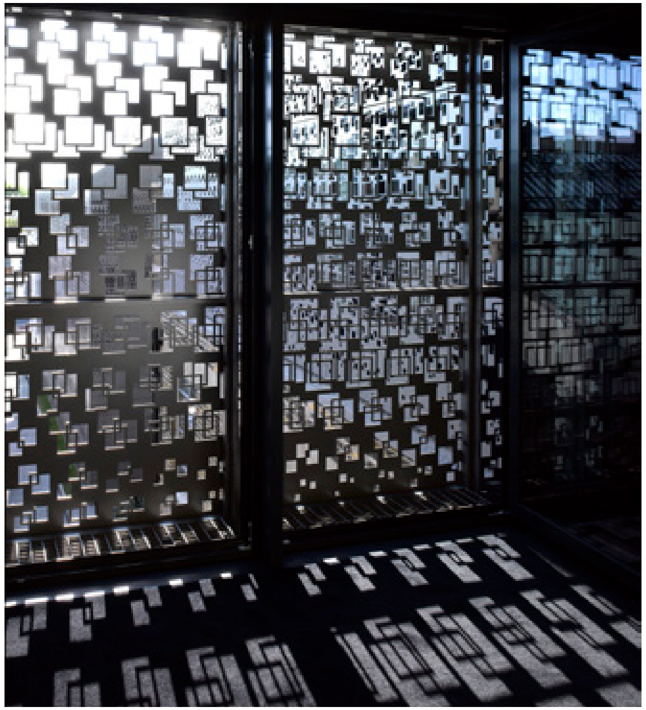


Fig 2.95 View from inside a hotel room

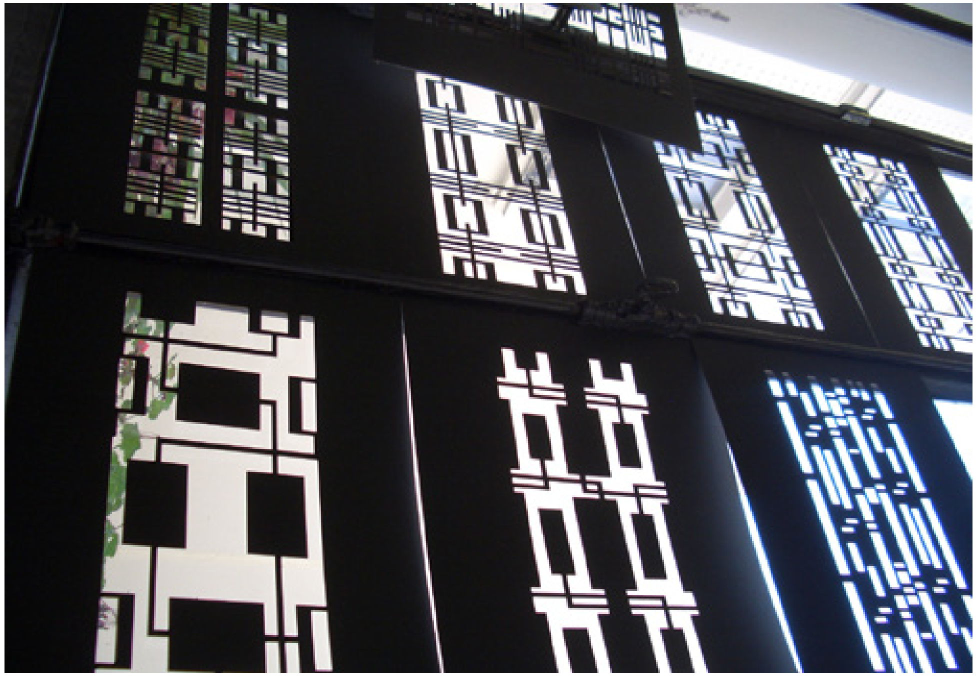


Fig 2.96 Options for the perforated aluminium solar screens

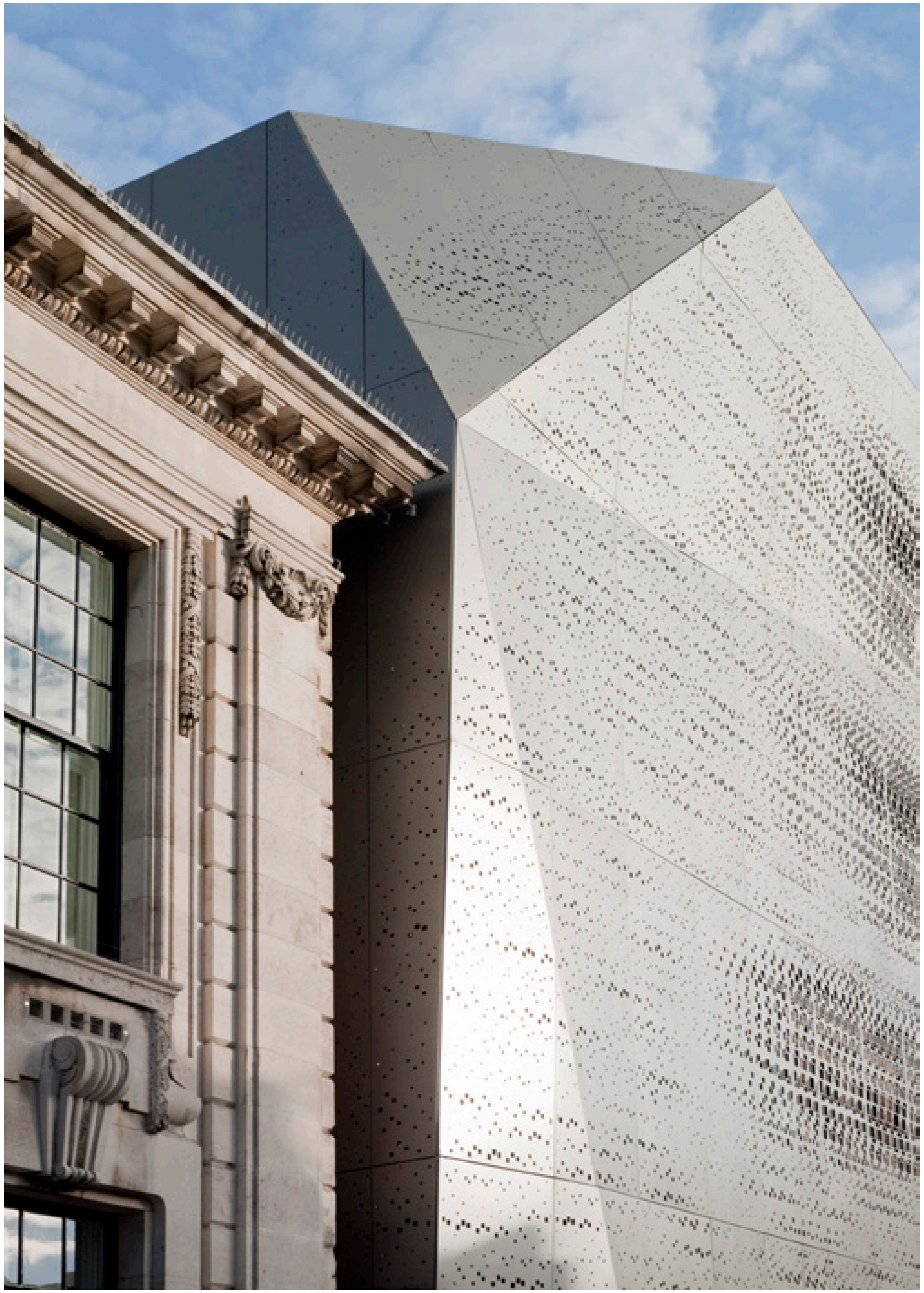


Fig 2.97 A façade of Portland Stone from 1910 with a laser cut aluminium skin from 2010

Some residents of Bethnal Green may be dismayed by the reuse of their Town Hall, once the seat of local government, as a smart hotel. However, by the 1980s the Town Hall had fallen into disrepair and was on English Heritage's Risk Register (now Historic England's). This project in the east end of London is a dynamic balance of early twentieth and early twenty-first century architecture. Precisely 100 years apart, a juxtaposition of architecture formed of Portland Stone with Welsh Slate and a skin of anodised aluminium has been created.

Fig 2.98 A balcony of the Town Hall Hotel

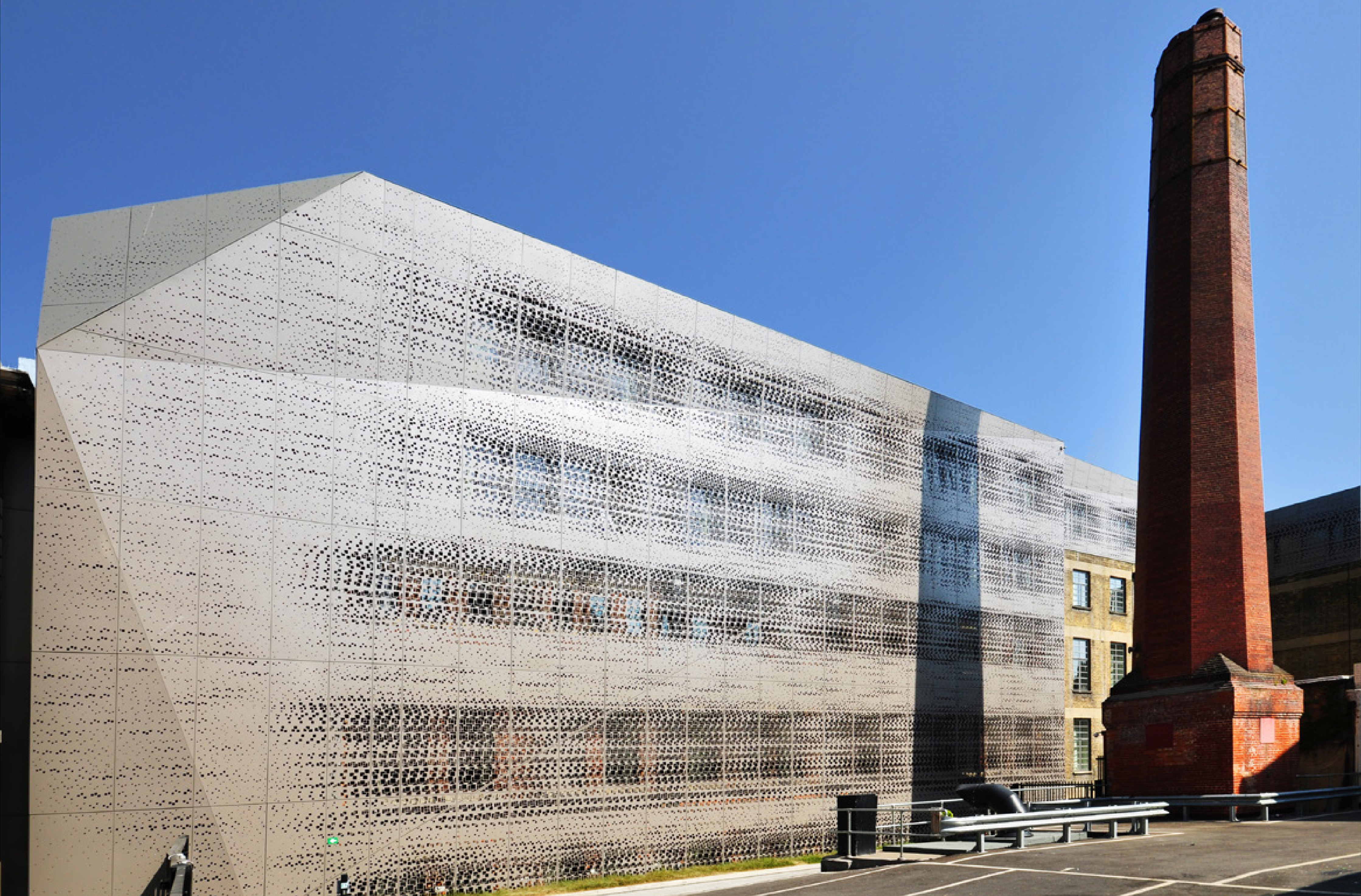


Fig 2.99 Town Hall Hotel, RARE Architecture, 2010

Protocell Meshwork, Nottingham and London, England and Cambridge, Ontario, Canada: Architect Philip Beesley, 2012-2013

Philip Beesely, who studied fine art and architecture, has created a body of work that dates back to 1997. He is a pioneer of digital fabrication, in part as a founder of the Integrated Center for Visualization, Design and Manufacturing (ICVDM) at the University of Waterloo School of Architecture, in 2000. Since 2003 he has produced immersive installations, primarily from flat stock materials. He has taken one process, laser cutting and initially two materials, acrylic and Mylar and produced an inventive and immersive three-dimensional installation. Cut from flat stock sheets and using minimal materials with the minimum of waste.[40] The minimisation of waste is produced by using a carefully considered packing geometry. In 2012, working in collaboration with the author, Dr Chantelle Niblock, their students, and the Architecture + Tectonics Research Group of The University Nottingham, Philip Beesley designed the Protocell Mesh. For the first time he used laser cut aluminium components to form the hyperbolic grid shell of this installation. Philip Beesley takes inspiration from Richard Buckminster Fuller, yet the geometry is more organic. Protocell was part of *Living Architecture* research programme, a collaboration between the Universities of Waterloo, Nottingham, and Universitet Syddansk, funded by The Social Science & Humanities Research Council of Canada. It was the key installation in the Prototyping Architecture Exhibition 2012-13, organised by the author and exhibited in Nottingham and London, England and Cambridge, Ontario, Canada.[41]

Fig 2.100 Protocell Mesh at the Prototyping Architecture Exhibition in Cambridge, Ontario

Fig 2.101 Assembling the Protocell Mesh as part of the Prototyping Architecture Exhibition at Cambridge Galleries, Ontario

Protocell Mesh is constructed from a series of chevron shaped components that are arranged to form a suspended meshwork canopy. Emma Eady, Dominic Ward and Vikash Patel, final year students at the Nottingham School of Architecture, reported on their experience of prototyping Protocell:

> Fabrication began at the University of Nottingham, with acrylic components being laser cut in the Built Environment's Centre for 3D Design and with aluminium components laser cut in Derbyshire by FC Laser, true file to factory production, which bypassed the Atlantic Ocean. The unit group of 15 students, was split into groups of 3 and 4 to begin assembly of the acrylic lilies. After a series of successful generations, a system of standardised sets of parts had been developed with a tested laser-cut snap-fit joint. Whilst on the site visit to Beesley's practice in Toronto, he explains, 'methodology in the initial production focuses on the component itself, clarifying and refining the composition.'[42] This proved to be fundamental to the mesh's successful construction, given the construction team's unfamiliarity with the initial design.[43]

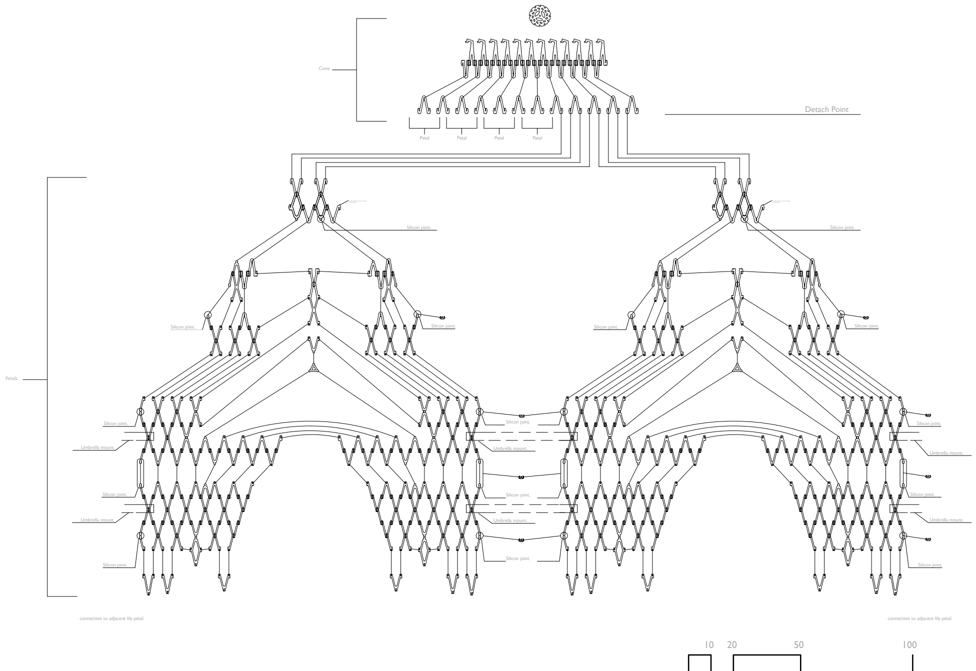
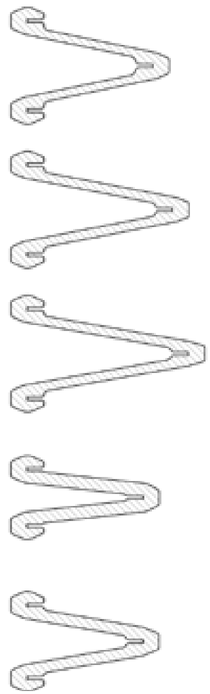
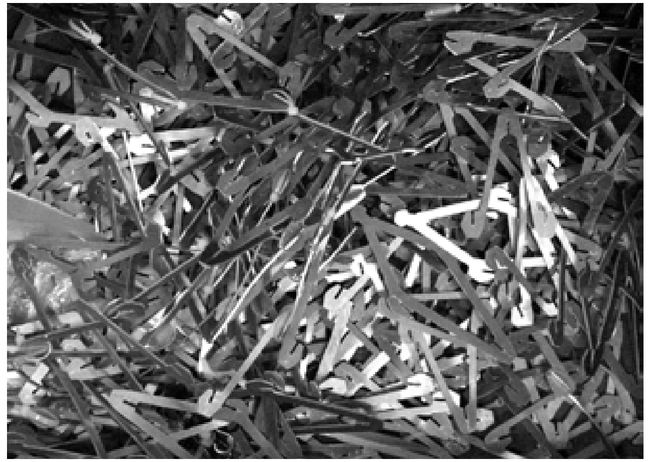


Fig 2.102 Philip Beesley Architect's drawing of the lillies

Fig 2.103 The lillies are assembled at ground level





The umbrella stays were fabricated from 3.2mm thick aluminium and the chevrons 1.6mm thick. Both were laser cut from 3003-H14 aluminium alloy and left mill finish. These components proved somewhat challenging to ones fingers, as they were assembled by hand. The temper also proved to be too ductile during disassembly, which occurred three times, Nottingham, London and Cambridge, Ontario. A higher stiffer temper would make a better specification in future.

Fig 2.104 [above] Drawings of the aluminium chevron components

Fig 2.105 [above right] Drawings of the aluminium chevron components

Fig 2.106 [right] The third assembly of the Protocell Mesh, some aluminium components show a need for greater robustness in repeated assembly and disassembly

Fig 2.107 Students assembling the Protocell Lillies in Nottingham

Fig 2.108 The Protocell Mesh is almost complete

Fig 2.109 Dextrus hands are essential for assembling the components of the Protocell Mesh

The new Energy Technologies Building of The University of Nottingham was constructed in 2011-12, on a former industrial site on Triumph Road, the site of the Raleigh Bicycle factory, demolished in 1996. To construct the Protocell Mesh, this new research building once again became a factory, with volunteer piecework by Nottingham Architecture students led by Philip Beesley and Jonathan Tyrell from his office. Although this work was repetitive, to assemble relatively small-scale laser cut parts into a meshwork that is immersive and of a spatial architectural scale. This was not the monotony experienced by wage slaves in the mid- twentieth century, when mechanisation had taken command. The meshwork was assembled on time for the opening of *Prototyping Architecture*, in time for all to return to the School of Architecture to listen to Philip Beesley explain his approach to architecture.[44]

The Protocell Mesh integrates first-generation prototypes that include aluminium meshwork canopy scaffolding and a suspended protocell carbon-capture filter array. The scaffold that supports the Protocell Mesh installation is a resilient, self-bracing meshwork waffle. Curving and expanding, the mesh creates a flexible hyperbolic grid-shell. The meshwork is composed of flexible, lightweight chevron-shaped linking components. The chevrons interconnect to create a pleated diagonal grid surface. Bifurcations in mesh units create tapering and swelling forms that extend out from the diagrid membrane, reaching upward and downward to create suspension and mounting points. Floating radial compression frames provide local stiffening and gather forces for anchorage. Arrayed protocells are arranged within a suspended filter that lines this scaffold. The array acts as a diffuse filter that incrementally processes carbon dioxide from the occupied atmosphere and converts it into inert calcium carbonate. The process operates in much the same way that limestone is deposited by living marine environments.[45]

In Prototyping Architecture, the author observed:

> This architecture is on the frontier of new possibilities; some might say is this art or architecture? In a sense that is not what is important about this piece, it is really in the thoughts and provocations it produces, where its importance lies. It is more like literature than conventional architecture. It is how the imagination of the viewer is stimulated, where the cultural importance of the work of Philip Beesley lies.[46]

Fig 2.110 Protocell Mesh designed by Philip Beesley, first assembled Nottingham 2012

Waterjet cutting

To cut metals with a waterjet cutter, it is necessary to add abrasives to the pressurised water. The mixture of water and abrasives is typically delivered through a nozzle at 40 million Pascals. In common with all digital fabrication technology waterjet cutters, are computer numeric controlled (CNC). The bed of a waterjet cutter is a protective sacrificial matt. The cutting process does not heat the aluminium being cut, however, the process is very noisy. Five-axis waterjet cutting is capable of producing three-dimensional components from sheet aluminium of an appropriate gauge.

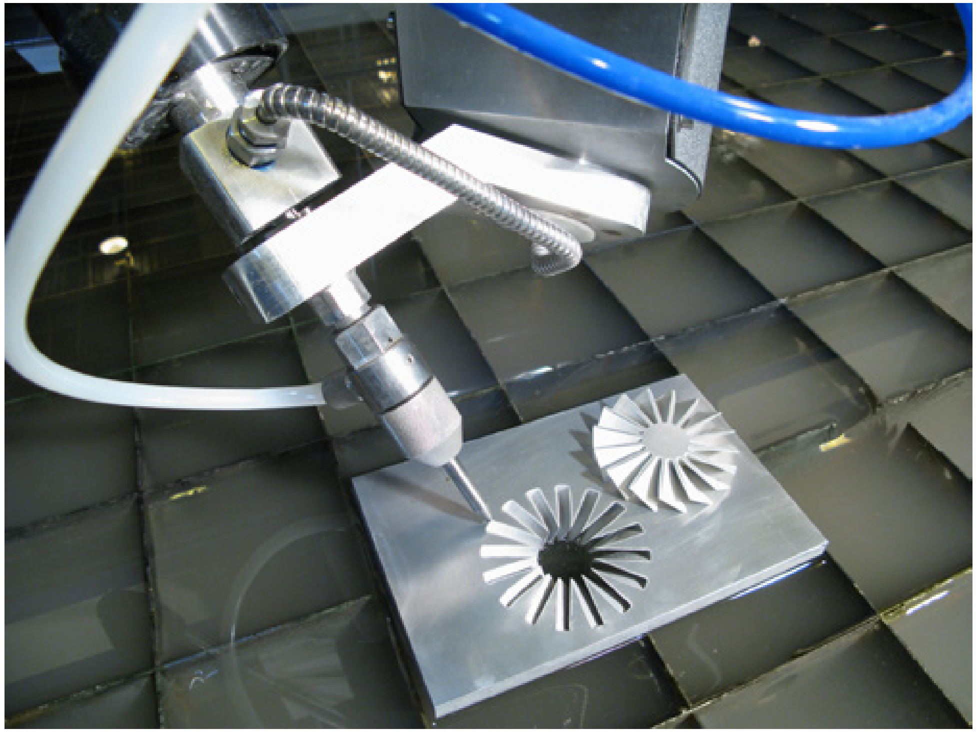


Fig 2.111 Five-axis waterjet cutting of a turbine blade

Fig 2.112 8mm thick waterjet cut anodised aluminium solar shading of the Everyman Theatre, Liverpool, England, architect Haworth Tompkins

Kielder Probes, Northumberland, England: Architect sixteen*(makers), 2004

The Art and Architecture Partnership at Kielder (AAPK) awarded sixteen*(makers) an architecture residency in October 2003. The Kielder Probes were situated in a manufactured landscape, an industrially farmed forest surrounding a flooded valley in Northumberland, England. This is a research rich architecture that set out to 'explore difference in micro-environments across the territory of Kiedler in order to inform strategies for future explorations'.[47] In 2009, sixteen*(makers) went on to design a walkers and mountain biker shelter at Kiedler, Shelter 55/02.[48] During 2004, the probes were installed on an approved site offering a diversity of contexts, dense woodland, a recently harvested area and a stand of saplings, a representative example of the farmed ecology of Kielder. Bob Sheil records that:

> The probes were designed to measure differences over time rather than static characteristics of any given instance. Powered by solar energy, the probes gathered and recorded 'micro-environmental data' over time. The probes were simultaneously and physically responsive to these changes, opening out when warm and sunny, closing down when cold and dark.[49]

Kielder Probes are an experimental example of responsive architecture that was designed to accommodate change and thus gain a greater specificity and achieves a synthesis with the behaviour of visitors to this parkland via micro climatic conditions.

The primary components of Kielder Probes were waterjet cut out of aluminium by Access Engineering and left mill finish. The prefabricated components were sized for transportation, in this case the back of the architect's car. After time in the field, the components were retrieved and exhibited at the Building Centre, London.[50]

The solar shading of the Everyman Theatre, Liverpool, England designed by architect Haworth Tompkin is discussed in Chapter Three, see pages 254–261.

Fig 2.113 Kielder is the UK's largest reservoir and Europe's largest managed forest

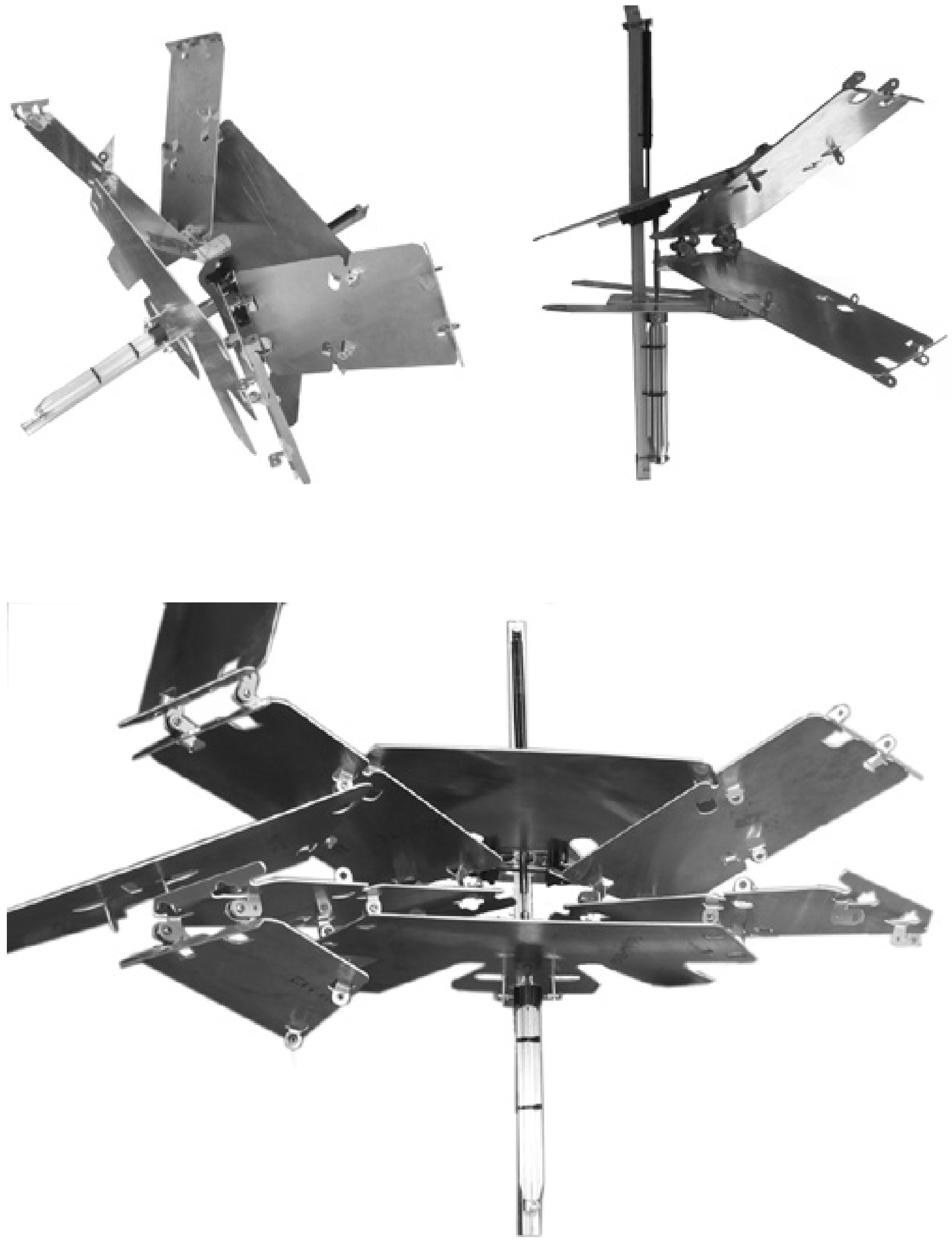


Fig 2.114 The bespoke aluminium probes were designed to act as monitors and responsive artifacts

Fig 2.115 Waterjet cut components of Kielder Probes

Fig 2.116 Impromptu trial assembly outside Access Engineering who waterjet cut the components

Fig 2.117 The waterjet cut aluminium components of Kielder Probes

Fig 2.118 The prefabricated aluminium components are sized for transportation in the architect's car

Fig 2.119 Preparing the Kielder Probes on site in Kielder

Fig 2.120 The Probes on a site where the trees have been recently harvested

Fig 2.121 The Probes are monitoring and responding to the environment, opening out when warm and sunny, closing down when cold and dark

Fig 2.122 [left] Testing the Kielder Probe

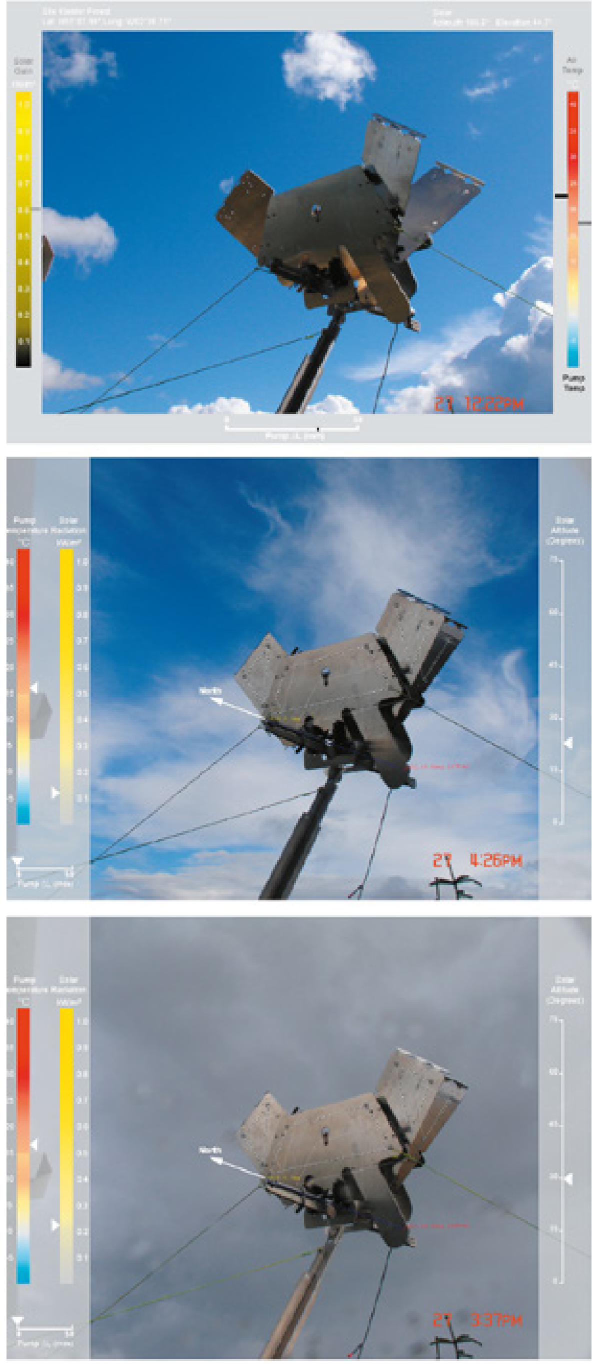


Fig 2.123 A digital analogue composite of a Kielder Probe, superimposition of 30 models and time lapse photo generating software

Fig 2.124– Fig 2.126 Kielder Probes designed by sixteen*(makers) as part of a research programme into evolutionary design and adaptive architecture

The Hive, UK Expo Pavilion, Milan, Italy: Artist Wolfgang Buttress, 2015

The overall theme of the Milan Expo, held in 2015, was: 'Feeding the Planet: energy for life'.[51] The overall masterplan of the Expo was designed by Herzog & de Meuron. Wolfgang Buttress, an artist based in Nottingham, England, won the commission to design the UK Pavilion in a limited competition, which included A_LA, Paul Cocksedge, Barber & Osgerby, David Kohn and Asif Kahn. A diverse selection of artists, designers and architects chosen by the client, UK Trade & Investment, a non-ministerial department of the British government. As observed in *Aluminium Recyclability and Recycling*, pavilions are very public, highly visited and the closest our industry has to an experimental architecture.[52]

Wolfgang Buttress' response to the theme of the expo was to focus on the humble honeybee, its role as key pollinator of crops and the current risk to the well being of the apian population. He observed: 'Bees are incredibly sensitive to subtle variations and changes in conditions and their environment… So the bee can be seen as a sentinel of the earth and a barometer for the health of the Earth.'[53]

Fig 2.127 The Hive, UK Expo Pavilion, Milan, 2015, artist Wolfgang Buttress

He also took inspiration from Richard Buckminster Fuller; ecologically, philosophically and for the tectonics of the Hive. In particular Buckminster Fuller's Montreal Biosphere, the United States' 1967 Expo Pavilion.

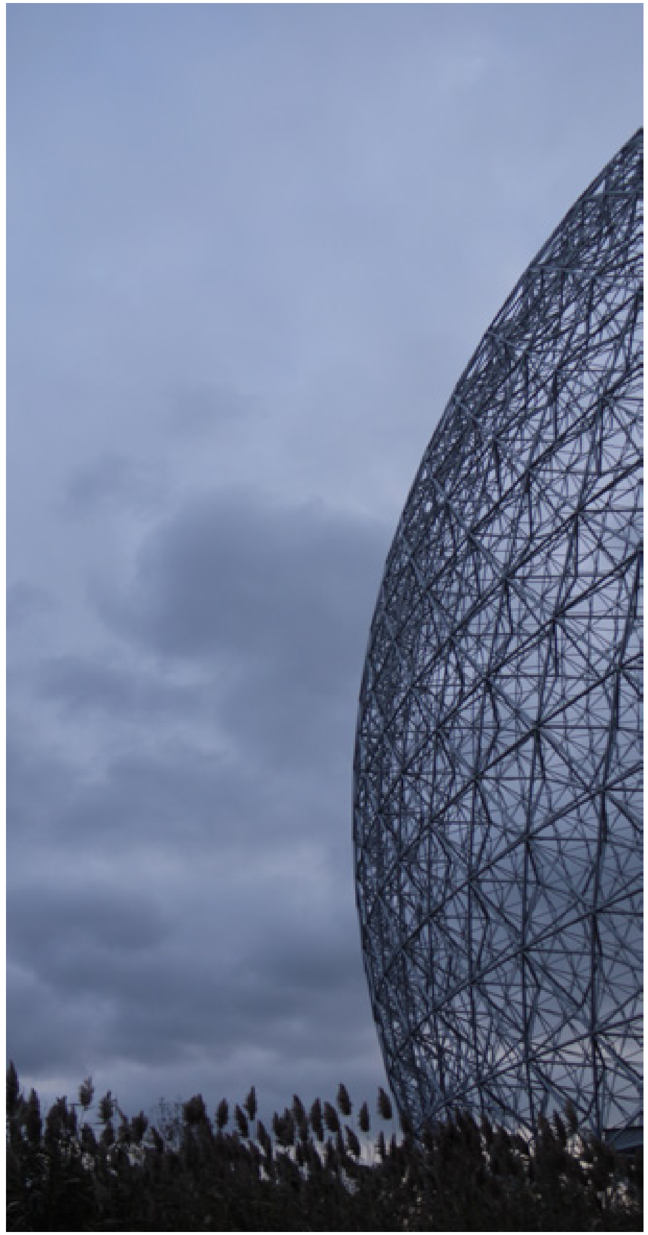


Fig 2.128 Richard Buckminster Fuller's Montreal Biosphere, the United States' 1967 Expo Pavilion, photographed 2015

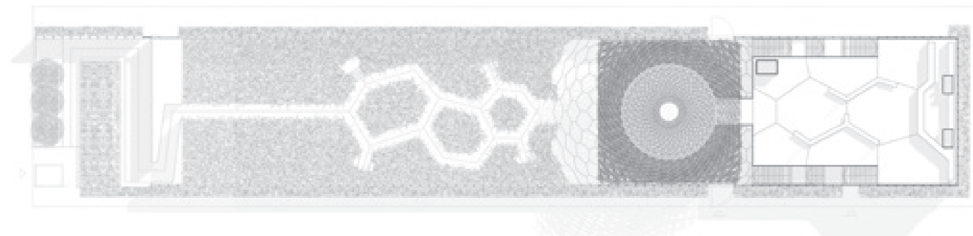
The delivery of the complete experience at the UK Pavilion involved Wolfgang Buttress' studio embracing a series of multidisciplinary collaborations. His ambition for the UK Pavilion was 'to integrate art, architecture, landscape and science.'[54] To design and deliver the Hive Wolfgang Buttress led a multi-disciplinary team of collaborators including: executive architect BDP Manchester, who were also the landscape architect, and structural engineer Tristan Simmonds of Simmonds Studio. His experience of complex geometries included working on Marsyas sculpture for Anish Kapoor, whilst at Arup. This digitally delivered lightweight fabric structure spanning 135m enveloped the space of the Turbine Hall at Tate Modern, London, during 2002.

Fig 2.129 Wolfgang Buttress talking to Prince Harry of Wales at the opening of the Hive in Milan

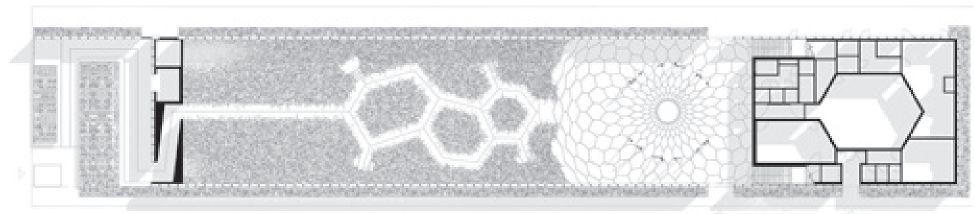
Fig 2.130 The Hive in Milan during the opening day, 1 May 2015

The pavilion site in Milan was 100m deep. It was laid out as a narrative journey through an idealised fragment of a British landscape, with an orchard and a wild flower meadow culminating in the Hive. Placing the pavilion firmly within the English picturesque landscape tradition, delivered utilising twenty-first century technology. However, no bees were imported into Milan from the UK.

The Hive is a fascinating combination of Euclidean geometry and accretive complexity that is probably only possible using three-dimensional computer modelling. It is a 14m cube with a 9m spherical void at its core and it is lifted 3m off the ground plane by 18 circular hollow section steel columns, which are 139.7mm × 5mm. These columns rise 5 meters to meet a 10.8m diameter ring beam. The hive was assembled in 32 horizontal layers of aluminium components, with 6 layers below the ring beam to complete the base of the spherical void. It is assembled accretively as bees would a hive. The layers are linked to form truss-like assemblies. Aluminium was chosen in preference to stainless steel for economy, weight and relative ease of machining the components.



Ground floor



First floor

Fig 2.131 Plan drawings of the Hive, nts

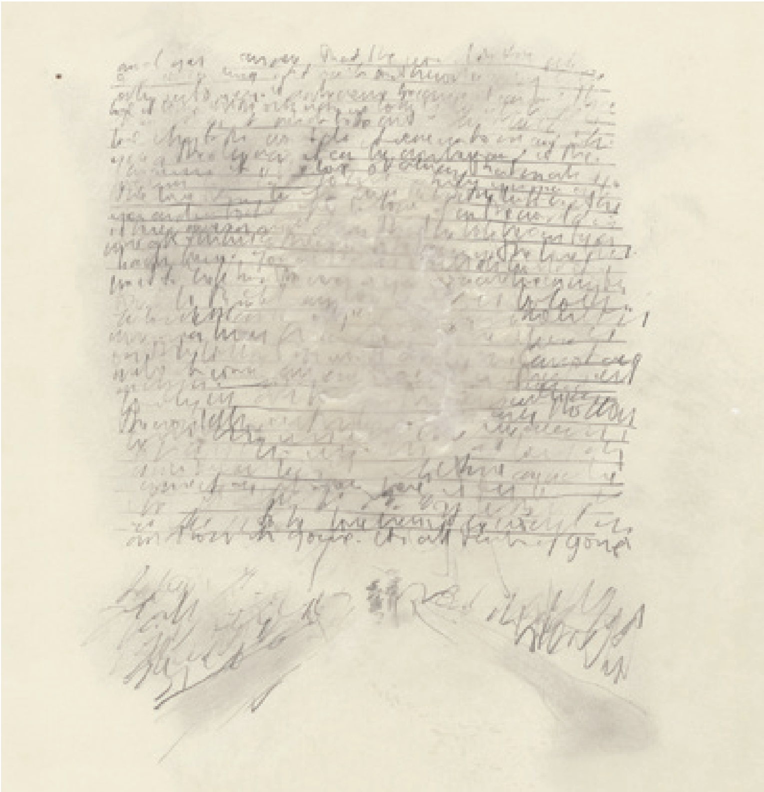


Fig 2.132 Wolfgang Buttress' early sketch of the Hive

The structure was parametrically optimised via close collaboration between Wolfgang Buttress Studio and the structural engineer Tristan Simmonds, to communicate the idea of a beehive, yet forming a robust structure. Tristan Simmonds describes the 'basis of the Hive geometry is a radial hexagonal grid that is rotated slightly at each layer to give a twist. It is generated by repetition'.[55] He recalls the design process:

> Wolfgang Buttress' Hive stood out from other early ideas immediately. The beehive is one of the most iconic structures in nature. We find beauty in its geometry and surprising precision but it is also a piece of pure functional efficiency that has been honed by a billion generations of bees. The initial sketches succinctly conveyed a beehive with three main simple ingredients: the hexagon, horizontal layers and an internal void. The fourth ingredient was that it wasn't simple. The underlying concept was simple but the object itself, filigree and complex.[56]

Describing the evolution of the design as 'a quick Darwinian process'.[57] Simmonds observes:

> The process could only be achieved by writing software. We assumed that every task in the design would have to be carried out time and time again and so each task was automated as much as possible. We spent day and night writing code, however, the assumption proved correct. Eventually a complete redesign involving detailed analysis models, design code checking, structural optimisation of 70,000+ elements and outline drawings could be turned around in a few days. On a conventional project this can take months and typically only happens once.[58]

Specialist fabricators Stage One were appointed as main contactor by UKTI before the design completion and advised on the selection of the design team. Stage One fabricated the components of the Hive in York, using approximately 50tonnes of aluminium. The total number of components that form the Hive is 169,300 and almost all of them were fabricated from aluminium.[59]

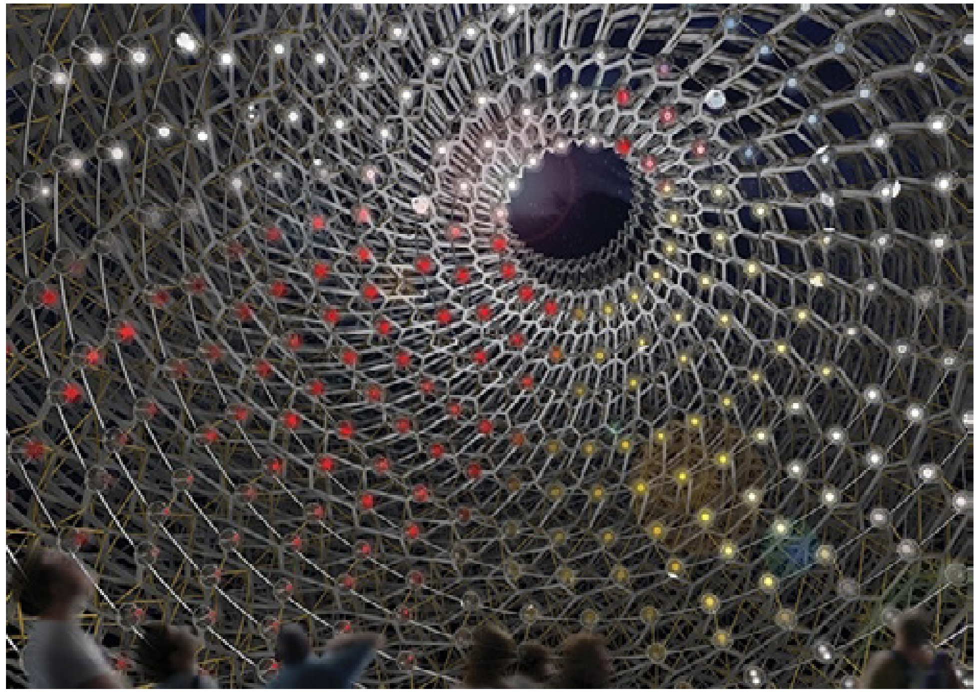


Fig 2.133 Inside the spherical void at the heart of the Hive

Balustrade Panels	72
Chord Plates	5,711
Columns	18
Fittings	80
Glass Floor Panels	38
Hex Studs	16,549
LED Ductwork	378m
LEDs	891
Nodes	33,098
Node Bolts	33,098
Ring Beam Segments	4
Rods	28,782
Splice Bolts	2,856
Spacer Plates	31176
Upper Node Cap Locators	16,549
Total Number of Components	169,300

Table 2.4 The components of the Hive

The components of the Hive were fabricated from 6082 TS aluminium alloy and all remained mill finished. For Wolfgang Buttress rawness was a key principle specifying materials 'throughout the pavilion [that] are generally unprocessed and patinate naturally.'[60] The components are primarily cut from 10mm thick aluminium sheet, however 15mm and 8mm gauged aluminium were also used. Aluminium tubes or rods join the flat plate top and bottom cords of each truss-like layer. Stage One used laser cutting, waterjet cutting, and machining to fabricate the components. The spacer plates in the node connections were laser cut. All the radial and circumferential truss plates were waterjet cut and the rods and node tops were machined.[61] Mark Johnson, CEO of Stage One, records:

> Over 4,500 CAD hours went into developing workshop drawings before machining, finishing and packaging each component in specific batches. Each item was etched with its own reference number relating to specific positions within the Hive's complex warren of hexagonal cells, ensuring our crew could complete the on-site construction in good time.[62]

The manufacturing took Stage One five months, working 16 hours a day. The total time on site in Milan, from starting the ground works in November 2014, was only six months. Stage One deployed 12 people on site, working piece by piece. The first layer was completed in January and the structure of the pavilion was all installed by April, in readiness for the opening of the Expo on May Day 2015.

Fig 2.134 Machined aluminium alloy nodes of the Hive, in Stage One's Workshop

Fig 2.135 Waterjet cut 6082 TS aluminium alloy components of the structure of the Hive

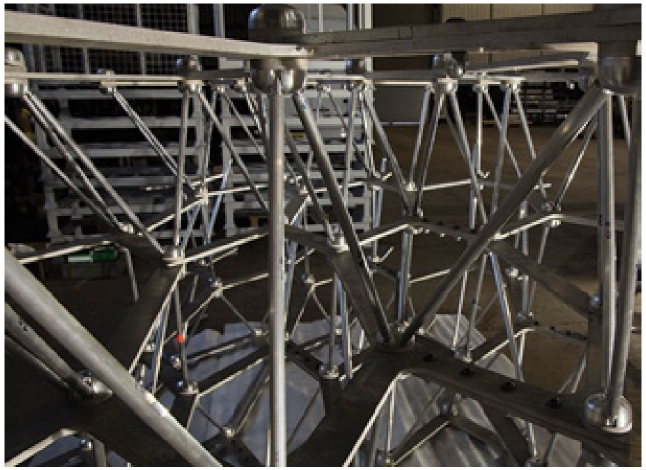


Fig 2.136 A trial assembly of several layers of the meshwork structure

Fig 2.137 Fabrication took Stage One five months

Fig 2.138 Machined ends of the aluminium connection rods

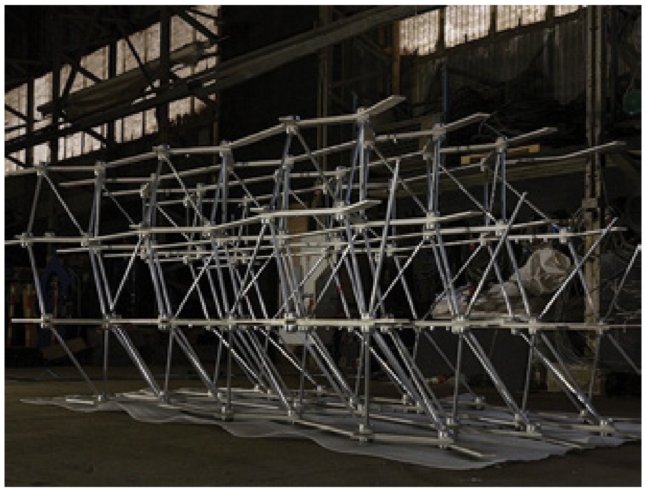


Fig 2.139 Trial assembly of a layer of the meshwork structure of the Hive

Early in the process of designing the Hive, Wolfgang Buttress found that Dr Martin Bencsik was conducting research in the behaviour of bees, based at Nottingham Trent University, School of Science and Technology. Wolfgang Buttress considered him to be undertaking amazing research. ‘By measuring vibration signals, he can interpret bee communications. This is a significant step towards understanding their behaviour and the impact of external conditions and changes. Our central idea was to use these research techniques to connect a beehive in the UK to our pavilion in Milan.’[63]

In the void at the core of the Hive visitors experience sound and light that is a direct response to beehives in Nottingham. The bespoke LED light sources respond to accelerometers within the beehives. Stage One ‘designed, prototyped, refined and manufactured one thousand four-colour (RGBW) ‘pixels’ [LEDs] bright enough to be seen in daylight’.[64] The 891 light sources are arrayed around the void on each of the 32 levels. Stage One’s use of real time three-dimensional computer based ‘visualisations of the many lighting effects saved a great deal of time once on site.’[65]

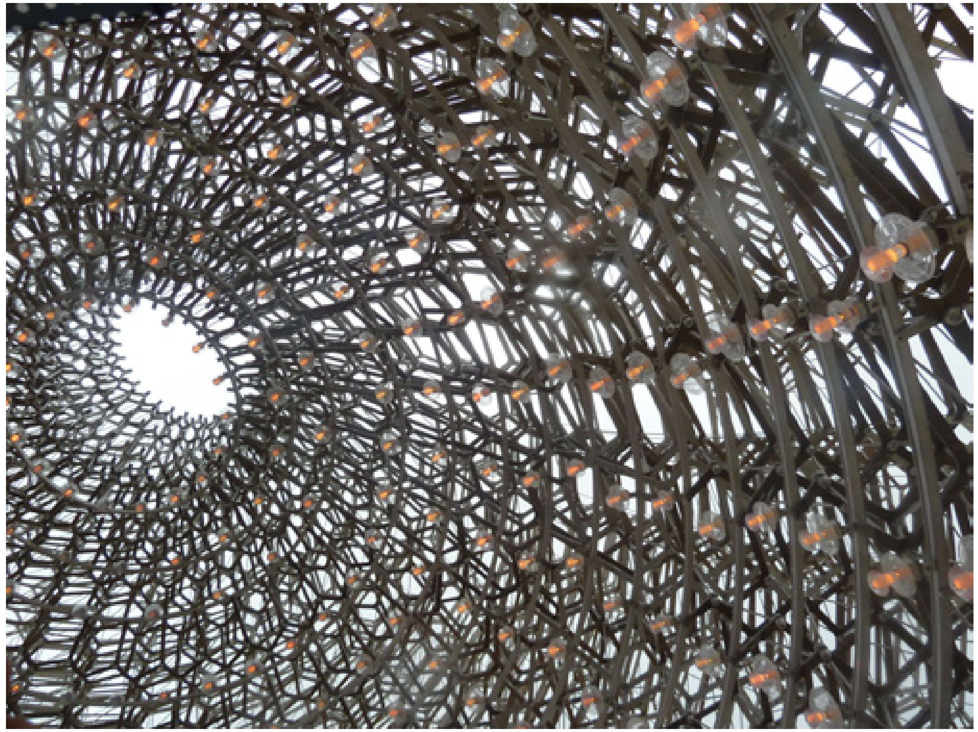
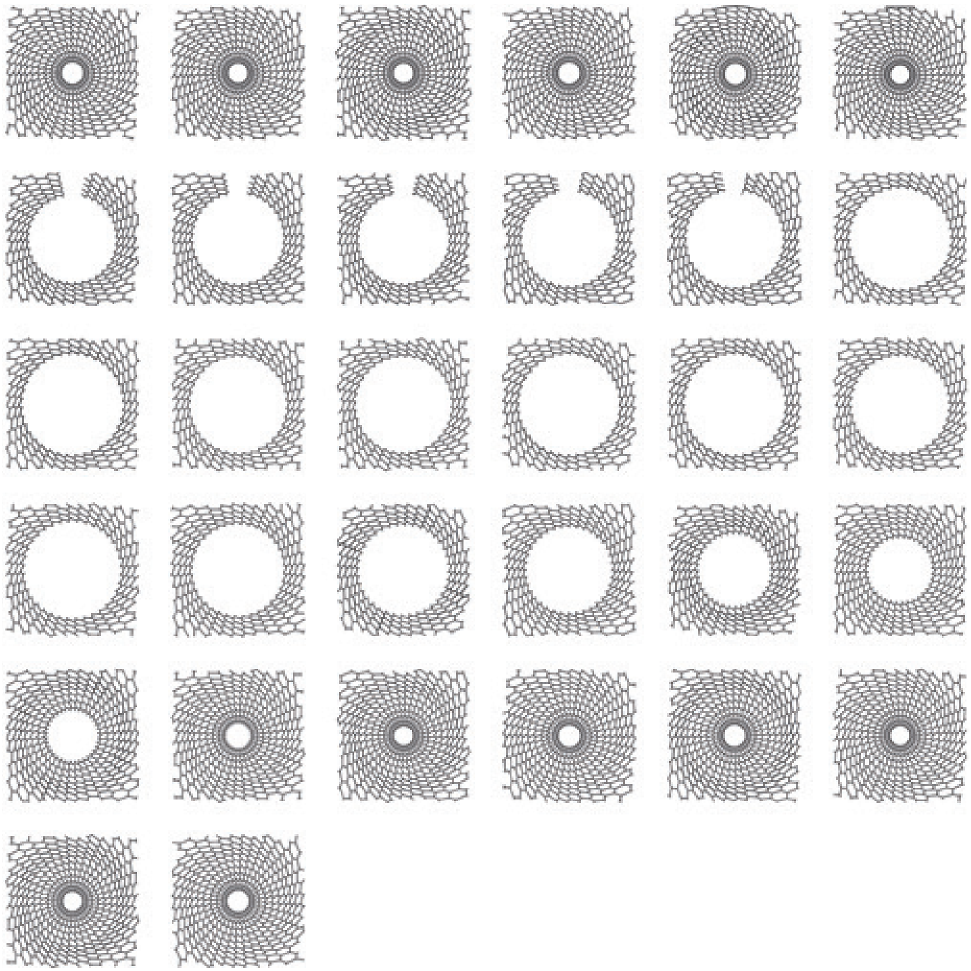


Fig 2.140 The layers of the aluminium meshwork are illuminated by programmable LED lights

Dr Martin Bencsik and Dr Yves Le Conte are collaborators on research funded by EU Framework Programme 7 that aims to help arrest the decline in European Bee population.[66] Both scientists were delighted to contribute to the UK Pavilion:

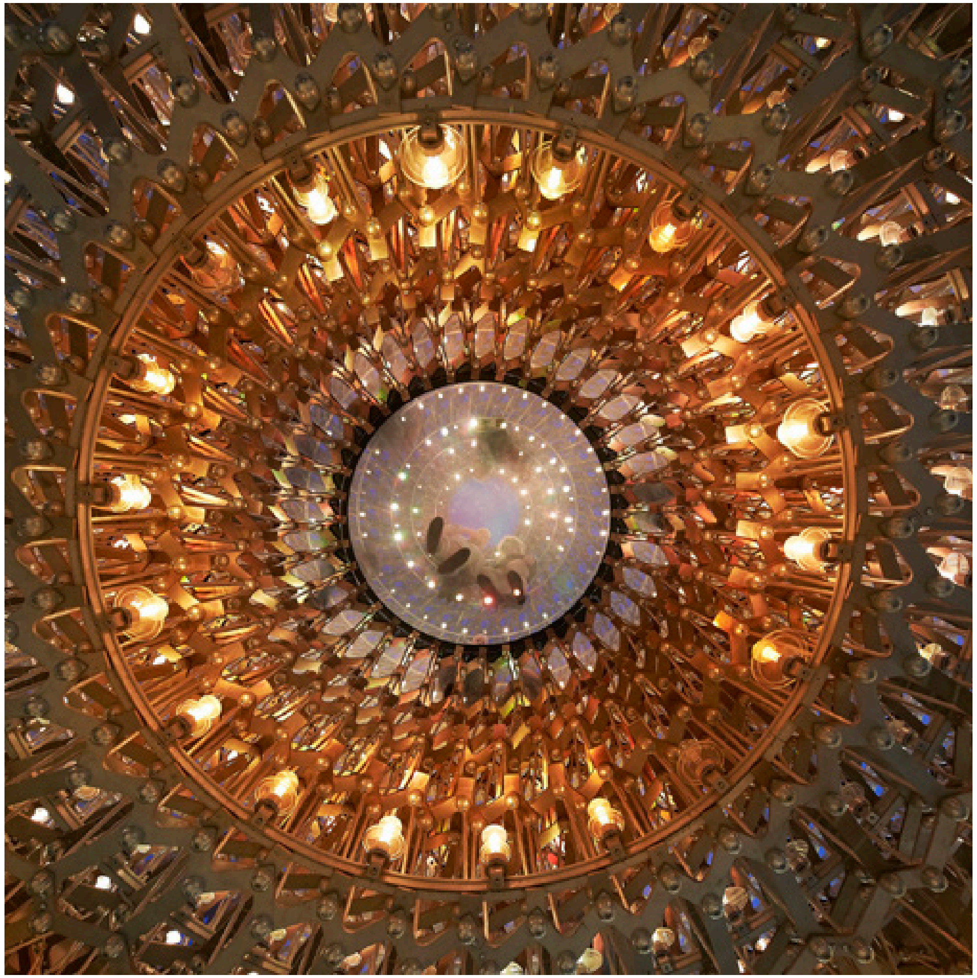
> The results of scientific explorations are most thrilling for the researcher, when he/she is at the forefront of human knowledge. By inviting us to contribute to his artwork, Wolfgang Buttress has given us the opportunity to allow the visitor to share the thrill of scientific discovery. We have supplied live honeybee vibrational data to the UK pavilion, for the visitor to hear both bees' sounds and vibration pulses.[67]

Fig 2.141 The 32 layers of the Hive on plan, from layer 1 top left to layer 32



The experience in this void is sound and vision, 'a dynamic soundscape, ever changing and unique at each moment: a collaboration between human and honeybee. A live feed from Nottingham beehives is streamed to the pavilion in Milan, which 'trigger noise gates at particular thresholds, opening sympathetic harmonious stems pre-recorded by musicians, This is mixed with sounds captured from the bee colony'.[68]

Fig 2.142 Looking up to the glass floor of the Hive, which is at terrace level

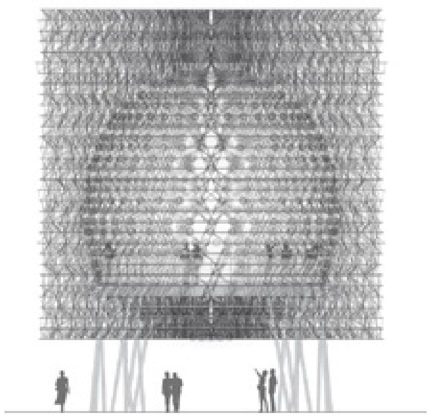


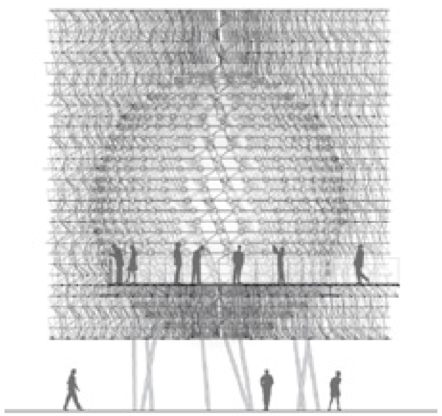
Philip Beesley, of Philip Beesley Architect and Professor of Architecture at the University of Waterloo, reflects on the Hive.

Wolfgang Buttress's Hive is structured as a dense cloud of hexagonal aluminium plate cells filling a ghost-like rectangular solid boundary, rendering a dissolving monolith that rises high above the fairground. Within this bubbling foam is cut the central form of a sphere, forming a pure void within the hovering mass. An oculus caps the sphere, opening the mass to the sky. The lower end of the sphere is positioned one storey above the ground level of the site, covered by a transparent glass floor whose perimeter echoes the oculus above and supports a compact space for occupants housed within the diffusive mass within the heart of the hive. Groups of angled legs raise this spherical chamber high above the level of the ground, clearing the site below. The lower level presents an aerial shadow-play where the figures of occupants exploring the inner space above float, visible through the dense filtering screens of the hexagonal meshwork structure. The floating scene is surrounded by the converging swarm of thousands of structural cells, progressively organized into multiple horizontal layers with gradients of warping organized around a converging polar array with chiral orientation focused around the oculus above and floating floor below. The horizontal aluminium plate cells are stayed by vertical arrays of angled tubular struts radiating from each cell vertex. LED fixtures mounted on each vertex facing the void interior make the interior spherical boundary into a constantly-shifting chimera.

Fig 2.143 [below] Elevation and section of the Hive (NTS)

Fig 2.144 [opposite] Contemplating the future of pollinators in the void of the Hive





Is this a distinctly new architectural form-language? The Hive exemplifies a deliberately unstable, open boundary, defined by delicacy and resonance – perhaps the very antithesis of the firmitas that has defined Western architecture since Vitruvius uttered his famous paradigm. Monumental scale is achieved by aggregating small-scale elements using simple progressive gradients of progressively shifting dimensions made possible by contemporary parametrics and digital machining. Inflections of component jointing systems within profiles and castings provide an understated celebrated ornament, an embroidered cellular textile writ large.

Following the implications of this hovering, diffusive aggregate, we could imagine families of architecture founded on adaptation and uncertainty. A building system using an expanded range of reticulated screens and canopies is implied, constructed from minutely balanced filtering layers that can amplify and guide convective currents encircling internal spaces. Writ large, these qualities speak of involvement with the world. Within this vanguard city fabric, the thermal plumes surrounding clusters of human occupants offer a new form of energy that could be ingested, and diffused, and celebrated. The resonant, dissolving swarm of Buttress and collaborator's aluminium the Hive provides a potent example of a distinctly new kind of adaptive architecture.[69]

The aluminium of the Hive has not been recycled after the closure of the Milan Expo. A better option was found. The pavilion was disassembled and reassembled in Kew Gardens, London. It reopened to the public on Saturday 18 June 2016. The detailing of the Hive with all bolted connections has facilitated is relocation, it is another example of the benefits of **design for disassembly** (DfD), as discussed in *Aluminium Recyclability and Recycling*.[70] Kew Gardens, founded in 1840, is the world's largest collection of living plants and a very appropriate second location for a pavilion inspired by pollinators.

Fig 2.145 The aluminium meshwork structure of the Hive being assembled by Stage One in Milan

Fig 2.146 Honey Bees in a hive in Notingham

Fig 2.147 [overleaf] The aluminium meshwork of the Hive

Welding

Aluminium should no longer be considered difficult to weld, the skin and structure of the Networker 465 commuter train (1991) is formed from welded sheet aluminium to form a smooth outer profile and a **monocoque** construction. Similarly, the hulls of the Sea Cat catamaran are formed of welded aluminium. The **TIG or Tungsten Inert Gas** welding process was invented in the 1940s. In this process an arc is struck between a non-combustible tungsten electrode and the work piece, with filler rod being fed independently. Fluxes are unnecessary and oxidisation is prevented by a shield of inert gas, such as argon, that envelopes the weld area.

In **MIG or Metal Inert Gas** welding a direct current of reverse polarity is struck between the work piece and a continuously fed welding rod, which acts as filler and electrode. Penetration the work piece cannot be as closely controlled as in TIG welding.

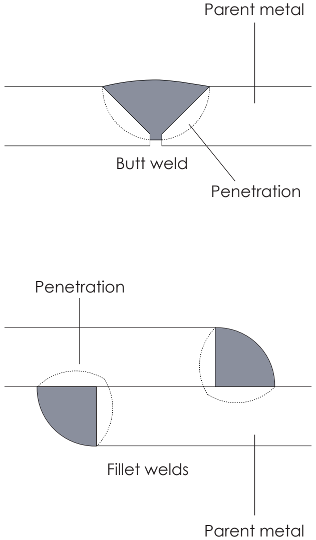


Fig 2.148 Fillet and butt welds

Fig 2.149 Welding of extruded aluminium structure for the Vague Formation, a mobile music pavilion designed by soma, 2011

Friction Stir Welding

Friction stir welding (FSW) was invented in December 1991 at The Welding Institute (TWI), England, with W.M. Thomas named on the UK patent 9125978.8. It is typically used for joining aluminium extrusion and sheets. FSW is a solid-state joining process, where the metal is not melted; rather it is soften by a friction-induced increase in temperature and joined by mechanical pressure. FSW is in essence quite simple, although a brief consideration of the process reveals many subtleties. The principal features are shown in Figure 2.150. A rotating tool is pressed against the surface of two abutting or overlapping plates. The side of the weld for which the rotating tool moves in the same direction as the traversing direction, is commonly known as the 'advancing side'; the other side, where tool rotation opposes the traversing direction, is known as the 'retreating side,' advise P L Threadgill of TWI and his academic colleagues.[71]

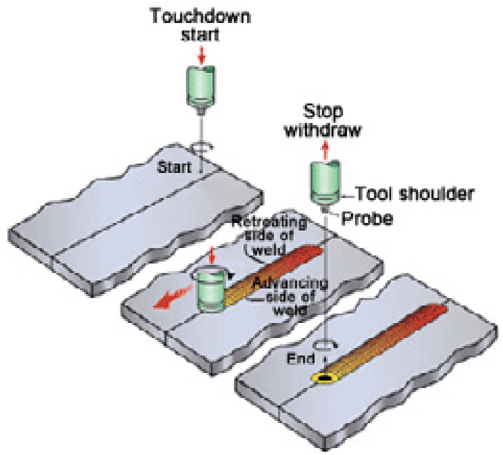


Fig 2.150 The principle processes in friction stir welding, courtesy of TWI

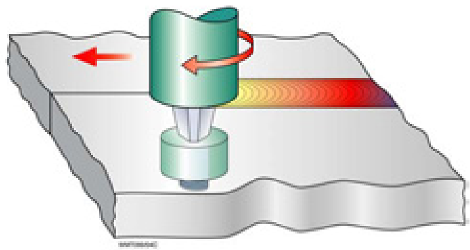


Fig 2.151 Self-reacting bobbin stir welding, showing near and far side shoulders, courtesy of TWI

Since 1991 TWI has continued to research and develop FSW, W. M. Thomas advises that: 'Bobbin stir welding is different form conventional FSW in that there is no need of an anvil support plate. The constraint and support necessary of the bobbin weld region is provided by near and far side shoulders of the tool. Friction stir welding using a self-reacting bobbin tool has been shown to be effective for joining hollow extrusions and lap joints.'[72] Noting that primary advantages of bobbin stir welding will 'eliminate partial penetration, lack of penetration or root defects.'[73] Current applications of FSW include the welding of extruded aluminium bridge deck sections, as discussed in Chapter Five.

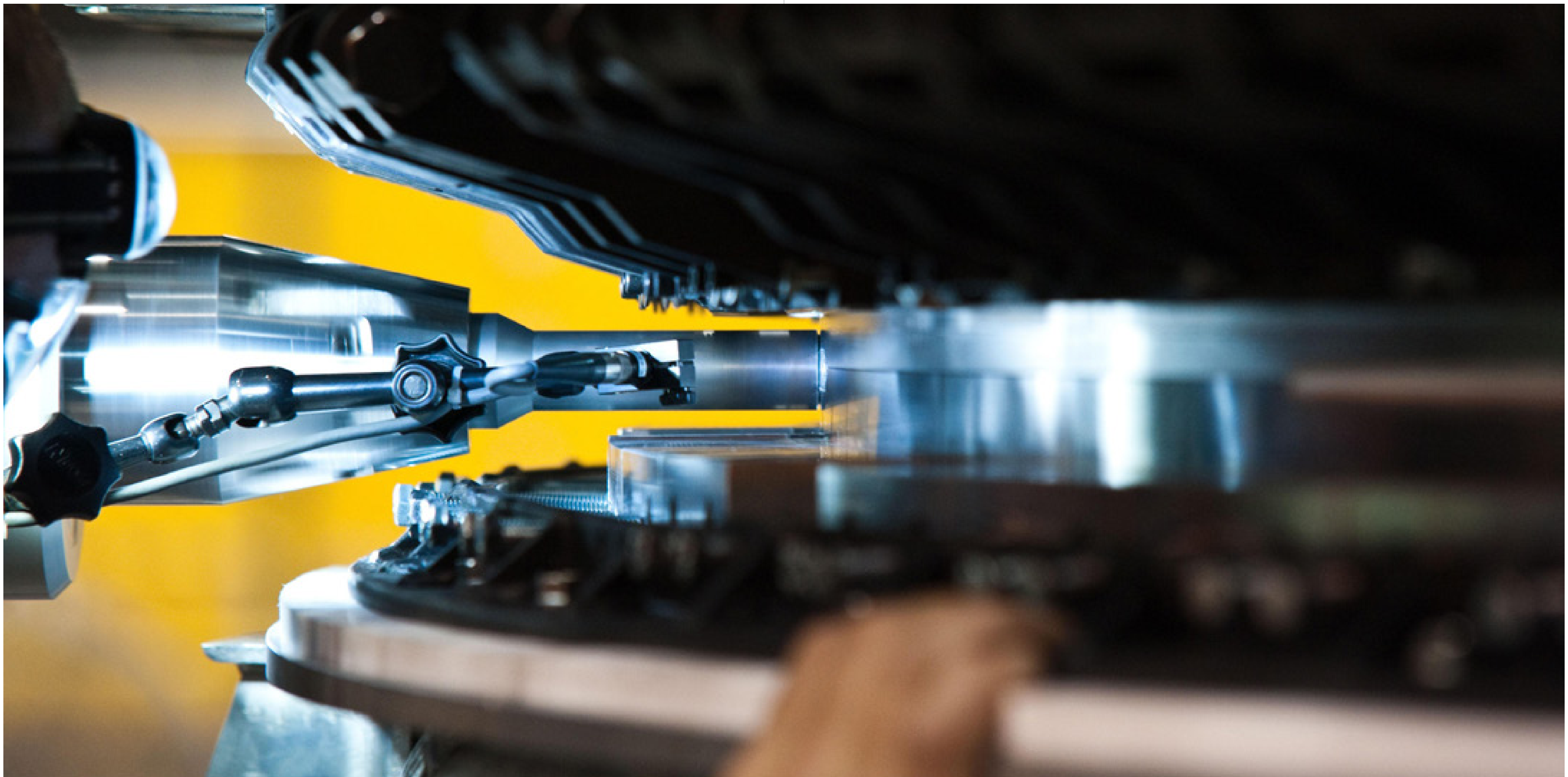


Fig 2.152 The bulkhead and nosecone of the Orion spacecraft are joined using friction stir welding, courtesy of NASA

Digital Printing of Aluminium Components

In 1988, stereolithography and the 'stl' 3D digital file format was introduced. Initially the 3D printers were based on polymers and mineral powders, with the printers layering up the geometry topographically.[74] By the middle of the first decade of the twenty first century, these and related techniques such as multi-jet wax printing were widely adopted by pioneering architects and engineers as a method 3D representation, modelling and rapid prototyping.[75] Or as a stage in a casting process, such as the aluminium cast solar shading of Nasher Sculpture Center by Renzo Piano Building Workshop and engineers Arup, as shown in Figure 2.17.[76]

In the second decade of the twenty first century, it is now possibly to directly print metal parts and components. The process, known as additive manufacturing (AM), is the direct fabrication of end-use products and components employing technologies that deposit metals layer-by-layer. It enables the manufacture of geometrically complex, low to medium volume production of components in a range of materials, with little, if any fixed tooling or manual intervention beyond the initial product design.[77]

Many consider that the role of additive manufacturing is most suited to aerospace and automotive applications, and it is used to rapidly produce components for Formula One racing cars. However, Nematox II is a digitally printed aluminium node for curtain walling, which was researched and developed by Holger Strauss of Hochschule Ostwestfalen-Lippe, Detmold, Germany. It is an example where there is no technological time lag between aerospace/automotive industries and architecture.[78]

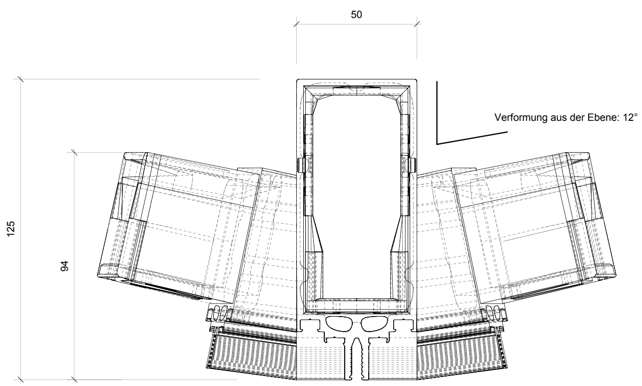


Fig 2.153 Plan drawing of a Nematox II node

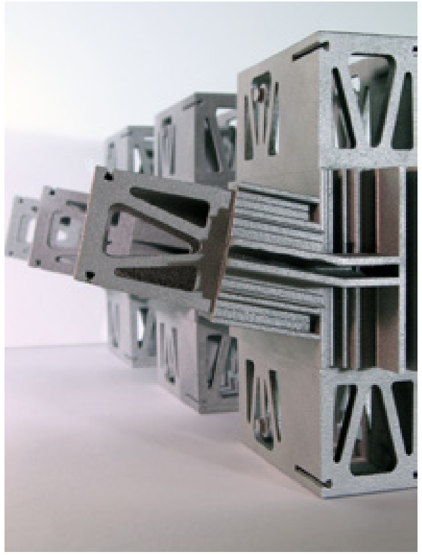


Fig 2.154 Digitally printed aluminium Nematox II nodes

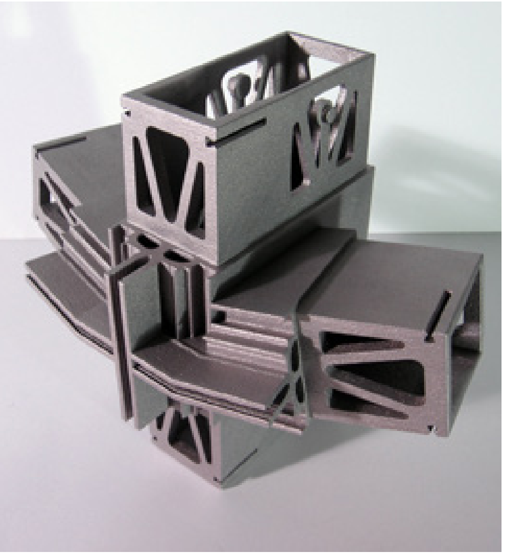


Fig 2.155 The geometrical complexity is printed in the Nematox II nodes

The context for the development of Nematox II is the technological progression of building envelopes in the twentieth and early twenty first century. Nematox II seeks to address the geometric complexity of many contemporary façades by digitally printing an integrated node. Additive manufacturing (AM) offers a path to seamlessly integrate this complexity into a directly printed aluminium component. By digitally merging the mullion and transom of the curtain walling, all the deformations and joints of the members within a façade system are virtually planned, checked and prepared for AM production. Digital planning and digital fabrication eases the difficult details in the production shop and on site, requiring simple 90° cutting of extrusions providing pre-planned geometric precision. Nematox II nodes are digitally printed in aluminium. It is the first component arising from the change in construction engineering logic, resulting from the application of additive manufacturing. This major advance was generated by the collaboration between ConstructionLab in Detmold, Germany and the global systems company Kawneer-Alcoa as part of the *Influence of Additive Processes on the development of façade constructions* initiative. Additive Manufacturing is no longer on a technology transfer wish list, it is available as part of the repertoire of the contemporary construction industry. [79]

Aluminium Extrusions

The aluminium extrusion process enables architects, engineers, and designers to have sections made to their exact requirements at a surprisingly low cost. It is also a very direct process, allowing close control over the quality of the product. This section is intended as source of guidance for designers who may be considering aluminium extrusions as a component of their buildings or product assemblies.

There are four distinct routes whereby aluminium extrusions can become part of a building:

- as part of a system, for example curtain walling;
- from stockholders' stock lengths, for example standard sections such as T-bars, round tube, Zs and box sections (dimensions are often still in imperial!);
- from extruders' stock dies, for example mouldings, flashings, trims and edgings;
  and
- from specially designed custom dies, for example for bespoke sections for a particular design.

Proprietary systems: most manufactures would consider altering their system for special projects, but only where the installed value of the (sub)-contract is substantial, that is, say over £500,000. The key is the weight of aluminium required and the complexity of the new section. In some nations it is also possible to get government grant aid for the cutting of new dies as part of a product or project research and development process.

Stock lengths: One disadvantage of using stock items is that there is a limited range of sections and a traditional dependence on existing imperial dimensions. This often makes them incompatible with close tolerance metric assembly.

Stock dies: All extruders will produce aluminium sections from their range of stock dies, which are the copyright of the extruder, not its customer.

Although a wider range of sections is obtainable than from stockholders, the only real advantage of stock dies over custom designed dies is that the die exists. This therefore eliminates the drawing approval period, die cutting and associated costs, thus reducing the time from the order to the availability of the section.

Custom dies: There are many companies, in most regions of the world, that can provide aluminium extrusions to customers' orders.

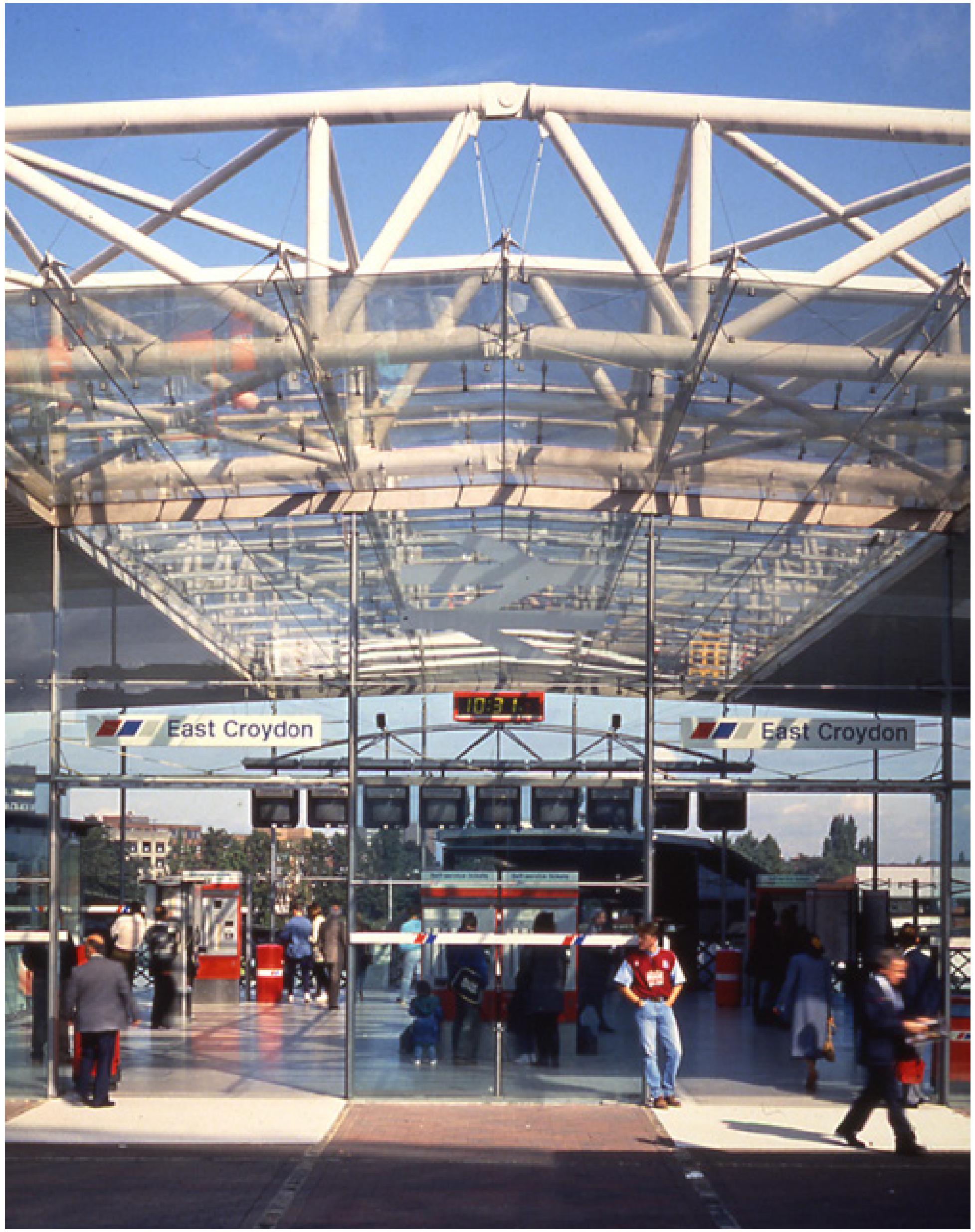


Fig 2.156 Entrance to East Croydon Station, architect Brookes Stacey Randall Fursdon, 1992

Companies such as Constellium Singen, Kaye, Sapa or Nedal will provide bespoke extrusions to order. A typical timescale is six weeks to approve the sample extrusion, and a further four weeks for production. The steel dies required to extrude a given shape are relatively inexpensive, the cost being related to the size and complexity of the section (see below).

TSC Report One: *Aluminium and Durability* recorded the influence of finite element analysis combined with computer aided design and computer aided manufacture in the 1980s, which had led to reductions in extruded aluminium section weight without loss of strength. Leslie Parks observed in 1986: 'Extensive use is made of the CAD/CAM approach to section design to save weight without penalising strength in extruded [aluminium] sections. Average percentage weight reductions achieved 1982–1985 by industry are: building sections 10.2, window sections 26.4, carpet edging 22.7 and greenhouses 33.9.'[80]

Extruders offer a prompt service, producing die drawings including sectional strength characteristics, weight and surface area. This software is available for architects and engineers to use directly in the design process. Die makers Wefa, formerly part of Alusuisse, have worked with ETH in Zurich to develop flow-modelling software of the forging process of extruding aluminium. This has been further developed into a standardised design knowledge database that enables dies produced by Wefa to run first time, effectively eliminating extrusion trials. Joachim Maier of Wefa observes 'to compete in the contemporary global aluminium market a die maker needs to be capable of extruding more complex sections, with high surface quality and better extrusion speed – balancing the competing factors thus proving certainty to the extruders'.[81]

Extrusion Process

In the production of aluminium extrusions cylindrical or elliptical **billets** of aluminium, typically weighing about 200kg, are first heated to a temperature of around 500°C before being placed in a steel **container** and forced, while still in a hot plastic state, through a steel die by a hydraulic ram to form the extrusion. The shape of the resulting section is governed by the die and by the ram forces applied. By using pre-heated billets and an autoloader, the hydraulic press can produce a continuous extrusion, the force of the ram being sufficient to weld the front of the new billet to the rear of the old as they are forced through.

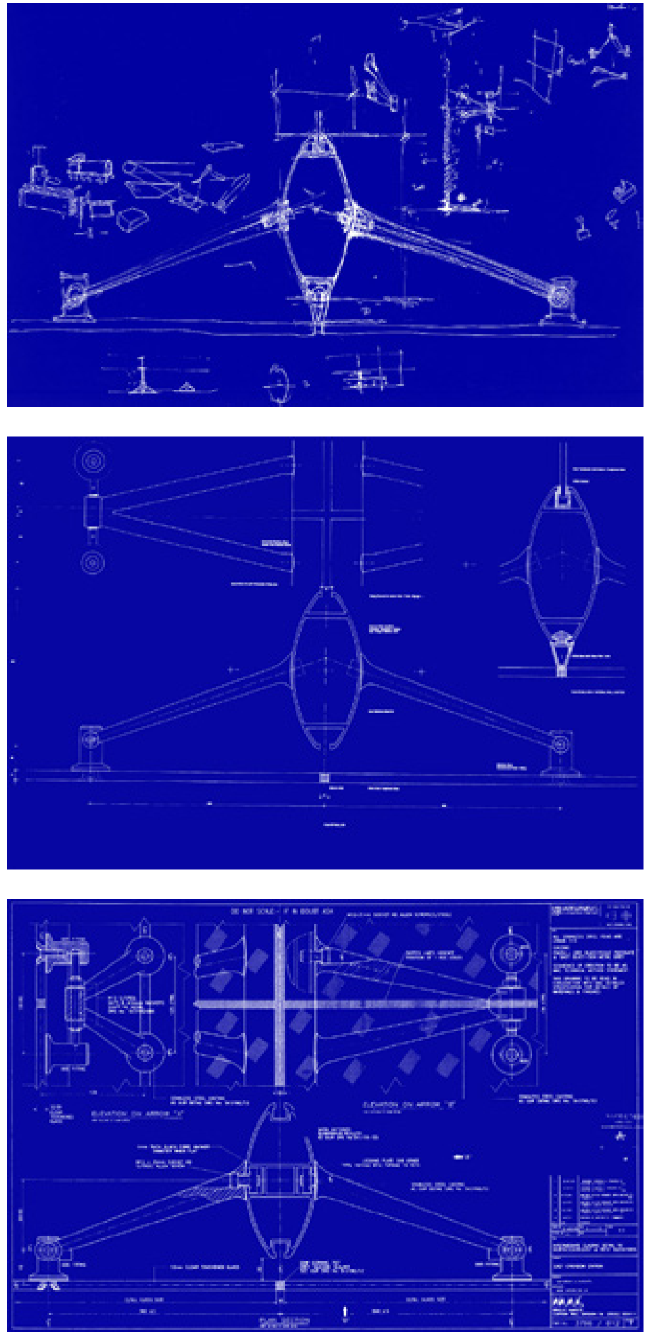


Fig 2.157 East Croydon mullion: author's initial sketch, Brookes Stacey Randall Fursdon's tender drawing and MAG's inspected shop drawing

The emerging section is air cooled and guided down a run-out table of rollers before being automatically cut into production lengths of up to 40m, this is governed by the length of the run-out table. A controlled stretch is then applied to each length to straighten it before being cut to order. The length may need to be oversize to allow for anodising or other finishing processes.

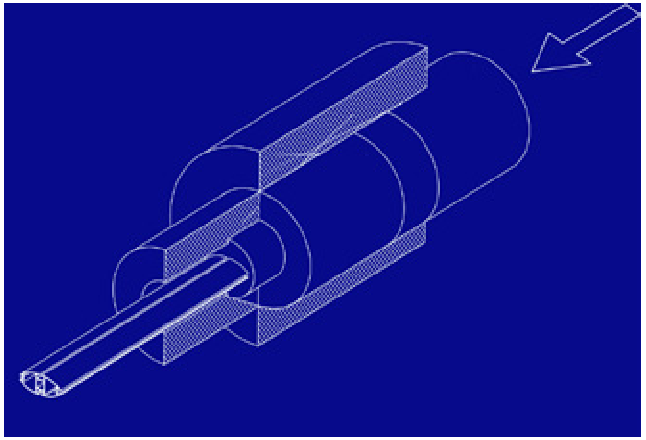


Fig 2.158 Diagram of an extrusion press

The process is rapid. A hydraulic press can extrude at rates in excess of 20m/min, depending upon the size and shape of the section. For heat treatable alloys, the process is completed by a precipitation or ageing treatment, the extruded length being 'baked' in an oven at 175°C for five to fifteen hours.

The size of an extrusion is dependent on the size and ram pressure of the press; predominately circular die chambers and cylindrical billets of aluminium are used. The size of the die is therefore determined by the circumscribing diameter (CCD), which is defined as the minimum diameter that can contain the extrusion. Hydraulic presses are described by their ram pressure and by the maximum size extrusion that can be produced (see Table 2.5). The maximum size extrusion section is therefore governed by the combination of the maximum ram pressure and the size of die the press can accommodate. The common size within the UK is 180mm press, which leads to a maximum size of 170mm to allow for the structural stability of the steel die. Extrusions up to 400mm CCD can be produced in the UK. Constellium Singen (formerly known as Alusuisse) has developed a press with a wider slot, like a London Underground sign, which enables it to extrude sections up to 600mm in diameter or 800mm wide, but only 100mm high. This

Fig 2.159 Extruded aluminium tubular sections, before straightening, at Sapa Tibshelf Plant, Derbyshire, England, design by Foster Associates, 1973

was first developed for the floor pan of the German high-speed ICE train, in the 1990s. Often the constraint of the size of the die can be overcome by design, enabling a number of extrusions to form the overall component, as in bridge decks for example.

Very small extrusions are usually produced by the **indirect method** where the billet is held firm and the die is pressed into the softened aluminium. For very small extrusions the cost per kilo becomes disproportionately higher due to the tight tolerances required, the care needed in their production and the fine detail of the die. Applications for very small extrusions in building construction are rare.

Fig 2.160 Aluminium billets waiting to be extruded at Joseph Gartner's works, note the alloy code is stamped on each billet

Extrusion presses are expensive pieces of capital equipment; however, the steel dies are relatively inexpensive. The relative economy of a new extrusion die means that to produce a purpose-made extrusion does not require a multimillion-pound R&D budget. The cost of a new die is dependent on size and complexity: a die for an extrusion without voids, which could fit within a diameter of 180mm, can cost £2,800 to £3,000. A hollow die of a similar size can cost £4,000 – £5,000.[82] The cost of the extruded section is related to the weight of aluminium used, measured in kilograms, and is influenced by the complexities of the section such as the number of enclosed voids. Secondary processes, for example rolling in high performance pultruded polyamide thermal breaks, are available directly from the extruder but add to the sectional cost.

Fig 2.161 A die maker from Wefa installing a porthole die for extruding a hollow aluminium section

The die cost of specially made extrusions, then, is rarely a significant proportion of extrusion cost where typical commercial quantities are ordered. The cost of extruded metal per kg is influenced by dimensions and configuration of the section, metal thickness, alloy, speed it can be extruded, tolerance limits and required surface finish. Wefa offer dies that are coated with its patented CVD coating technology, producing dies that are durable, offer higher productivity and are almost maintenance free. In Wefa's coated extrusion dies (CED©) the bearing channels are protected from wear and tear by the patented coating.[83]

Extrusion costs per kilogram are lowest for solid shapes and highest for complex hollow shapes, so effort should be made to obtain the desired structural result with extrusions that are as simple as practicable. An extrusion with a semi-hollow or deep recess requires a tongue in the die, whereas a fully enclosed void requires a two-part die with a **mandrel** supported by a bridge or webs. Both types must be supported securely to enable the die to withstand the extrusion pressure. Such features add to the die cost and usually reduce extrusion speed. Often only a slight change in a shape converts it to a less expensive classification, yet without compromising its function or appearance. To obtain a good extrusion, the designer will benefit from observing certain principles and early dialogue with the extruder.

Fig 2.162 Dies for extruding open sections, manfucatured by Wefa

Design Features

The extrusion process can enable specially designed shapes to be produced at relatively low cost. The designer has to observe certain principles to obtain a good extrusion cost effectively, remembering that details such as screw grooves can be designed in effectively at no extra cost. These are listed below:

- **Extrusion factor**: The thinner the section, the greater the likelihood of distortion during extrusion. Check the ratio between the **circumscribing circle diameter** (CCD) and the section thickness.
- **Thickness uniformity:** The metal thickness throughout the extrusion should be as uniform as possible. Where changes are required, for example to increase the strength of a section at a particular part of the extrusion, these changes should be as gradual as possible.
- **Symmetry:** The section of the extrusion should be as symmetrical as possible to reduce the effect of the section twisting as it leaves the die, but like many rules, this is often broken at a cost.
- **Open to hollow:** Open sections with open voids, such as a C-shape, are produced using a tongue or plug in the die. These are generally easier to extrude than sections with enclosed voids, which are produced using two part dies comprising a mandrel, which is held in place by bridges or webs.
- **Corners:** Corners should be curved where possible. A minimum radius of 0.5mm is commonly used, which is still visually crisp. Internal corners are governed by the need to produce a readily extruded section or the fit of mating components, such as internal jointing sections.
- **Grooves:** Avoid deep narrow slots as much as possible. A good aspect ratio is 3:1, or 4:1 with radii on entry.
- **One section or two:** It can be easier to design a component as two interlocking extruded sections rather than one single section.
- **Design in:** screw grooves, screw guides, snap fit and other details that provide process advantages in production and assembly.
- **Finish and tolerance:** The designer needs to identify the critical faces of the extrusion. The tolerances, laid down in BS EN 755 and BS EN 12020, provide permissible deviations on thickness, length, straightness, angular and sectional dimensions.

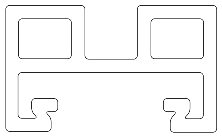


Fig 2.163 Initial design

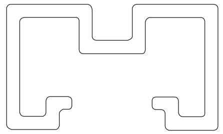


Fig 2.164 Final design — where possible design out voids and sharp corners

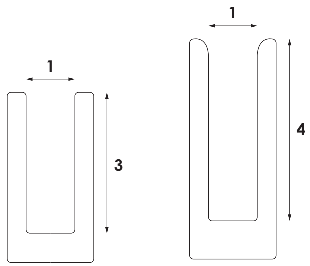


Fig 2.165 Guidance on groove depth: 3:1 can be increased to 4:1 with increased radii on entry

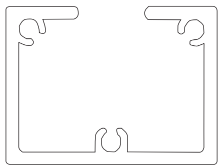


Fig 2.166 Screw grooves and other details can be designed in to an aluminium extrusion at no extra cost

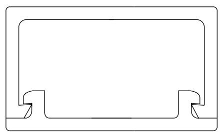


Fig 2.167 A snap-fit joint between two aluminium extrusions

There is general agreement within the industry that the size of die, area balance, and section thickness affect the economics of an extrusion. The speed with which an extrusion can be produced will affect its price per kilogram. However, it is notable that in the past 25 years leading extruders have pushed the boundaries of the possible when the architects and engineers have good reason to be demanding be this a heat sink assembly for an IP data bank or the H-Post extrusion for the freestanding option in Dieter Ram's 606 Universal Shelving System.

Die Size

The size of a die is determined by the circumscribing circle diameter (CCD), which is the minimum diameter of the circle within which the section of extrusion may be contained. In order to keep an unbroken structural ring around the die; the CCD is usually at least 40mm less than the internal diameter of the billet container and a minimum of 5mm from the edge of the die. Both die cost and minimum allowable wall thickness increase as the CCD increases.

Fig 2.168 Aluminium porthole dies or mandrel dies, manufactured by Wefa, for extruding hollow aluminium sections

Area Balance

As far as possible the cross section of the extrusion should be distributed equally around the centre of the CCD. Metal flow is slower towards the outside of the die in any extrusion, so a more even flow of metal can be obtained by placing thicker parts of the section near the periphery. A well-balanced cross section aids extrusion because it reduces cross flow of metal on the billet side of the die, so the extrusion speed may be higher. Carefully designed unbalanced shapes, however, are usually readily extrudable, but at slower speeds and higher costs.

Thickness of metal is probably one of the most important factors governing extrudability and is more complex than simply quoting a fraction of CCD, which is often used as a method of estimating thickness. Section thickness affects extrudability both by its actual and relative position in the die. Small positioning lugs are not considered as having a significant effect on thickness, but excessively thin details and thin ends of elements should be avoided. Thick-thin junctions are also to be avoided, but if required should be cornered by rounding or use of fillets. Even a 0.5mm radius improves the metal flow compared with a sharp corner. Compared with a cold rolled or hot rolled steel section these radii are not perceptibly rounded.

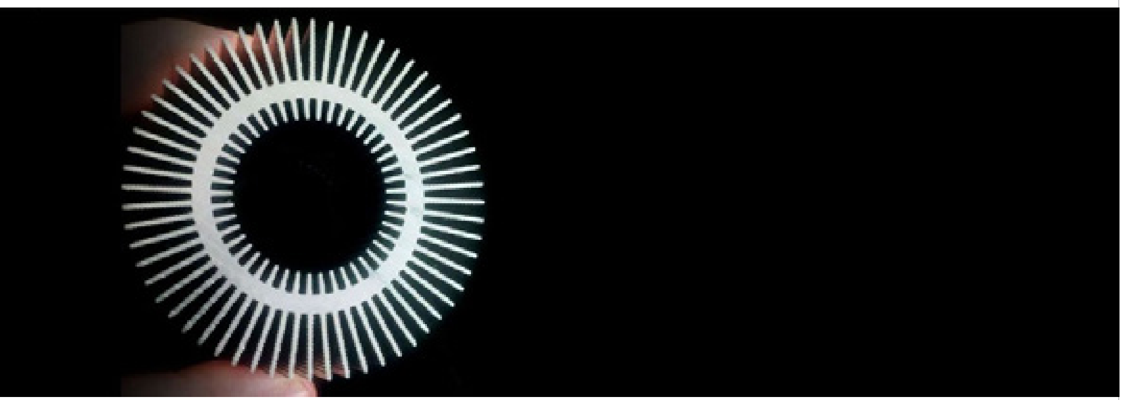
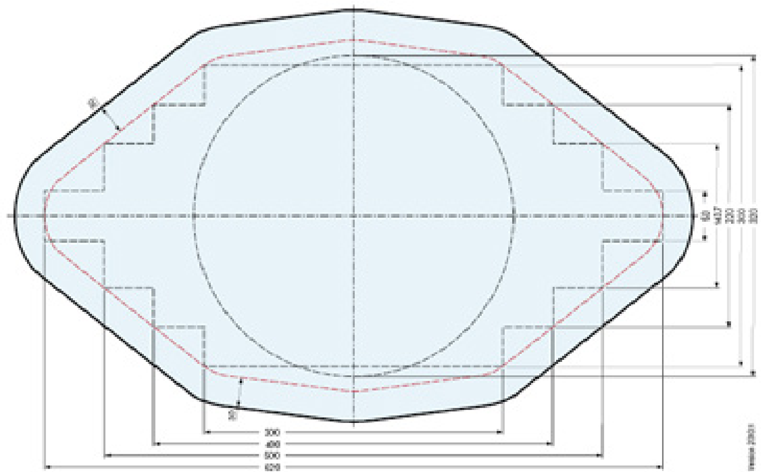
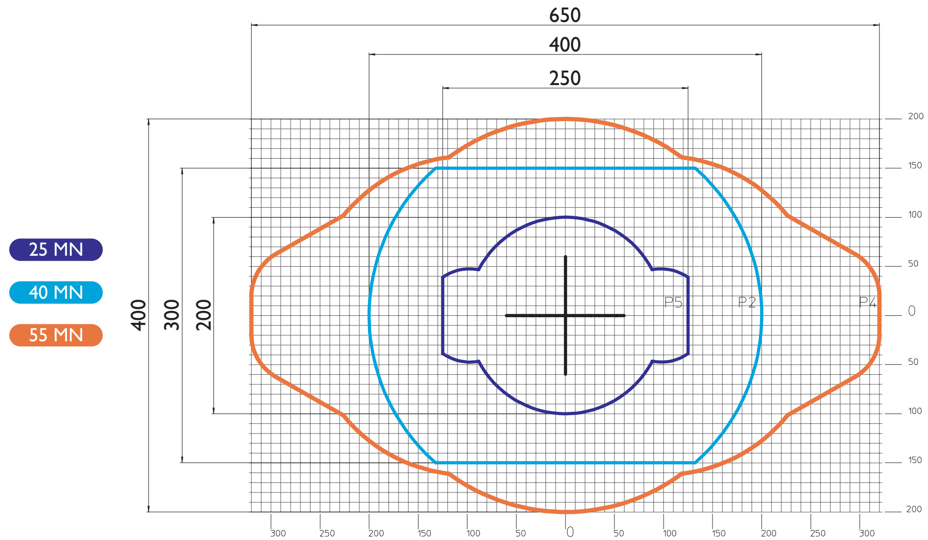


Fig 2.169 Extruded aluminium heatsink, courtesy of Aluminium Shapes

Fig 2.170 [opposite] Maximum die sizes at Sapa and Nedal



Sapa



Nedal

	Max. Ram Pressure (tonnes)	Extrusion Size (circumscribing circle diameter in millimetres)
Aluminium Shapes, UK	1,200	150
BOAL, Moorsele, Belgium	1,600	180
BOAL, de Lier, Netherlands	2,000	205
	1,600	180
BOAL, Shepshed, UK	3,500 1,600	230 180
Capalex, UK: indirect press	600	72
Constellium, Singen, Germany	10,000	400 Elongated extrusions 800 x 100
Kaye Aluminium, UK	2,000 1,600	203 178
Nedal, Netherlands	5,000	400 Elongated extrusions 650 x 200
Sapa (overall maximum)	6500	406 Elongated extrusions 620 x 20
Smart, UK	2200 1600	200 150

Table 2.5 Table of selected aluminium extruders, architects, engineers and designers should consult about their specific requirements

However, as with all areas of human invention, guidance on the design of aluminium extrusions is only a starting point and extruders can produce sections, which bend the rules or even redefine the possible. The stair tread of Lloyds of London is a perfect example, the general rule is to minimise or avoid the use of voids. This single extruded aluminium tread produced by Nedal in Holland has multiple voids. Apparently the inspiration for this design was John Young of Richard Rogers + Partners seeing a stack of rectangular extrusions in Joseph Gartners' works in Germany. Still in service at Lloyds, stair tread section can now be seen in the Science Museum, London, as an exemplar of the use of the aluminium extrusion process.

Tolerances

In many cases, the close control of the tolerance of the aluminium extrusions is critical to the success of an application. The tolerances for aluminium extrusion are set out in a number of Euro Norms including: BS EN 755, BS EN 12020 and BS EN 13957. Tolerances are given for cross sectional dimensions, wall thickness, straightness, contour, convexity and **concavity**, **twist**, **angularity** and radii of corners. This is not an exhaustive list and direct reference to the standards is recommended, however most extruders can achieve two-thirds of the tolerance levels given in the Euro Norms.

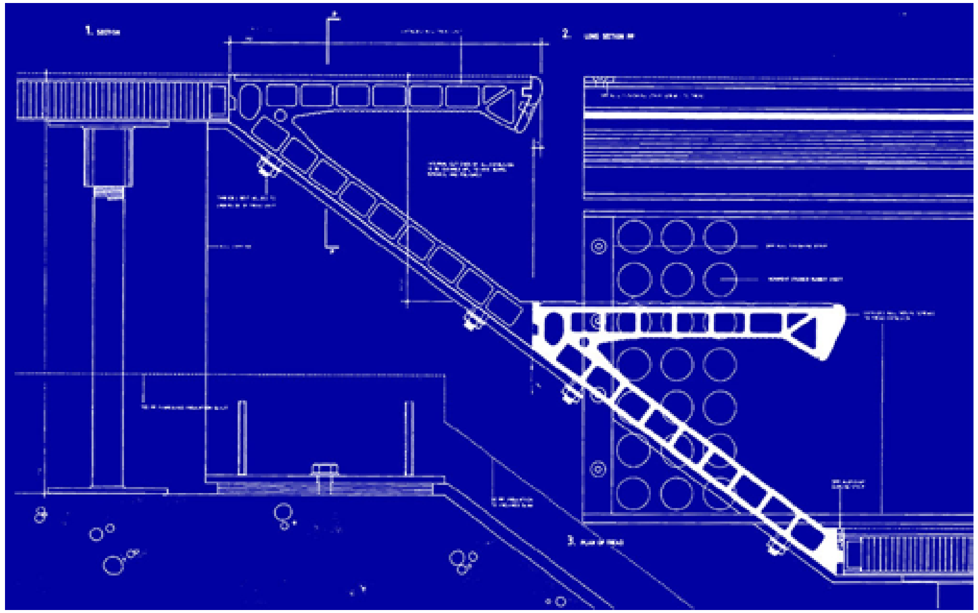


Fig 2.171 Stair tread detail section of Lloyds of London, designed by Richard Rogers & Partners

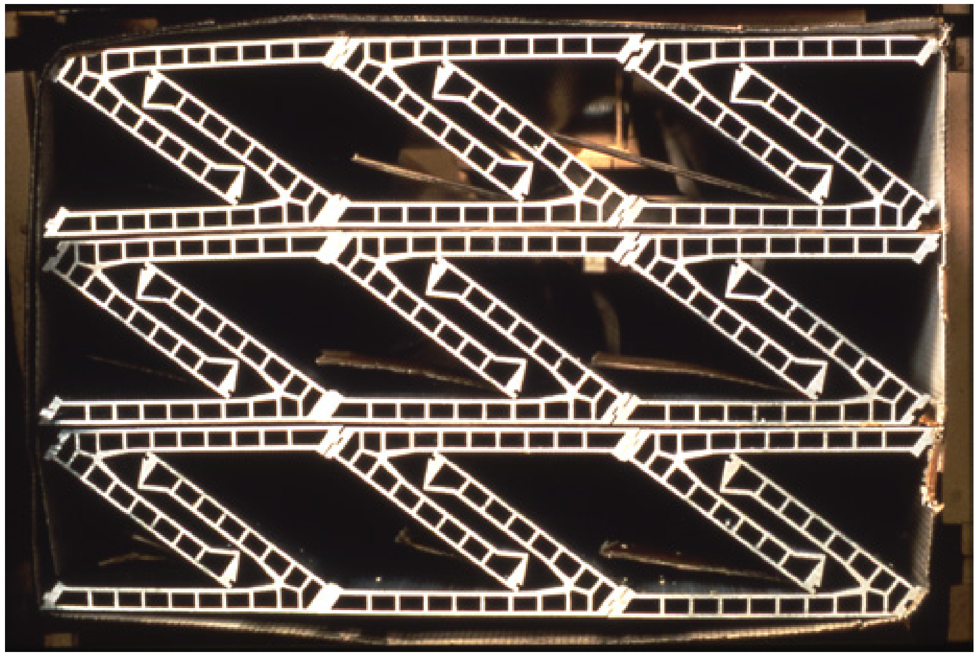


Fig 2.172 Stair treads of Lloyds of London

Glazing System for East Croydon Station, England: Architect Brookes Stacey Randal Fursdon, 1992

The new East Croydon Station, designed by Brookes Stacey Randall Fursdon, completed in 1992, was designed to serve 14 million passengers a year and is South East England's busiest through station, in 2015 it served over 20 million passengers. The glazing system is an example of a purpose made extrusion used to produce a project specific assembly, although the overall contract of the new station was under £4,500,000.

The structure spans onto the existing abutments at either side of the six railway tracks, creating a 55-metre clear space. This minimised disruption to the railway and created a column free interior. Below the external masted steel structure is a highly glazed envelope, which provides a sophisticated shelter. The glazing system, specially developed by Brookes Stacey Randall Fursdon for this project provides maximum transparency, yet is robust enough to meet the day-to-day demands of a railway station.

Fig 2.173 Extruded aluminium mullion, stainless steel castings and 10mm toughened glass wall assembly of East Croydon Station being weather tested at Taywood Engineering

Fig 2.174 The extruded aluminium mullion of East Croydon Station, designed by Brookes Stacey Randall Fursdon

The glazing system aims to maximise the potential of the toughened glass and the extruded aluminium supporting structure. Each pane of clear toughened glass is only supported at four points. The aluminium extrusion supports the glazing assembly and primarily resists wind loads via stainless steel cast arms that reach 300mm into the 3m width of the glass pane, thus reducing the effective span to 2400mm and accessing a beneficial hogging moment. Thus deflection of the glass is limited to span over 112. The form of the extrusion is elliptical to achieve an elegant and rigid structural form with minimum profile. It is the use of stainless steel castings at the head end of the base, which transforms the essentially linear extrusion into a three-dimensional building component. East Croydon Glazing System was tested at Taywood Engineering to BS 5368, parts 1–3.

The extrusion was also designed with front and rear grooves, it is a symmetrical and well balanced section. The front groove is used to receive extruded silicone gaskets, acting as closure pieces at wall junctions and the groove to the rear of the extrusion has been designed to carry door tracks, signage and receive internal glazing, as shown in Figure 2.157. This economical solution is flexible and provides a visual alternative to the standard curtain walling box profile.

The author chose to finish the mast sections with silver anodising to retain the inherent metal aesthetic of the aluminium, with the benefit of anodising which is a very hard fused oxide layer. However, care should be taken in its use and the following issues considered:

- Ensure significant services are communicated to all concerned - to avoid jig marks;
- Suitable protection in transit is essential;
- Protection on site from mechanical damage and mortar is also essential. The mortar or concrete will cause the anodising to go permanently 'milky' as a result of an alkaline reaction, which is impossible to reverse;
- Location of the mandrel bridges in extrusions with voids should be agreed, as the chemical structure of the aluminium varies as it resolidifies after the mandrel. This can form a crystalline or dichroic structure, which has a different reflectance to the section generally. Thus modifying the appearance of the anodising in this zone;
  and
- Die marks - the acceptable level should be agreed at the outset and checked on the trial run.

Dieter Rams: less is better

Before discussing the 606 Universal Shelving System, designed by Dieter Rams for Vitsœ, it is worth examining the career of one of the most important designers of the twentieth century.

> 'Ram's ability to bring form to a product so that it clearly, concisely and immediately communicates its meaning is remarkable. The completeness of the relationship between shape and construction, materials and process, defines his work and remains a conspicuously rare quality.' Jonathan Ive [84]

Dieter Rams was born in Wiesbaden, Germany, in 1932. Aged 15 he went to the re-opened Arts & Craft College in Wiesbaden to study architecture and interior design. Professor Hans Soeder, after the Second World War, re-founded the college on Bauhaus principles 'emphasising the relationship between architecture and design. Students there were required to complete a full training in craftsmanship before going onto two years of master classes.'[85] Rams actually undertook a full three-year apprenticeship as a carpenter before completing his studies at college, where he became aware of German modernism. In 1953, he graduated with a diploma in interior design. He then worked for Otto Apel in Frankfurt. Sophie Lovell observes: 'Rams was particularly influenced by the industrial-oriented post-war modernism that came back to Germany from the United States through Apel's collaboration with the Chicago-based firm Skidmore, Owings & Merrill on the construction of US consulates in Germany'. Rams considered this experience to be vitally important to his career at Braun 'here I could expand my knowledge of high-rise building.' Thus there is a clear link between Rams and Skidmore, Owings & Merrill, a practice that was one of the key aluminium pioneers, as discussed in *Aluminium and Durability*.[86]

Rams joined Braun in 1955 as its in-house architect, securing this position with a sketch of a Braun showroom, which had been requested of all the short-listed candidates.[87] On the back wall included in this sketch, which Rams populates with Knoll furniture, is the genesis of the design of the 606 Universal Shelving System (originally the RZ60).

Dieter Rams was the head of design at Braun from 1961 to 1995. Between 1975 and 1985 he devised 10 principles for good design reflecting on his experience from both Braun and Vitsœ.[88] However, they are still relevant today and reveal Rams as a pioneer of sustainable design:

Fig 2.175 The 606 Universal Shelving System, designed by Dieter Rams for Vitsœ + Zapf in 1960

Fig 2.176 Dieter Rams' 1955 sketch of a Braun Showroom

1. **Good design is innovative** — The possibilities for innovation are not, by any means, exhausted. Technological development is always offering new opportunities for innovative design. But innovative design always develops in tandem with innovative technology, and can never be an end in itself.

2. **Good design makes a product useful** — A product is bought to be used. It has to satisfy certain criteria, not only functional, but also psychological and aesthetic. Good design emphasises the usefulness of a product whilst disregarding anything that could possibly detract from it.

3. **Good design is aesthetic** — The aesthetic quality of a product is integral to its usefulness because products we use every day affect our person and our well-being. But only well-executed objects can be beautiful.

4. **Good design makes a product understandable** — It clarifies the product's structure. Better still, it can make the product talk. At best, it is self-explanatory.

5. **Good design is unobtrusive** — Products fulfilling a purpose are like tools. They are neither decorative objects nor works of art. Their design should therefore be both neutral and restrained, to leave room for the user's self-expression.

6. **Good design is honest** — It does not make a product more innovative, powerful or valuable than it really is. It does not attempt to manipulate the consumer with promises that cannot be kept.

7. **Good design is long-lasting** — It avoids being fashionable and therefore never appears antiquated. Unlike fashionable design, it lasts many years – even in today's throwaway society.

8. **Good design is thorough down to the last detail** — Nothing must be arbitrary or left to chance. Care and accuracy in the design process show respect towards the user.

9. **Good design is environmentally friendly** — Design makes an important contribution to the preservation of the environment. It conserves resources and minimises physical and visual pollution throughout the lifecycle of the product.

10. **Good design is as little design as possible** — Less, but better – because it concentrates on the essential aspects, and the products are not burdened with non-essentials.
Back to purity, back to simplicity![89]

Although Dieter Rams is providing guidance about the design of products, it applies equally well to architecture, especially if the architecture is prefabricated. Rams intends these principles to be a 'means for orientation and understanding. They are not binding. Good design is in a constant state of redevelopment – just like technology and culture.'[90]

Fig 2.177 606 Universal Shelving System, designed by Dieter Rams in 1960

606 Universal Shelving System: Designer Dieter Rams, 1960

At the core of the 606 Universal Shelving System today are four purpose made aluminium extrusions: an E-Track, a X-Post, a H-Post and a cross rail. Dieter Rams designed the 606 Universal Shelving System for Vitsœ + Zapf in 1960. 606 is a universal system as all the details are fully reversible and the shelves can be reconfigured and extended with more components depending on the needs of the user, be this a home owner, librarian or office worker. It was designed for ease of assembly and disassembly about twenty years before design for disassembly (DFD) had been coined; see *Aluminium Recycling and Recyclability* for a brief history and the importance of DfD.[91]

Vitsœ + Zapf was founded by Niels Vitsœ and Otto Zapf in 1959 with the express intension of making furniture designed by Dieter Rams. 'In 1959, Dieter Rams asked Erwin Braun if he could design furniture for Niels Vitsœ and Otto Zapf. Braun's spontaneous answer was "Yes. It will help the market for our radios." [92] Although Rams worked for Braun he became a partner in Vitsœ + Zapf, a role he gave up when he became Head of Design at Braun in 1961.

If Rams' 1955 sketch is the origin of the idea, the extruded aluminium E-track is the founding component of 606 Universal Shelving System. He had used this extrusion in an earlier product RZ57, a 1957 montage system of highly flexible shelves and cupboards made of perforated anodised aluminium profiles and white beech panels.[93] The extruded aluminium E-track was used to support the sliding doors of the storage units.

Rams' design for 606 Universal Shelving System (originally named RZ60) uses the extruded aluminium E-track, 20 × 20mm, as the structural component of the shelving system, which is screw fixed to a supporting masonry wall. The shelves are attached to the E-track with simple notched turned aluminium pins. The powder coated folded mild steel shelves have two holes and can be hung either way up. The ease of interchangeability of the components encourages day-today rearrangements or complete reconfigurations. 'The system was remarkably simple, lightweight and unobtrusive and, like the RZ57, relied on precision manufacture of a relatively small number of repeating components.' [94]

Fig 2.178 606 Universal Shelving System in the bookshop of Victoria & Albert Museum, London

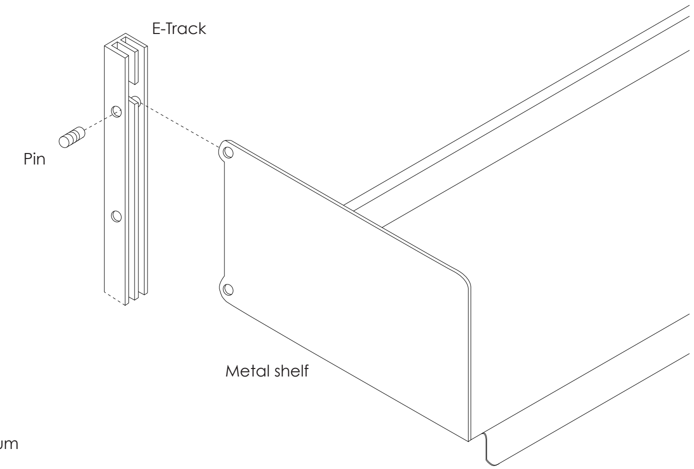


Fig 2.179 Extruded aluminium E-track, turned aluminium pin and steel shelf

In the early 1970s, Rams designed the X-post hollow extruded aluminium section, which can receive fixings and or the E-track in four directions to enable the 606 Universal Shelving System to be free standing, compressed between floor and ceiling or semi supported, as well as wall mounted, even a combination of all three in a single assembly. The bracing of the freestanding option is achieved by a horizontal extruded aluminium section, with a single hollow, known as a cross rail. The original E-track in 1950s is a small-scale open extrusion; the X-post designed in the 1970s is a relatively complex, if fully symmetrical, hollow extrusion.

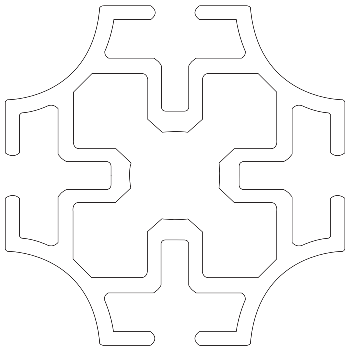


Fig 2.180 Section of the extruded aluminium E-track, 1:1

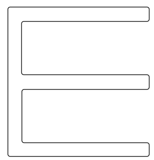


Fig 2.181 Section of the extruded aluminium X-post, 1:1

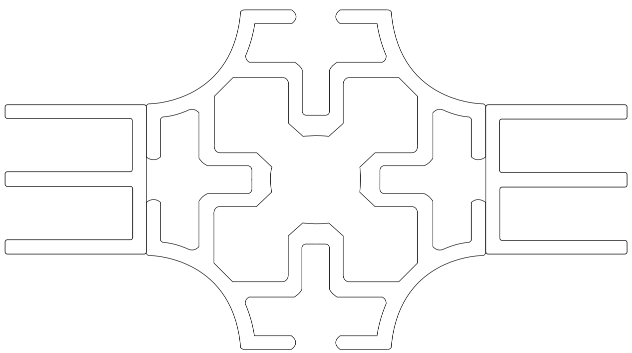


Fig 2.182 Section of the X-post with E-tracks attached, 1:1

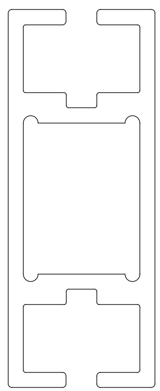


Fig 2.183 Section drawing of the extruded aluminium cross rail, 1:1

Fig 2.184 Free standing 606 Universal shelving in the library of Holland Park School, architect Aedas

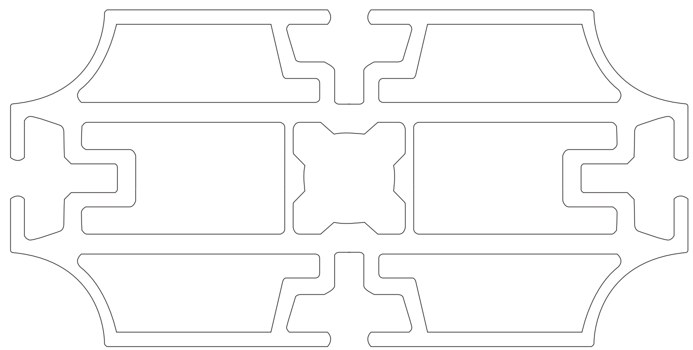


Fig 2.185 Section drawing of the extruded aluminium H-section, 1:1

Fig 2.186 The extruded aluminium E-track

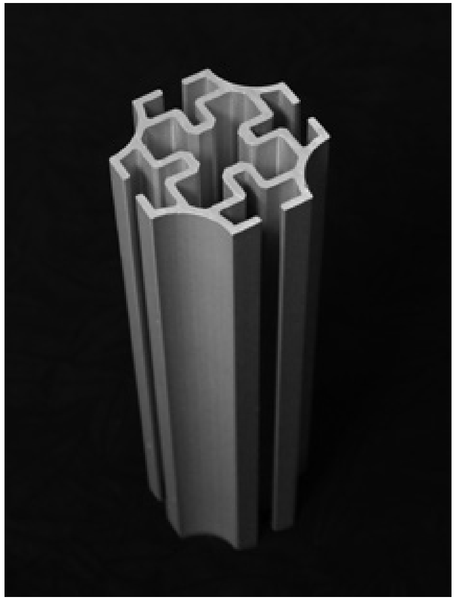


Fig 2.187 The extruded aluminium X–post

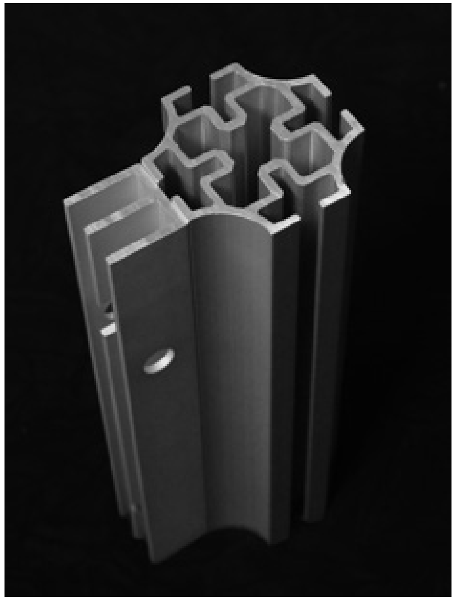


Fig 2.188 The extruded aluminium X–post with an E-track attached

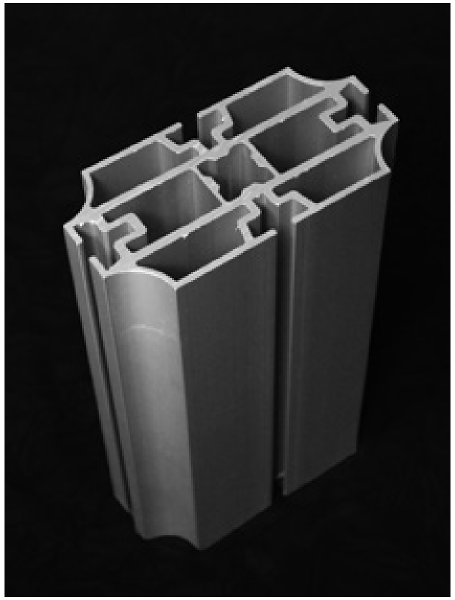


Fig 2.189 The extruded aluminium H–section

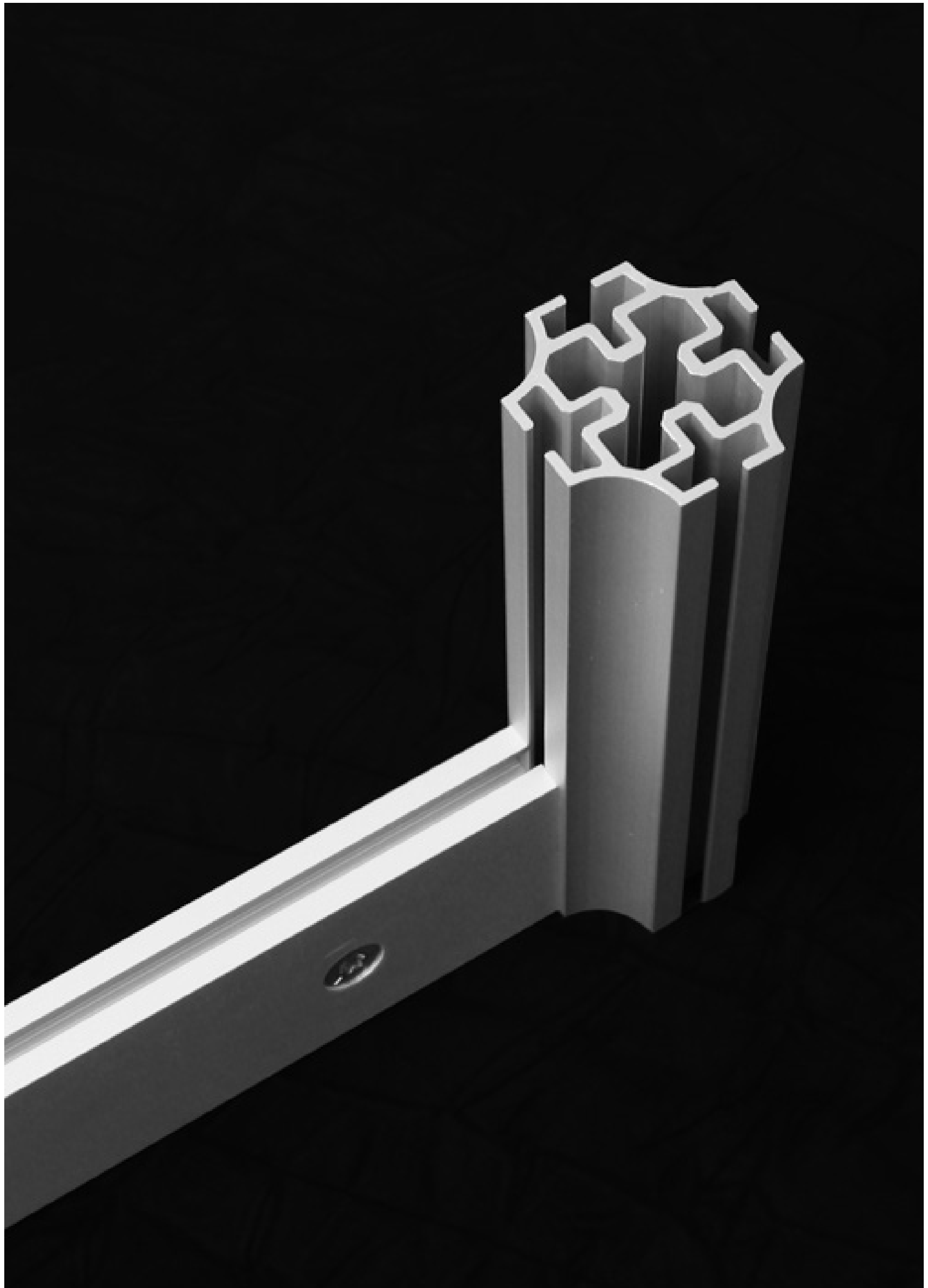


Fig 2.190 The extruded aluminium X-post with cross rail attached

'In addition to the shelves, Rams designed a whole range of elements that slotted into the system, including cabinets with sliding doors or fold-down door, desks and table modules and LP record rack and holders for the Braun 'audio 2' stereo-system components, including speakers. By 1980 the Vitsœ catalogue listed more than 150 different positions for the 606 system'.[95] 'Of all Rams' products, the 606 Universal Shelving System is perhaps his most successful in fulfilling his own principles of good design. It is still in production today, some fifty years after its conception.'[96]

> 'My heart belongs to the details. I actually always found them to be more important than the big picture. Nothing works without details. They are everything, the baseline of quality.'
>
> Dieter Rams in conversation with Rido Busse (1980)[97]

Rams' vision of furniture was as a 'liberation from the dominance of things.' Stating that: 'A Vitsœ furniture system is designed to survive decades of use, extension, alteration and relocation without damage and it does.'[98]

Fig 2.191 X-post 606 Universal Shelving System in the Faculty of Divinity Library at the University of Cambridge, architect Cullinan Studio, 2000

Fig 2.192 Dieter Rams in his home, Kronberg, Germany

In 1969 Niels Vitsœ had bought out Otto Zapf's share of the company, he continued to run Vitsœ-Wisse until he was eighty in 1993. Mark Adams, who had marketed Vitsœ furniture in the UK since 1985, took up the challenge with the blessing of Niels Vitsœ's family, focusing initially on the 606 Universal Shelving System. In 1995, he decided to relocate the production of this system to the UK. With Rams he optimised the components of the system to maximise its cost effectiveness. Building on a base of loyal customers the 606 Universal Shelving System is sold as a long-term sustainable purchase. In 2013, Vitsœ secured the exclusive wordwide licence of Dieter Rams' complete collection of original furniture designs.[99] Today in 2016, to fill an alcove with 606 Universal Shelving, including two E-tracks and six shelves 912mm wide, costs £526, which can be added to and adapted as required. Sophie Lovell observes 'a customer who bought a shelf unit in 1967, for example, was still able to add a cupboard, a shelf or a table unit or extend it with further shelves in 1977 or 2007.'[100] 'A fact of which we are especially proud: at any one time, more than half of the orders we are taking are from existing customers.'[101] Vitsœ managing director Mark Adams sees 'recycling as a defeat. That's what you have to do if you fail to re-use.'[102].

Dieter Rams retired from Braun in 1997, however, he continues to work with Vitsœ. The 606 Universal Shelving System demonstrates the sustainability of aluminium in the hands of a world-class designer and a thoughtful company. The development of the system from 1960s to the present day also demonstrates the flexibility of aluminium in terms of design and how aluminium extrusions work so well as components of a system, with precise dimension and component interfaces designed into the extrusions. The design flexibility of extruded aluminium enables a system to grow and develop in response to opportunities and needs of specifiers and end users. The H-Post section was designed in 2012 as seven void extrusion, in essence a doubling of the X-Post. This enabled the 606 Universal Shelving System to be provided free standing in the spacious atrium-like library space of Holland Park School. This school was designed by architect Aedas and it opened in October 2012.

Fig 2.193 A domestic workstation formed from the 606 Universal Shelving System with a DSW chair by Charles and Ray Eames and iMac by Jonathan Ives

Aluminium is flexible in terms of design, flexible in the range of forging, casting, fabrication and finishing process, yet provides components that meet high performance standards in terms of strength and stiffness, while providing long-term durability. In the hands of well-informed and skilful architects and engineers as the case studies demonstrate aluminium is also powerful by design.

Fig 2.194 A starter kit: an alcoves worth of 606 Universal Shelving awaiting books

Notes

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Solar Shading

This chapter reviews the role of aluminium in aiding the control of daylight and solar heat gains in buildings, enabling buildings to significantly reduce the day-to-day need for **primary energy** on a regional and site-specific basis. Avoiding overheating and glare from solar gains whilst ensuring the maximum use of daylight, when available. The beneficial use of solar gains during heating seasons is also discussed. Solar shading is at its most effective when outside the glazing and therefore the durability of aluminium is of vital importance. Six case studies are set out chronologically from 1959 to 2014, each one demonstrates a holistic approach to the design of high quality and comfortable architecture, in which energy and material resources are used wisely. In TSC Report 1: *Aluminium and Durability* the author observed Skidmore, Owens & Merrill's use of adjustable aluminium louvers on the façades of the Reynolds Metals Company Offices in Richmond Virginia completed in 1958.[1] The following year Minoru Yamasaki's design for the Reynolds Metals Regional Sales Office in Southfield, Michigan was completed with a filigree solar shading veil of aluminium.

The chapter begins with a review of climatic regions of the world, followed by a guide to the design of solar shading, written by Professor Brian Ford for this report.

Fig 3.1 Filigree aluminium solar shading of the Reynolds Metals Regional Sales Office, architect Minoru Yamasaki, 1959

Fig 3.2 Entrance level of Reynolds Metals Regional Sales Office

Fig 3.3 Inside the Reynolds Metals Regional Sales Office

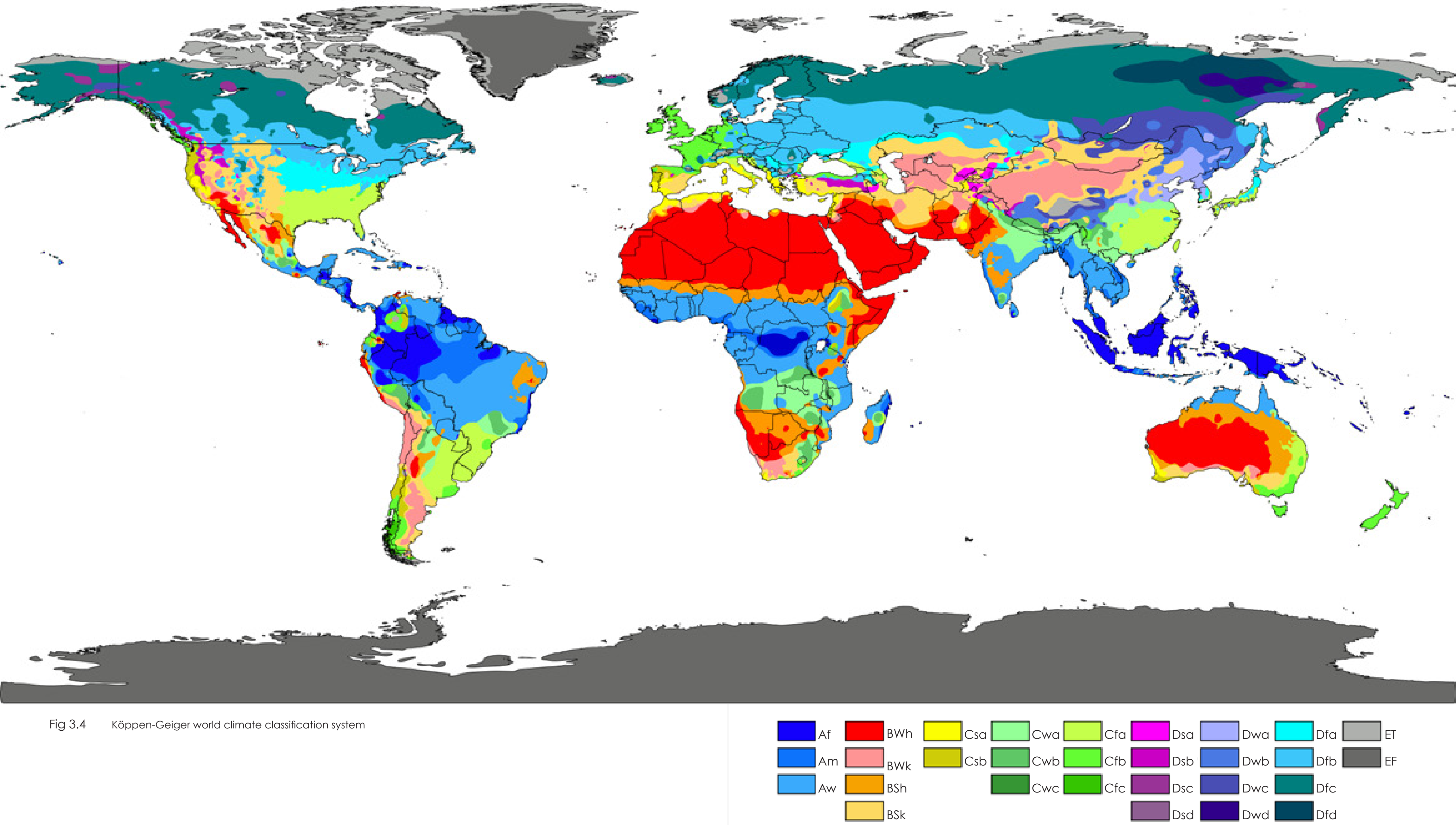


Fig 3.4 Köppen-Geiger world climate classification system

Climate

The climate of planet Earth is both a shared global resource, which humankind needs to look after, and a defining quality of place. Climate is a key characteristic of each region that has defined human activity, agriculture, culture and vernacular architecture. A context specific understanding of the climate pertaining to a site of a proposed architectural project is a fundamental starting point for the design process, which may well include personal observation of the site as well as the gathering of historic weather data and the use of computer based modelling including the risk of future climate change. Climate is influenced by location, attitude, topography and proximity to water.

The International Aluminium Institute has been collecting data on the global use of aluminium since the 1950s, based on the following regions:

- China;
- Europe;
- Japan;
- Latin/South America;
- The Middle East;
- North America;
- Other Asia;
  and
- Other Producing Countries.

The following section combines the Köppen-Geiger climate classification, developed by Wladimir Köppen and updated by Rudolf Giger, and the regions used by IAI to collect data.[2,3,4]

China: is a diverse land mass yet the climate is dominated by a humid subtropical climate (Cwa) and humid subtropical climate (Cfa), with areas of tropical savannah climate (Aw), tropical monsoon climate (Am) and tropical rain climate (Af).

1st	2nd	3rd	Description
A			Tropical
	f		–Rainforest
	m		–Monsoon
	w		–Savanna
B			Arid
	W		–Desert
	S		–Steppe
		h	–Hot
		k	–Cold
C			Temperature
	s		–Dry Summer
	w		–Dry Winter
	f		–Without dry season
		a	–Hot summer
		b	–Warm summer
		c	–Cold Summer
D			Cold (Continental)
	s		–Dry Summer
	w		–Dry Winter
	f		–Without dry season
		a	–Hot summer
		b	–Warm summer
		c	–Cold summer
		d	–Very cold winter
E			Polar
	T		–Tundra
	F		–Frost (Ice cap)

Table 3.1 Köppen-Geiger climate classification table of symbols and descriptions

Fig 3.5 Solar shading of the SIEBB in Beijing, China, 2006, designed by MarioCucinella Architects, see Chapter 8 for the case study of this project

Fig 3.6 Solar shading of St Catherine's College, Oxford, England, architect Arne Jacobsen, completed in 1963

Fig 3.7 Silver and gold anodised aluminium solar shading of Rich Mix, London, England, designed by Penoyre & Prasad Architects, completed in 2006

Europe: has many climatic regions, however, it is dominated by a warm humid continental climate (DFb), with oceanic climate (Cfb) as experienced in the UK, hot–summer Mediterranean climate (Csa), warm–summer Mediterranean climate (Csb) and humid subtropical climate (Cfa).

Japan: the dominant climate of this island nation is a humid subtropical climate (Cfa) as experienced in Tokyo for example, combined with hot humid continental climate (Dfa), warm humid continental climate (Dfb), oceanic climate (Cfb) and subarctic climate (Dfc).

Fig 3.8 Extruded aluminium structure and solar shading of the Aluminium House System, Kyushu, Japan, architect Riken Yamamoto & Fieldshop

Latin/South America: has many different climates but is dominated by tropical savannah climate (Aw) with areas of humid subtropical climate (Cfa), oceanic climate (Cfb), tropical rainforest climate (Af) and cold desert climates (BWk).

The Middle East: the dominant climate of this region is a hot desert climate (BWh) with areas of cold desert climate (BWk), hot semi-arid climate (BSh), warm Mediterranean climate (Csa), oceanic climate (Cfb) and temperate continental climate (Dsb).

North America: has a great diversity of climates including, warm humid continental climate (Dfb), humid subtropical climate (Cfa), hot humid continental climate (Dfa), tropical savannah climate (Aw) and hot semi-aride climate (BSh).

Fig 3.9 Bespoke extruded aluminium solar shading for Yale Sculpture Building and Gallery, designed by KieranTimberlake in collaboration with Schüco, completed in 2007

Other Asia comprises:

Indonesia: has many different climatic regions, however, it is dominated by tropical rainforest climate (Af) with areas of tropical monsoon climate (Am), tropical savannah climate (Aw), oceanic climate (Cfb) and subtropical highland oceanic climate (Cwb).

Malaysia: has three climatic regions and is dominated by tropical rainforest climate (Af), the other climatic regions are tropical monsoon climate (Am) and oceanic climate (Cfb).

Singapore: has a tropical rainforest climate (Af).

Taiwan: has a humid subtropical climate (Cfa).

Thailand: has many climatic regions, but it is dominated by tropical savannah climate (Aw) with areas of tropical monsoon climate (Am), humid subtropical climate (Cwa) and tropical rainforest climate (Af).

Vietnam: has many climatic regions, but it is dominated by tropical savannah climate (Aw) and humid subtropical climate (Cwa), with areas experiencing a tropical monsoon climate (Am), subtropical highland oceanic climate (Cwb) and tropical rainforest climate (Af).

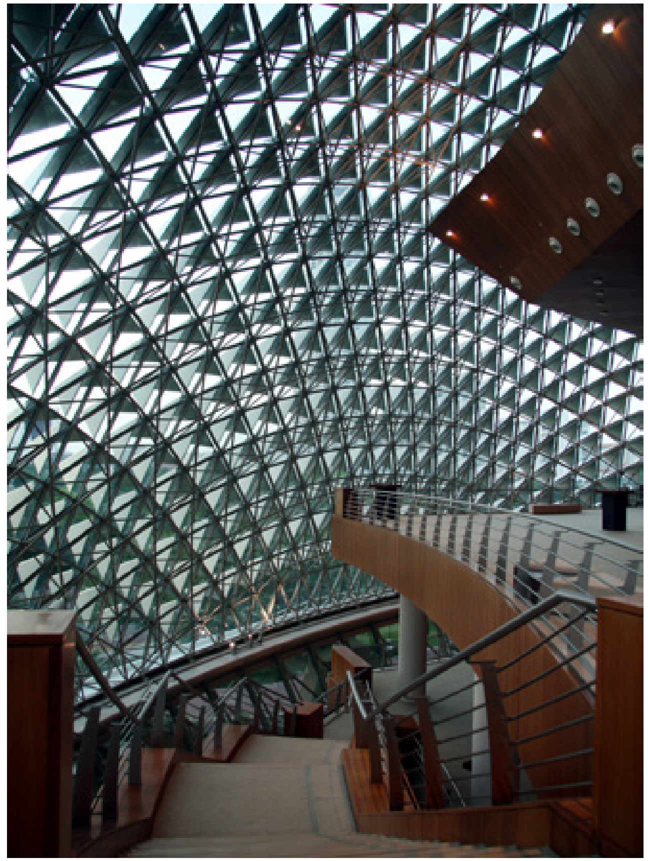


Fig 3.10 Folded aluminium solar shading of Singapore Arts Centre, completed in 2003: Architect Michael Wilford & Partners, façade consultants Brookes Stacey Randall

Fig 3.11 The filigree aluminium solar shading in a range of silvers and shades of gold of the National Gallery, Singapore designed by architect studioMilou, which opened during November 2015, was sourced from Guangzhou in China by Beijing Jangho Curtain Wall Co

Other Producing Countries includes:

Australia: the predominant climatic regions are humid subtropical climate (Cfa) and oceanic climate (Cfb), with areas experiencing cold semi-arid climate (BSk), hot semi-arid climate (BSh) and warm–summer Mediterranean climate (Csb).

Cameroon: has many climatic regions, but it is dominated tropical savannah climate (Aw) with areas experiencing tropical monsoon climate (Am), hot semi-arid climate (BSh), subtropical highland oceanic climate (Cwb) and tropical rainforest climate (Af).

Egypt: has three climatic regions, hot desert climate (BWh), cold desert climate (BWk) and hot semi-arid climate (BSh).

Guinea: has two different climatic regions tropical savannah climate (Aw) and tropical monsoon climate (Am).

Kazakhstan: the dominate climate is a warm humid continental climate (Dfb), with areas experiencing hot humid continental climate (Dfa), cold semi-arid climate (BSk), cold desert climate (BWk) and hot humid continental climate (Dsa).

New Zealand: has two different climates and it is dominated by and oceanic climate (Cfb) with areas of sub-polar oceanic climate (Cfc).

Russia: has many different climates, but it is dominated by a warm humid continental climate (Dfb), with sub-arctic climate (Dfc), hot humid continental climate (Dfa) and humid subtropical climate (Cfa).

Sierra Leone: has two climatic regions, tropical monsoon climate (Am) and tropical savannah climate (Aw).

South Africa: has many climatic regions, hot semi-arid climate (BSh), oceanic climate (Cfb), cold semi-arid climate (BSk), subtropical highland oceanic climate (Cwb) and humid subtropical climate (Cfa).[5]

Solar Shading – A Brief Design Guide: written by Brian Ford, architect and Emeritus Professor, University of Nottingham

The thermal performance of building envelopes has improved dramatically over the last 20 years across Europe and North America. However, an unintended consequence has been to also increase the risk of overheating. In developing countries, the need to protect buildings from unwanted solar gain has long been recognised, leading to careful consideration of orientation and potential need for protection of openings with shading devices. Wherever we are in the world, the design of appropriate sun-shading devices for buildings requires the designer to have a basic understanding of solar geometry, climatic variation, occupant needs, and available design tools.

The three key considerations for an architect are:

1. Solar Geometry;
2. Climatic Variation;
   and
3. Occupant Needs

These are discussed below, alongside potential design tools.

1. Solar Geometry

The geometrical relationship between the earth (the building) and the sun is determined by the tilt of the earth (23.5 °) as it spins on its axis, relative to the plane of the earth's orbit around the sun. The latitude of the building's location (north and south of the equator) is therefore a fundamental determinant of the diurnal and seasonal variation in the sun's apparent movement around the building. The closer we are to the equator, the higher the sun will be in the sky at the middle of the day. This means that in many parts of the world the roof of a building receives the most solar radiation, leading to the use of protective 'parasol' roofs on many buildings within the tropics. Outside the tropics the amount of solar radiation received on different surfaces will vary significantly depending on the season. Generally, throughout the world, east and west facing building facades are more difficult to protect from unwanted solar gain than north or south facing surfaces. However, buildings are rarely oriented to the cardinal points of the compass, and these generalisations are not sufficient to determine an appropriate shading strategy. It is therefore necessary to understand both solar geometry and climatic variation in more detail.

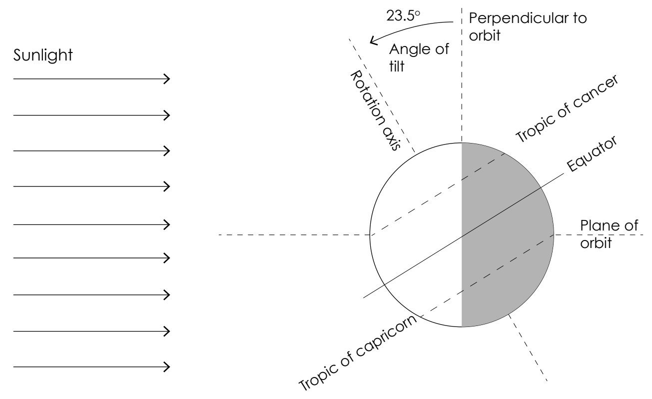
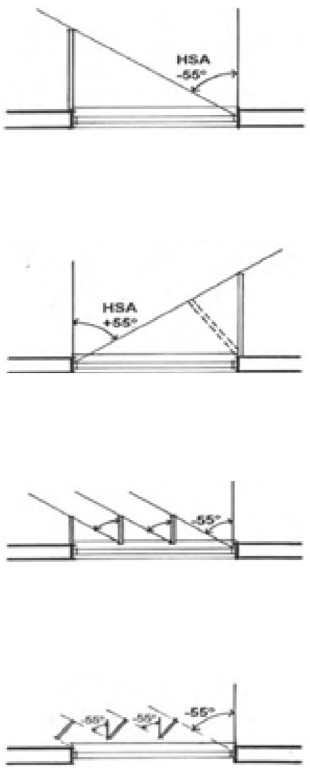


Fig 3.12 Tilt of the earth (23.5 °) as it spins on its axis

2. Climatic Variation

The earth's orbit around the sun determines the broad climatic variations experienced around the world, but seasonal variation is rarely symmetrical around the solstices. For example, in Europe the summer solstice (21st June) is often referred to as mid-summer's day, but the hottest summer months are normally July and August. Similarly, the winter solstice (December 21st) is not normally the coldest time of year (normally February). This dislocation between solar geometry and heating and cooling seasons creates a problem for designers when determining an appropriate 'cut-off' angle (horizontal or vertical shadow angles) for fixed shading devices. Indeed, this is also why some designers opt for moveable shading devices, in spite of high capital and maintenance costs, and frequent subsequent failure. Generally, however, fixed shading devices, if carefully designed, can be very effective in reducing unwanted solar gain and avoiding the associated cooling load. In the northern hemisphere, south facing vertical glazing is generally assumed to be vulnerable, but for most locations, south -facing facades may be protected by means of simple horizontal shading devices. A horizontal shade, designed to cut out the sun at noon on the equinox, will prevent any direct radiation entering the façade throughout the six summer months. However, a horizontal shade will not be effective in preventing solar heat gains to east and west elevations at any time of year. Hence the use of vertical shades, and sometimes 'egg-crate' shading devices, on east/west elevations. Within the tropics, east/west facades are vulnerable to solar gain even if they are opaque, and any opening may become vulnerable to intense reflected radiation. Within North Africa and the Middle East the traditional 'mashrabiya' screen evolved to protect the building occupants from both solar heat gain and glare. Similar 'jali' screens evolved in India. A good introduction to solar geometry is provided by Steven Szokolay in his eponymously titled paper, which is the source of Figures 3.13 and 3.14.[6] Understanding of solar geometry and climatic variation can provide a sound basis for an appropriate shading strategy if it also reflects a clear understanding of the needs of the occupants, and the pattern of occupancy of the building. This knowledge has informed the language of both the Islamic and Hindu architectural traditions. Reconnection with this approach will help architects meet the challenges of our low-carbon future.



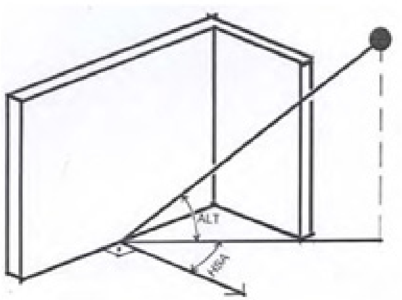


Fig 3.13 Diagrams of vertical solar shading by Steven Szokolay

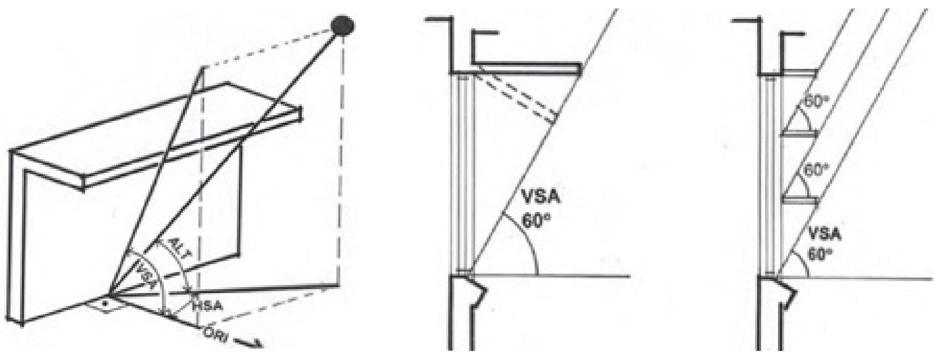


Fig 3.14 Diagrams of horizontal solar shading by Steven Szokolay

3. Occupant Needs

Building typology (for example; office, home, school and hospital), and the pattern of occupancy (seasonal and diurnal) is likely to have a fundamental influence on a successful strategy. Indeed the orientation and zoning of different functions, circulation and transition spaces, can all support a strategic response to sun and climate. Working spaces normally occupy the perimeter (6m deep) zone, benefiting from light and views, while support space (for example; washrooms, servers, storage) occupy a central core, a plan of severed and servant spaces. Thermal and visual comfort in the occupied perimeter zone will impact on the health, well-being and productivity of the occupants. Maintaining occupant satisfaction requires a shading strategy, which can respond to the needs of the different activities behind the façade, as well as to diurnal and seasonal variations. The designer therefore needs to assess and respond to a set of complex dynamic relationships, which can be facilitated by a range of different design tools.

What design tools are now available to analyse and respond to these considerations? In the past architects have analysed sunlight penetration using physical models in conjunction with sun-dials or heliodons. Physical modelling can still be a quick and effective way to evaluate the effectiveness of a shading strategy. Photographs (and animations) can record the apparent movement of the sun around and into a building. At early design stages, sketches and drawings can be evaluated by reference to 2D sun-path diagrams, which provide solar altitude and azimuth angles for any latitude. (2D and 3D sun-path diagrams can be obtained from Andrew Marsh's website: http://andrewmarsh.com/apps/releases/sunpath2d.html___http://andrewmarsh.com/apps/releases/sunpath3d.html) Solar geometry has of course now been digitised, and incorporated in a number of different software packages. Until recently one of the most user friendly software tools for early stage shading design and analysis came within the Ecotect package, originally developed by Dr. Andrew Marsh and acquired by Autodesk in 2008. However, support for Ecotect was discontinued by Autodesk in 2015, and new tools emerged to meet the needs of environmental designers and engineers. Most of these tools now integrate the benefits of parametric design and BIM, making them more compatible to the modelling software currently available in the market. One of the most promising tools (and already adopted by many architectural and engineering firms in the UK and abroad) is Ladybug-Honeybee, developed by Mostapha Sadeghipour Roudsari in 2013. Ladybug and Honeybee are two open source plugins for Grasshopper and Rhinoceros drawing software. Among other capabilities, the tool allows solar radiation, sun-hours and shading analysis based on climate data (see: www.grasshopper3d.com/group/ladybug). Contemporary

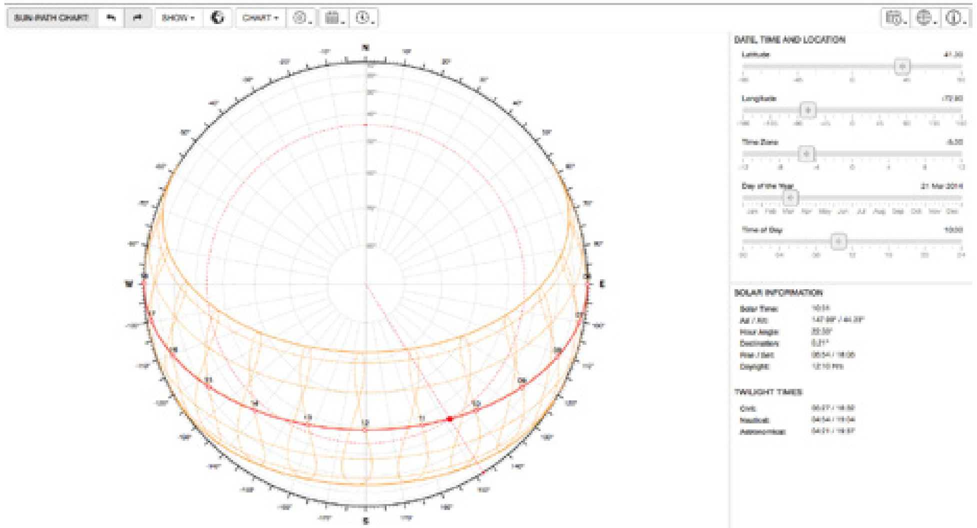


Fig 3.15 2D stereographic sun path diagram for Yale, New Haven, Connecticut, from Andrew Marsh website

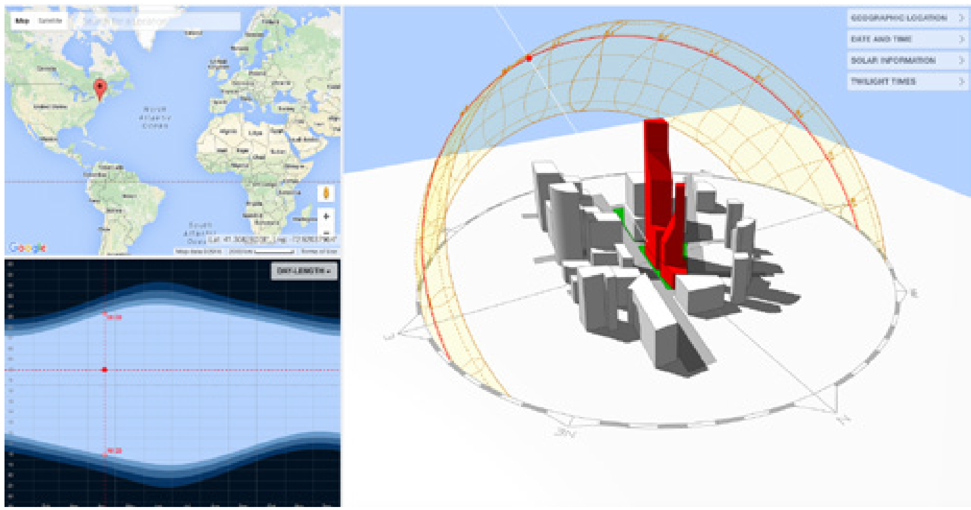


Fig 3.16 3D sun path diagram for Yale, New Haven, Connecticut, courtesy Andrew Marsh

design teams of architects and engineers have the means to understand the climatic context of a projects specific site and thus have the means to achieve comfort, whilst using the least possible energy, combined with informed selection of materials for the building fabric to achieve this, as demonstrated in the case studies of this chapter.

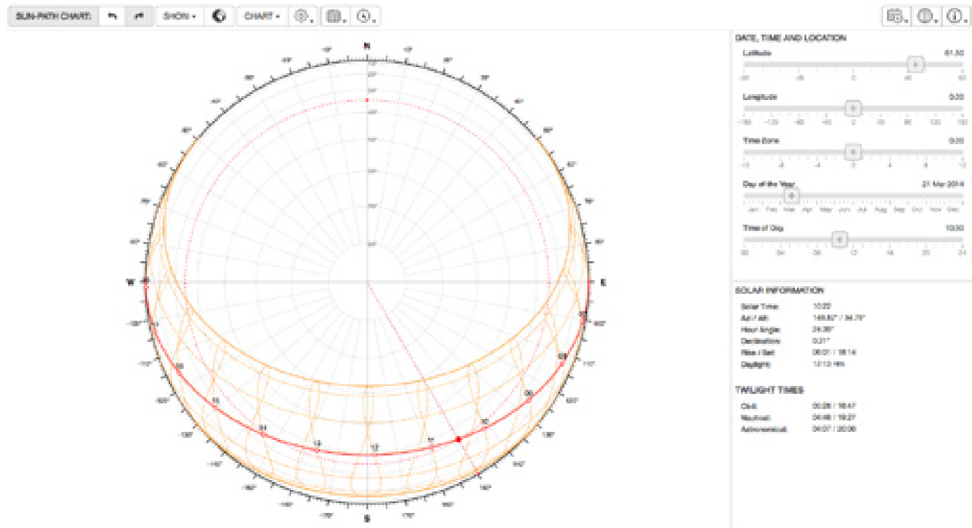


Fig 3.17 2D stereographic sun path diagram for Greenwich, London, from Andrew Marsh website

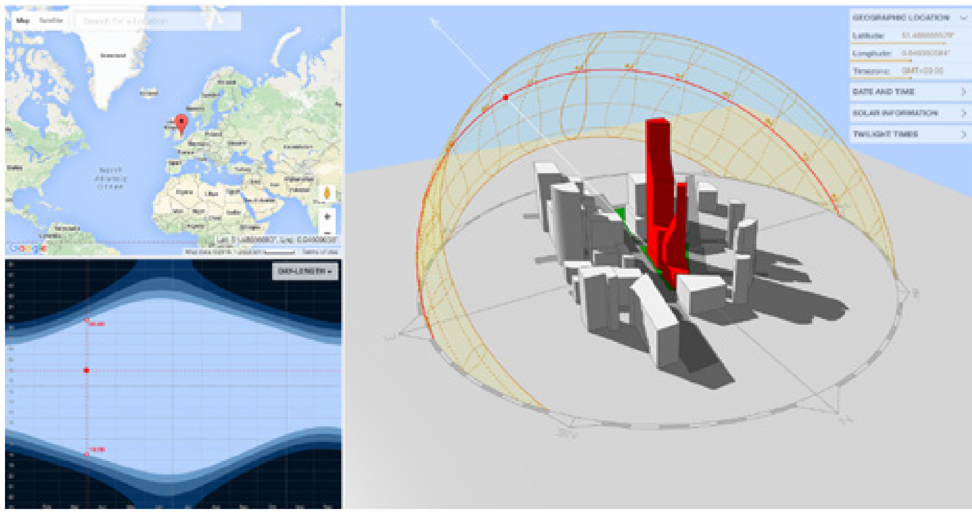


Fig 3.18 3D sun path diagram for Greenwich, London, courtesy Andrew Marsh

St George's Secondary School, Wallasey, Merseyside, England: Architect, Emslie A. Morgan, 1961

This case study explores the use of aluminium in the solar wall of St George's Secondary School, one of the first examples of passive solar low energy architecture in the world. Emslie A. Morgan, the architect of St George's, was in 1961 the principal assistant to the Borough Architect of Wallasey, yet he is heralded by Rainer Banham in his ground breaking book *The Architecture of the Well-tempered Environment* (1969) as a pioneer of environmental design.[7] Emslie A. Morgan designed this extension to St George's Secondary School to require no heating. The boiler and radiators were installed just as a back up and have only been used on rare occasions. He is one of the first pioneers of low-carbon architecture. The school is now Grade II listed by Historic England and is currently functioning as a school for pupils with additional educational needs.[89] As architecture students in the 1970s, the author, Jim Eyre and colleagues visited it when it was still a secondary school.

The design of St George's Secondary School is deceptively simple: a south facing solar wall, a high level of thermal mass and plenty of insulation. Emslie A. Morgan's design premise was, in this context, in winter a combination of solar gains, heat from artificial lighting and heat from the occupants would avoid the need for additional heating via the back up boiler. Summertime overheating would also be prevented by ventilation and strategically placed aluminium reflectors. Dean Hawkes describes it as a seminal example of passive solar design: 'Its clear-cut form, with a steeply sloping monopitch roof rising from a virtually windowless north façade to the top of a 9m-high solar wall, is a direct expression of the fundamental principles in the exploitation of solar gain to heat a building.'[10]

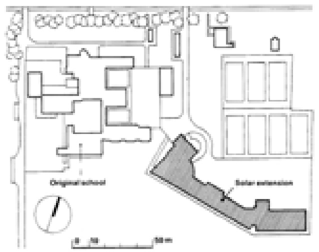


Fig 3.19 Site Plan of St George's Secondary School, 1:5000

Fig 3.20 St George's Secondary School, Wallasey, designed by Emslie A. Morgan, 1961, photographed in 2016

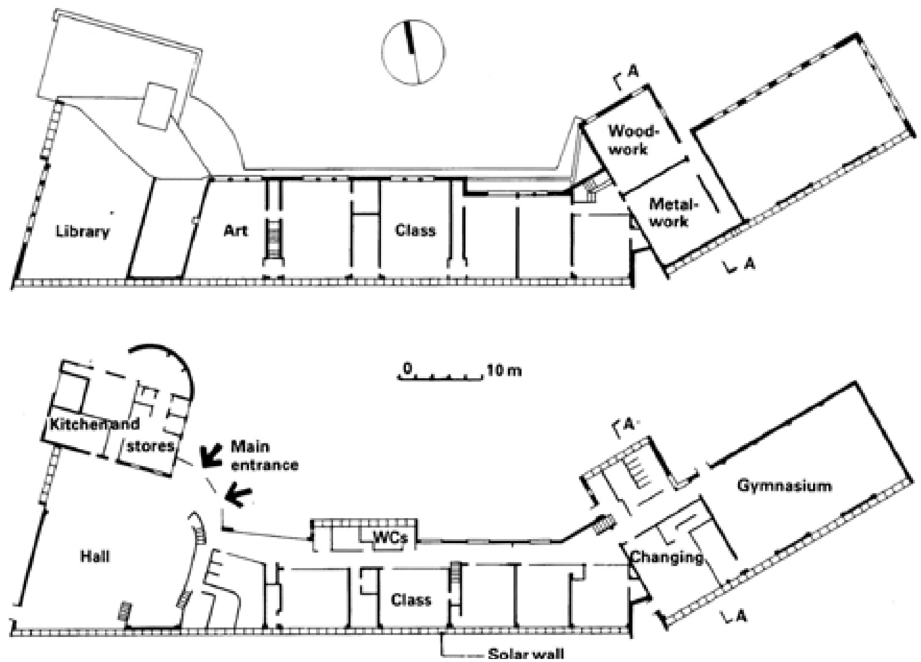


Fig 3.21 Ground and first floor plans of St George's Secondary School, 1:1000

Research, undertaken by Dr M. G. Davies of the University of Liverpool and published in Energy Design (1987) based on Emslie A. Morgan's notebooks, reveals that he was self-taught in the principles of thermodynamics and building physics.[11] Dr M. G. Davies and colleagues also undertook post-occupancy evaluation of the school during 1969 – 1970.[12]

The first phase of St George's School was completed in 1954 and has quite a conventional orthogonal plan of discrete classroom blocks. Whereas Emslie A. Morgan's extension, completed in 1961, has a linear plan with the solar wall oriented south to maximise solar gains. The hall and kitchen are adjacent to the main entrance, with a circulation corridor and toilets placed on the north side, whereas the classrooms enjoy a southerly aspect. The eastern end of the plan is cranked after the classrooms, with the woodworking and metalworking rooms and gymnasium articulated as a separate block, but still principally facing south. The first floor classrooms and library are full width, as they are approached via stairs set within the section. It was built on an ordinary local authority budget, without any grant support. In 1961 the extension cost £120,000.

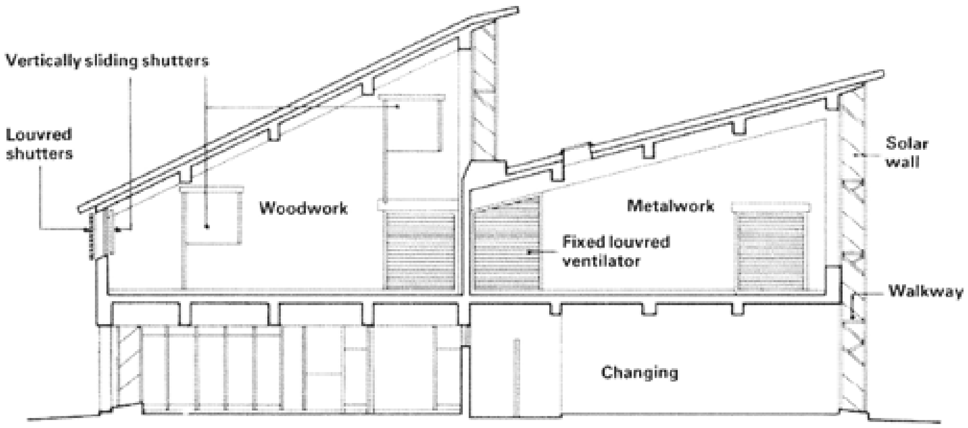


Fig 3.22 Transverse section through solar wall of St George's Secondary School,1:200

The thermal mass of the 175mm concrete roof and 220mm brick walls are both exposed internally and protected with 125mm of expanded polystyrene insulation, providing a calculated U-value of 0.28 W/m²K. The solar wall is over 8m tall and primarily comprises two single skins of glass, set 600mm apart, supported by a light steel frame that incorporates access walkways every 2m in height. It is constructed from a 1,050mm module with 1,050 x 600mm panes of external clear single glazing. The inner skin is a combination of clear and translucent glass – the aim was to diffuse solar radiation evenly over the room. The classrooms are also equipped with pinboards, which conceal aluminium panels that were designed to be reversed on a seasonal basis. One side is faced in aluminium

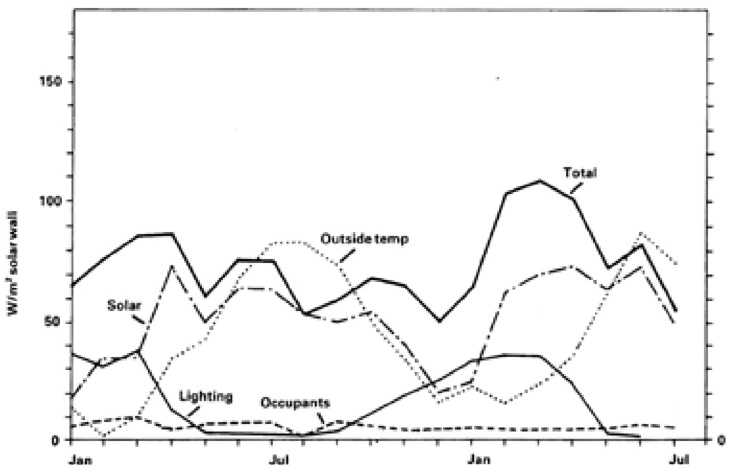


Fig 3.23 Energy inputs and ambient temperature of St George's Secondary School, courtesy of Dean Hawkes

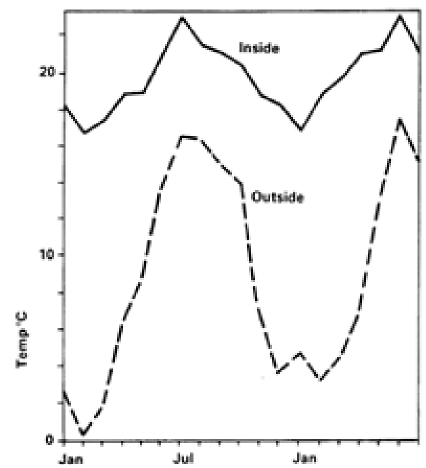
to reflect solar radiation in summer and the other face painted black to absorb solar gains in winter. Ventilation is provided via horizontally pivoting windows in the two skins, arranged to be weather and burglar proof.

About 12 per cent of the inner leaf of the solar wall is 220mm blockwork, these areas of walls are equipped with pivoting aluminium shutters painted white on one side and mill finished on the other. Morgan's intension in winter was for the shutters to be set at 90 degrees to the black painted masonry wall, with the aluminium faces enhancing solar gains. In summer the shutters are closed against the masonry wall reflecting unwanted solar gains back out through the single glazing. In the upper classrooms and the gym cross ventilation is achieved by opening insulated shutters in the north wall.

The ventilation rate within the school has been criticised, when visiting St George's it smelt intensely of school. Dean Hawkes suggests: 'If the void in the Wallasey solar wall had been used as a channel to draw air into the building it is likely that adequate winter ventilation could have been achieved without a serious thermal penalty.'[13]

On 6 April 1961 Emslie A. Morgan applied for a patent for *Improvements in Solar Heated Buildings*, granted under UK Patent Specification 1 022 411 in 1966. In the considered opinion of Dean Hawkes – St George's demonstrates that in 'the British temperate climate a south-facing glazed wall can, if carefully designed, produce a net heat gain over the whole of the heating season.'[14]

Fig 3.24 Ambient and internal daily mean temperatures of St George's Secondary School, courtesy of Dean Hawkes



Empress State, London, England: Architect WilkinsonEyre, 2003

This 1960s office tower underwent a deep retro fit, designed by WilkinsonEyre, with the refurbishment undertaken between 2001 and 2003. The Empress State was designed by Stone, Toms and Partners and built between 1958 and 1961. On completion, it was briefly the tallest building in London, before being overtaken by the Millbank Tower, designed by Ronald Ward And Partners.

The Empress State office tower, originally occupied by the Minister of Defence, with its distinctive Y-shaped or tricorn plan is a distinctive landmark in west London, however, it is not listed by Historic England. It had an in-situ concrete frame, stone clad access towers and a highly glazed south facing curtain walling. WilkinsonEyre's brief was to modernise the building in a sympathetic manner and to provide significant additional flexible office space, as well as improving the environmental efficiency of the building.[15]

Fig 3.25 Empress State before the refurbishment, in 2001

Fig 3.26 Empress State in 2003, after its refurbishment, architect WilkinsonEyre

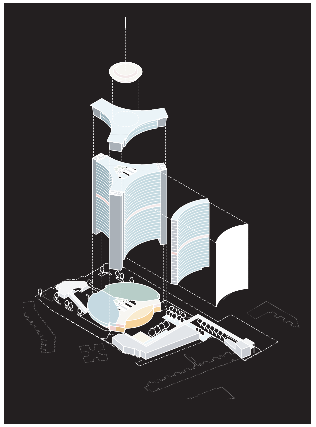


Fig 3.27 The primary elements of the Empress State refurbishment

Fig 3.28 The gently faceted eleptical aluminium louvres of Empress State

WilkinsonEyre conceived this refurbishment as four new elements, enhancing and working with the original architecture and structure of the Empress State: a new plaza and entrance drum, extending the office floors to the south, with a new curtain walling system and full-height brise soleil, adding three new floors at the top of the tower with full height curtain walling and horizontal solar shading. This series of elements culminates in a circular and revolving observation bar.

Having removed the original curtain walling, WilkinsonEyre extended the office floor plates by 5.5m on the south façade of levels 3 to 26. Installing new curtain walling, a maintenance access zone and full height elliptical extruded aluminium brise soleil that unite the façade. Proving much needed solar shading, whilst increasing the lettable area of the building, WilkinsonEyre not only retain the curved plan of the offices the form is improved despite the use of flat double glazing and straight brise soleil extrusions. The original curtain walling was faceted in seven distinct and articulated flat planes. Although still facetted, the new assembly forms the curve gently in 15 straight modules. The new depth of plan also further articulates the offices from the circulation towers. The curtain walling and brise soleil are all polyester powder coated.

The three new floors have a separate expression, set back from the visual field of the brise soleil below, forming a timber-decked balcony. The full height glazing is articulated by cantilevered horizontal solar shading at levels 27 and 29. Topped by the observation bar with its spectacular views of London, back to St Paul's and the London Eye, this is now a 30-storey office building.

Empress State has been retained and enhanced as a landmark in west London and the offices are now occupied by the Metropolitan Police. WilkinsonEyre's contribution to this project appears to have an effortless simplicity, demonstrating the clarity of thoughtful architecture that this practice regularly achieves on a diverse portfolio of projects.

Fig 3.29 The south façade during construction

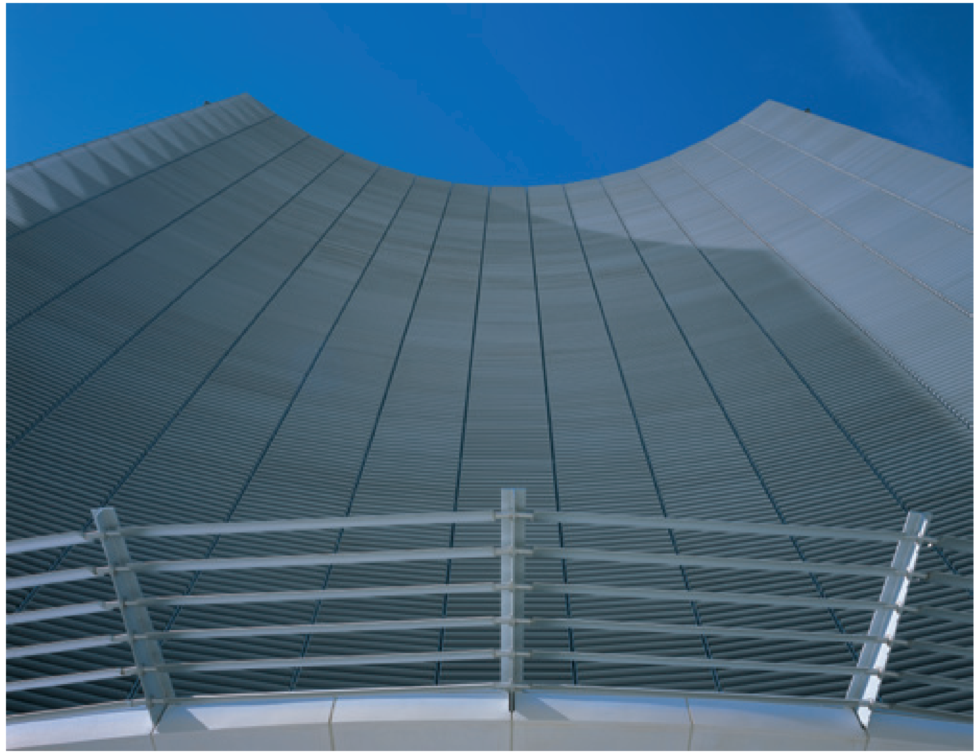


Fig 3.30 The completed south façade

Fig 3.31 Outward curving solar shading of the Empress State Building, architect WilkinsonEyre

High Museum of Art Expansion, Atlanta, Georgia, USA: Architect Renzo Piano Building Workshop, 2005

The city of Atlanta was founded in 1837 at the junction of two railway lines in Georgia, in the deep south of the USA. The High Museum itself was founded in 1905 moving into a 'stately home' on Peachtree Street, central Atlanta in 1926. 1983 saw the completion of Richard Meier's major new building for the High Museum, on its current site off Peachtree Street. This essay in white modernism is clad in 900mm square porcelain enamel steel panels. With a burgeoning collection of modern art, on the eve of the millennium, the gallery directors Ned Rifkin and Michael Shaprio decided it needed to double in size. Apparently, at first, Renzo Piano was reluctant to take on this commission, describing Meier's building as the 'beautiful ballerina'.[16] Collaborating with local architects Lord, Aeck & Sargent, the design and delivery of the High Museum Expansion took Renzo Piano Building Workshop (RPBW) six years, it opened to the public on 12 November 2005.

Renzo Piano's starting point for the Expansion was the design of a new public square. The size and proportions of this square is based on Piazza San Lorenzo in Genoa, near by RPBW once had its offices. Peter Buchanan describes the new piazza for the High Museum as 'a serenely beautiful place, well judged in dimensions and proportions, and capable of many moods as it hosts a wide variety of uses from performances to alfresco family meals and solitary reading'.[17] The hard landscape of this piazza is a combination of

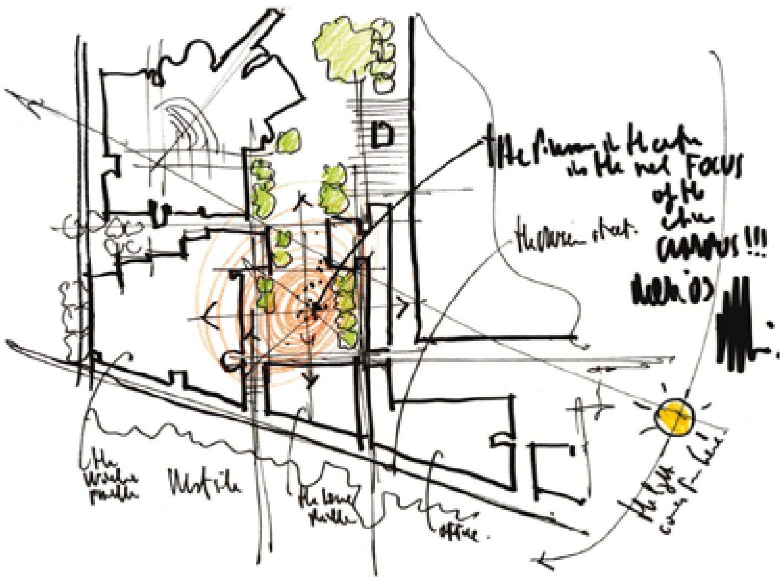


Fig 3.32 Renzo Piano's sketch plan for the Expansion - the new piazza is the heart and focus

Fig 3.33 The Expansion by Renzo Piano Building Workshop, 2005, viewed from outside Richard Meier's 1983 building for the High Museum

Fig 3.34 Approaching Richard Meier's 1983 new building for the High Museum

Cordoso stone bands and, predominately, brush concrete. Piano insisted in the use of this humble material, as it forms the sidewalks of Atlanta, and he wanted it to be 'an ordinary part of the public realm, a place where anyone would feel at home'.[18] Buchanan suggests this is not just an imported European piazza, but a 'place to be discovered and to go to specially. It is not framed and grounded in place by heavy buildings of stone or brick whose porticos, arcades and windows interlock the buildings and the piazza… but it is edged by buildings with light thin claddings that float over transparent ground floors'.[19] Suggesting Renzo Piano has 'invented a new form of piazza for automobile-oriented Atlanta and American construction traditions'.[20]

Fig 3.35 Ground floor plan with new construction in yellow and pools and canopies in blue:

1 Peachtree Street
2 Sixteenth Street
3 Fifteenth Street
4 Arts Center Way
5 MARTA station
6 Richard Meier's High Museum of Art, now Stent Family Wing
7 Memorial Arts Center
8 Piazza
9 Wieland Pavilion
10 Anne Cox Chambers Wing
11 Administrative Centre
12 Student residence
13 Restaurant

Although the space is reminiscent of Early Renaissance Italy and the paintings of Piero della Francesca, Buchanan considers its lightness in colour and materiality is analogous to 'the weightless version of European classicism found in colonnaded plantation houses of the American South.'[21] Suggesting that the High Museum Expansion 'demonstrates Piano's sensitivity to place and local culture'.[22]

Having decided at an early stage to make the proportion of the cladding vertical and for it to be **rainscreen** construction, RPBW evaluated both timber and Venetian plaster for the cladding of main buildings of the High Museum Expansion. The timber was rejected on cost and maintenance concerns. The prototype panels

Fig 3.36 The Wieland Pavilion viewed from the piazza

of Venetian plaster were constructed but did not prove durable in Atlanta's humid subtropical climate that also experiences cold continental winters. At this stage, the cladding was salmon pink in colour. This was retained for the new student accommodation on the corner of Arts Center Way and 15th Street, in the form of self-finished fibre reinforced cement panels, set within an expressed steel frame. Via a design development process of models, mock-ups and prototypes, 6mm painted aluminium was selected for the rainscreen and the shading cowls in pale beige, which was later changed to High Museum white.

The new galleries are primarily arranged in two blocks: the Wieland Pavilion and the Anne Cox Chambers Wing. Both have two basement levels, and galleries on ground and first floors, with loft-like roof lit galleries on the top floor. However RPBW faced the dilemma that the orientation of the spaces was generated at 90° to the route between Arts Center Way and Peachtree Street, by the new piazza, significantly off the cardinal points, making excluding the

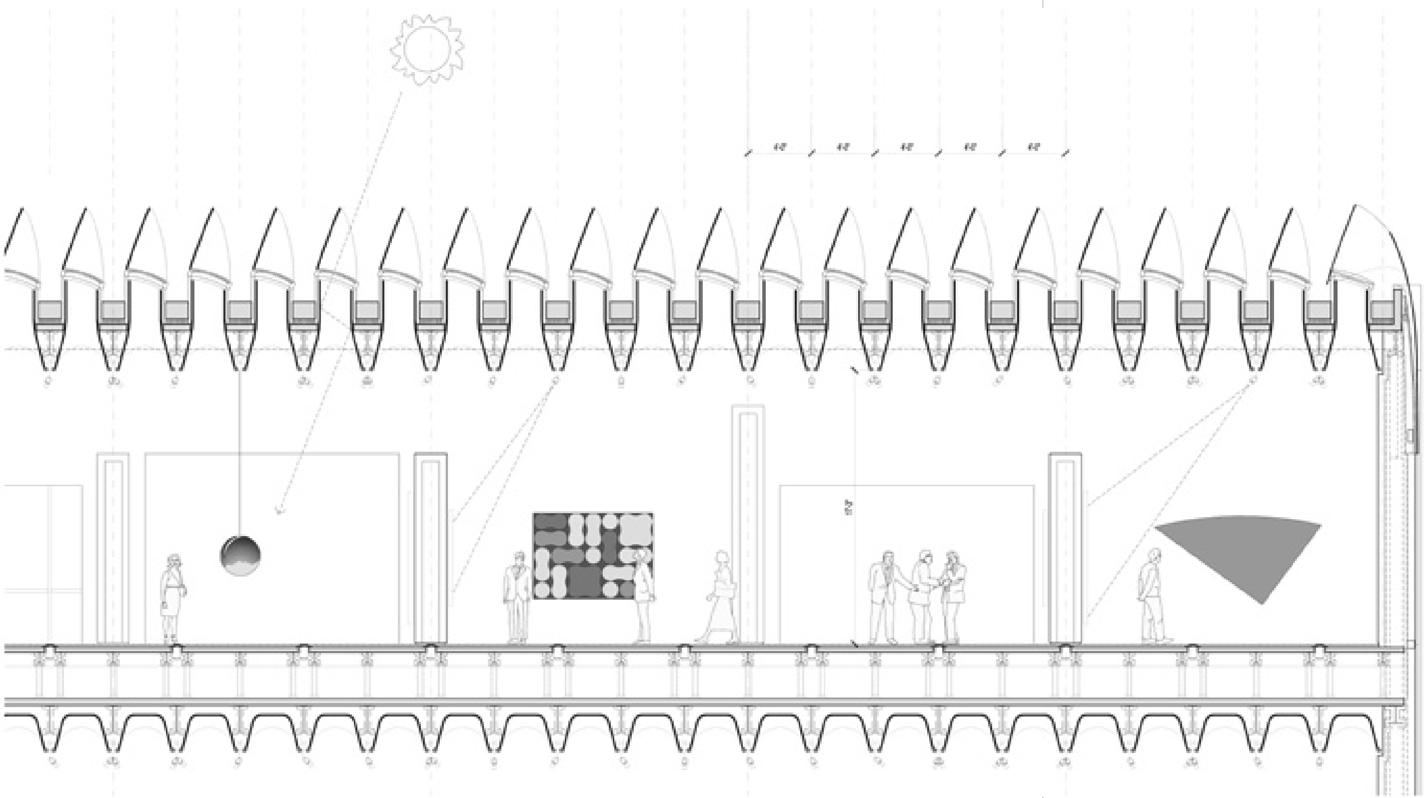


Fig 3.37 Section through a top lit loft-like gallery of the Expansion

sun difficult. An overall roof was rejected on the grounds of cost, which was being used by RPBW for The Modern Wing of The Art Institute of Chicago (2009). RPBW therefore revaluated the linear sail like shading elements of the Menil Collection (1982-86) starting with vaulted beams. Working closely with the client, Arup and Arup Lighting, the vaulted internal expression was retained in the form of a ceiling comprising Glass Fibre Reinforced Gypsum (GFRG) modules that are closed on the lower floors and perforated on the top floor when linked to circular roofights admitting daylight, but shaded from the sun by cowls. Thus freeing the daylight from the geometry of the buildings, enabling the cowls to exclude direct sun – just like the cast aluminium solar shading of the Nasher Sculpture Center in Houston Texas, which was designed by the same team of consultants and is discussed in TSC Report 2 *Aluminium: Recyclability and Recycling*.[23] RPBW described the solar shading devices of the High Museum as velas, the Italian for sails. They are much larger in scale than the cast aluminium shades

Fig 3.38 Prototype façade for the student accomodation

of Nasher. The cowls and rainscreen panels were two separate elements at this design stage, as seen in the study model shown in Figure 3.45.

Some 1000 rooflights and cowls form the roofscape of the two buildings. The double glazed rooflights also incorporate an interlayer that excludes ultraviolet light to protect the artworks below. Reviewing the opening of the High Museum Expansion, Brenda Goodman of the New York Times observed that the 1000 rooflights and cowls:

> are angled to catch only northern light, prized by artists for its softness. The controlled brightness in the galleries below recreates the tawny moment when a moth-eaten cloud will pass in front of the sun. It is the kind of light that makes colors pop and wood glow. It is the kind of light that makes paint look magical.[24]

Fig 3.39 Prototypes of the aluminium sun cowls or velas

The design studies by RPBW show the realisation that on the edges of both buildings, the 6mm aluminium sheet cladding could transform into to the first row sails or cowls, simply by cold forming the aluminium via a press brake, see Figure 3.46. Buchanan celebrates this tectonic:

> The result is an immensely striking roofscape, made even more so by the way the uppermost cladding panels on the walls extend past the roof parapet and twist to form the cowls along each edge of the roof, one of the most ingenious and beautiful devices ever invented by RPBW.[25]

This synthesis of two elements, cladding and cowl, is a very clear demonstration of Renzo Piano's approach to the design of architecture. With his in-house team and carefully chosen consultants, such as Arup, he keeps all the component of the building under consideration simultaneously. Going beyond the bounds of integrated design. His practice is in essence the opposite of the conventional packaging and layering of many contemporary building projects.

Fig 3.40 The 6mm sheet aluminium sun cowls of the Expansion's galleries

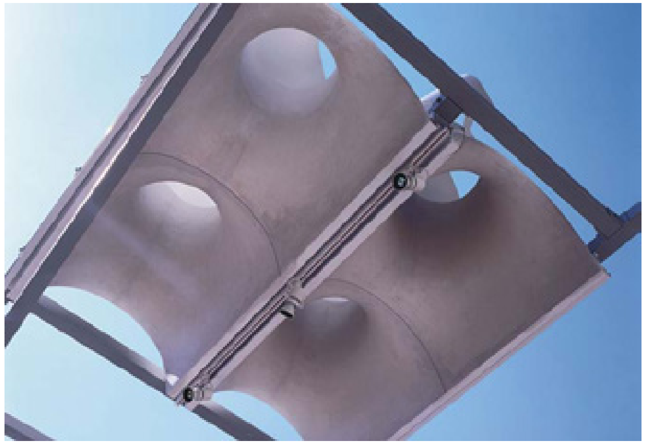


Fig 3.41 The prefabricated GFRG vaulted ceiling panels will link with the rooflights and sun cowls

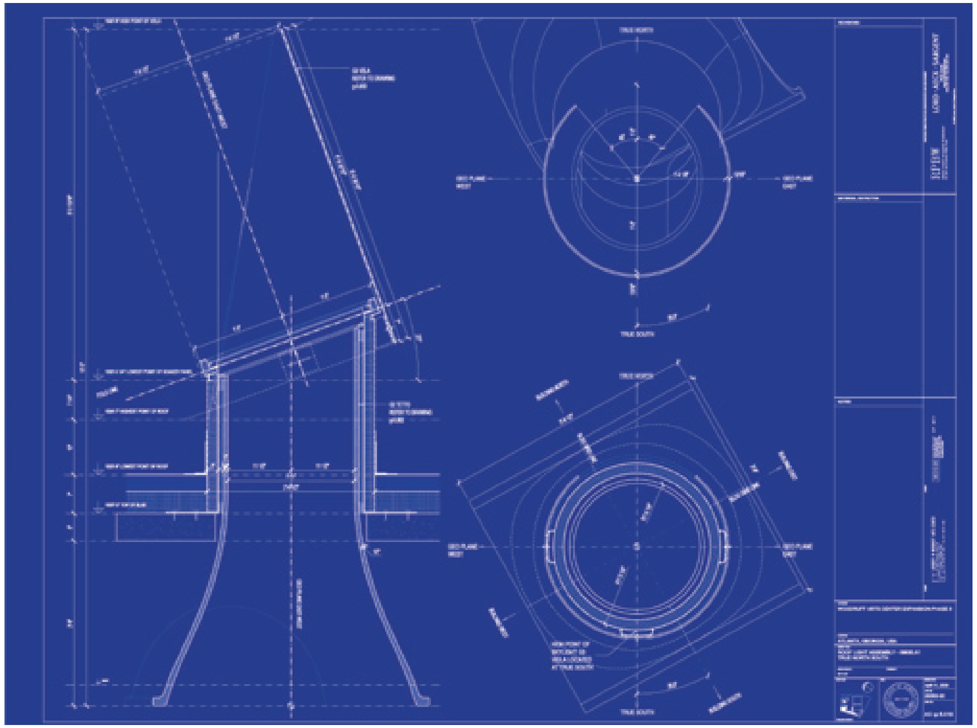


Fig 3.42 RPBW's working drawing of a sun cowl and rooflight assembly

Fig 3.43 Fabricating the GFRG vaulted ceiling panels

Fig 3.44 A worker reveals the scale of the velas or sun cowls

Fig 3.45 At the design stage, represented by this model, the sun cowls and aluminium cladding were seperate elements

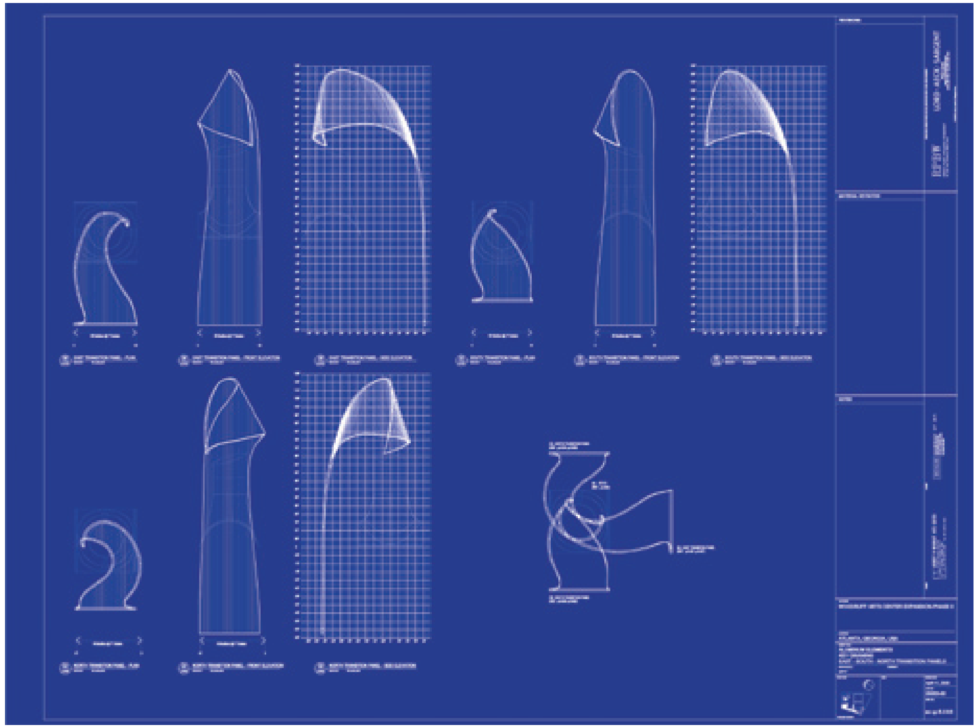
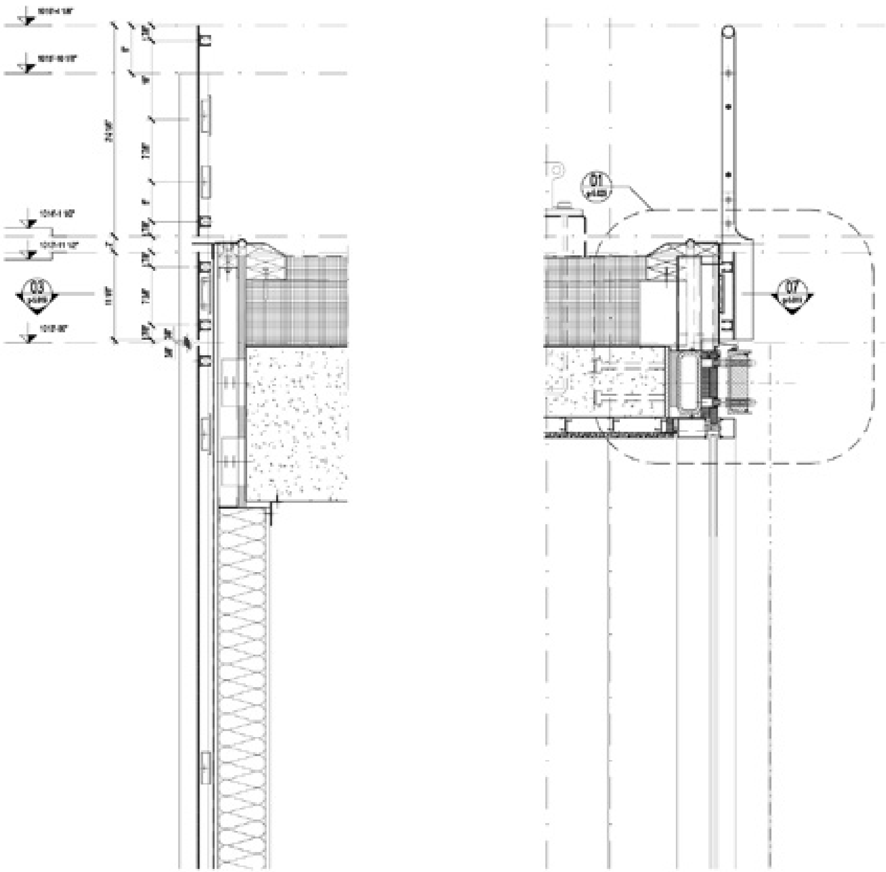
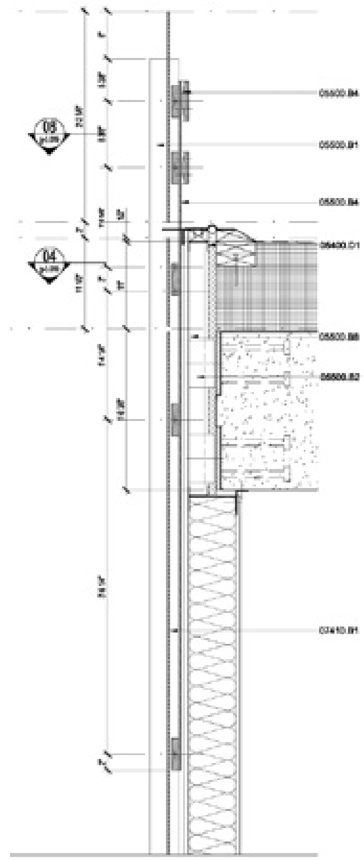
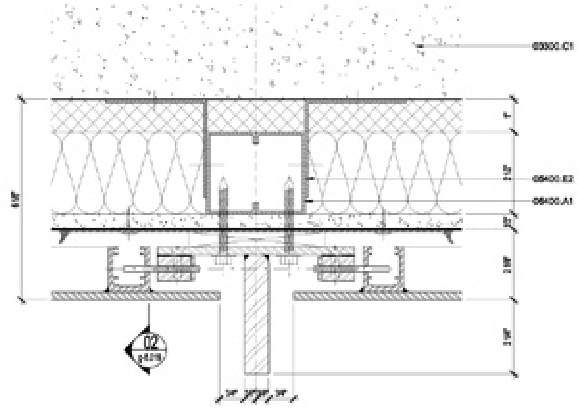


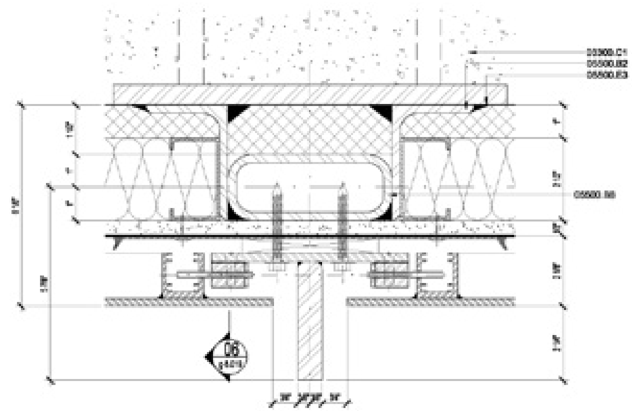
Fig 3.46 The digital evolution of the integration of the cladding and sun cowls into one element

Fig 3.47 Prototype of the sun cowls to test the daylight and integration of components









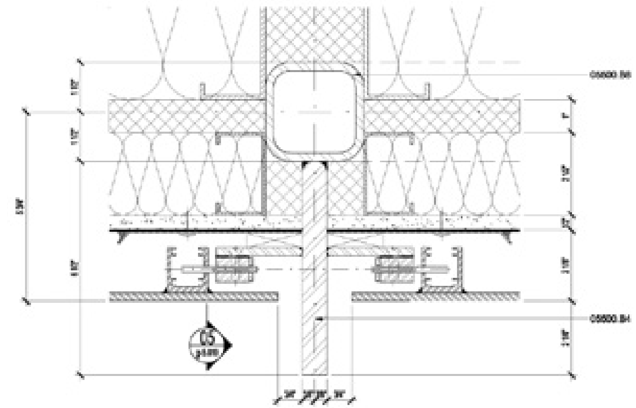


Fig 3.48 [above] Sectional details of cladding. left to right: typical condition; above glazing with balustrade above; at end of cantilevered roof slab

Fig 3.49 [left] Detail of 6mm aluminium rainscreen cladding meeting in-situ concrete base

Fig 3.50 [opposite] Plan details at end of floor and roof slab showing fixings of rainscreen cladding. top to bottom: typical condition, at end of cantilevered slab; above glazing

Fig 3.51 Craning a cowl-panel into place

Fig 3.52 The fixing sequence of cowl-panels

The cladding module is nominally 1150mm on the east façade and 1200mm on the west façade. Reusing the 900mm module of the Meier building was considered at an early stage, however it proved too narrow in terms of internal and external proportions and maintenance of the light funnels. The vertical junctions of rainscreen cladding are articulated by protruding steel flats that are painted white like the aluminium panels. These flats modulate the façades and internal steel structure to which each is fixed, also become the springing points for the frameless glass canopies sheltering the perimeter of the piazza, which are suspended delicately below the cladding. Although the cladding in its verticality reveals the architect is cognisant of sheet aluminium being a roll formed product, the façades are also modulated by horizontal shadow gaps that delineate the intermediate floor levels. The 6mm aluminium sheet cladding and cowls have a matt white paint finish, which is a warmer white than the glossy porcelain enamel panels of the Meier building (now called the Stent Family Wing).

Fig 3.53 An abseiler painting the steel flat between the aluminium rainscreen panels

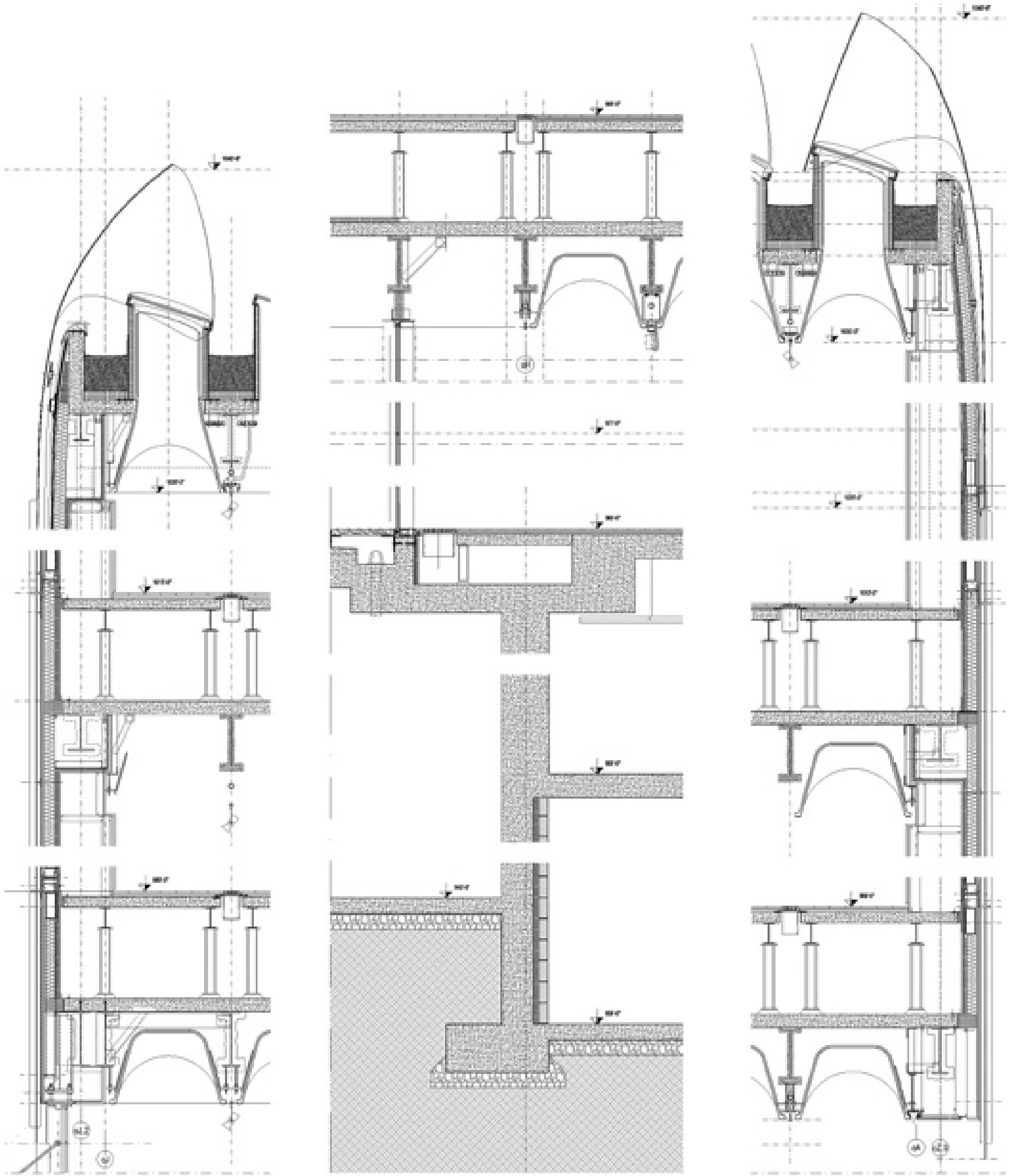


Fig 3.54 Renzo Piano Building Workshop's detail section through the gallery spaces

Fig 3.55 Buchanan describes 'the twist to form the cowls along the edge of the roof, one of the most ingenious and beautiful devices ever invented by RPBW

Skanska was the main contactor for the High Museum Expansion, which was built between 2003 and 2005 at a capital cost of $105million. It is a beautifully detailed village of the arts and many consider that Renzo Piano has made sense of Richard Meier's Building by setting it in a new urban context, combined with tall, hansom and flexible day lit galleries that balance the scale of the original atrium. Renzo Piano has created a work of architecture and urbanism that Peter Buchanan describes to be 'as timeless as the museums contents'.[26]

Fig 3.56 A top floor day lit gallery in the Expansion

Fig 3.57 Approaching the entrance to the High Museum of Art, observing RPBW's sophisticated and harmonious integration of the components of the building fabric

Yale Sculpture Building and Gallery, New Haven, Connecticut, USA: Architect KieranTimberlake, 2007

The Sculpture Building and School of Art Gallery seeks to forge a new relationship between the city of Connecticut and Yale University. KieranTimberlake's design is a considered response to the urban conditions found on this brownfield site, 'while much of the campus clusters about cloistered quadrangles that exclude the city, the new sculpture building and art gallery sought to invert those historic patterns and invite the city into and through the site.'[27] The design of the project extends the University art district westward and engaging the city with pedestrian routes and active street frontages. Stephen Kieran and James Timberlake observe, 'at night the Sculpture Building illuminates the block, creating a safe passage from the main campus to the residential area at the campus edge. The east-west path through the site is planned as an outdoor sculpture garden that connects all the way back to Louis Kahn's Yale University Art Gallery and the rest of the arts district.'[28] The buildings are a mixture of uses, encompassing an art gallery, studios, classrooms, workshops, retail space and parking. The art gallery is a separate block on the north side of the site facing Edgewood Avenue and it relates to the historic housing in scale and cladding. It is clad in a rainscreen of reclaimed western red cedar.

Fig 3.58 The north façade of the Yale Sculpture Building with a glimpse of the western red cedar of the School of Art Gallery

The architect addressed three key issues, using a holistic approach to the designing of the project: light, air quality, and energy. KieranTimberlake sought to balance maximising daylight with energy efficiency in an all glazed façade that incorporates; solar shading, triple glazed low-emissivity clear vision panels, openable windows and translucent spandrel panels. The 4.3m (14') high studio spaces are washed with daylight. Even the translucent spandrel panels admit 20 per cent daylight. The architect's commitment to daylighting has been fully integrated with the building lighting design through the installation of daylight dimming. Yale Sculpture Building and School of Art Gallery benefited for earlier research into active facades by KieranTimberlake, including Melvin J. and Claire Levine Hall, at the University of Pennsylvania, see pages 552–555.

Fig 3.59 The bespoke extruded aluminium solar shading of the south façade and the visible Kalwall of the west façade

Analysis of the climate of New Haven indicated a strong seasonal variation, with significant heating required during the winter and cooling in the summer. Based on sun path analysis, KieranTimberlake choose to orient the Sculpture building north-south, minimising eastern exposure and almost eliminating western exposure. Observing the lack of overshadowing from adjacent buildings, the architect determined that horizontal shading was needed along the southern and eastern façade.

In New Haven, the summer sun is very high in the sky at midday and reaches from northeast in the morning to the northwest in the evening. The winter sun is only a 25.5° at midday and travels from southeast to southwest. KieranTimberlake designed and developed bespoke extruded aluminium solar shading, in collaboration with Schüco, to block summer sun and admit winter sun using the midday sun angle of 25.5° as the design cut off. The extruded aluminium curtain walling and solar shading are finished with a three coat PVDF wet applied paint system.

The overall curtain walling assembly was designed as a collaboration between KieranTimberlake, Schüco and Kalwall. The predominately south facing glazing enables the building to receive beneficial solar gain during the winter months, thus reducing the energy demands of the heating season. In turn, the solar shading cuts out the risk of overheating in the summer months. The spandrel panels comprise a low-e double glazed unit, an air cavity and a translucent Kalwall panel filled with aerogel.

Kalwall is a composite panel with glass reinforced polymer (GRP) skins and an internal extruded aluminium structure with visual antecedence in Japanese shoji screens. It was invented in 1955 by Robert R. Keller.[29] Kalwall is now available with thermally broken aluminium extrusions and filled with translucent aerogel insulation, providing U-values as low as $0.28W/m^2K$. Aerogel was invented by Samuel S. Kistler in 1931. It is such an efficient insulator as it traps air on a molecular basis. Two sets of spandrel panels on the east and south façades were tested on site by the architect. Although temperatures of 60 degrees Celsius were recorded, this is below the operating temperature of the glue of the laminated construction of Kalwall. KieranTimberlake also identified the need for further post-occupancy research. Indoor air quality is achieved via a displacement ventilation system, which introduces air at low velocities, but higher than usual temperatures in part using stratification to increase energy efficiency and thermal comfort. This is another first on the Yale campus. Figure 3.61 shows KieranTimberlake's psychromertic chart of the comfort zone for this project created by the cooling potential of the available natural ventilation.

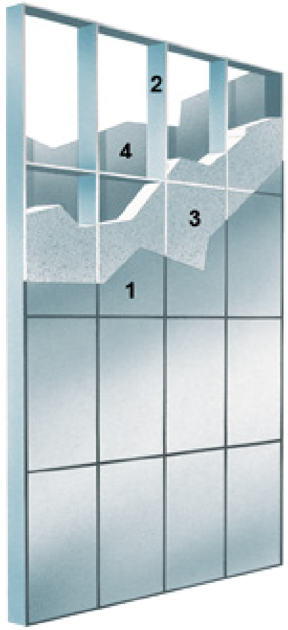


Fig 3.60 Kalwall panel module:

1 Translucent glass fibre reinforced polymer (GFRP) exterior face
2 Structural Grid Core (aluminium extrusion or thermally-broken aluminium extrusions)
3 Translucent insulation (TI) thermal packages including aerogel
4 Translucent glass fibre reinforced polymer (GFRP) interior face

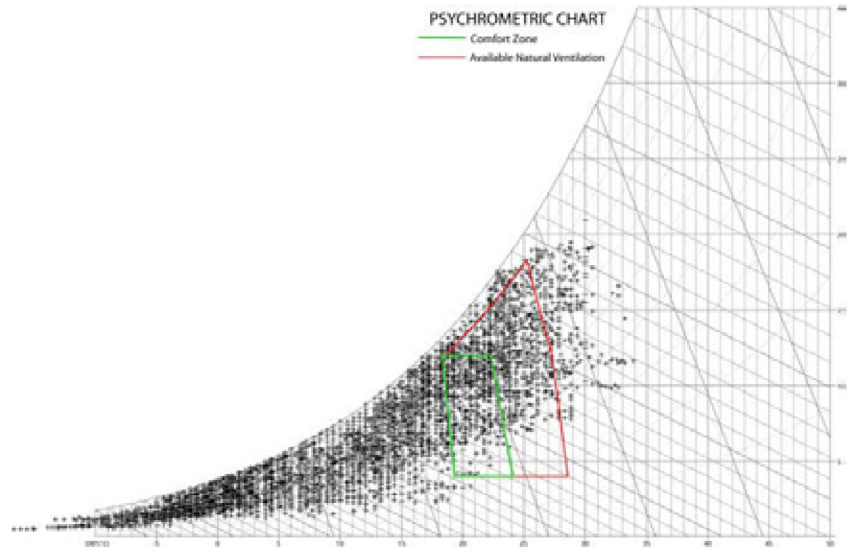


Fig 3.61 KieranTimberlake's psychrometric chart of the comfort zone for this project

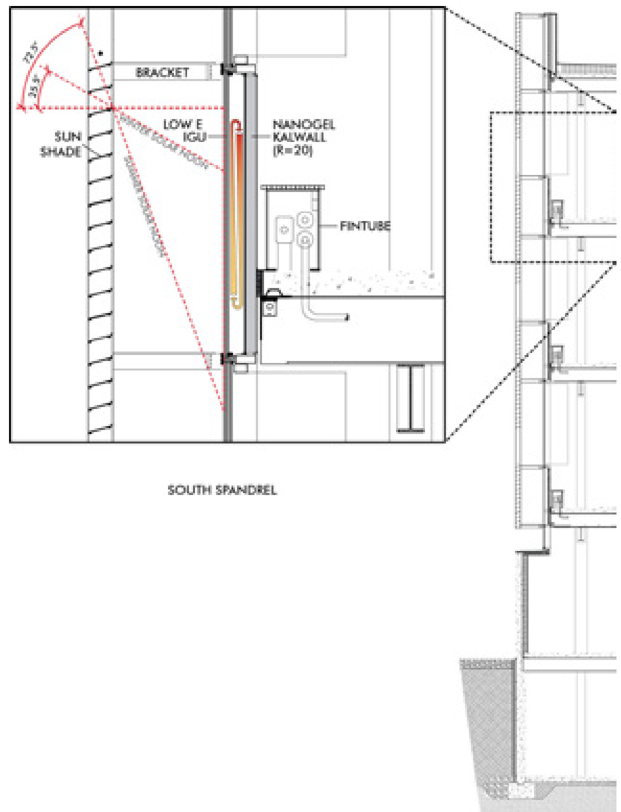


Fig 3.62 KieranTimberlake's detail of the façade, showing the key solar angles for the design of the louvres

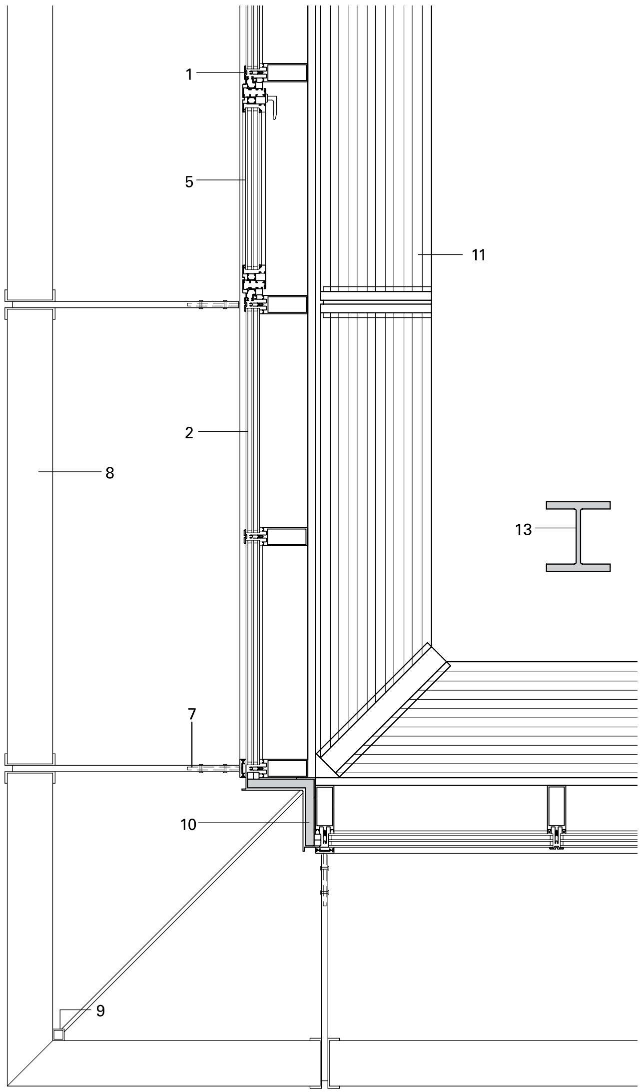
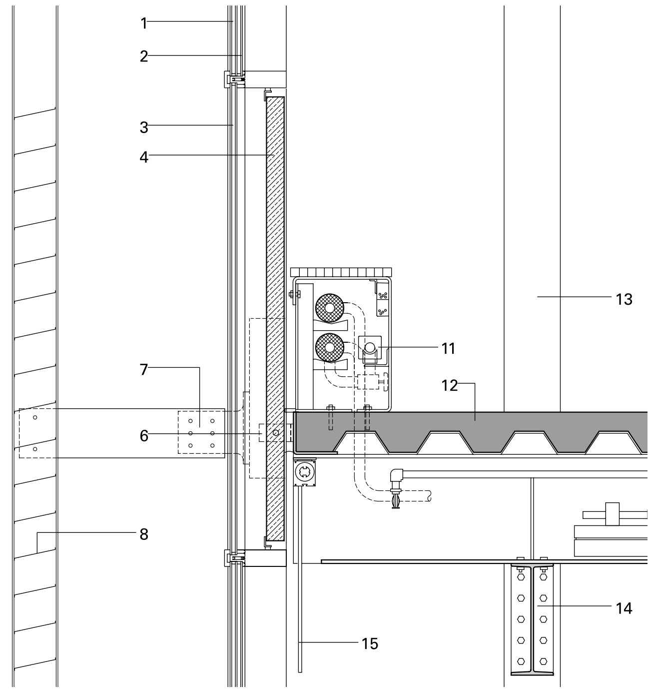


Fig 3.63 Solar shading plan detail shown at 1:25

1 Aluminium curtain wall mullion/transom
2 44 mm (1¾") triple glazed low-E IGU
3 25mm 1" double glazed low-E IGU
4 Aerogel filled translucent fibreglass faced Kalwall
5 Triple glazed inward opening casement window
6 Steel bent plate, U-anchor welded to pour stop
7 Aluminium bracket and sunshade support arm
8 Aluminium sunshade blade
9 Aluminium tube at sunshade blades only
10 Press break formed aluminium panel closure
11 Hydronic fin-tube heating assembly
12 Concrete slab on metal deck
13 Steel wide flange column
14 Steel wide flange beam
15 Roller shade

Fig 3.64 Solar shading section detail shown at 1:25

1 Aluminium curtainwall mullion/transom
2 44 mm (1¾") triple glazed low-E IGU
3 25mm 1" double glazed low-E IGU
4 Aerogel filled translucent fibreglass faced Kalwall
5 Triple glazed inward opening casement window
6 Steel bent plate, U-anchor welded to pour stop
7 Aluminium bracket and sunshade support arm
8 Aluminium sunshade blade
9 Aluminium tube at sunshade blades only
10 Press break formed aluminium panel closure
11 Hydronic fin-tube heating assembly
12 Concrete slab on metal deck
13 Steel wide flange column
14 Steel wide flange beam
15 Roller shade



KieranTimberlake consider that the 'envelope not only offers exceptionally high performance but also creates an aesthetically unified building. Along the south wall, as seen against Yale's gothic structures beyond, the effect is an elegant contemporary gothic tracery derived entirely from the need to mitigate solar gain.'[30] The Sculpture Building and School of Art Gallery 'utilizes grey-water and storm water harvesting, reclaimed and recycled materials and extensive day lighting' and was the first project in Connecticut to achieve LEED Platinum.[31]

Fig 3.65 KieranTimberlake's interpretation of Gothic tracery in a high performance façade creating context and amenity, with panache

Children's Eye Centre, Moorfields Eye Hospital, London, England: Architect Penoyre & Prasad, 2007

This is a world-class centre of research and treatment of children's eye conditions, building on the excellence of Moorfields Eye Hospital, taking research directly from lab to bedside. The Richard Desmond Children's Eye Centre was designed by Penoyre & Prasad to dispel 'preconceptions of hospitals to create an holistic, child-focused and welcoming environment'.[32] It works as an extension to Moorfields Eye Hospital, providing a hospital within a hospital, in the words of the architect this 'dedicated centre provides outpatient clinics, day surgery, research facilities & overnight accommodation facilities for patients & families & addresses highly prescriptive clinical requirements without losing sight of a supportive & child-friendly patient environment.'[33]

The welcoming public elevation of the Children's Eye Centre is a south facing glazed façade that offers views of the public gardens across Peerless Street. This façade is playfully protected from solar gain by folded silver polyester powder coated aluminium louvres, which appear to be a suspended shoal of 'silver darlings' in front of the façade. Providing shade yet providing views to the gardens across the street. Overall the architect aimed to create a building that 'offers a textured and engaging experience, and a sense of discovery for patients whose ages range from 0 to 16 and who may find their treatment lasting for months or even years.'[34]

Fig 3.66 South façade of the Children's Eye Centre at Moorfields Eye Hospital

The louvres are cut and folded from 6mm aluminium sheet and finished with silver polyester powder coating. From a range of modelled options, a single fold in the aluminium and three suspension points were selected by the architect, in collaboration

Fig 3.67 Folded and silver polyester powder coated aluminium solar shading of the Children's Eye Centre

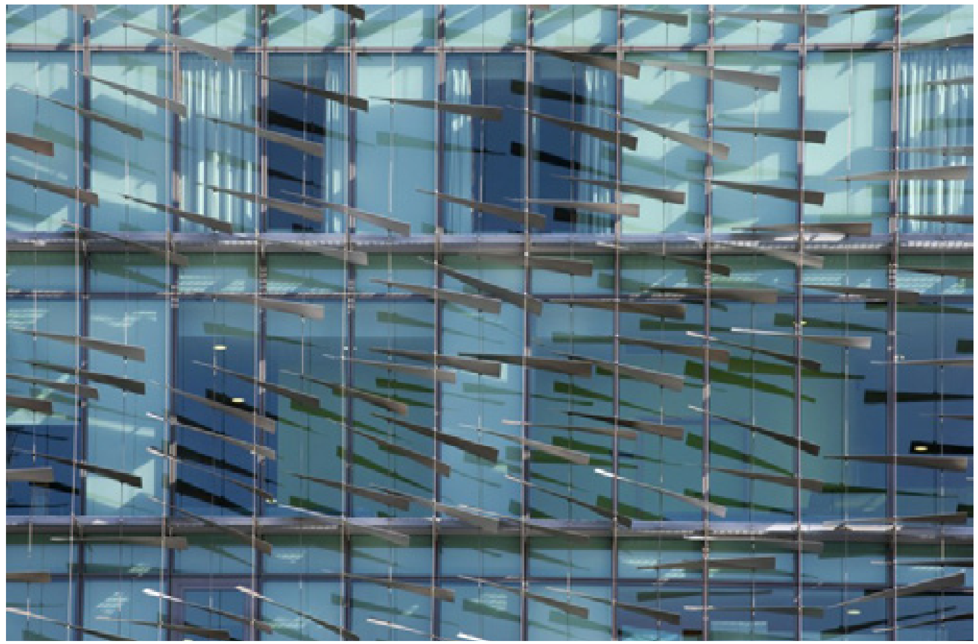


Fig 3.68 The playful aluminium solar shading is like a shoal of silver darlings in the day time

with Arup, as the minimum required to produce stable louvres. The louvres are suspended on 10mm stainless steel wire sourced from Carl Stahl Architecture. The curtain walling and louvres were installed by Plusswall.

At dusk the south façade is further animated by a programmed display of coloured LED lights that exploit the reflectivity of aluminium to flood 'the building with dynamic, glowing colours.'[35]

Fig 3.69 Children's Eye Centre, at dusk

Penoyre & Prasad designed louvre array and animation of this child-focused architecture in collaboration with Alison Turnbull. Specialist subcontractors, Light Projects, supplied the LED lighting.

Fig 3.70 At dusk the façade is lit by programmable colourful LED lights

Everyman Theatre, Liverpool, Merseyside, England: Architect Haworth Tompkins, 2013

The Everyman Theatre, Liverpool, opened in 1964 in the reused shell of a nineteenth century chapel, Hope Hall, that had previously been used as a cinema. It became a very successful 'theatre of the people' nurturing both acting and writing talents including: Julie Walters, Bernard Hill, Jonathan Pryce, Pete Postlethwaite, Alison Steadman, Antony Sher, Bill Nighy, Alan Bleasdale, Willy Russell, Barbara Dickson, Matthew Kelly, Cathy Tyson, David Morrissey, Stephen Graham and the Liverpool Poets.[36] The author studied architecture in Liverpool in the 1970s and early 1980s and was lucky enough to enjoy many excellent productions and ad hoc performances by Liverpool poets in the basement Bistro. By the millennium it had became clear that the theatre needed to be renewed. As a RIBA National Awards judge, the author visited the new theatre in summer of 2014, with some trepidation; had the rebuilding of the theatre destroyed the spirit of this place? Only to discover Haworth Tompkins had 'expertly met a difficult challenge: that of creating an entirely new and sustainable building, whilst retaining and revitalising the best-loved features of its predecessor.'[37] Creating 'a new building with a striking exterior and elegant interior, all with exceptional attention to detail and sustainability credentials.'[38]

The theatre is adjacent to Liverpool's Catholic Metropolitan Cathedral, designed by Sir Frederick Gibberd and completed in 1967, and it is in the context of listed eighteenth and nineteenth century buildings. Sir Giles Gilbert Scott's Anglican Cathedral, completed in 1978, stands at the opposite end of Hope Street. The design and realisation of the Everyman Theatre took Haworth Tompkins almost ten years of close collaboration with the theatre and local community: 'An earlier feasibility study had considered replacing the Everyman and Playhouse [Liverpool's other major theatre] and in a much larger and more expensive building on a new site, but Haworth Tompkins argued for the importance of continuity and compactness on the original site.[39]

Fig 3.71 Hope Hall on Hope Street Liverpool in 1949

Fig 3.72 The new Everyman Theatre, Hope Street, Liverpool, 2013

The Everyman Theatre is an internationally recognised production company. The new theatre includes: a 400 seat adaptable auditorium, a studio for youth, education and community activities, a large rehearsal room, public foyers, a café, a bar, a bistro, a writers space and administrative offices. Haworth Tompkins used large 1:25 physical models to study the public spaces of the theatre. Noting of the final design the 'building makes use of the complex and constrained site geometry by arranging the public spaces around a series of half levels, establishing a continuous winding promenade from street to auditorium. Foyers and catering spaces are arranged on three levels including a new Bistro, culminating in a long *piano nobile foyer* over looking the street.[40] The special quality of the foyer space and community room are reminiscent of the social spaces design by Sigurd Lewerentz in his later churches, including St Peter's Klipan (1965). Natural ventilation is provided for all the main performance and workspaces. For most of the summer and during autumn and spring, outdoor air is supplied to the main auditorium without the need for mechanical assistance. This was carefully studied using computational fluid dynamics undertaken with services engineers Watermans. The theatre is very well built by main contactor Gilbert-Ash, who also constructed the Lyric Theatre in Belfast, designed by O'Donnell and Tuomey and completed in 2011. The capital cost of the Everyman was £13.4 million in 2013.

Haworth Tompkins observe 'having minimised the space and material requirements of the project the fabric was designed to achieve a BREEAM Excellent rating, unusual for an urban theatre building.'[41] From the outset, Haworth Tompkins conceived the Everyman as an exemplar of sustainable good practice. The interior is characterised by the use of reclaimed nineteenth century bricks, the fabric of the original chapel, and exposed concrete providing thermal mass and cultural continuity, combined with a very Scouse sense of glamour – a good night out in a peoples palace. The main auditorium is mimetic of this space in the 1970s, its almost a double take, yet it is adaptable and fully accessible for mobility impaired performers and audience members alike – a theatre for everyone.

The west and main Hope Street façade is primarily composed of 105 moveable aluminium solar shades, each carrying a life-sized waterjet cut portrait of a contemporary Liverpool resident. The only criterion for the selection was each citizen was not famous. They all received a ticket for life at the theatre. The architect worked with local photographer Dan Kenyon to engage 'every section of the city's community in a series of public events, so that the completed building can be read as a collective family snapshot of the population in all its diversity.' [42] The 8mm black anodised and waterjet cut aluminium solar screens were organised by specialist subcontractors James and Taylor. The black anodising is 25μm thick in accordance with BS 3987 (1991) for external applications. This façade is a key part of Haworth Tompkins's environmental strategy for the theatre, alongside the exposed concrete and brick of the interior providing thermal mass, 'the orientation and fenestration design optimises solar response – the entire west façade is designed as a large screen of moveable sunshades.'[43] Each aluminium panel has a central pivot and is held in place top and bottom by curved aluminium flats with holes at regular centres, reminiscent of a sextant. Opposite the Everyman is a former Catholic Convent, which still houses a Madonna in a niche, cited by Steve Tompkins during a tour of the theatre, as part of the inspiration for populating the façade of the theatre.[44] On the first floor of the theatre, the bar spills out on to a balcony over looking Hope Street, thus on summer evenings the one–to-one portraits are underscored by the theatregoers of Liverpool.

Fig 3.73 Madonna in a niche of the former Convent of Notre Dame, Hope Street, Liverpool

Fig 3.74 The first floor balcony of the Everyman Theatre on Hope Street

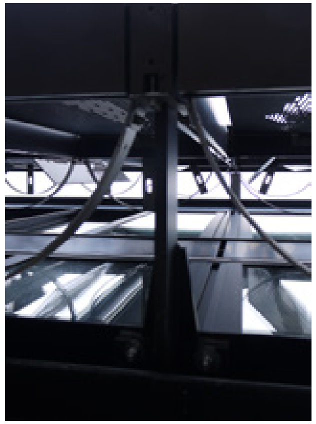


Fig 3.75 Looking up into the sextant like mechanisms of the solar shading to the theatre

Fig 3.76 The 105 moveable aluminium solar shades can be set at any angle

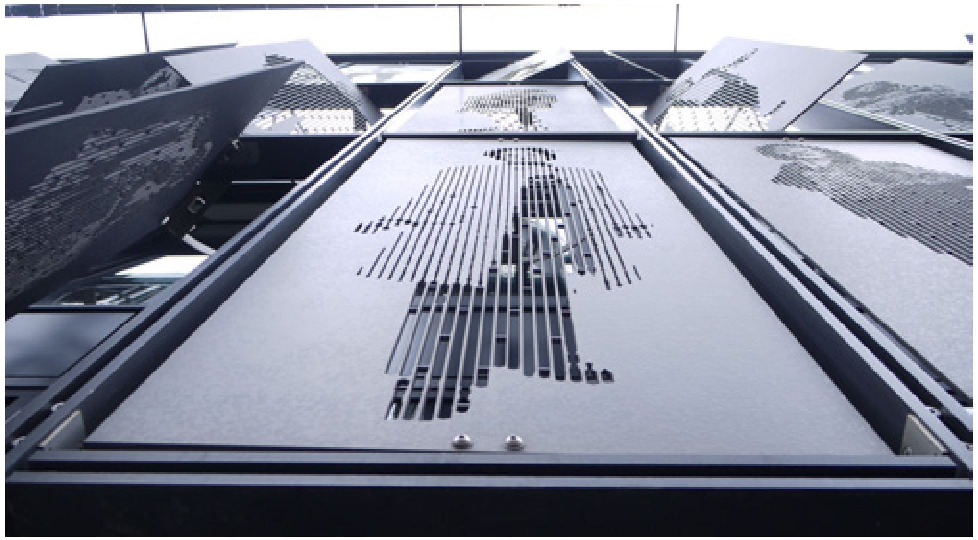


Fig 3.77 The life size portraits of the people of Liverpool are waterjet cut into the 8mm black anodised aluminium sunshades

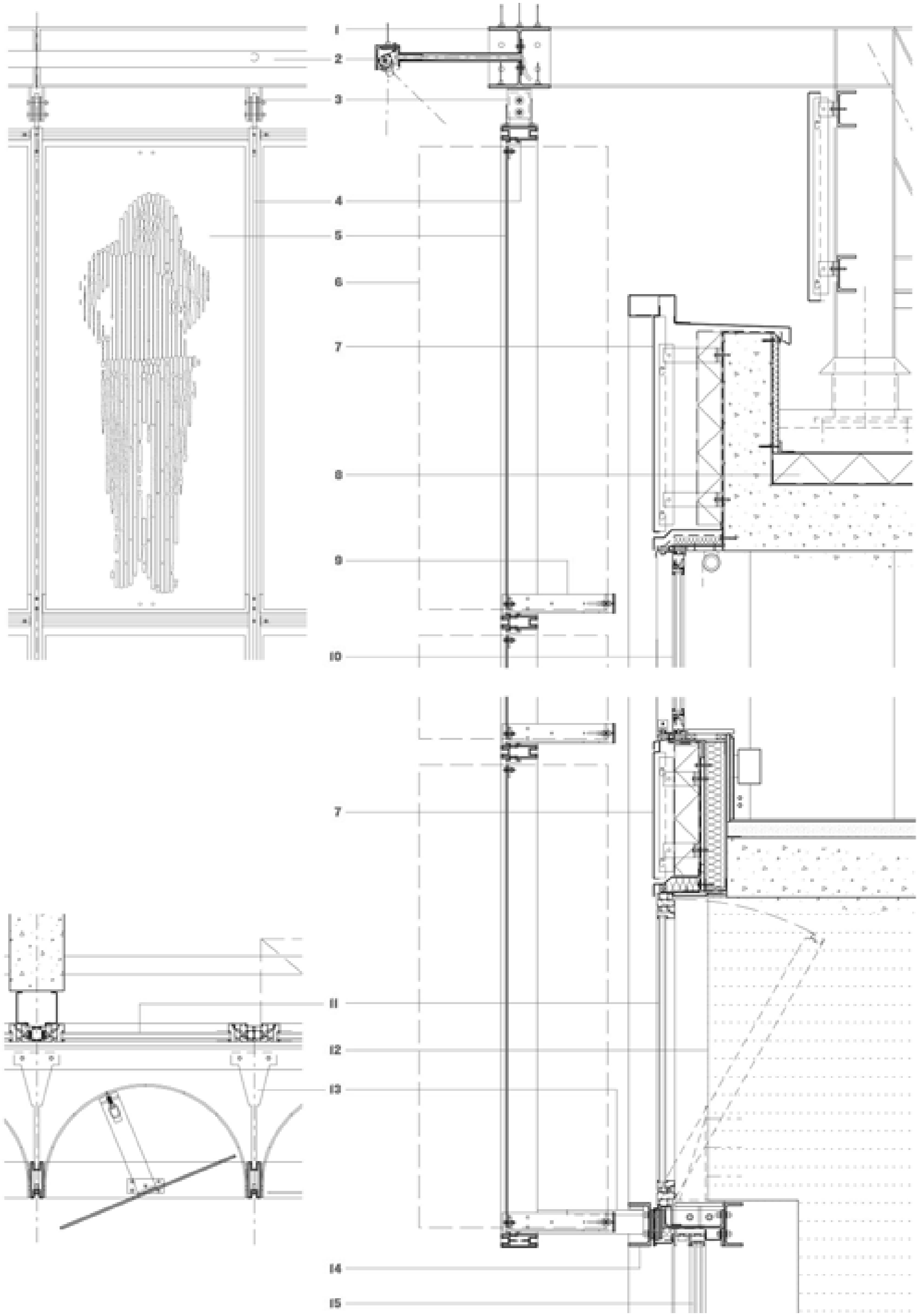


Fig 3.78 Solar shading detail elevation, section and plan (NTS):

1 Painted steel beam fixed to cantilever brackets
2 Painted steel bracket and channel with LED downlight
3 Aluminium tab fixed between steel tabs
4 Extruded aluminium frame, dark bronze anodised
5 8mm aluminium shutter panel with pivot bearing
6 Shutter panel set in 90° position
7 Aluminium rainscreen panels, dark bronze anodised
8 Single membrane roofing on rigid insulation
9 Pivot arm of lower bracket engages via spring pin with hoop
10 Sliding and tilt and turn windows with aluminium frame, dark bronze anodised
11 Bottom hung windows with aluminium frame, dark bronze anodised
12 Boardmarked concrete column and downstand beam beyond
13 Bottom restraining bracket, dark bronze anodised aluminium
14 Painted steel channels
15 Aluminium framed sliding doors

The Everyman Theatre designed by Haworth Tompkins won the 2014 Stirling Prize from the Royal Institute of British Architects (RIBA). The judges citation states:

> The new Everyman in Liverpool is truly for every man, woman and child. It cleverly resolves so many of the issues architects face every day. Its context - the handsome street that links the two cathedrals – is brilliantly complemented by the building's scale, transparency, materials and quirky sense of humour, notably where the solar shading is transformed into a parade of Liverpudlians. The ambience of the theatre is hugely welcoming with three elegant and accessible public foyers for bars, lounges and café/bistro. Clever use of materials with interlocking spaces and brilliant lighting make this an instantly enjoyable new public space for the city.

The Everyman Theatre is a triumph of collaboration, determination and skill by the client, architect, design and delivery team.

Fig 3.79 The Everyman works within its context, whilst articulating its role in the cultural future of the city


everyman

Notes

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32 www.penoyreprasad.com/projects/the-richard-desmond-childrens-eye-centre-moorfields-eye-hospital/ (accessed January 2016)
33 Ibid.
34 Ibid.
35 Ibid, including a video clip of this façade at dusk
36 http://www.everymanplayhouse.com/everyman-history (accessed March 2016).
37 www.architecture.com/RIBA/Contactus/NewsAndPress/PressReleases/2014/TheEverymanTheatreinLiverpoolbyHaworthTompkinsarchitectswins2014RIBAStirlingPrizeforthebestnewbuildingoftheyear.aspx (accessed March 2016)
38 Ibid.
39 Haworth Tompkins, Liverpool Everyman Theatre: BREEAM Case Study, www.haworthtompkins.com/built/proj44/drawings/EverymanTheatre_BREEAM_CaseStudy.pdf (accessed September 2015).
40 Ibid.
41 Ibid.
42 Haworth Tompkins, Liverpool Everyman Theatre: BREEAM Case Study, www.haworthtompkins.com/built/proj44/drawings/EverymanTheatre_BREEAM_CaseStudy.pdf (accessed September 2015).
43 Ibid.
44 Steve Tompkins in conversation with the author and Meredith Bowles at the theatre, 3 July 2014.

FOUR

overcladding

Overcladding

Aluminium has a very significant role in providing overcladding for poorly performing existing buildings, typically protecting insulation fixed to the outside of the existing building fabric, thus resolving any cold bridges and areas of thermal discontinuity. Aluminium is an excellent choice for overcladding as it is stiff, light, easily worked and very durable. Towards Sustainable Cities Report 1 *Aluminium and Durability* (2014) sets out the durability and longevity of aluminium used in architecture and infrastructure over the past 120 years. Towards Sustainable Cities Report 2 *Aluminium Recyclability and Recycling* (2015) demonstrates the benefits of overcladding and reglazing existing buildings. Thus saving both embodied energy of existing construction and future operational energy. This report also illustrates projects that have been stripped back to the frame and reinvented with a new architectural vision. The key decision between overcladding and reinvention is whether the building needs to remain occupied and operational during the construction process. If this is the case, overcladding becomes the best option.[1]

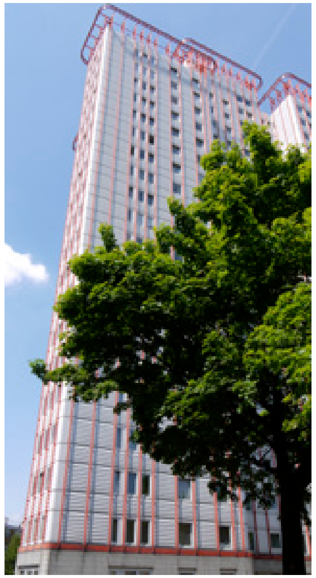


Fig 4.1 The overcladding of Parsons House is a system of polyester powder coated aluminium panels and windows with articulated mullions designed by Peter Bell & Partners, 1986

Overcladding and re-glazing a project often addresses two major issues simultaneously, firstly the poor physical condition of the original building fabric, and secondly, the need to improve the performance of the building envelope to reduce the running costs, create comfort and lower the environmental impacts of the building. As an example, Parsons House demonstrates the need to address the poor constructional quality prevalent in construction in the UK in the 1960s and 1970s. Parsons House, a 21-storey apartment building built by Westminster City Council in 1969 with a concrete frame, brick skins and timber windows, was within 20 years in very poor condition. The timber windows were rotten and the concrete spalling badly. This was addressed by overcladding with a polyester powder coated aluminium system of panels and windows with articulated mullions, designed by Peter Bell & Partners and installed by Schmidlin in 1986.[2] The case study of Guy's Hospital Tower, set out below, is essentially the same process with a longer time frame and a quantified outcome for the benefits of the overcladding. This is followed by an earlier exemplar-overcladding project, 10 Hills Place, London, designed by Amada Levette Architects (A_LA).

Fig 4.2 Parsons House completed in 1969 was constructed from brick, concrete frame and timber windows

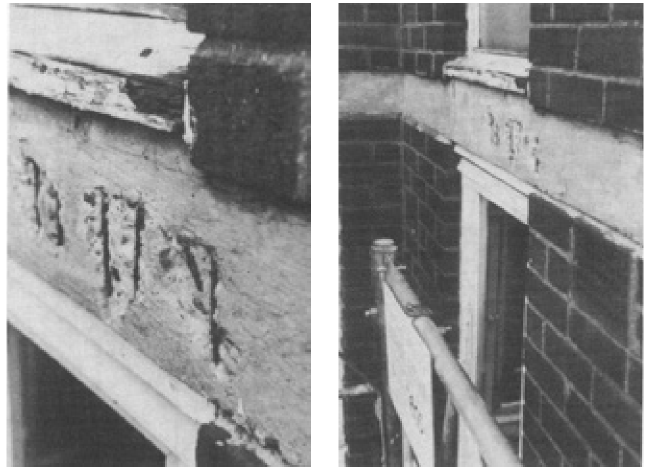


Fig 4.3 Parsons House prior to overcladding – spalling concrete and rotten timber windows

Fig 4.4 Detail of the façade of Parsons House

Guy's Hospital Tower, London: Architect Watkins Gray Architects, 1974 and Penoyre & Prasad Architects, 2014

Fig 4.5 [left] Guy's Hospital Tower overcladding designed by Penoyre & Prasad Architects with Arup Facades

Guy's Hospital Tower was designed in 1960s by Watkins Gray Architects, construction started in April 1968 and it opened in 1974. Guy's Hospital Tower actually comprises two towers; the User Tower with its simple uninterrupted floor plates of 1200m^2, which have readily accommodated changes over time, and the Communications Tower that houses the stairs, lifts, ventilation and services risers. This tower is dramatically capped by a lecture theatre that cantilevers out above the 28th floor. The vertical nature of the Communications Tower is emphasised by ribbed concrete, whereas the User Tower has a horizontal expression primarily from the concrete balconies. The Communications Tower comprises 34 storeys and at a height of 143m this was the tallest hospital in the world. Guy's Hospital Tower was designed, with exposed concrete, in a direct constructivist manner, an example of what some describe Brutalist architecture.

Fig 4.6 Guy's Hospital Tower designed by Watkins Gray Architects and completed in 1974, note the vertically ribbed concrete of The Communications Tower and the whiter horizontal balconies of the User Tower

In 2008, inspections and a feasibility study identified that the concrete of the communications was spalling badly, the concrete balconies were in a better condition however they did require cleaning. The double-glazed steel windows were badly corroded, with some fogged double glazed units and, on testing, were found to offer poor thermal performance.

Between the April of 2012 and spring of 2014, Guy's Hospital Tower was overclad and re-glazed with curtain walling, designed by Penoyre & Prasad, working with Arup Facades, who were the

Fig 4.7 When inspected in 1998, the concrete was found to be spalling

Fig 4.8 The inspection also found the steel windows were corroding badly

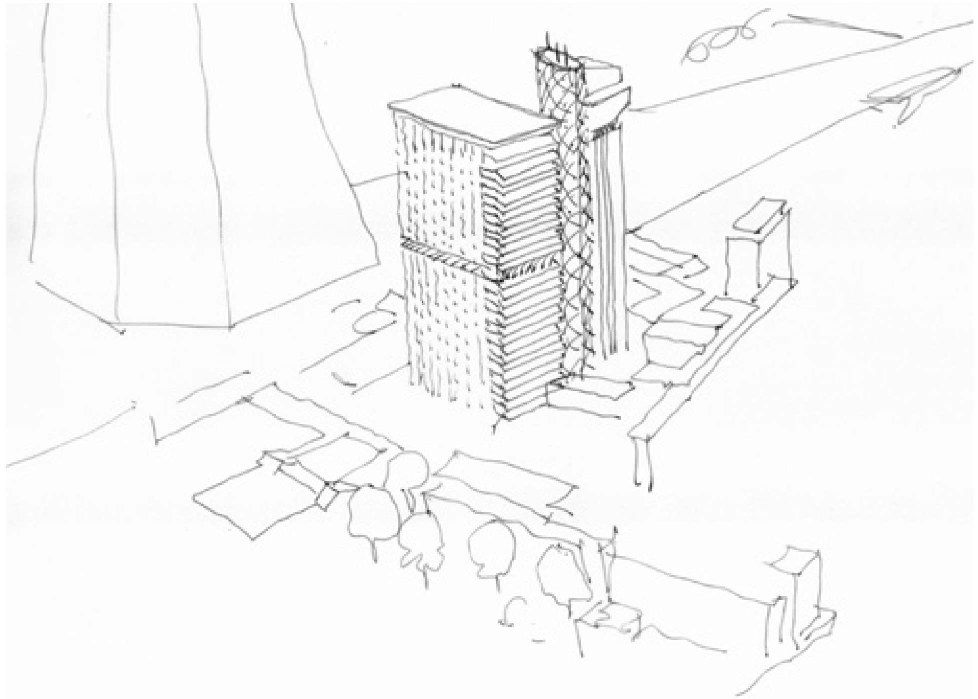


Fig 4.9 Penoyre & Prasad Architects' sketch of the proposed overcladding of Guy's Hospital Tower

lead consultant and project mangers. Laura Macfarlane of Arup Facades reflected that 'this very successful project was in part a result of the close collaboration within the multi-disciplinary design team and with the client, contactors and specialist fabricators of the aluminium façade systems.'[13] The capital cost of this project, to deliver significant improvements to Guy's Hospital Tower, was £40million. Arup carefully thermally modelled options for the overcladding to achieve a strong visual appearance, comfort and significantly reduced running costs.

The overcladding primarily comprises folded medium blue grey anodised aluminium rainscreen panels. Penoyre & Prasad carefully considered how the two towers of Guy's Hospital would read from the street context and across the cityscape of London, articulating the reinvigoration of the hospital, yet retaining the constructivist expression of the original design. The overcladding and curtain walling was fabricated and installed by Permasteelisa.

The overcladding protects 180mm of additional mineral wool insulation and achieves a U-value of 0.15 W/m^2K combined with new double-glazed curtain walling providing a U-value of 1.44 W/m^2K. The curtain walling is approximately 50 per cent glazed, with an argon-filled doubled-glazed unit, held in thermally broken extruded aluminium framing. The double-glazed units utilised a solar-selective glass to balance between solar gain in spring, summer and autumn and high levels of natural light. The spandrel panels comprise anodised aluminium with foamed polyurethane insulation. The curtain walling and spandrel panels are finished in a pale umber anodising that respond to the existing white concrete balconies, once that had been cleaned, and to provide counterpoint to the medium blue grey anodised overcladding. This is a carefully considered family of aluminium components.

The refurbishment and overcladding of Guy's Tower included the cleaning of 34,500m^2 of concrete, which was repaired, where necessary, by team of 20 workers from Kafften. Following the cleaning and repair of the concrete, Permasteelisa employed a team of 70 workers to install the 8,000m^2 of aluminium cladding panels and 12,000m^2 of glazing units. During this carefully phased project the hospital remained operational throughout the contract. Joe Cachia, Construction Manger for main contractor

Fig 4.10 The family of aluminium components designed for the overcladding of Guy's Hospital Tower

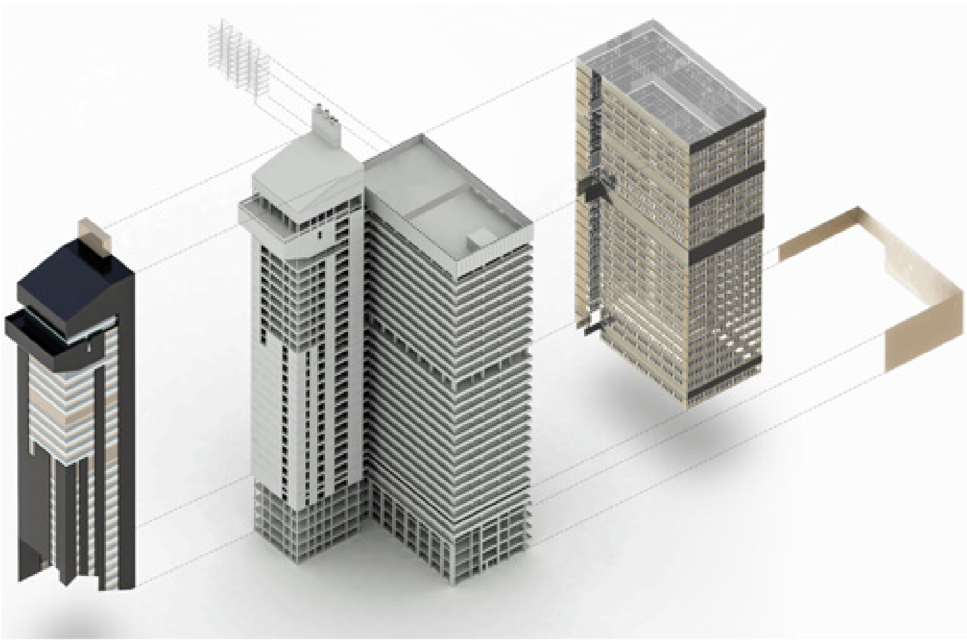
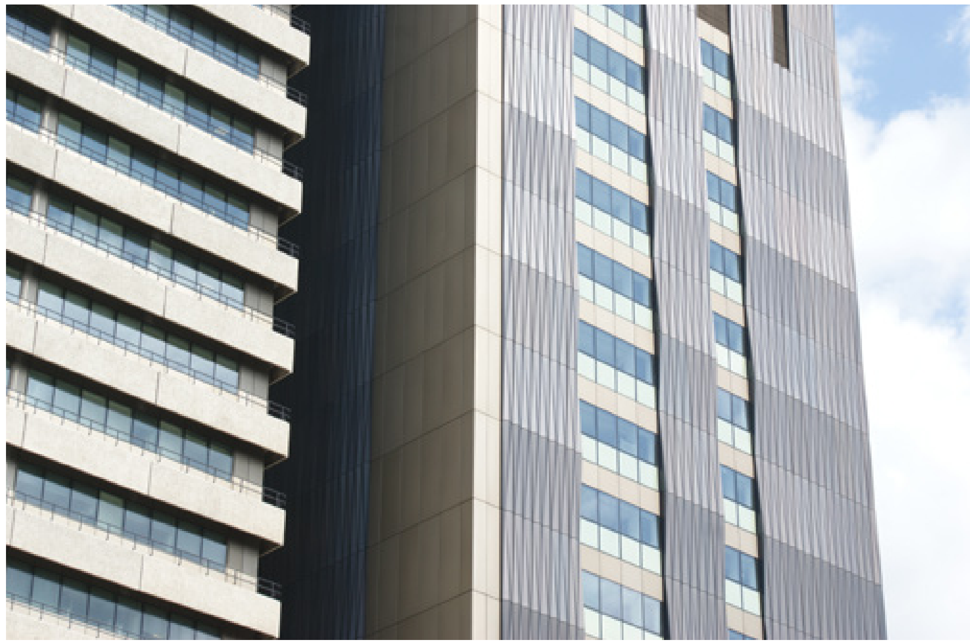


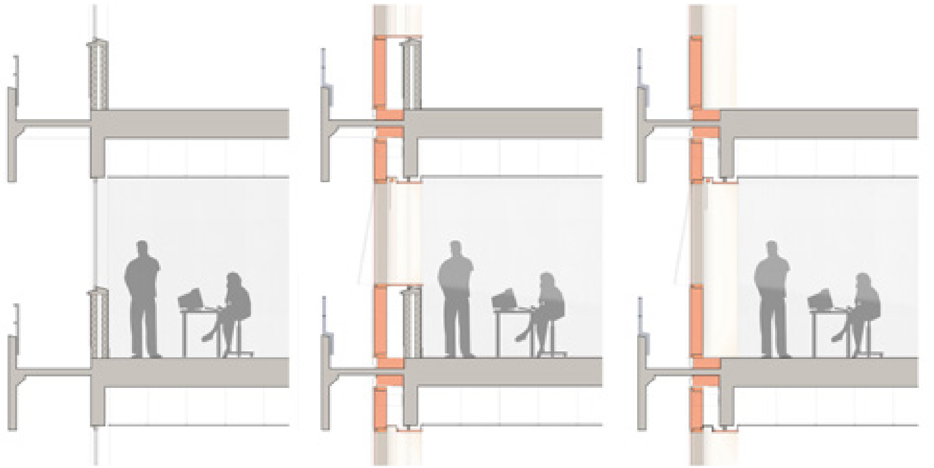
Fig 4.11 To refurbish Guy's Hospital Tower the precast concrete balconies needed to be cleaned and the exposed concrete structure needed to be insulated

Balfour Beatty, observed 'there was always 80 per cent of the floor area available to hospital staff and patients'.[4] The curtain walling of the User Tower was installed outside the existing building fabric, enabling continuity of occupation and the removal of the steel windows from inside. The existing fabric was tide-in by the installation of head and cill closers. In the future, Guy's and St Thomas' NHS Foundation has the option to remove the dwarf walls of the original construction, thus increasing the area of usable floor space.

Penoyre & Prasad designed the origami folded anodised aluminium panels to provide a sculptural quality, 'seen from a distance it gives the Tower a solid hewn feel',[5] yet on bright and sunny days the angled facets light up providing a play of light across the expansive faces of this Tower. At Permasteelisa, a two-man team folded 3,500 aluminium panels by hand with a press brake. These panels were fabricated using 3mm thick aluminium, as the folded panels were required to span vertically between two fixing rails almost 4m apart. There is and interesting correspondence to the folded anodised aluminium panels of the Alcoa Building in Pittsburgh (1953), designed by Harrison & Abramovitz, which were inspected in 2013 as part of this research, see Report One: *Aluminium and Durability*, and observed to have weathered well, in part due to the faceted surfaces.[6]

Fig 4.12 The overcladding primarily comprises folded dark grey anodised aluminium rainscreen panels with pale umber anodised aluminium curtain walling and spandrel panels

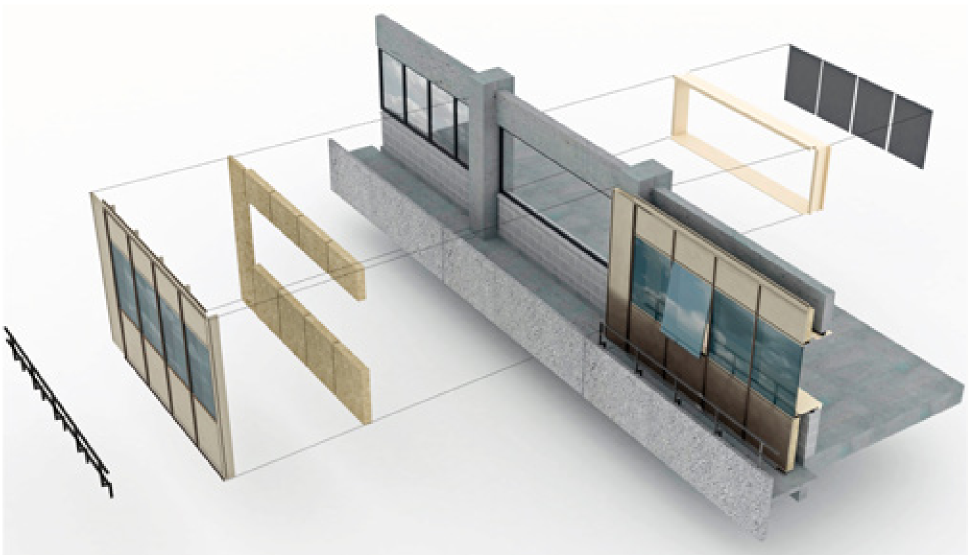


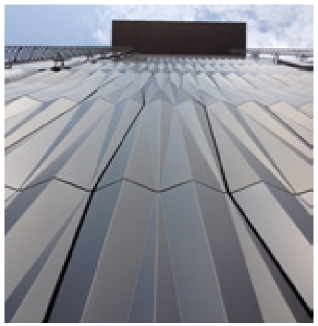


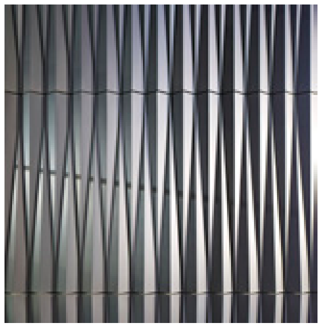
Existing

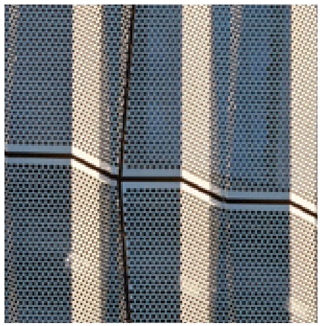
Proposed: as installed

Potential Future: internal wall removed









The folded aluminium panels of Guy's Hopsital Tower are finished in medium blue grey anodising (Anolok II B715) applied in accordance with BS 3987 (1991) at 25µm by United Anodisers in its Uxbrigdge plant. United Anodisers is a Qualanod registered company and thus subject to period quality inspections. United Anodisers provide a life time guarantee on its anodising.[7] The pale umber anodising (Anolok 541) primarily used on the curtain walling, was also applied by United Anodisers at 25µm in its plant in Huddersfield, to the same standard and quality regime.

Fig 4.13 [left] Section through the User Tower: showing existing and proposed overcladding as installed, and potential future removal of internal walls

Fig 4.14 [left] The overcladding strategy for the User Tower; primarily composing pale umber anodised aluminium curtain walling and spandrel panels, insulation and reveals

Fig 4.15 [bottom left] To realise this project a two-man team at Permasteelisa folded 3,500 aluminium panels by hand and a press brake

Fig 4.16 [top right] The facades of Guy's Hospital Tower were carefully modulated by Penoyre & Prasad Architects in form and colour

Fig 4.17 [right] Permasteelisa installing a folded aluminium rainscreen panel at Guy's Hospital Tower

Fig 4.18 The cantilevered lecture theatre is clad in dark grey anodised aluminium flat rainscreen panels to emphasise its presence

The cantilevered lecture theatre is clad in medium blue grey anodised aluminium rainscreen panels, however, using flat panels to emphasise its presence. Folded anodised aluminium panels are used at the base of the Communications Tower, except that they are perforated and finished in pale umber anodising. Junctions between the glazing and cladding system are carefully considered, 90° returns resolve the folded geometry and form precise window reveals.

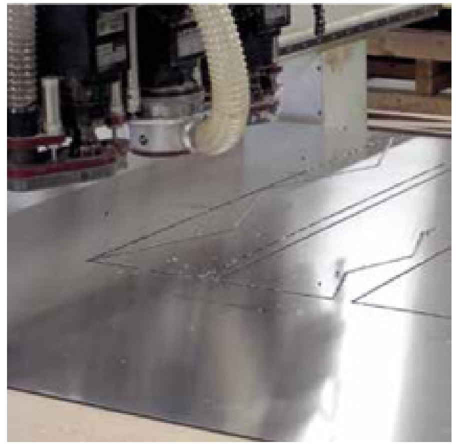


Fig 4.19 [right] Cutting out an aluminium closure panel at Permasteelisa

Fig 4.20 [below] Junctions between the folded aluminium cladding and the glazing are carefully considered

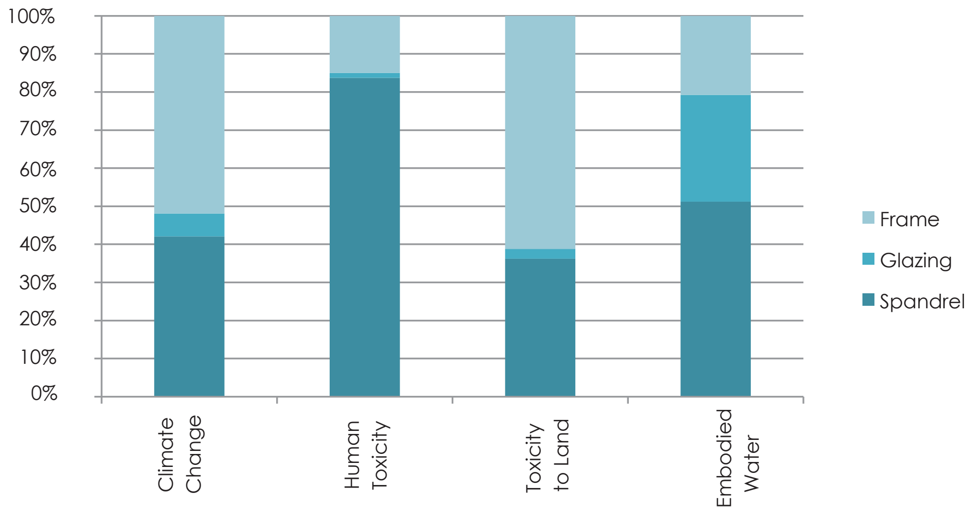


Fig 4.21 Environmental impacts of the overcladding of Guy's Hospital Tower from Arup's LCA study of the User Tower curtain walling, attributed by primary components

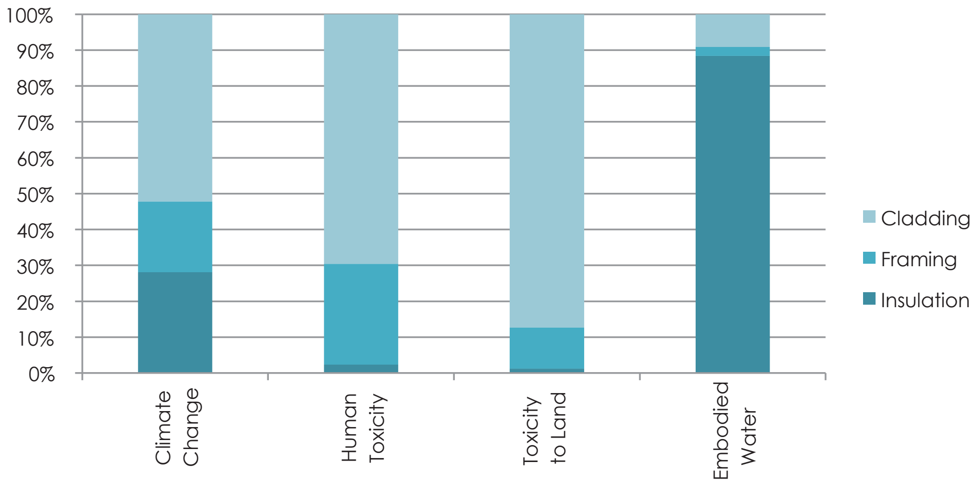


Fig 4.22 Environmental impacts of the overcladding of Guy's Hospital Tower from Arup's LCA study of the Communications Tower overcladding, attributed by primary components

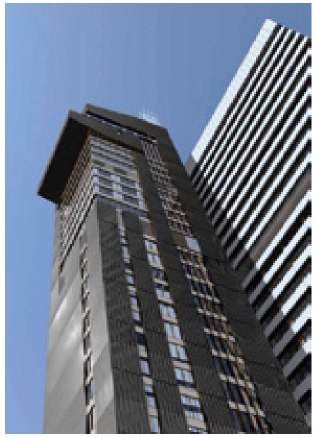


Fig 4.23 Early visualisation of the Communications Tower showing architect's vision by Penoyre & Prasad

To inform the design development of the overcladding of Guy's Tower, Andrea Charlson of Arup conducted a **Life Cycle Assessment** (LCA) using GaBi (PE International).[8] Although this study was undertaken by Arup, Charlson noted: 'Both the client, Guy's and St Thomas' NHS Foundation Trust, and the architect, Penoyre & Prasad, had a keen interest in the overall sustainability of the project and as part of this it was decided to look at the life cycle impacts of the façade.'[9]

This LCA was based on a quite conservative overall service life of 30 years. This was combined with cautious component service life expectancies of:

- Double Glazed Units –15 Years;
- Spandrel Units – 30 Years; and
- Overcladding – 30 Years.

The cleaning frequency used in this LCA was: Glazing one month, Spandrels three months and Overcladding 12 months. The later appropriate for the guarantee provided by Permasteelisa on the anodised aluminium overcladding, noting that cleaning of the spandrel panels could also have been annual to fulfil this guarantee. The calculated carbon payback period for this overcladding and curtain walling is 12.5 years. Based on the 30-year period studied in this LCA, the new building envelope will save over 8300tonnes of CO_2e.[10]

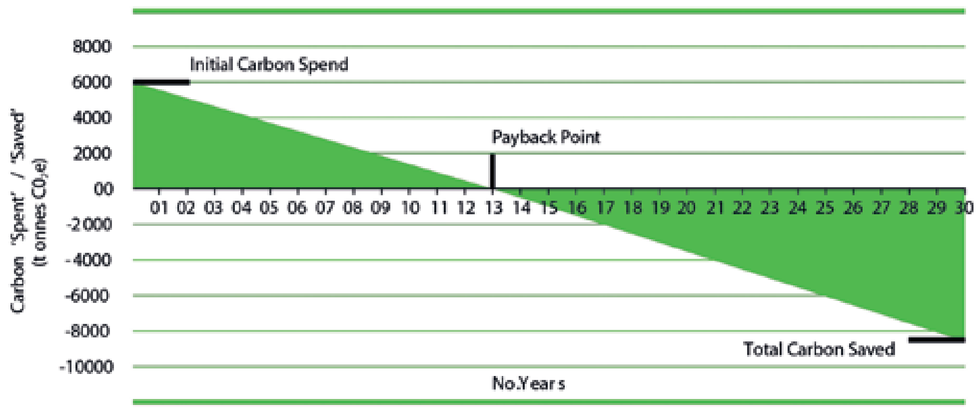


Fig 4.24 The carbon pay back period for the overcladding of Guy's Hospital Tower is under 13 years

In response to the context of significant buildings on the London skyline, both new and old, from Sir Christopher Wren's St Paul's Cathedral to the Gherkin (30 St Mary Axe) by Foster + Partners and the Shard by Renzo Piano Building Workshop, the Communications Tower is now topped by a light sculpture. Won in competition by German artist Carsten Nicolai and developed with Penoyre & Prasad, Arup Structure and Arup Lighting. It was funded by Guy's and St Thomas' Charity that 'has a long history in investing in the arts to improve health and healthcare in Guy's and St Thomas' Hospitals and the London boroughs of Lambeth and Southwark'[11] By day it crowns the building and at night it becomes an installation illuminated by LED lights. The 14m tall sculpture by Carsten Nicolai, entitled aeolux, raises the height of Guy's Hospital Tower to 148.65m. Thus it is once again the tallest hospital in the world.

However, located next to London Bridge station, Guy's Hospital Tower is often viewed in the immediate context of the Shard, which was completed in 2013. It has an all glazed unitised aluminium curtain wall that rises to 306m, with 73 floors above ground. The highest occupied level is 244.3m. The unitised curtain walling was also fabricated and installed by Permasteelisa. The Shard was conceived by Renzo Piano as a vertical city and a response to the spires of London's seventeenth century churches. The purpose of the Shard changes as it tappers from offices at the base, floors 2 to 28, to restaurants on levels 31-33, a hotel from floor 34 to 52 and then residential apartments on levels 53 to 65. It culminates in a viewing platform, levels 68 to 72, and sits as a fractured lantern on the London skyline.

The overcladding of Guy's Hospital Tower is an exemplar of the work the National Health Service needs to commission on its extensive and aging estate in the UK, providing comfort whist saving primary energy and carbon dioxide emission. The carbon payback period has been calculated to be less than 13 years, more than justifying the capital expenditure, providing comfort for the staff and patients whilst saving CO_2e. Furthermore the anodised aluminium has a durability of over 80 years, thus the savings will continue into the next millennium.

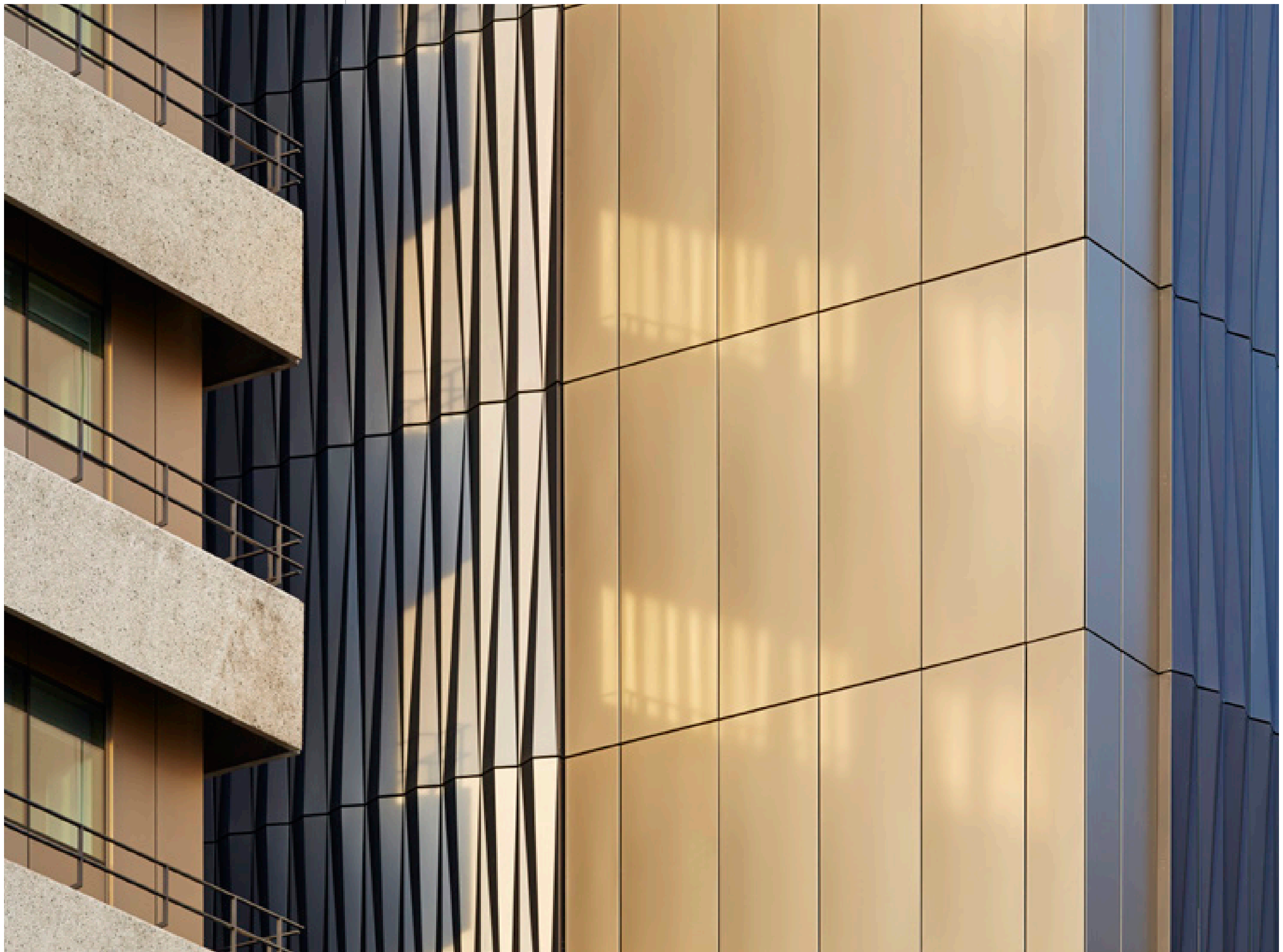


Fig 4.25 Juxtaposition of the User Tower balconies and a corner of the Communications Tower

10 Hills Place, London: Architect Amanda Levette Architects, 2009

This project combines the overcladding of an existing brick building with vertical an extension of four floors of offices. It demonstrates how an unprepossessing brick building, an existing retail unit, in a narrow city street can be transformed by the skills of a talented architect into attractive and highly letable offices. Furthermore, the project tackles the issue of neglected and underused side streets that exist in many cities throughout the world.

10 Hills Place has just one, east facing, street façade. Amanda Levette Architects begins with translucent glazing at street level, with apparently simple aluminium overcladding to the five storeys above, which enhances the thermal performance of the building. However, as the façade rises up the offices swell out to form light catching sky windows that maximise the daylight in this narrow urban street on all four-office floors, one of which was part of the existing building. The top floor has the widest sky window.

Fig 4.26 [left] 10 Hills Place before work started

Fig 4.27 10 Hills Place, designed by Amanda Levette Architects, viewed from Oxford Street

The sky windows comprise large format double glazed units, with self-cleaning glass for the outer pane and laminated inner panes, stiffened internally by clear glass fins. The sky windows, or eyelids, are drained by integrated hidden gutters. Hills Place runs south of Oxford Street, London's longest retail street. In A_LA's words 'site constraints were leveraged to become opportunities and drivers behind the design.'[12]

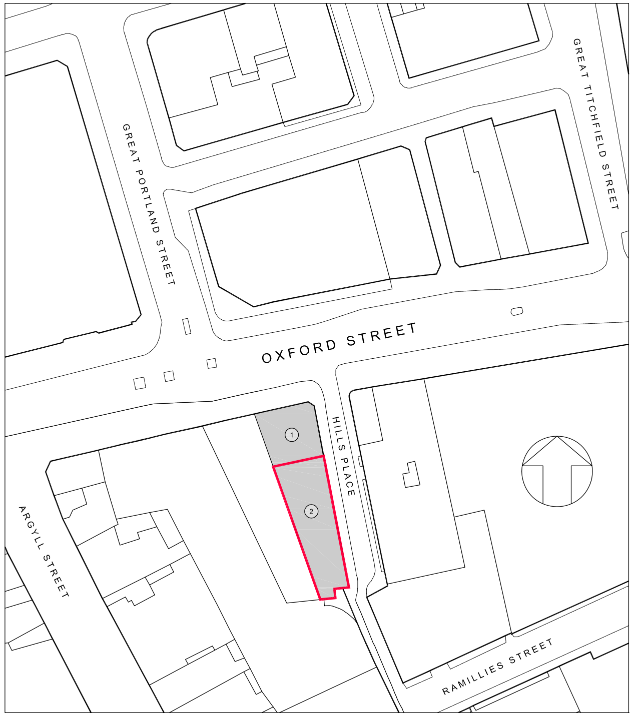


Fig 4.28 Site location plan

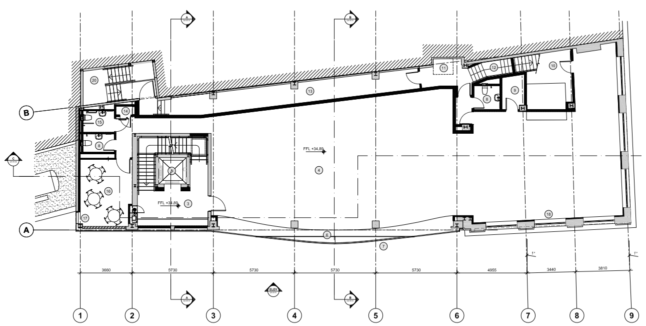


Fig 4.29 Third floor plan, shown at 1:500

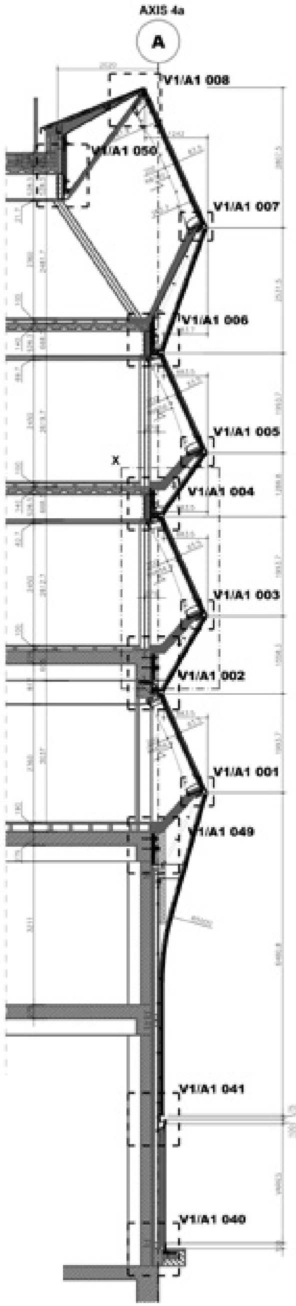


Fig 4.30 Construction section, shown at 1:200

Fig 4.31 Voluptuously detailed aluminium cladding of 10 Hills Place

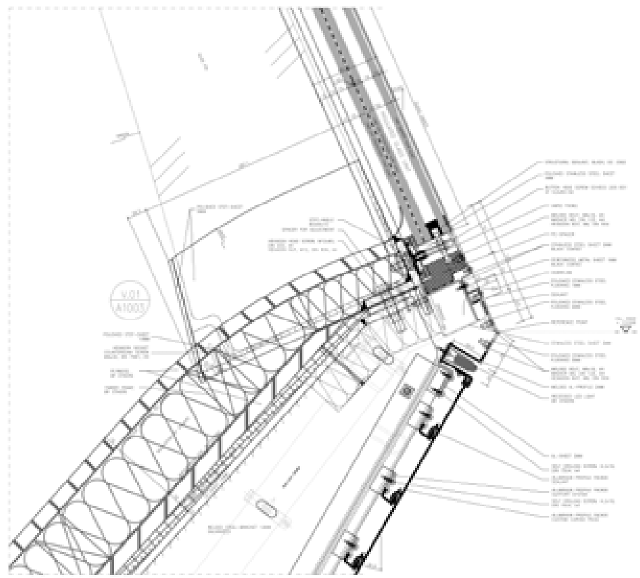


Fig 4.32 Sky window detail, 1:10

Prototyping the façade with specialist subcontractor Frener & Reifer was critical to the design development of 10 Hills Place. Unusually this doubly curved façade is built up of 140mm shiplap aluminium extrusions with horizontal gasket seals. It is supported by horizontal extruded-aluminium clips on vertical extruded-aluminium cladding rails, see Figure 4.36. The extruded aluminium cladding has a silvery metallic finish, a specially formulated wet applied high performance and durable paint system – AWLGrip manufactured by Marineware, which is typically used on the hulls of super yachts.

In 2009, 10 Hills Place won the Council for Aluminium Building: Overall Award. Although completed during the global finical crisis the project was let in a matter of weeks. A_LA had transformed a building of little value into comfortable and attractive offices, both a destination and place of work.

Fig 4.33 Façade prototype of an 'eye lid' or sky window and aluminium cladding being assembled in Frener & Reifer's workshop

Fig 4.34 Sky window — cladding interface of the 10 Hills Place prototype

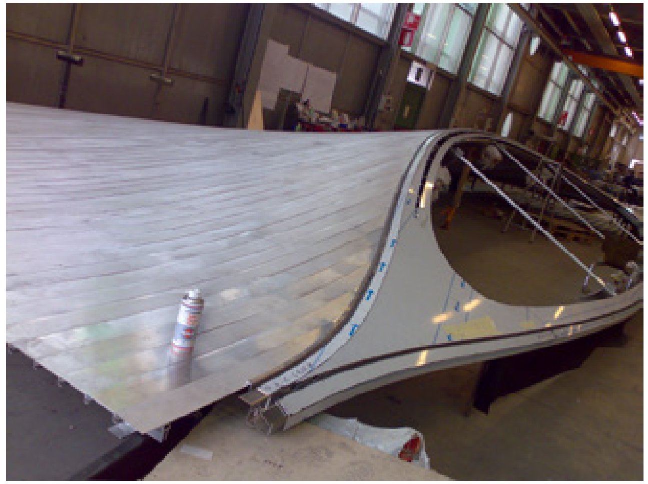


Fig 4.35 On the prototype the shiplap extruded aluminium cladding is only mill finish

Fig 4.36 Detail of the gasketed extruded aluminium cladding and carrier system

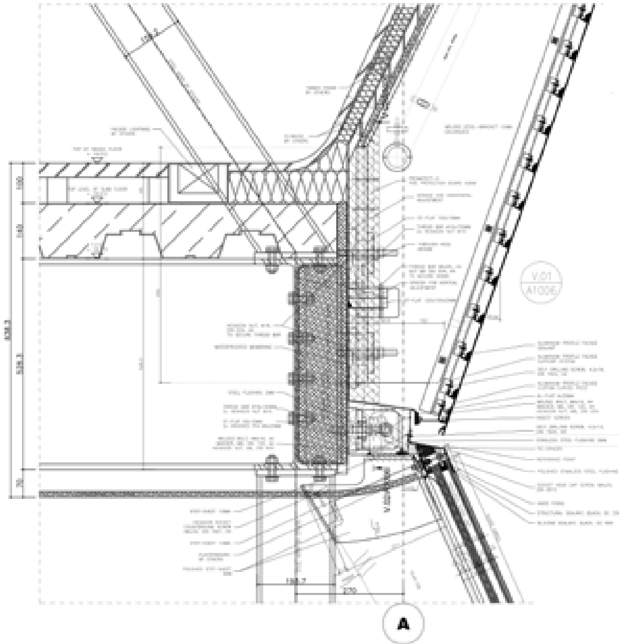


Fig 4.37 Aluminium cladding and sky window interface detail, 1:20

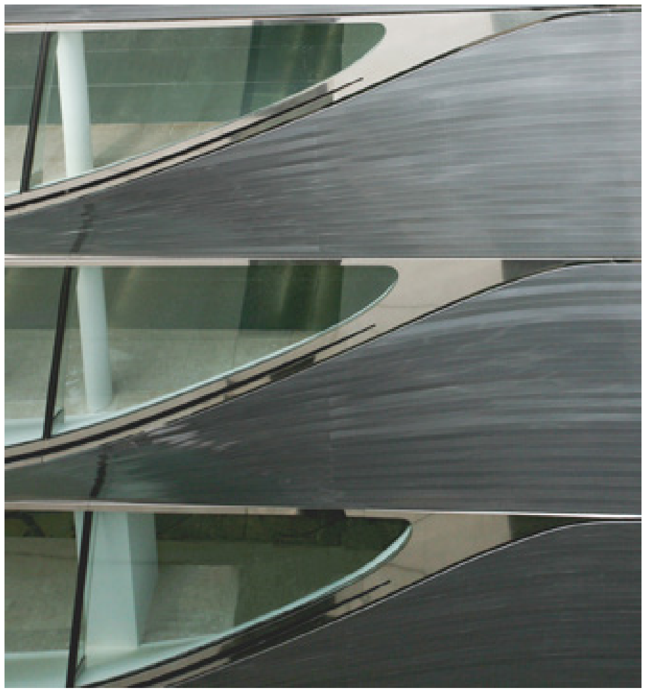


Fig 4.38 Sky window and extruded aluminium cladding of 10 Hills Place designed by Amanda Levette Architects

Fig 4.39 [right] 10 Hills Place is transformed into comfortable offices, just-off Oxford Street

Notes

1 M. Stacey (2015) *Aluminium Recyclability and Recycling: Towards Sustainable Cities*, Cwningen Press, Llundain, pp.13–93
2 M. Stacey (2014) *Aluminium and Durability: Towards Sustainable Cities*, Cwningen Press, Llundain, second edition 2105, pp. 180-185
3 Laura Macfarlane of Arup Facades in conversation with the author at Arup's Offices, London, 21 May 2015
4 J, Davies, ed., (2014) *Guy's Tower: 40 years on*, Essentia Guy's and St Thomas' NHS Foundation Trust, South London, p. 34
5 Ibid., p. 23
6 M. Stacey (2014) *Aluminium and Durability: Towards Sustainable Cities*, Cwningen Press, Llundain, second edition 2105, pp. 61–63 and 160–163
7 United Anodisers' Qualanod Certificate is LN:1305, 6.10.1976 to 31.12.2016**.** For a review of the guarantees available on aluminium finishes see M. Stacey (2014) *Aluminium and Durability: Towards Sustainable Cities*, Cwningen Press, Llundain, second edition 2105
8 A. Charlson, (2011) *Counting Carbon: Practical Approaches to Life Cycle Assessment in Facade Engineering*, ICE, London, pp. 1–13
9 Ibid., p. 4
10 Ibid., p.11
11 J Davies, ed., (2014) *Guy's Tower: 40 years on*, Essentia Guy's and St Thomas' NHS Foundation Trust, South London, p. 39Laura
12 www.ala.uk.com/wp-content/uploads/2015/10/AL_A.pdf (downloaded March 2016).

aluminium: flexible and light

light and strong

Aluminium: Light and Strong

The role of lightness may appear to be less obviously apparent in architecture and the built environment, when compared to aerospace and transportation. Perhaps lightness is a useful metaphor when designing to touch the earth lightly. In many applications lightness is equally important in architecture, be this the craning of large prefabricated building assemblies, the placement of slab formwork for the casting of concrete or the carrying of components by hand by a single worker, which, needs to be under 25kg to follow contemporary health and safety guidance.[1] The high strength to weight ratio of aluminium produces building components that use less energy to transport, less energy to install and less energy to disassemble or, in the case of formwork, to strike.

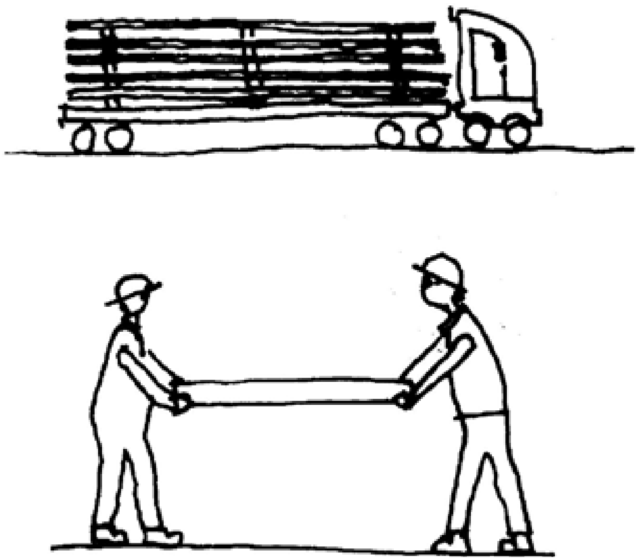


Fig 5.1 The high strength to weight ratio of aluminium produces building components that use less energy to transport, less energy to install and less energy to disassemble or, in the case of formwork, to strike.

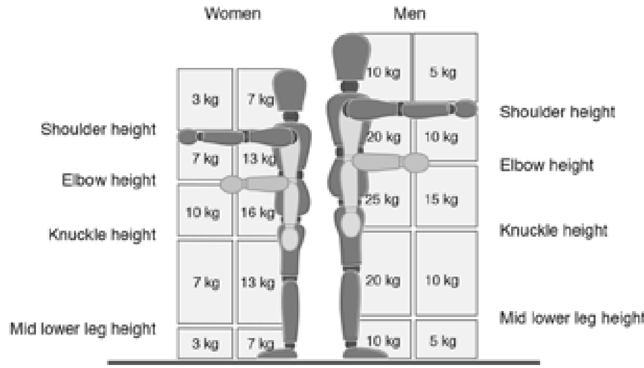


Fig 5.2 Guidance on lifting and lowering from HSE Manual Handling Operations Regulations (1992)

Fig 5.3 Craning the aluminium based prefabricated roof light of the Lowe Apartment, London, designed by Brookes Stacey Randall Fursdon

Inspired by the precedent of Richard Neutra's Lovell Health House (1929) the clients brief for an apartment in central London with views of St Paul's was to be able to sleep under the stars, despite the apartment being part of a warehouse conversion. A key element of Brookes Stacey Randall Fursdon's response to this brief was simply to open up a complete section of roof above the sleeping mezzanine. This was achieved by working with four specialist subcontractors, synthesising their contributions and delivering the rooflight as a complete prefabricated product. Therefore the lightweight and strength of aluminium was key in the framing and in the solar shading. The total weight of the rooflight was important for transportation and the crane lift into place. It is also of vital importance to the hydraulic operation of this rooflight on a day-to-day basis.

Fig 5.4 The rooflight forms a complete section of roof the Lowe Apartment, architect Brookes Stacey Randall Fursdon, which opens up to enable the owner to sleep under the stars, even in central London

Fig 5.5 The sleeping mezzanine is accessed via a structural glass staircase designed by Brookes Stacey Randall Fursdon with engineer Tim Macfarlane

Fig 5.6 [right] The Lowe Apartment, London

A possibly more dramatic example of lightweight prefabrication using aluminium is Richard Horden's Ski Haus (1991) shown in Figure 5.7 being lowered onto the Swiss – Italian ridge in the Alps at about 3980m above sea level, one of a number of locations in the Alps that it has been deployed. This 'hard tent' needed to be lifted into place with a helicopter. Speaking at the RIBA, London, Richard Horden observed 'it is nearly 100 per cent aluminium and when empty weighs just over 300 kilos.' He continued 'the maximum weight for helicopter delivery to that altitude is about 700-800 kilos. Three shallow holes in the ice are all that is needed for security in allocation with 200km/hr gusts. [It] has been in place for 13 years with no problems with material performance.'[2] The Ski Haus serves very successfully as a climbers and skiers refuge. Another example of the use of aluminium to achieve lightweight total prefabrication is the Bridge of Aspiration by WilkinsonEyre, which was craned into position on a Sunday. It links the Royal Ballet and the Royal Opera House in Covent Garden, London. It is described in full with other aluminium-based bridges later in this chapter.

Fig 5.7 The Ski Haus designed by Richard Horden Architects being lowered into place in the Alps

The next section of Aluminium: Light and Strong reviews three case studies of aluminium roof structures with two related examples, followed by a contemporary vertically cantilevered aluminium shell structure. The chapter then reviews the use of aluminium: to make concrete formwork, to fabricate bridges and to assemble prefabricated architecture.

Fig 5.8 Bridge of Aspiration designed by Wilkinson Eyre Architects being craned into place in Floral Street, Covent Garden, London

de Havilland Comet Test Flight Hangar, Hatfield, England: Architect James M. Monro & Son, 1953

In 1941 de Havilland developed a jet aeroplane, code named the Spider Crab, using a jet engine of its own design, but based on Frank Whittle's invention, lodged with the Patent Office in 1935. This jet fighter, with its all-aluminium construction, first flew in 1943, becoming the successful DH 100 Vampire fighter. It entered service with the RAF in 1945. However, Sir Geoffrey de Havilland's primary interest was civilian aircraft and in February 1945 his company commenced the design development of the de Havilland DH 106 Comet, the world's first production commercial jetliner.[3] On 27 July 1949, test pilot John Cunningham flew the Comet I prototype for the first time, from de Havilland's Hatfield Airfield, Hertfordshire, England.

To test, develop and maintain the Comet, de Havilland realised it needed a hangar and other facilities to support this process at Hatfield. The Welwyn Hatfield Times reporting in 1953 on its construction, observed that the hangar was sized to 'accommodate six airlines with comfort and eight at a pinch'.[4]

Fig 5.9 de Havilland Vampire fighter jets and Comet jetliner in the Comet Flight Test Hangar, 1955

Based on its experience using aluminium to build aircraft, de Havilland encouraged their architect James M. Monro & Son to use this light metal for the construction of the hangar.

The Comet Hangar has a clear span of over 66m (217′) comprising 12-aluminium portals set at 9.14m (30′) centres with the roof generously oversailing the full-width sliding folding doors at the southern and northern ends. Across the span the portals have a constant depth of 3.05m (10′) and the legs are 2.44m (8′) deep, except at the knee brace that links these two elements forming a stiff portal. The structure was designed to the loading criteria in BS 449: 1948.

This structure creates a useable floor space of 61m × 100.58m (200′ × 330′) combined with a clear height of 13.72m (45′).[5] The aluminium structure was designed by Structural and Mechanical Developments Engineers Ltd in close collaboration with the architect. The components of this riveted aluminium structure were extruded using HE 10 WP aluminium alloy in accordance with BS 1476 supplied by Southern Forge Ltd and T. I. Aluminium Ltd. The foundations were designed by J. Bak and poured by Gilbert Ash (main contractors of the new Everyman Theatre, see pages 254–261). The roof takes the form of a saw tooth with trapezoidal roll formed aluminium alloy sheeting, supplied by British Aluminium Co., 12.7mm (½″) of insulation and two layers bitumen felt with a mineralised finish on the southern roof pitches. The roof sheeting was roll formed from NSE ¾ H aluminium alloy in accordance with BS 1476. Each portal supports 23 north light trusses. The north lights are 2.82m (9′25″) deep with extruded aluminium glazing bars at 2.82m (9′25″) centres supporting 6.3 mm (¼″) thick Georgian wired clear cast glass. The precise orientation of the north lights is north-north east. The Comet Flight Test Hangar is a generously day lit workplace.

The HE 10 aluminium alloy was selected for its high strength to weight ratio. This aluminium portal framed structure weighs only one-seventh of an equivalent steel structure. Aluminium was chosen for its material efficiency and it enabled large-scale prefabrication and rapid assembly on site. The components of the aluminium structure were cold riveted in controlled factory conditions. The cold-squeezed rivets were made from NE5 and NE6 aluminium alloys and were 9.53mm (⅜″) and 15.88mm (⅝″) in diameter. The cold-squeezed rivets are driven by a yoke exerting 22.68-tonne (25-ton) pressure, and do not contract on cooling as experienced in hot riveting, thus each rivet totally fills the hole in the sections being fixed together.[6]

Fig 5.10 Cold riveting the aluminium trusses using a suspended ½ ton yoke

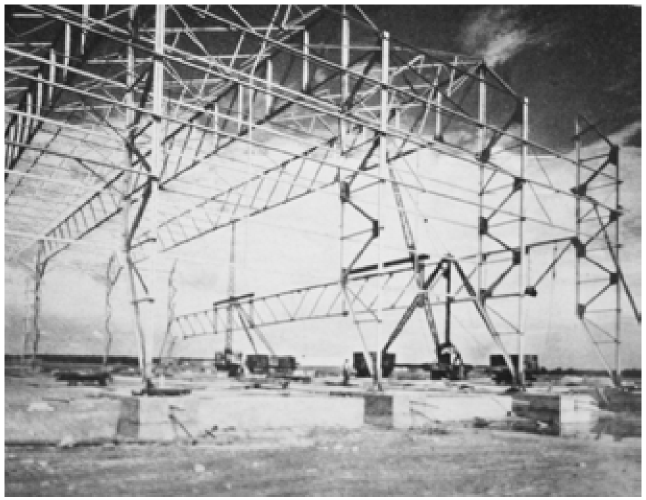


Fig 5.11 A portal beam, having been assembled on the ground is being lifted into place, during 1952

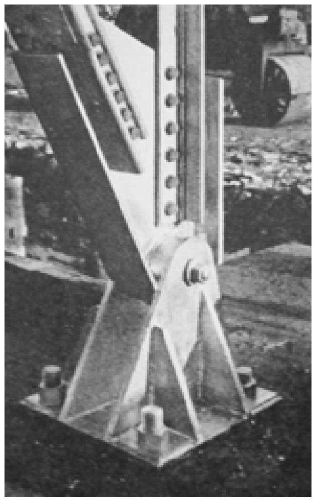


Fig 5.12 The fabricated steel pin detail at the base of the aluminium portals

This aluminium structure was erected in 13 weeks by 18 people using little scaffolding and two 4.4-tonne (5-ton) hand operated cranes.[7] The Architects Journal Technical editor, R. Fitzmaurice, noted that aluminium was chosen as 'large factory elements can be more easily transported and more work done in the factory'.[8] The prefabricated components of the aluminium structure were bolted together on site using sherardized turned and fitted steel bolts and spun black galvanised bolts connecting the sections with gusset plates, comprising either 9.53mm (⅜″) or 12.7mm (½″) thick aluminium. The pins at the base of the portals are prevented from spreading by 457.2 × 457.2mm (18 × 18″) prestressed concrete ties, using the Freyssinet system.[9] The east façade and west façade, above the brick offices, are clad in sinusoidal aluminium sheeting.

If the 18-year old Norman Foster, yet to attend Manchester School of Architecture, had in 1953 asked James Monro how much does your aluminium structured aircraft hangar weigh? Either of them could have turned to the table published in Architect and Building News, reproduced in Table 5.1 with metric or SI units for contemporary readers.[10] Less than 182 tonnes of aluminium were used to fabricate and clad this aircraft hangar, with an almost equal quantity of other materials. The hangar area is 6131.6m² (66,000 square feet) and it weighs 58.44kg per m² of 12.5lb per square foot.

Element or Components	**Aluminium**		**Other Materials**	
	tonnes	tons	tonnes	tons
Structural Sections	96.13	106		
Plate	36.29	40		
Sheeting	9.07	10		
Roof Decking	36.29	40	113.40	125
Glazing	3.63	4	25.40	28
Lining			9.98	11
Steel Components			28.12	31
Total Weight of Aluminium	181.44	200		
Total Weight of Other Materials			176.90	195
Total Weight	358.40	395		
Weight per m² in kg	58.44			
Weight per ft² in lb		12.5		

Table 5.1 The weight of the Comet Flight Hangar at Hatfield, and its components

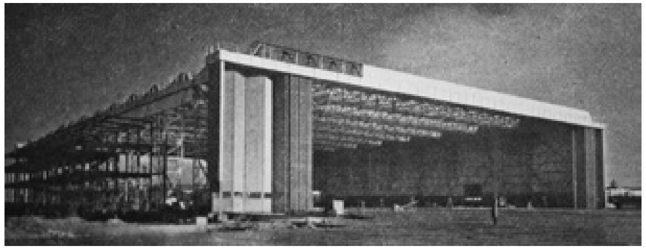


Fig 5.13 January 1953, the Comet Flight Test Hangar is almost complete

The Welwyn Times observed de Havilland had ‘this hangar completed within twelve months of asking for it.’[11] The mill finish structure also offered corrosion resistance and would not need periodic repainting. Contemporary observers also noted that the reflectivity of the aluminium structure helped to brighten the north light day lit interior. Architect and Building News found ‘it interesting to note that in a building of this size, aluminium structures are economically competitive with steel and reinforced concrete, particularly when ease of erection and availability of material is taken into consideration. Furthermore, the structural designers may calculate the economic size of a member and have an extrusion die made so that the exact section required is used.’[12] John Peter in 1958 heralded the hangar as ‘a structure every bit as dynamic as the jetliners it shelters’.[13]

On 21 September 1998 Historic England (formerly know as English Heritage) listed the complete Comet Flight Test Hangar, Offices, Fire Station and Control Tower – Grade II*. The listing observes the ‘Comet Hangar was the most sophisticated example of aluminium construction, and was also the world’s largest permanent aluminium structure at the time, comparable with the demolished Dome of Discovery at the Festival of Britain and more innovative than the hangar at London Airport’.[14] This smaller aluminium structured hangar with a 45.72m (150′) clear span[15] at London Heathrow Airport, renamed in 1966, has also been demolished. The offices and control tower at Hatfield were completed in 1954.

Fig 5.14 Comet Flight Test Hangar, Offices, Fire Station and Control Tower, shortly after completion in 1954

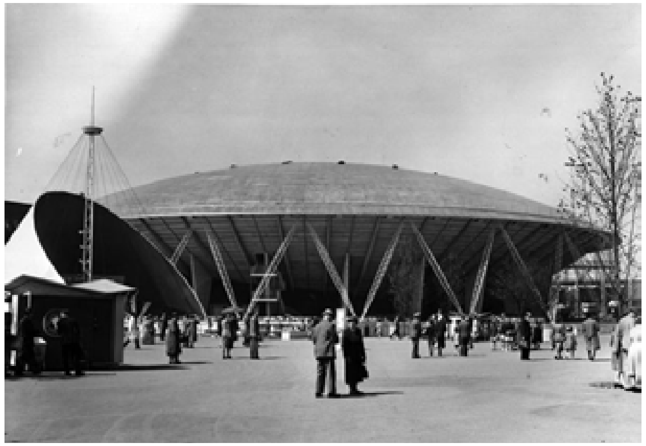


Fig 5.15 The Dome of Discovery at The Festival of Britain, 1951

The Dome of Discovery designed by Ralph Tubbs with consulting engineers Freeman Fox & Partners, had a diameter of 111.25m (365') and a height of 28m (93'), making it at the time the largest in the world, when the Festival of Britain opened in 1951. The extruded aluminium structure of the Dome of Discovery was designed to be symmetrical, thus, reducing the number of distinct parts and ensuring they could be readily prefabricated. The external aluminium trusses combine a structural role with architectural and aesthetic functions; the external aluminium structure provided resistance to the dome's outward forces, whilst creating sheltered external space, and aesthetically creating an ever-changing vista for the visitor walking around the perimeter. As discussed in TSC Report 2 *Aluminium Recyclability and Recycling*, the Dome of Discovery was demolished and recycled in 1952, when it could have been reused or feasibly relocated to the former site of the Crystal Palace.[16] In 1960 Richard Buckminster Fuller with architects Murphy and Mackey completed The Climatron, a 53m-diameter geodesic dome in St Louis, Missouri, which houses a conservatory with a range of climatic conditions ranging from tropical rainforests to dry tropical and oceanic climates. The external structure of aluminium tubes and aluminium rods is sealed by an acrylic skin, which is held in place by neoprene gaskets. Having been refurbished with a glass envelope, between 1988 and 1990, this conservatory is still performing well, see Figure 1.17.[17]

Fig 5.16 The aluminium structure of the Dome of Discovery used repetitive prefabricated elements and had visual clarity

Fig 5.17 The Dome of Discovery designed by Ralph Tubbs at night with the Skylon designed by Powell and Moya

A later example is the Spruce Goose Dome, an all-aluminium geodesic structure, which is 126m in diameter and 40m high. It was assembled, on the quayside of Long Beach, California, next to RMS Queen Mary,[18] to display Howard Hughes' giant seaplane, the Spruce Goose or H-4 Hercules, which flew only once in 1947. The Spruce Goose Dome was assembled in 1983 by Tremcor, using the Richter Polyframe system design by Don L. Richter. This aluminium geodesic structure is clad in 1.3mm aluminium alloy sheet, 3003-H16, which acts as a structural stressed skin. Although constructed in the 1980s, this dome has gusset plate connection details similar to the Comet Flight Test Hangar. However, it, only weighs 12Kg/m^2, based on surface area.[19] The Spruce Goose was primarily built of birch, the dome to display it was assembled from aluminium.

Although designed for disassembly and relocation, this dome is still standing next to the RMS Queen Mary, and is mostly now used as conference venue and film production.[20] The Spruce Goose in now exhibited in the Evergreen Aviation & Space Museum, McMinnville, Oregon.

Fig 5.18 The Spruce Goose Dome and RMS Queen Mary. Long Beach, California, photographed in 2016

Fig 5.19 RMS Queen Mary, assembled on the Clyde, Scotland in the 1930s, primarily from steel along side the all aluminium Spruce Goose Dome, assembled at Long Beach, California in the 1980s

Fig 5.20 The all aluminium, 126m diameter, geodesic Spruce Goose Dome, assembled 1983

The south and north walls of the Comet Flight Test Hangar can be fully opened by operating the electrically powered sliding folding doors. These doors, which are 13.64m high, were fabricated from aluminium sheet and aluminium alloy extrusions by Esavian (ESA) in Stevenage, Hertfordshire, England. The design and fabrication of these doors was the subject of multiple patents, see Figure 5.21.

Fig 5.21 [above left] Plate displaying the patents of the Esavian doors

Fig 5.22 [above] The controls of the electrically operated Esavian doors show 63 years of patination

Esavian was the trade name of Educational Supplies Association (ESA), founded in 1871 and as its name suggests it specialised in supplying books, equipment and furniture to schools. Making ESA, in part, an English but much less famous equivalent to Jean Prouvé's metalwork company, which was more prolific in making school furniture than prefabricated buildings. ESA's wooden classroom partitions found a role in early aircraft hangars, leading to the development of a range of hangar doors. It is still possible to specify Esavian Hangar doors today, and ex-ESA employee Nigel Jewers bought out the rights in 1987 and his sons offer the doors as part of the Jewers Doors range. On the south façade extremely tall doors only have a single glass vision panels at walking head height, in part to ensure the safe operation of the doors. On the north façade the doors have two banks of glazing above the vision panels, to further enhance the north light in the hangar. These vision panels have an outer aluminium frame fixed to the aluminium sheet of the door leaf, but are internally glazed with screw fixed and unpainted hardwood glazing beads.

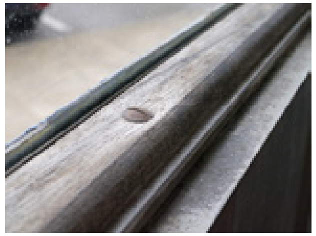


Fig 5.23 Screw fixed and unpainted hardwood glazing bead of a vision panel, photographed 2016

Fig 5.24 Steel bolts, steel wheels and steel track, fixing, supporting and guiding the aluminium Esavian doors, photographed 2016

Fig 5.25 The hinge detail of the aluminium Esavian doors, underneath the vision panels of the north façade, photographed 2016

The first BOAC Comet Jetliner completed a scheduled fare-paying journey on 2 May 1952, flying from London to Johannesburg. With its fast smooth operation, large almost square windows and pressurised cabin, the Comet appeared to be a great success at first, even Queen Elizabeth II, the Queen Mother and Princess Margaret flew on a Comet as guest of Sir Geoffrey and Lady de Havilland during 1953. However, the United Kingdom's pioneer of mass air travel was soon to meet a series of fatal setbacks. Historic England frequently cites technological reasons for the listing of buildings, both innovative means of construction or ground-breaking work by the users of a work of architecture. However, the listing (13766561) for the Comet Flight Test Hangar is the only listing citation to discuss fatal air accidents, 'between 1953-4 three Comets exploded in the sky, and 11 people were killed.'[21]

All Comet aircraft were withdrawn from service and the Cohen Committee was established to investigate. A complete Comet fuselage was subject to pressurisation and depressurisation in a specially constructed water tank at Farnborough. These tests found that the stress at the corners of the windows was much higher than expected. The failure was caused by metal fatigue, due to stress reversal resulting from the pressurisation cycles. Furthermore, the problem was exacerbated further by the windows having abruptly radiused corners and the windows had been punch riveted, when they had been engineered to be glued and riveted. Historic England observe this series of tests and analysis became the model for future jet aircraft design, 'including the problem free Comet 4, inaugurated in 1958 – just ahead of the Boeing 707.' The Comet 4 first flew on 27 April 1958; the first flight of a Boeing 707 was 17 October 1958, de Havilland had lost its lead in the design and construction of jetliners.

During 2004 the Comet Flight Test Hangar and related facilities were converted by Roberts Limbrick Architects into a Tennis Club and Hotel for Next Generation Clubs. In 2007 David Lloyd Club merged with this company in a 'reverse takeover'.[22] It now has its Headquarter Offices in the Hatfield Hangar. In the spring of 2016 the author and colleagues revisited the Comet Flight Test Hangar at Hatfield. The airfield is long gone replaced by housing, business buildings and a university campus. However the 66m span aluminium hangar remains and is full of people engaging in exercise, even on a weekday.[23] This early high-tech shed has become a fun-palace. The most visible activity is tennis being played and tutored in generous daylight, yet the players of all ages are protected from the vagaries of the weather of the British Isles, just as the Comet jetliners were in the 1950s. This is probably the best space in Britain to learn tennis, the best place to be a future Andy Murray. The Comet Flight Hangar appears to be a triumph for the listing of technologically and culturally significant architecture as the spirit of the space lives on, yet it is full of life.

Fig 5.26 A BOAC Comet I jetliner outside the Flight Test Hangar in Hatfield during 1954

Fig 5.27 A Comet I jetliner under testing, circa 1952

Fig 5.28 [below top] In 2004 the Comet Flight Test Hangar was converted into a Tennis Club and Hotel

Fig 5.29 [below bottom] Tennis in the Comet Flight Test Hangar, photographed in 2016 looking North

Fig 5.30 View across the two of the tennis courts in the Comet Flight Test Hangar, looking south, photographed in 2016

The mill finish aluminium structure, which was pressure washed in 2004, is brightly reflective after over 50 years. The diagonal cords of the trusses are picking up reflected daylight and the bottom cords appear a little orange in Figure 5.33 as the sections are reflecting the orange carpets of the courts below. The aluminium Esavian doors remain in place, however, on the south façade they have been fixed open and a double glazed aluminium curtain walling has been installed, following the principles of Historic England these details are fully reversible in the future should the opportunity arise. The southern end of the hangar is spatially more affected by the placement of gyms and a swimming pool, compared to the indoor tennis courts located in the northern section of the hangar. Here the Esavian doors remain operational and can be opened on warm summer days. It would appear that two banks of additional glazing have been installed into the doors of the North elevation, above the original observation windows. As the aluminium structure and door hinges are inside the hangar, the use of steel bolts in the assembly and the risk of bimetallic corrosion does not appear to be a problem for the longevity of this building.

The success of the Comet Flight Test Hangar begs the question why have there not been more roof structures built using aluminium? When the saving in self-weight is such an important issue for roof structure. Furthermore in the twenty-first century we have: vastly improved extrusion techniques, a wider range aluminium alloys and improved joining techniques for aluminium including welding, compared to the beginning of the 1950s.

Fig 5.31 North façade with the doors closed, photographed in 2016

Fig 5.32 After conversion the doors of the south elevation are fixed open and a double glazed curtain walling has been installed

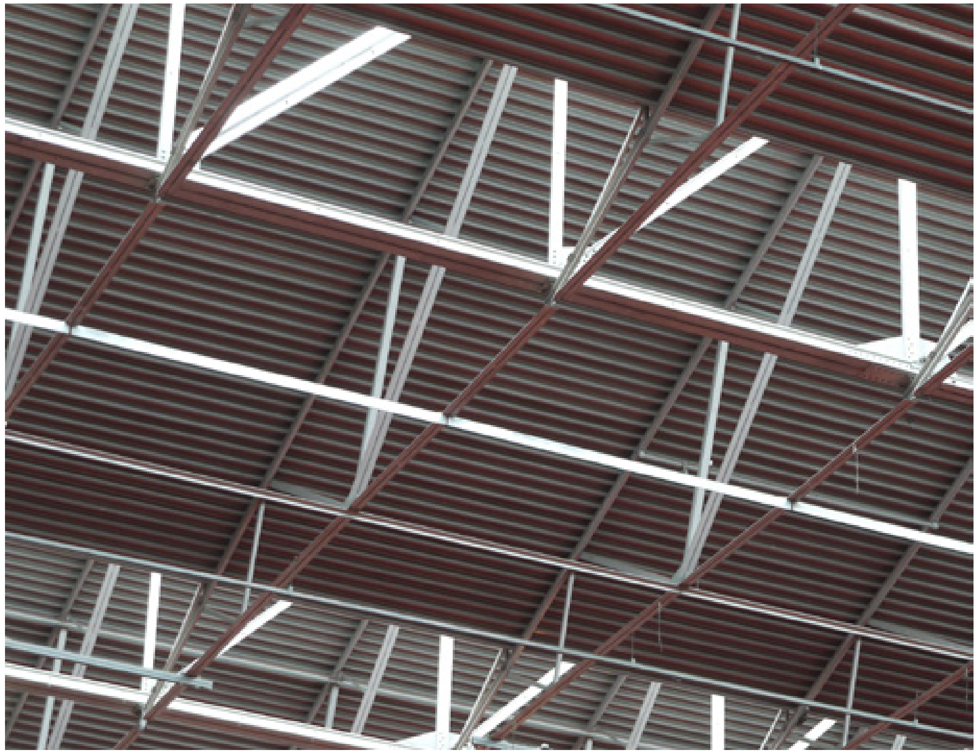


Fig 5.33 The Comet Flight Test Hangar aluminium structure and aluminium roof deck, photographed in 2016, remain highly reflective and looks like a roof of a contemporary project

Ghent Velodrome, Belgium: Architect M.J. Tréfois, 1964

The municipality of Ghent is in the Flemish region of Belgium. Ghent is the Dutch name of the city and it is spelt Gent in French. Located on the confluence of two rivers, the Lys and the Scheldt; by the late Middle Ages it had become one of the largest and richest towns in Northern Europe, with a population of 50,000 in 1300. Its wealth was based on the wool trade particularly with England and Scotland. Today, compared to Brussels, Ghent is Belgium's second city by population with over 600,000 inhabitants.[24] It has two velodromes. The Blaarmeersen cycle track that was built in 1998 and enclosed in 2005. It officially re-opened in 2006 as the 'Eddy Merkx Flemish Cycling Centre'. However, it is the earlier velodrome completed in 1964, which is the focus of this research, as it has a 67m clear span aluminium alloy roof structure and it remains a popular cycling venue. This velodrome known as the 't Kuipke hosts the world famous, and annual, Six Days of Ghent cycling event. It was designed by architect M.J. Tréfois and is located in Citadelpark, alongside The Fine Art Museum and next to SMAK, The Contemporary Art Gallery, which appears to illustrate the importance of cycling in the cultural life of Belgium.

143tonnes of aluminium alloys were used to assemble the roof of Ghent Velodrome. This can be broken down into: 117tonnes of Al-SiMg1 T6 alloy for the main structure; 7.5tonnes of Al-SiMg1 T6 alloy for walkways; and 18tonnes of A-5 H18 alloy for the roof. The aluminium roof trusses are 6.5m deep at the centre of the span.

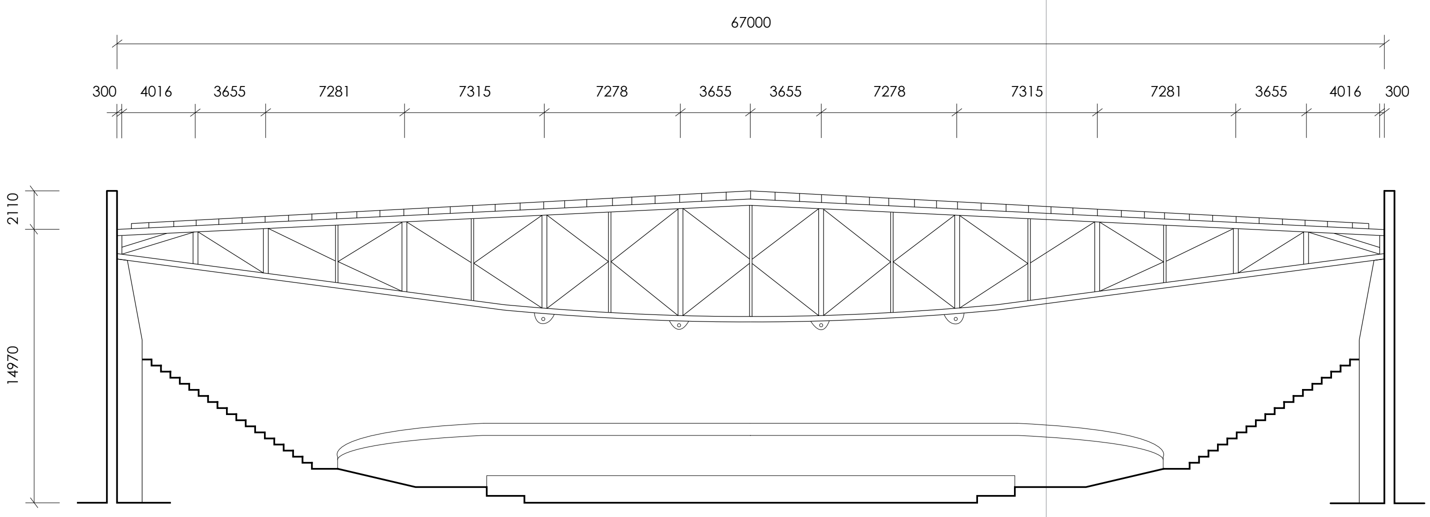


Fig 5.34 Indicative cross-section of Ghent Velodrome, at 1:400

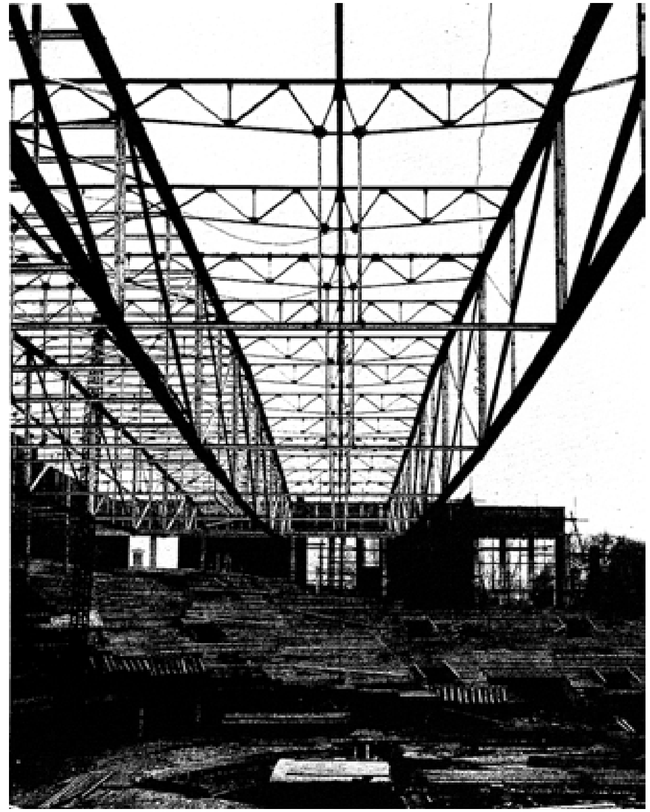


Fig 5.35 Ghent Velodrome under construction in 1963

Although built some 15 years after the Comet Flight Test Hangar (see previous case study) this is still detailed with aluminium gusset plates. It was assembled by Atelier de Constructions Métalligues Steyaert-Heene à Eeko (Belgium). The Ghent Velodrome is 85m long with 9 primary trusses at 8.403m centres, noting the end bays are site specific, see Figure 5.35, which also shows the bays that provide horizontal wind bracing. The area of the Ghent Velodrome is only 5695m^2 in comparison to the area of the Comet Flight Test Hangar of 6132m^2, the structural weight of the Velodrome at 25.1kg/m^2 compares positively to the structural weight of the Hangar, which is 29.6 kg/m^2.

The main aluminium extrusions used to form the roof structure of the velodrome are shown in Figure 5.36, including: extruded aluminium I-beams, 170 × 120mm with 4mm thick web and flanges, and 125 × 80mm with a 3mm thick web and 3.5mm thick flanges, noting the thickened edges of the flanges on both sections; extruded

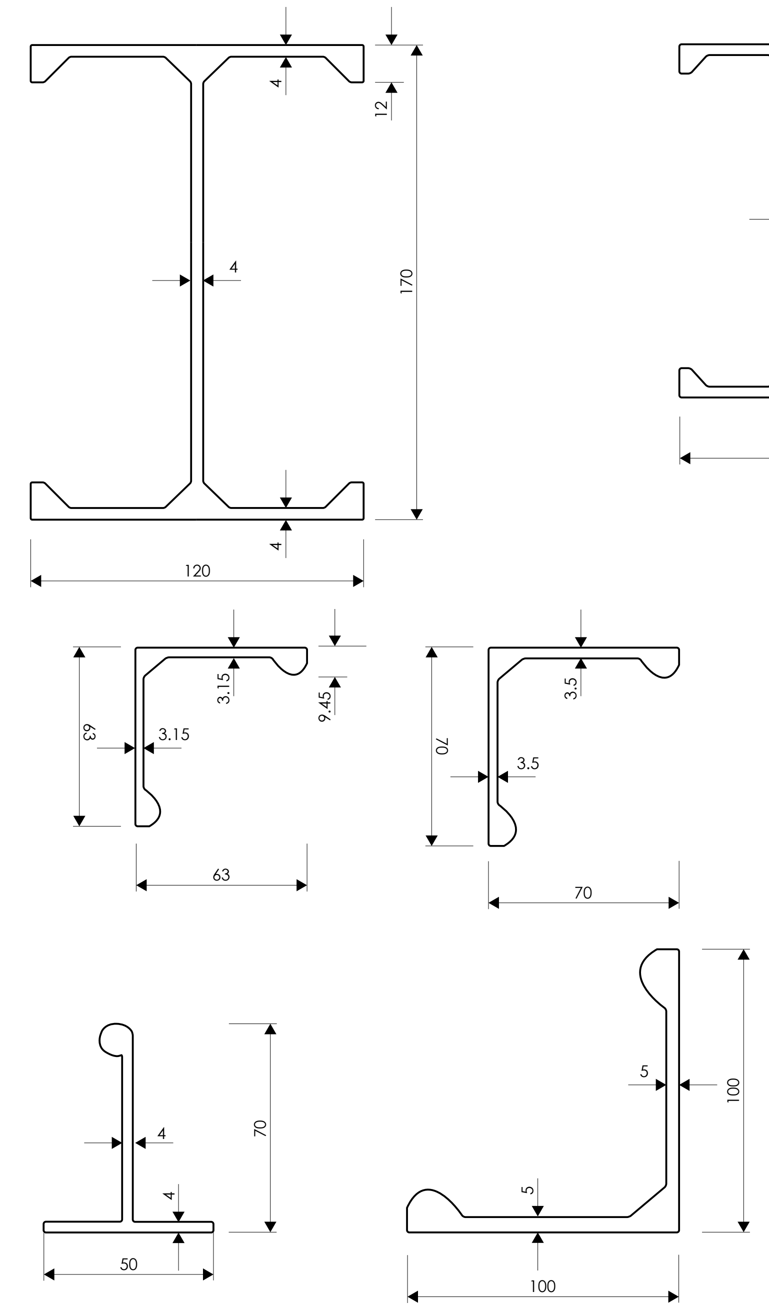


Fig 5.36 Principal aluminium structural sections of Ghent Velodrome, scale 1:2·5

aluminium angles 100 × 100mm, 5mm thick with an equilateral root and bulb like edges to stiffen the section, with similar smaller angles 70 × 70mm, 3mm thick and 63 × 63mm only 3.15mm thick. T sections 50 × 70mm, 4mm thick with bulb-like end stiffening were also used.

Ghent Velodrome has modest and somewhat utilitarian brick façades and the aluminium roof structure is concealed by a suspended ceiling. The fame of this velodrome resides in its 67m all-aluminium alloy structural span and the excellence of the cycling events on its track.

Cyriel Clauwaert, Director of the Belgium Aluminium Centre, who championed this project, biannually produces an aluminium design guide in Dutch and French, entitled *Aluminium Guide, (Richtlijen Voor de Aluminium Constructeur or Directives Concernant la Menuiserie en Aluminium)* 2016.[25] Table 5.2 shows a comparison of a steel I-beam with potential extruded aluminium I-Beams, prepared by Cyriel Clauwaert.

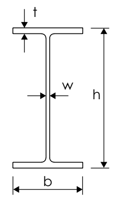
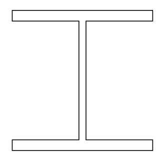
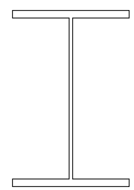
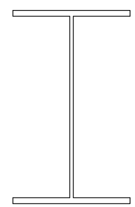
	Steel	Aluminium Alloy	Aluminium Alloy	Aluminium Alloy
				
h (mm)	240	240	300	330
b (mm)	120	240	200	200
t (mm)	9.8	18.3	12.9	10
w (mm)	6.2	12	6	6
Moment of inertia in mm^4	38.9 E6	116.6 E6	116.6 E6	117.3 E6
Young's Modulus E (N/mm^2)	8.17 E12	8.17 E12	8.17 E12	8.21 E12
(kg/m)	30.7	30.3	18.4	15.8

Table 5.2 Comparison of aluminium and steel sections, prepared by Cyriel Clauwaert

Lloyd Studio for Oxford Brookes University, School of Architecture: Architect Brookes Stacey Randall Fursdon, 1994

In the early 1990s Oxford Brookes University School of Architecture was a successful department and popular place to study architecture. However, it was running short of studio space, a not uncommon problem in schools of architecture. Brookes Stacey Randal Fursdon was commissioned by the university to study options for a new studio. The roof of the existing Lloyds building was identified as a possible site, as it offered step free access from adjacent studios and was only occupied by a small central lift core and plant room.

The project identified was to add a floor to the Lloyd Building, thus weight of the new project was of vital importance. Working with Bob Barton of Barton Engineers, the author identified that a gridshell of two layers of aluminium alloy extrusions could prove a lightweight and elegant option. The detailed design of the gridshell was developed using paired 6000 series extrusions, clad with a interchangeable aluminium composite panels and double glazed low-E panels based on the successful Aspect II integrated panel system (see TSC Report 2, *Aluminium Recyclability and Recycling,* pages 60–61). A key consideration in the design of a lightweight shell structure is to show that it develops sufficient stiffness in bending to resist wind loading, which this two-layer system of purpose made aluminium extrusions readily achieved.

Fig 5.37 Perspective of the proposed Lloyd Studio set in the townscape of Oxford Brookes University Headington Campus

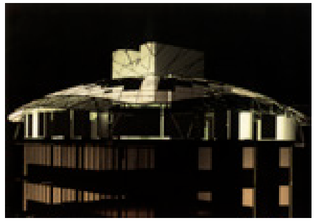


Fig 5.38 Computer based study of the Lloyd Studio at night

The solar shading of the studio was carefully studied using early computer modelling. The studio had full height clear low-E double-glazing to the perimeter, offering views. Each bay was provided with a pair of aluminium shutters with pin board on the inside, possibly inspired by St George's Wallasey (see pages 214-217). During term time these were for the architecture students' personal use, yet for the Summer Exhibition these would be closed against the glass to form the primary exhibition walls of the studio.

The Lloyd Studio gained planning permission from Oxford City Council in 1994, was fully costed and successfully tendered to a main contactor, yet it remains unbuilt for diverse and complex reasons.

Fig 5.39 Approaching the Lloyd Building from within The Headington Campus

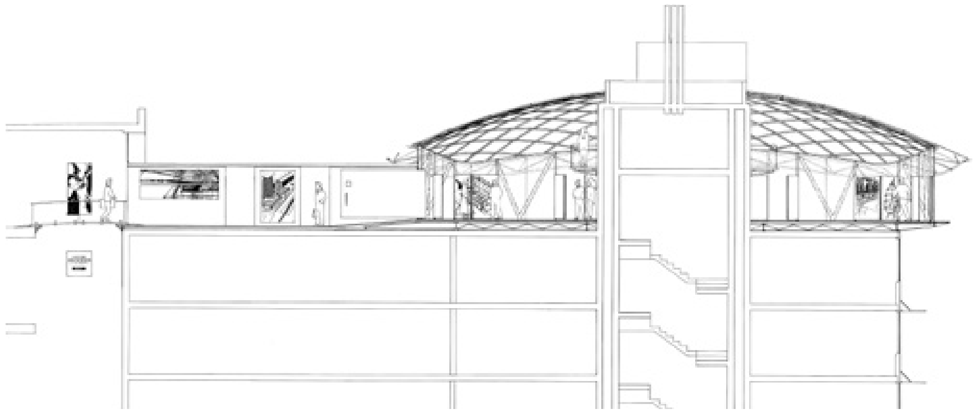


Fig 5.40 Section through the Lloyd Studio

Vertical Shell, artist Tobias Putrih with engineers Price & Myers, London, 2015

This purple-blue anodised aluminium sculpture is located in the triple height reception space of South Bank Tower. The form was inspired by the fragment of seashell collected by artist Tobias Putrih whilst walking on a beach on the river Thames. This form is depicted in slices, each of which is a 3mm thick aluminium plate that cantilevers 10m from the floor. The spacing of the fins varies from a minimum of 29mm to a maximum of 79mm. The engineers Price & Myers observe: 'Each individual plate would be far too slender to support itself over this height but working together the fins form a stable structure.'[26] Vertical Shell was fabricated and installed by Commercial Systems International (CSI). The 3.2mm flats are 300mm deep and are bolted together with 24mm outside diameter threaded aluminium tube, fixed to each fin with an M16 stainless steel bolt countersunk into a machined aluminium washer.[27] The anodised purple-blue colour proved to be variable and a colour range was agreed by CSI with Tobias Putrih.[28] This variability adds to the visual intrigue of the sculpture.

Price & Myers provided parameters for the density of fixings to Tobias Putrih, which increases towards the more highly stressed base of the sculpture. The vertical cantilevers of this discretely formed shell are secured by base plates that are concealed below the floor finish of stone tiles meaning that project engineer Will York of Price & Myers only had 100mm between finish floor level (FFL) and concrete structural slab level to form a moment connection base plate, this detail is shown in Figure 5.49. Thus Vertical Shell emerges apparently seamlessly from the ground.

Fig 5.41 Vertical Shell in the reception of the South Bank Tower

Fig 5.42 A digitally printed stereolithography model of Vertical Shell

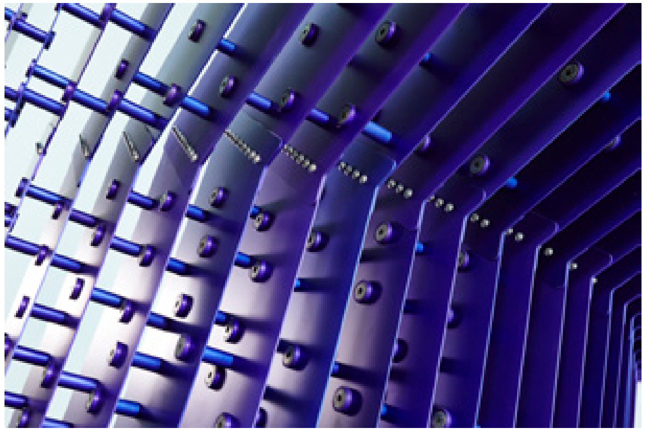


Fig 5.43 300 × 3.2mm anodised flats are bolted to form a stiff shell structure

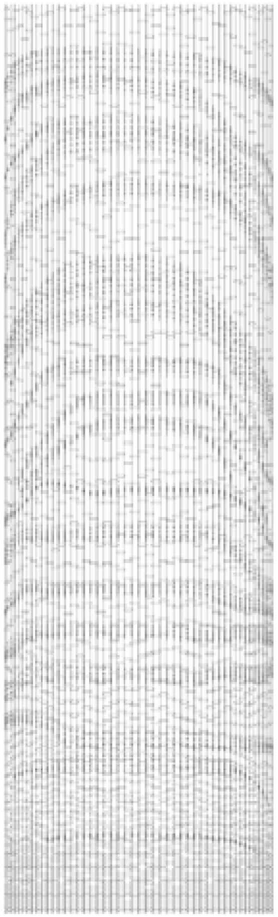


Fig 5.44 Vertical Shell elevation

Fig 5.45 Vertical Shell side elevation

Fig 5.46 Sketch by Artist Tobias Putrih

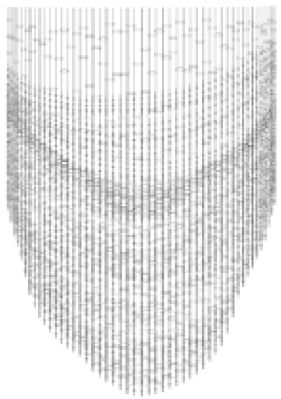


Fig 5.47 Vertical Shell plan

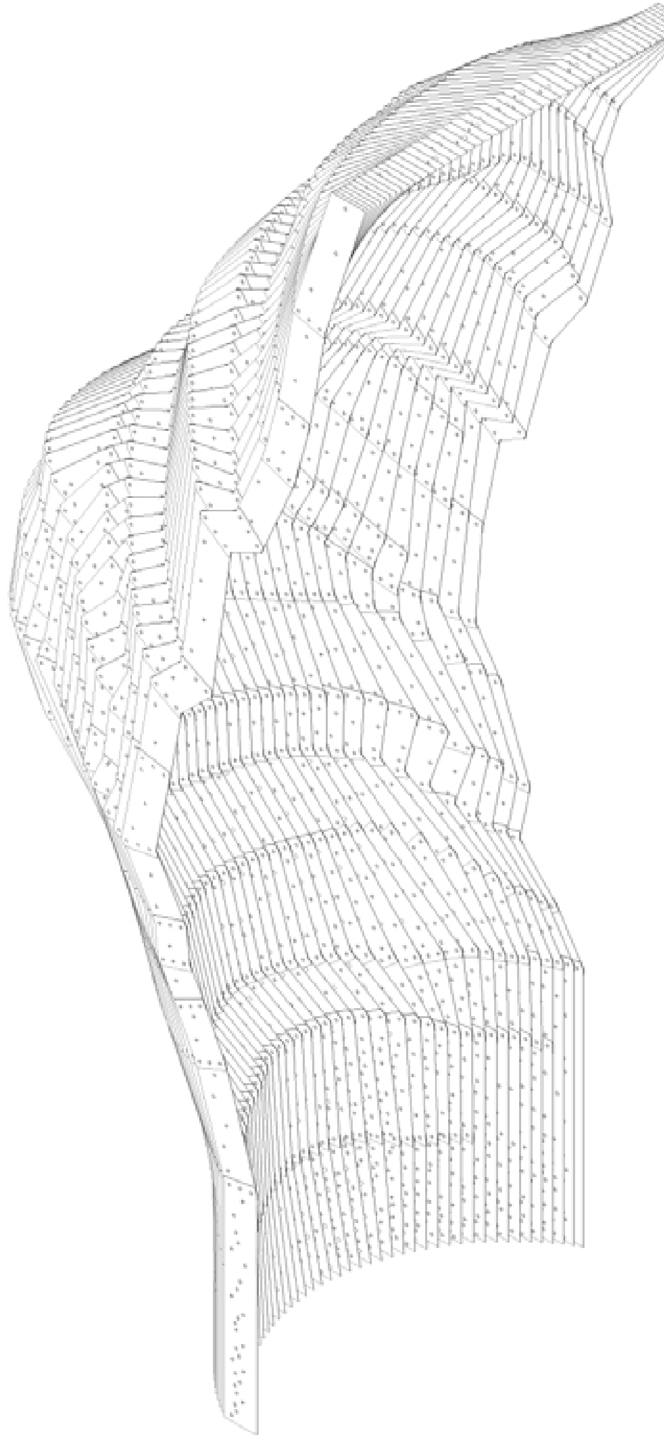


Fig 5.48 Digital model by Price & Myers of Tobias Putrih's Vertical Shell

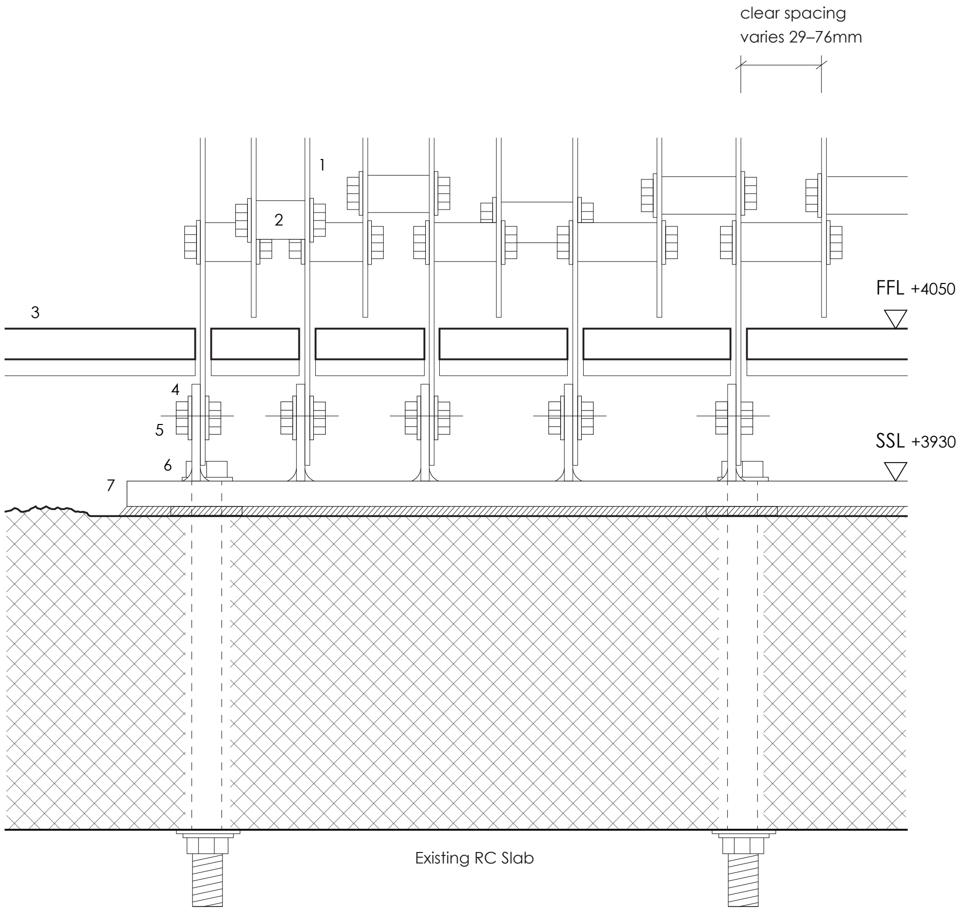


Fig 5.49 Vertical Shell baseplate detail, at 1:1

Drawing notes:

1 300 × 3.2mm thick aluminium fins
2 24 O.D. aluminium spacers with M16 aluminium bolts
3 Stone finish to architect's details
4 300 × 63mm (minimum) × 5mm thick steel fin plate every 2no. aluminium fins
5 5no. m16 A4 stainless steel bolts property class 70
6 6mm fillet weld
7 15mm thick steel baseplate on 5mm thick steel shims and freeflow grout, fixed to RC slab with 2no. M20 Hit-V secured through slab with nut and washer every 4no. fins. All steel grade S355

SSL Existing slab leveled and smoothed to SSL

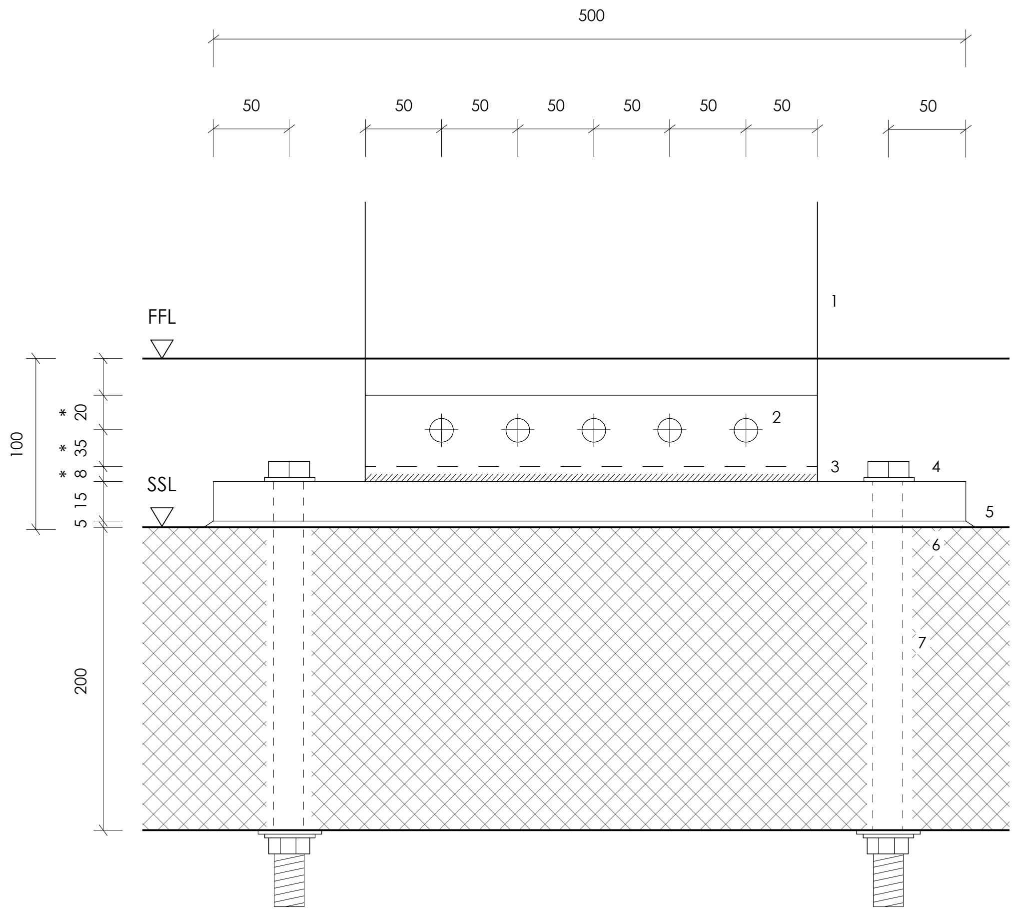


Fig 5.50 Vertial Shell baseplate detail - every 2nd fin, at 1:1

Drawing notes:

1 300 × 3.2mm thick aluminium fin
2 5no. M16 A4 stainless steel bolts, property class 70
3 500 × 55 × 5mm thick S355 steel upright every 2no. fins, 6mm fillet welded to baseplate in S355 steel
4 15mm thick baseplate in S355 steel
5 5mm thick shims and freeflow grout e.g. Fosroc Conbextra EP10
6 Existing slab locally levelled and smoothed with carborundum stone
7 M20 HIT-V bolts secured through slab with nut and washer 1no. pair every 4no. fins

* Minimum values to be increased if floor finishes allow. Zero tolerance in fabrication

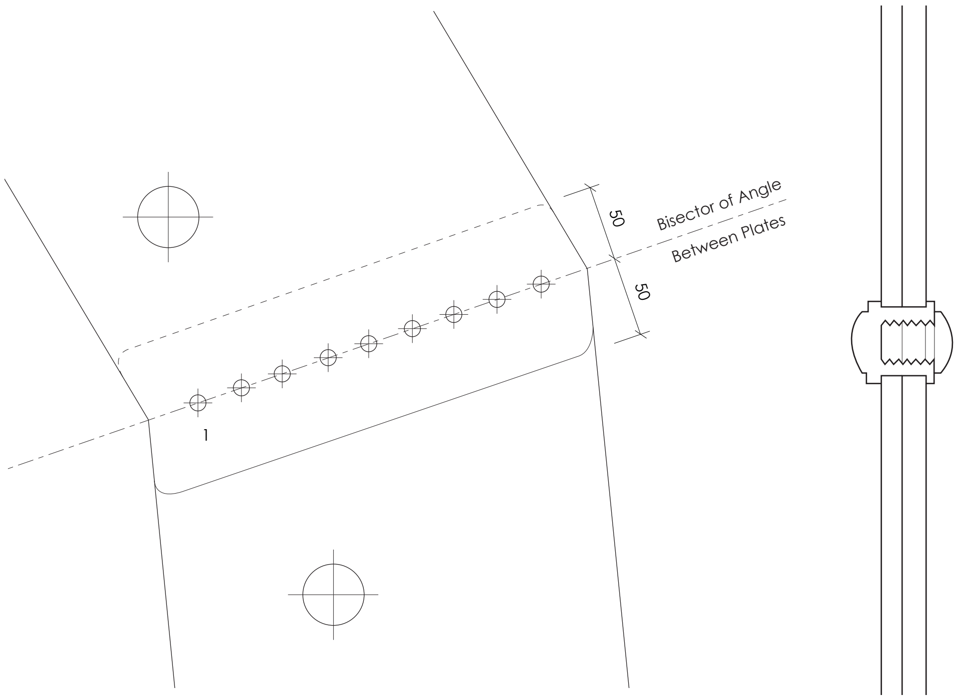


Fig 5.51 Fin splice connection details, shown at 1:1

Drawing Notes:

1 9no. M5 stainless steel bolts grade A4 property class 70 at 30mm c/c with stainless barrel nuts

All dimensions in mm

Notes

1 Health and Safety Executive (2004*), Manual Handling Operations Regulations 1992 (as amended) Guidance on Regulations*, L23 (Third Edition).
2 R. Horden, *Introduction to the Aluminium Federation Conference on the Sustainability of Aluminium Products in Building and Architecture at RIBA*, London, 13 October 2004, unpublished text received by the author as a participant in this conference. See also R. Horden, *Light Tec: towards a light architecture*, Birkhäuser, Basel, 1995, pp. 19–27.
3 *Great Airlines 11: de Havilland Comet*, Flight International, 14 March 1974, accessed March 2016 via www.flightglobal.com/pdfarchive/view/1974/1974%20-%200411.html.
4 16 January (1953) Biggest Aluminium Building in the World: will house fleet of Comets, Welwyn Hatfield Times, Friday 16 January 1951
5 R. Fitzmaurice, 29 January (1953), *Aluminium Flight Hangar for the Comet Airliner*, Architects Journal, pp. 169-170.
6 Ibid, with additional information from 29 January (1953), *Aluminium Hangar at Hatfield*, Architect and Building News, pp. 143–145.
7 R. Fitzmaurice, 29 January (1953), *Aluminium Flight Hangar for the Comet Airliner*, Architects Journal, pp. 169-170.
8 Ibid.
9 29 January (1953), *Aluminium Hangar at Hatfield*, Architect and Building News, pp. 143–145.
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11 16 January (1953) *Biggest Aluminium Building in the World: will house fleet of Comets*, Welwyn Hatfield Times, Friday 16 January 1951
12 29 January (1953), *Aluminium Hangar at Hatfield*, Architect and Building News, p. 143.
13 P. John (1958) *Aluminium in Modern Architecture*, vol.1, Reynolds Metal Company, Louisville, Kentucky, pp. 154–155.
14 Historic England, *The Flight Test Hangar, Offices, Fire Station and Control Tower*, Historic England List Entry Number: 1376561, https://historicengland.org.uk/listing/the-list/list-entry/1376561 (accessed November 2015).
15 R. Fitzmaurice, 29 January (1953), *Aluminium Flight Hangar for the Comet Airliner*, Architects Journal, p. 169.
16 M. Stacey (2015), *Aluminium Recyclability and Recycling: Towards Sustainable Cities*, Cwningen Press, Llundain, pp.167–169.
17 M. Stacey, ed., (2014), *Aluminium and Durability: Towards Sustainable Cities*, Cwningen Press, Llundain, second edition 2015, p. 80.
18 RMS Queen Mary ocean liner was launch on the Clyde River, near Glasgow Scotland on 27 May 1936. It was the flagship of the Cunard-White Star Line. It has been permanently moored at Long Beach California since 1967.
19 D. L. Richter (19930, *Polyframe: the system solution space structure*, in G.A.R Parke and C.M. Howard, eds., *Space Structures, 4*, Vol 1, Thomas Telford, London, pp. 1400-1408.
20 Ibid, other examples of aluminium space structures were built in between 1949 and 1983 by Don L. Richter and Tremcor, manly in the United States of America.
21 Historic England, *The Flight Test Hangar, Offices, Fire Station and Control Tower*, Historic England List Entry Number: 1376561, https://historicengland.org.uk/listing/the-list/list-entry/1376561 (accessed November 2015).
22 www.davidlloyd.co.uk/about-david-lloyd-leisure/the-david-lloyd-story (accessed March 2016)
23 During the 2004 conversion Robert Limbrick, under advice from structural engineers, Clarkebond Associates (Bristol Office), chose to prop the structure at one-third span, with a sliding connection. Project architect Mark Sadler advised that 'the props did not actually support the roof but allow it to 'bottom out' on the props under extreme snow loading.' Furthermore new gusset plates were installed as necessary. During the project the main contactor also consulted with engineers T.R. Collier & Associates. Mark Sadler in conversation with the author March 2016.
24 visit.gent.be/en/history-0?from_category=3304&context=tourist (accessed March 2016)
25 Accessible via www.aluminiumcenter.be/NL/AluminiumGuide.htm or www.aluminiumcenter.be/FR/Aluminium_Guide.aspx
26 http://www.pricemyers.com/geometrics/projects/vertical-shell-southbank (accessed December 2015).
27 Addition information on the assembly of Vertical Shell supplied by project engineer Will York of Price & Myers in conversation with the author in January 2016.
28 Maarten Kienhout of CSI in conversation with the author in April 2016.

Aluminium Formwork

Fig 5.52 [left] Prefabricated aluminium framed table formwork, which is also known as flying formwork

When casting flat in-situ concrete slabs aluminium formwork has become the first choice material, as this formwork is both light and strong, furthermore it can be reused hundreds of times. Craned into position it is known as flying formwork. This technique enables large areas of formwork to be rapidly placed, thus shortening the project build time. Whereas the design of formwork to be placed by hand, requires consideration of the weight of individual components, in order to maximise the effectiveness of a two-person assembly crew.

Fig 5.53 Aluminium framed table formwork ready for the casting of the next floor slab, on site at Canal Street, Nottingham

All components of the PERI SKYDECK aluminium formwork system weigh under 16kg for ease and speed of human handling –creating efficient and safely assembled formwork combined with a very high level of reuse. A high degree of usability has been designed into this system by PERI, a family owned firm with its Headquarters, and Research and Development department in Weissehorn, Germany. PERI was founded in 1969 and the SKYDECK aluminium formwork system and related MUTLIPROP was launched in 1992. MUTLIPROP is based on two aluminium extrusions with self-cleaning thread and a tape measure built into the inner tube to facilitate assembly. The collars are free running to facilitate adjustment.

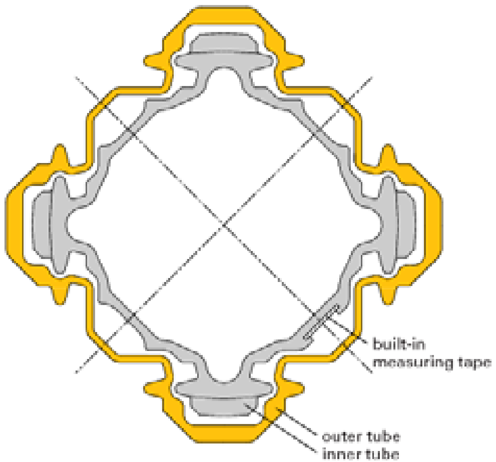


Fig 5.54 Cross section of PERI MULTIPROP - Two aluminium extrusions form the core of this formwork prop

Fig 5.55 PERI SKYDECK Aluminium formwork - all components weigh under 16kg for ease and speed of human handling

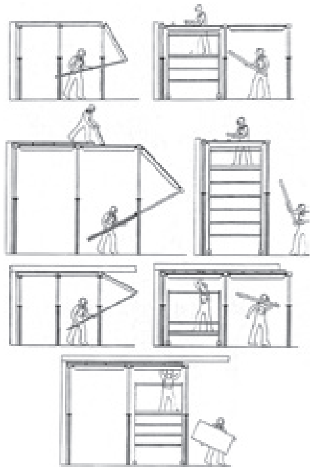


Fig 5.56 Two people assembling PERI SKYDECK formwork

Fig 5.57 PERI MULTIPROP adjustable prop and shoring has an integrated tape measure for accuracy, ease and speed of use

Fig 5.58 PERI SKYDECK Aluminium formwork

An MP350 MULTIPROP weighs only 19.40kg, has a maximum height of 3500mm with a bearing capacity of 91kN. The SKYDECK aluminium formwork system is a well-resolved design with a systematic assembly sequence. The beams of the formwork are polyester powder coated to facilitate cleaning and the edges of the formwork panels are self-draining. The drophead has a self-locking coupling for rapid assembly – however the key advantage of the drophead is that it enables the early striking of the formwork. The props remain in place whilst the panels and beams are removed, thus the formwork can be reused or off-hired and returned to PERI. Depending on slab thickness and concrete strength this can be achieved just one day after the pour.

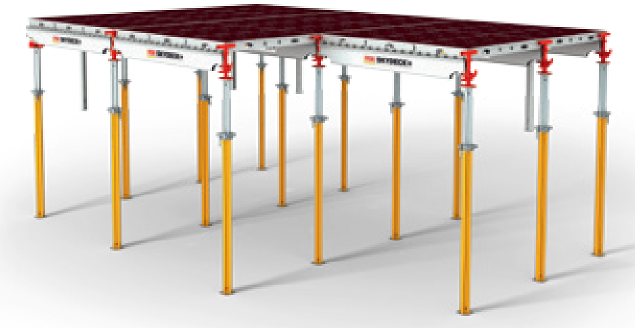
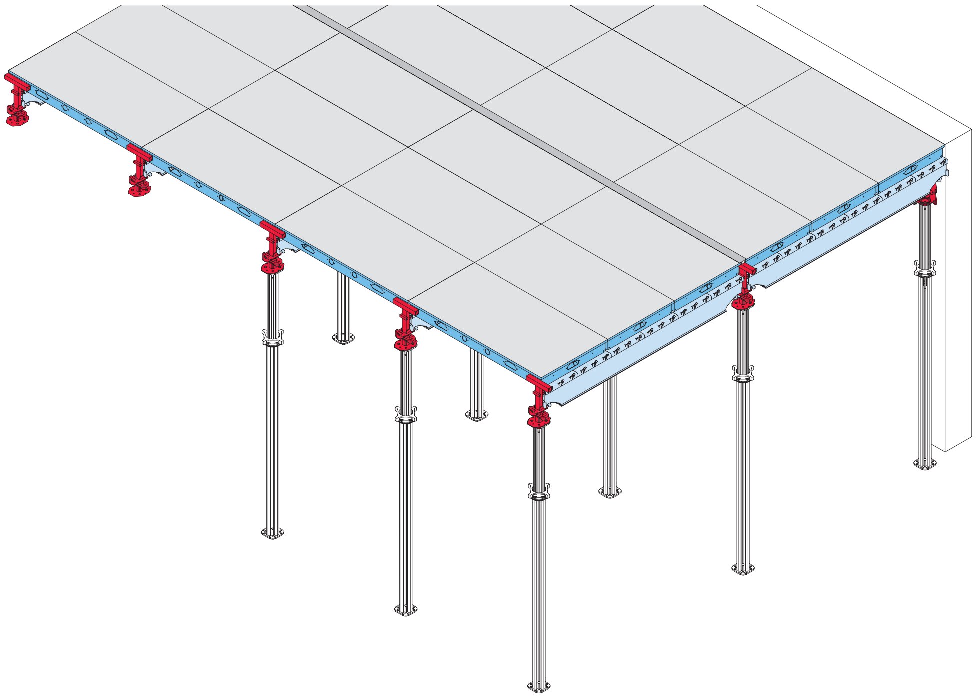


Fig 5.59 PERI SKYDECK Aluminium formwork note the dropheads, which are colour coded in red

Fig 5.60 At the University Club Tower, Milwaukee, Wisconsin Aluminium formwork was assembled without a crane

Fig 5.61 The dropheads enables the early striking of the formwork

Fig 5.62 Once all the formwork has been struck the MULTIPROPS alone remain in place



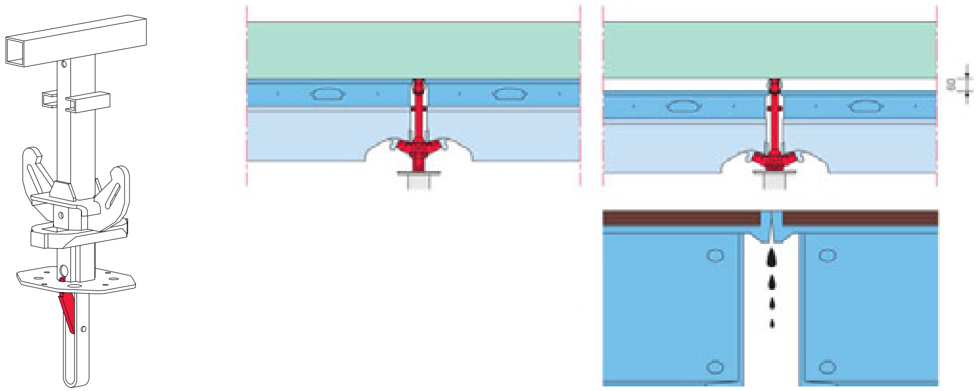


Fig 5.63 [left] The design flexibility of aluminium has enabled PERI to design in a wide range of advantages into the SKYDECK formwork system

Fig 5.64 Aluminium Beams of PERI SKYDECK can be cantilevered by 1.3m with a permissible load of 150 kg/m^2

SKYDECK and MULTIPROP are excellent examples of sophisticated aluminium-based products designed for the construction industry, based on the close study of casting in-situ concrete slabs combined with the inherent design flexibility of aluminium extrusions.

When large in-situ concrete flat slabs are required and crane access can readily be provided, PERI has developed SKYTABLE slab formwork, which is assembled from ply, timber, steel and aluminium. Figure 5.65 shows a 100m^2 PERI SKYTABLE slab formwork being lifted into place at Marina Bay, Singapore. The maximum slab area of this system is 150m^2.

Fig 5.65 100m² PERI SKYTABLE slab formwork being lifted into place at Marina Bay, Singapore, which is made from ply, timber, steel and aluminium

Fig 5.66 Aluminium formwork is a global concrete construction product

Country	Suppliers						
USA + Canada	Aluma	Doka		MEVA International		PERI	
Europe		Doka		MEVA International		PERI	ULMA Construction
Japan	Aluma	Doka				PERI	
China	Aluma - TLD Metalwork	Doka				PERI	
India		Doka	Ishaan Industries	MEVA International		PERI	
Russia		Doka		MEVA International		PERI	ULMA Construction
South America (Brasil)	Aluma	Doka				PERI	ULMA Construction
Australia		Doka				PERI	
South Africa		Doka					
Middle East	Aluma	Doka			MFE Formwork Technology		

Table 5.3 Aluminium formwork suppliers globally by region

Aluminium formwork is a globally available construction method, specifiable throughout the world. Table 5.3 shows the main providers of aluminium formwork on a regional basis. This is summarised in Figure 5.67.

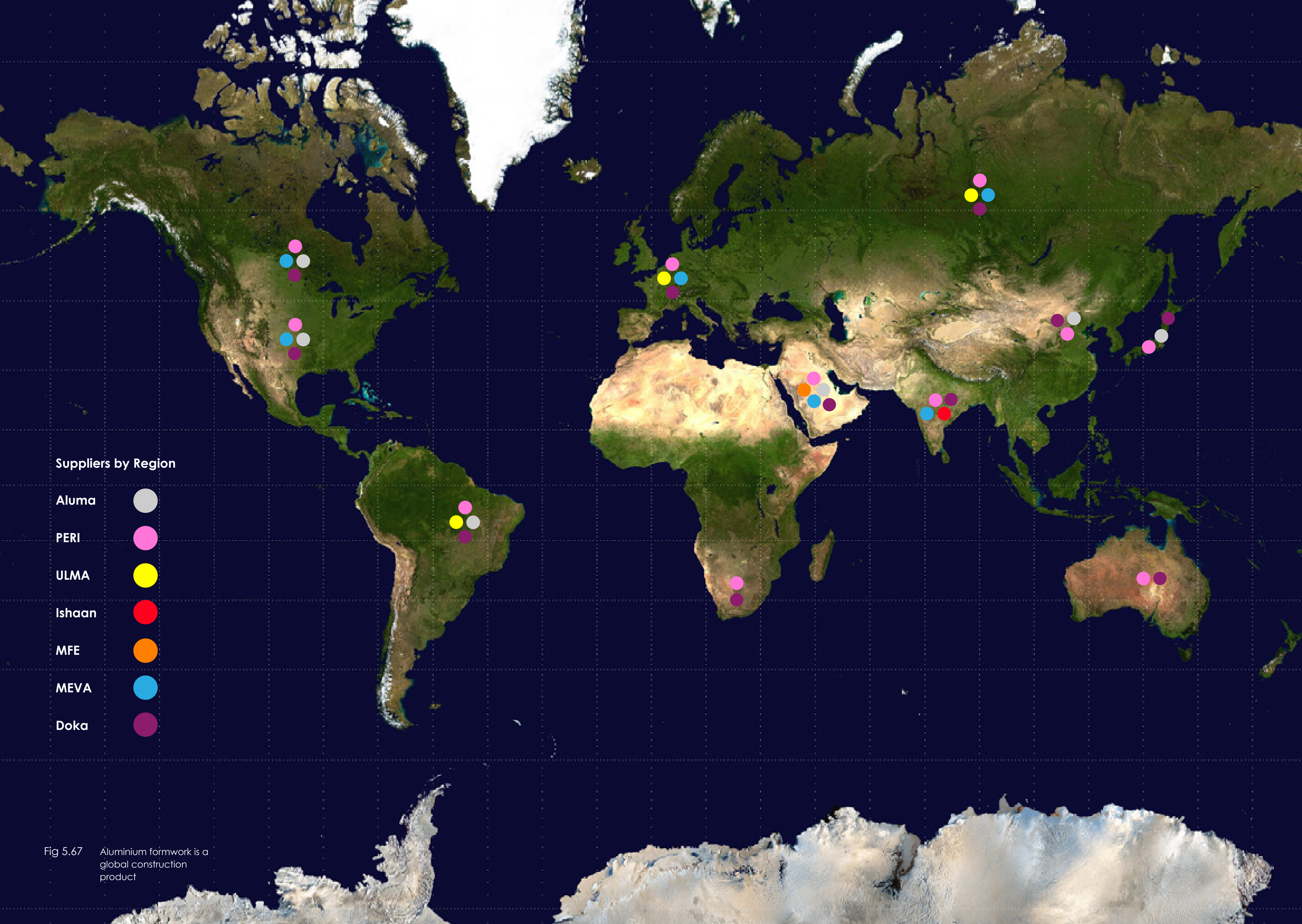


Fig 5.67 Aluminium formwork is a global construction product

Concrete Formwork: a Comparative LCA Study

This Life Cycle Assessment (LCA) compares the use of timber formwork and aluminium formwork for the casting of in-situ concrete. The environmental impacts of the use of each type of formwork can be identified as: global warming potential, ozone depletion potential, acidification potential, eutrophication potential, photochemical smog creation potential, depletion of fossil energy resources and use of renewable energy. Human and environmental toxicity results are not reported due to very high levels of statistical uncertainty in the underlying life cycle inventory methodology and characterisation.[1]

The three scenarios of this comparative LCA are:

1. Timber formwork that is used once;
2. Timber formwork that is reused 10 times; and
3. Aluminium formwork (PERI TRIO) reused 250 times.

Scenario One is based on the common twentieth century practice of the single use of timber shuttering and formwork, with 14.5 per cent timber recovered, 22 per cent incinerated with the energy recovery and 63.5 per cent sent to landfill (based on data from the USA). In Scenario Two the timber formwork is reused 10 times, based upon good practice in the USA, as reported by structural engineers D. Davies and R. Klemencic of Magnusson Klemencic Associates, in the construction of concrete structures of tall residential towers in San Francisco, California. For the supporting timber framework of this shuttering a 20 per cent replacement rate has been allowed for each reuse, with a similar end-of-life profile as Scenario One.[2] Scenario Three is based on the aluminium formwork being used 250 times. This is based on the experience of PERI using its TRIO system.[3] PERI TRIO aluminium formwork can be used 250 times before recycling, which equates to four years of use. Other providers of aluminium formwork reported reuse cycles of up to 350 times, however, the lower figure of 250 cycles has been used in this LCA. Scenario Three is also based on replacing the phenolic-faced plywood lining to the aluminium formwork after it has been reused 60 times.[4]

The LCA data has been generated using Tally, a LCA software linked to Autodesk Revit Building Information Model (BIM) software. Tally was developed by KieranTimberlake with Thinkstep (formerly PE International) and Autodesk. It was launched in 2014. Tally uses a GaBi life cycle inventory database and is currently based on a US **power mix** and US building practice. It runs the LCA using the end-of-life recycling method.[5]

Fig 5.68 Site fabricated timber formwork, Greenwich, England, photographed summer 2014.

Fig 5.69 Site fabricated timber formwork in Vancouver, Canada

Fig 5.70 PERI Modular formwork is colour coded: aluminium in yellow and steel in red.

The Functional Unit is a structural 200mm thick in-situ cast reinforced concrete wall, with a compressive strength of 35MPa (5000psi), external plan dimensions of 10 × 10m and a height of 2.5m, including the formwork needed to cast this wall. The plan area of the functional unit is 100m², which allows the resulting data to be readily scaled, if required. The casting of an in-situ concrete wall was selected to illustrate the relative embodied impacts of the use and potential reuse of types of formwork on this construction element. Clearly comparative LCA studies can equally be undertaken for concrete slabs and or concrete frame of construction, as long as the components are modelled accurately to represent the materials used during construction.

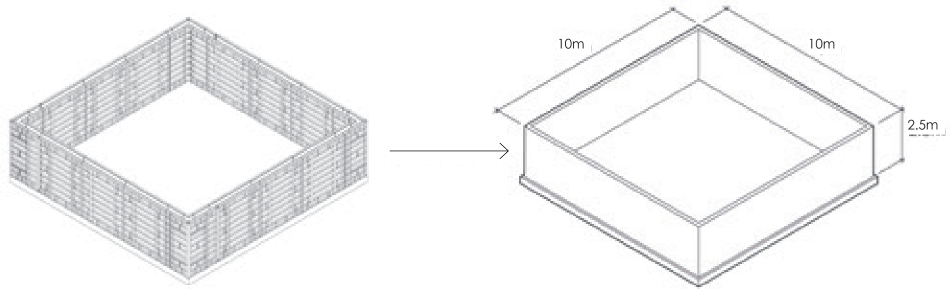
The Functional Unit was modelled in Revit BIM software accurately reflecting the complete build up of materials used to fabricate the formwork and cast the wall. Tally was used, by Michael Stacey Architects, to undertake an environmental assessment in real time as part of a design process. Whereas the environmental assessment in the comparative window frame LCA of Report Three was undertaken by specialist in LCAs.[6]

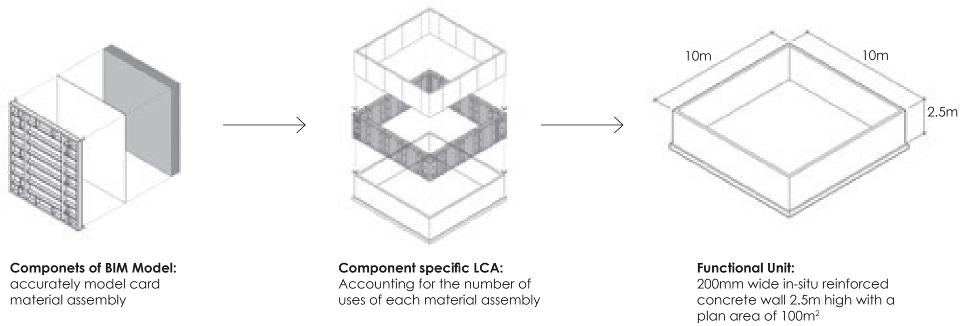
In order to account for the number of use cycles and working life of each material component, the LCA was run for each material making up the formwork. Tally has certain limits in terms of the life scenarios it can calculate – this LCA software only allows a material to be given a working life in years, therefore when materials have a number of reusable cycles, the data based on the working life of that material component needs to be interpreted outside of Tally. Where, for example, aluminium formwork has 250 reusable cycles, each environmental impact value is divided by this reusable rate. This ensures that the Functional Unit holds the correct proportion of the environmental impact of a reusable component. This, in turn, allows for the accurate measurement of environmental impacts for both temporary and permanent elements of construction.

For example, the LCA comparison for the aluminium formwork assembly includes:

A. Aluminium formwork reused 250 times;
B. Phenolic coated plywood form lining reused 60 times; and
C. Structural cast in-situ reinforced concrete wall, 53MPa (5000psi), with a service life of 60 years.[7]

Figure 5.71 shows the comparative pie charts for the three scenarios. The primary embodied energy of the concrete remains constant at 99,400MJ. In Scenario One: the single use of timber formwork, the concrete represents 55 per cent of the total energy





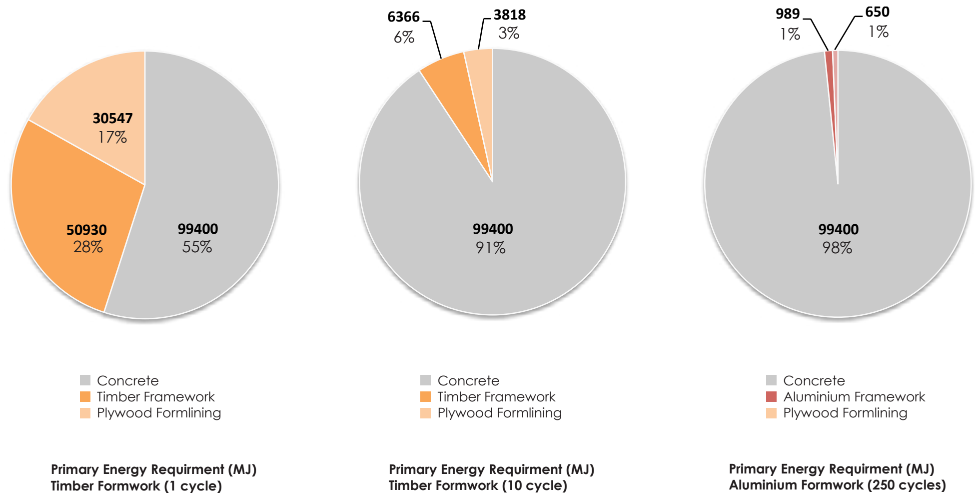


Fig 5.71 Comparative Formwork LCA: Primary Energy required by Timber Formwork (1 cycle) Timber Formwork (10 cycles) and Aluminium Formwork (250 cycles)

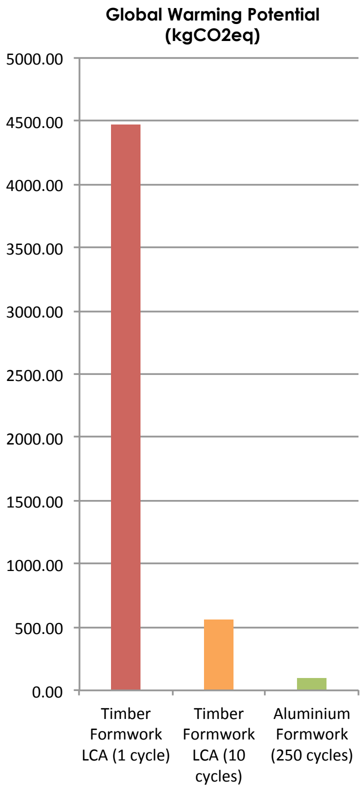
consumed, with the timber framework requiring 50,9300MJ or 28 per cent total energy consumed and the shuttering or form lining requiring 30,547 MJ or 17 per cent total energy consumed. In Scenario Two: timber formwork that is reused 10 times (with a 20 per cent replacement rate of the timber framework for each cycle, as the details are not fully reversible) the concrete represents 91 per cent of the total energy consumed, with the framework requiring 6,366MJ or six per cent total energy consumed and the shuttering or form lining requiring 3818MJ or three per cent of the total energy consumed. In Scenario Three: aluminium formwork reused 250 times and the phenolic coated plywood form lining reused 60 times the concrete represents 98 per cent of the total energy consumed, with the framework requiring only 989MJ about 1 per cent total energy consumed and the shuttering or form lining requiring 650MJ less than 1 per cent total energy consumed. Thus it is clear that the reuse of formwork reduces environmental impacts and embodied energy of in-situ concrete. Using aluminium formwork with fully reversible details, means the embodied energy

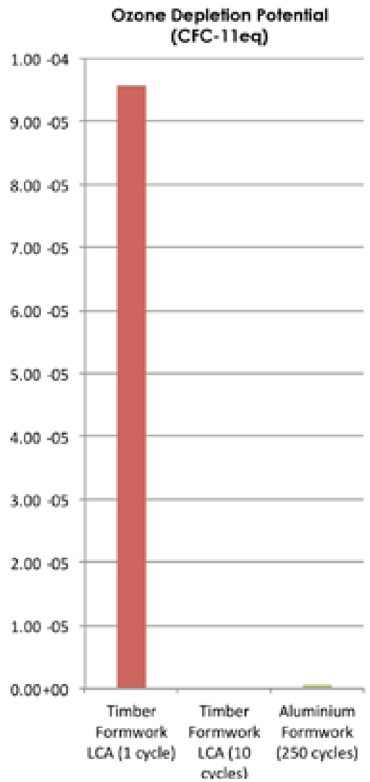
Fig 5.72 Comparative Formwork LCA: embodied impacts of Timber Formwork (1 cycle Timber Formwork (10 cycles) and Aluminium Formwork (250 cycles)

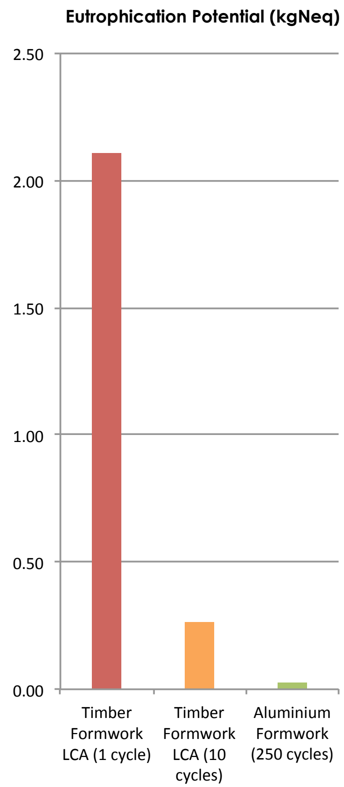
of in-situ concrete is generated almost totally by the permanent works, the concrete itself.

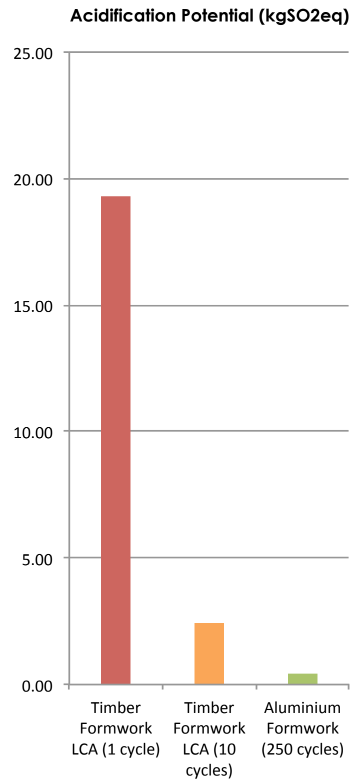
The range of environmental impacts studied for each formwork assembly is quantified in Figures 5.72 to 5.73 including global warming potential, ozone depletion potential, acidification potential, eutrophication potential, photochemical smog creation potential, depletion of fossil energy resources and use of renewable energy. It should be noted that timber formwork and linings specified in the USA benefit from its timber industry being primarily located in a region powered substantially by renewable hydro electricity. Furthermore, the ozone depletion potential for all three scenarios is very low.

The charts clearly show the potential savings in environmental impacts that can be achieved by the use of aluminium formwork, and through the use of reusable temporary components during construction. This could play a key role in the task of reducing the overall environmental impacts of the construction industry.





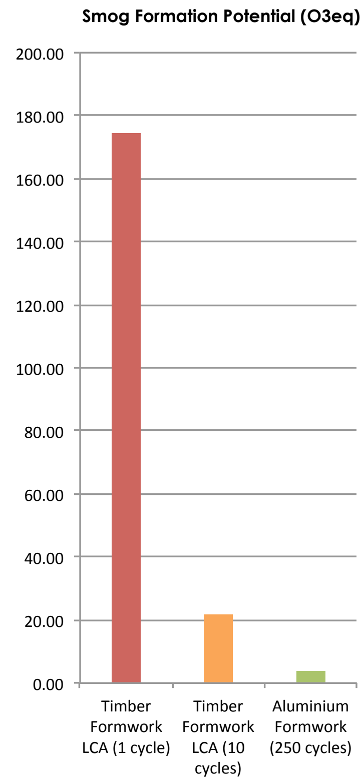


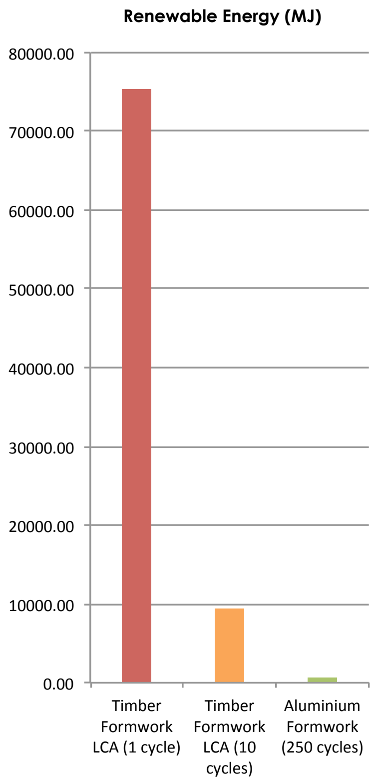


This LCA, which can be conducted during the design process, essentially on the fly, evidences the significant environmental impact savings that can be made by specifying reusable formwork components during construction, alongside other advantages inherent in the use of aluminium for this purpose, including:

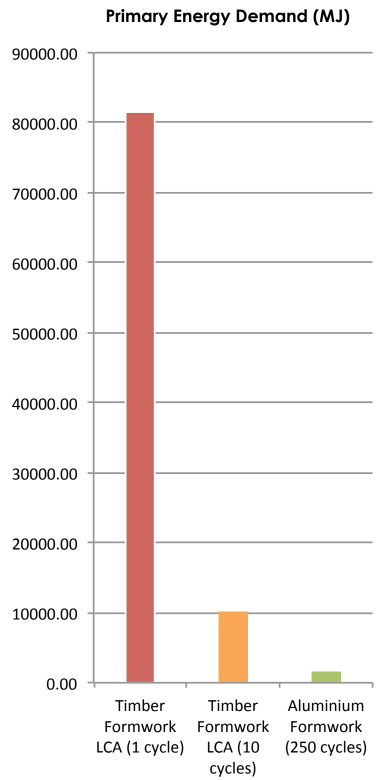
- Speed of assembly;
- Minimises the use of a crane, or maximizes a single crane lift;
- Components can be carried by one person;
- Fully reversible and reusable – up to 250 times;
- Economic savings (timber formwork costs around 40 per cent of in-situ concrete construction);
  and
- Significant savings in embodied energy and embodied CO_2.

Fig 5.73 Comparative Formwork LCA: embodied impacts of Timber Formwork (1 cycle Timber Formwork (10 cycles) and Aluminium Formwork (250 cycles)





Revit is a CAD software utilised by complete design teams in the realisation of architecture and infrastructure for its BIM capabilities. The benefits for architects and engineers of running a LCA via Tally directly through BIM is the ability to understand the environmental impacts of material decisions during the design process. This feedback of information, when working in three dimensional design space, allows architects and design team to visualise and analyse material decisions on many levels, from environmental impacts, appearance, durability, cost and efficiency - giving the design team an informed understanding of the holistic value and benefit of each element to a project. However the current limitations of these computer programmes need to be fully understood by architects and other collaborators in the design team. To generate a fuller understanding of the potential environmental impacts of a project, the addition of LCA expertise to the design team should be considered.



Notes

1 Based on the guidance in S. Carlisle, E. Friedlander and B. Faircloth (2015), *Aluminium and Life Cycle Thinking: Towards Sustainable Cities*, Cwningen Press, Llundain, p.42.

2 Formwork based on 12.5mm (1/2′) plywood with 10 cycles of re-use before replacement, as cited in D. Davies and R. Klemencic (2014), *Life Cycle Analysis: Are We There Yet?* CTBUH 2014 Shanghai Conference Proceedings, CTBUH, Chicago, IL, p. 521, available online at http://global.ctbuh.org/resources/papers/download/1865-life-cycle-analysis-are-we-there-yet.pdf (accessed June 2015).

3 C. McKillop, Engineering Manager, PERI Ltd., by email 27 June 2015, advised that PERI TRIO aluminium formwork by has a service life of 4 years based on an average usage of 60 times per year, with a limit of 250 cycles. The 4-year life can be reduced if not handled with care by contractors.

4 C. McKillop, Engineering Manager, PERI Ltd., by email, March 18, 2015,advised that PERI's phenolic coated plywood form lining has an average life of 1 year based on a usage of 60 times per year, with a limit of 70 cycles. The phenolic coating can be stripped and re-applied if the plywood is in a good condition.

5 See S. Carlisle, E. Friedlander and B. Faircloth (2015), *Aluminium and Life Cycle Thinking: Towards Sustainable Cities*, Cwningen Press, Llundain for a review of recycled content method and end-of-life recycling method.

6 S. Carlisle, E. Friedlander and B. Faircloth (2015), *Aluminium and Life Cycle Thinking: Towards Sustainable Cities*, Cwningen Press, Llundain.

7 Based on industry data: the average use of aluminium formwork is 62.5 times per annum, combined with a 250 uses of this formwork frame before recycling, the replacement cycle is approximately four years. Similarly the phenolic face is replace in just under one year. The number of uses not time is the basis of this LCA.

Aluminium in Bridge Design and Construction

The role of bridges in the built environment appears to be well understood and is as ancient as architecture itself. The earliest arched masonry bridge in Rome, the Pons Aemilius, was built between 179-142 B.C., and the Roman aqueduct in Segovia, Spain, completed around A.D. 109, functioned into the twentieth century.[1] Durability is very important in the design and construction of bridges. In the UK, bridges in the public realm are designed to last at least 120 years, subject to annual inspection and appropriate minor maintenance if necessary.

Since the mid 1990s, architects have increasingly become involved in bridge design – linking the art and science of construction. Typically bridges have a very clear identity and the design of bridges is not unlike product design. Martin Heidegger poetically describes the role of bridges in human experience: 'The bridge *gathers* to itself in *its own* way earth and sky, divinities and mortals.'[2]

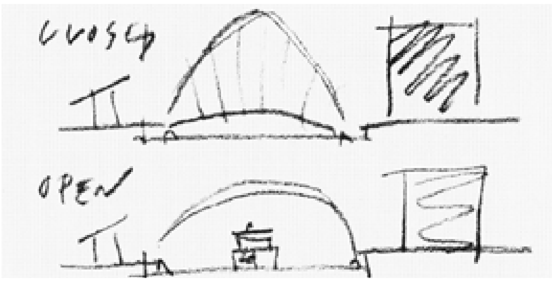


Fig 5.74 [left] Jim Eyre's sketches of the opening strategy of the Gateshead Millennium Bridge

Architects bring to a bridge design, skills in being able to access and analyse the context, releasing the spatial potential of the bridge. Architects can also bring a holistic approach to all of the components of a bridge, in essence the whole becomes greater than the sum of the parts. To take Jim Eyre's practice as an exemplar, he stresses the importance of collaborating with highly skilled engineers, he also observes 'when WilkinsonEyre is involved in a bridge project, more often than not the raw concept comes from that quarter.'[3] The contribution of architects and engineers is clearly evident in the case studies reviewed below. These case studies are set out in the following order:

- aluminium bridge structures;
- aluminium bridge decks;
  and
- aluminium guarding systems.

The case studies are listed chronologically within each section. Also included are aluminium staircases, as this constructional element demonstrates similar design criteria to bridges and are often made by specialist fabricators who also assemble bridges. The chapter concludes with a brief history of early aluminium bridges.

Fig 5.75 [right] Queen Elizabeth II dedicates the Millennium Bridge, London, 9 May 2000

Fig 5.76 The people of Suffolk at the opening of Ballingdon Bridge, 18 July 2003, unaware the balustrade can stop a 42 tonne truck

Royal Ballet School, Bridge of Aspirations, London, England: Architect WilkinsonEyre, 2003

The brief called for a bridge crossing Floral Street in Covent Garden, to link the Royal Ballet School with the E. M. Barry's Royal Opera House, and to provide direct access for the dancers to rehearsals and performances. It also encourages young dancers to mix with professionals in the cafés of the Royal Opera House. Two existing openings were identified, however, they were asymmetrically placed in terms of both plan and level above the street. Jim Eyre's initial sketch, sent to structural engineers Flint & Neill, (truly his first response) was a series of rotating squares in space translating the geometry between the two buildings and resulting in a gently ramped walking plane. This movement of frames in space is reminiscent of the display Ripley (Sigourney Weaver) is viewing in the landing sequence in Ridley Scott's science fiction movie *Alien*, released in 1979.

Fig 5.77 Bridge of Aspirations viewed from Floral Street

Fig 5.78 Jim Eyre at work

Jim Eyre recalled the rapid design development process:

> Initial investigations experimented with the idea of incorporating a twisting profile in order to exploit rather than suffer the effects of rake and skew on what might otherwise be rectilinear organisation to the elevations.
>
> A rapid evolution occurred with the thought that a series of square frames, all at once raking, skewing and twisting, could follow the direction of movement across the bridge. After a sample check to verify that the rotating squares would not be too large yet still allow sufficient space for users, the core principles of the concept immediately became apparent. Incidentally this was the only phase in the design and fabrication process, which was not digitally enabled.[4]

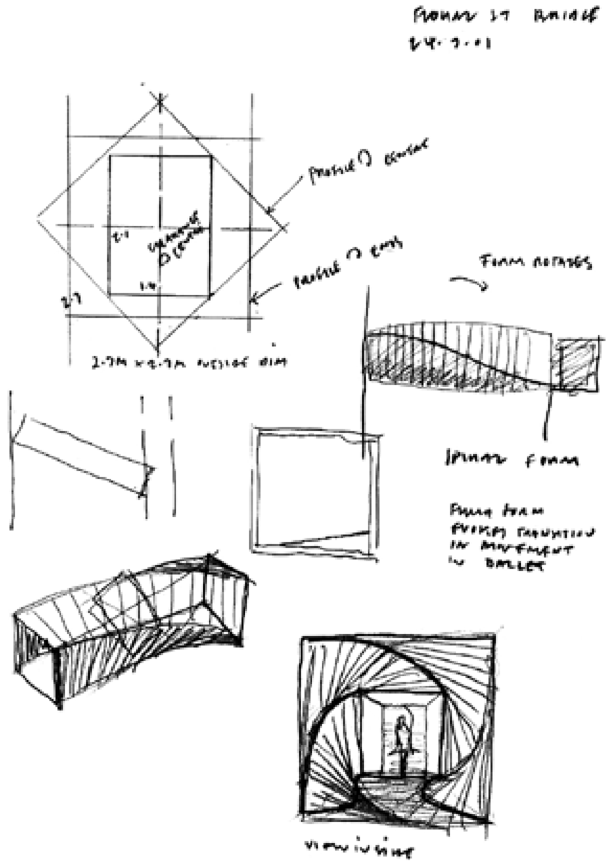


Fig 5.79 Jim Eyre's initial drawings of the Bridge of Aspirations, the ends and centre are key drawings in the design of all bridges

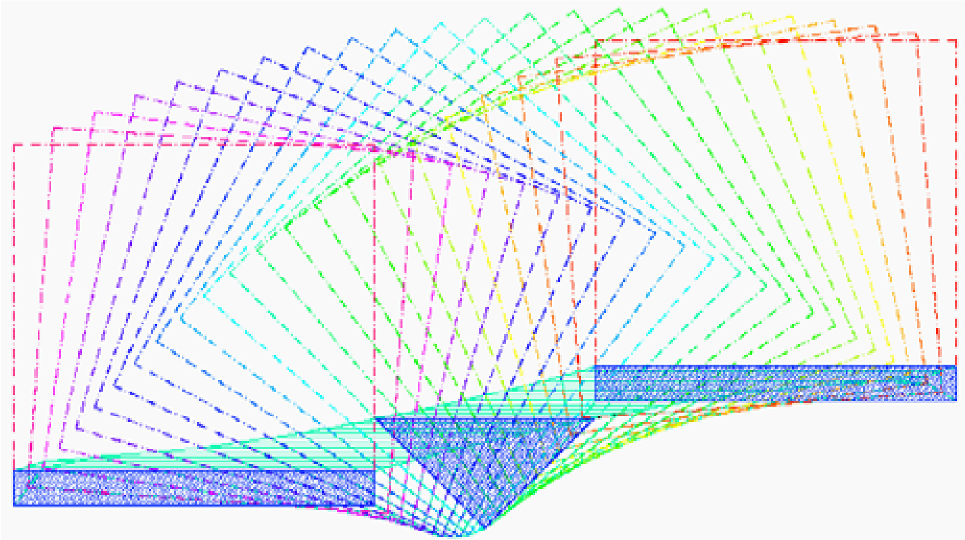


Fig 5.80 Bridge of Aspirations was delivered digitally following the initial sketches – the 23 rotated frames of the bridge

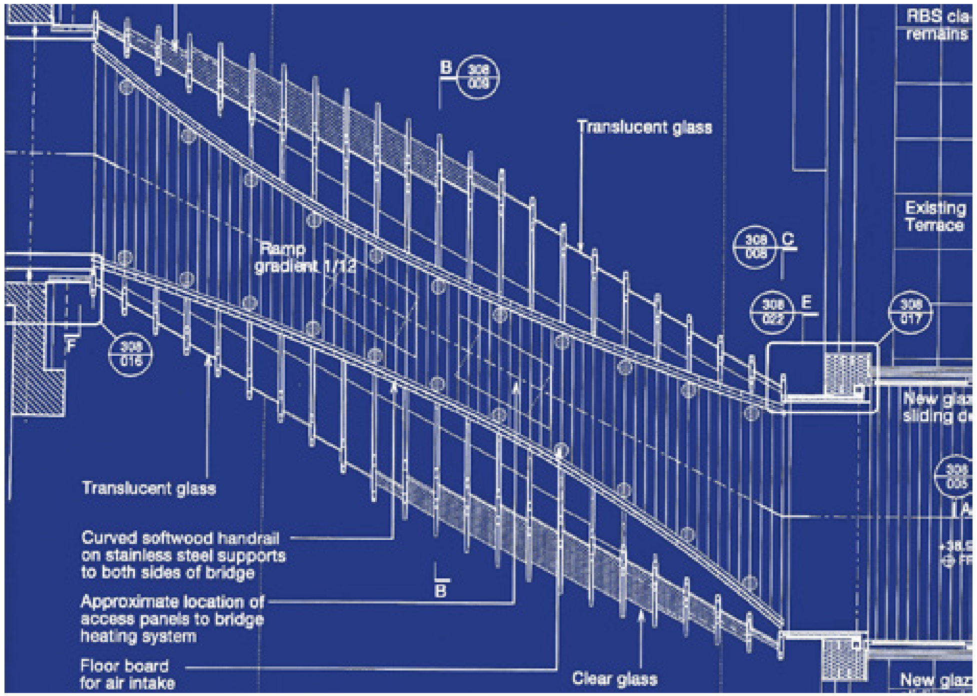
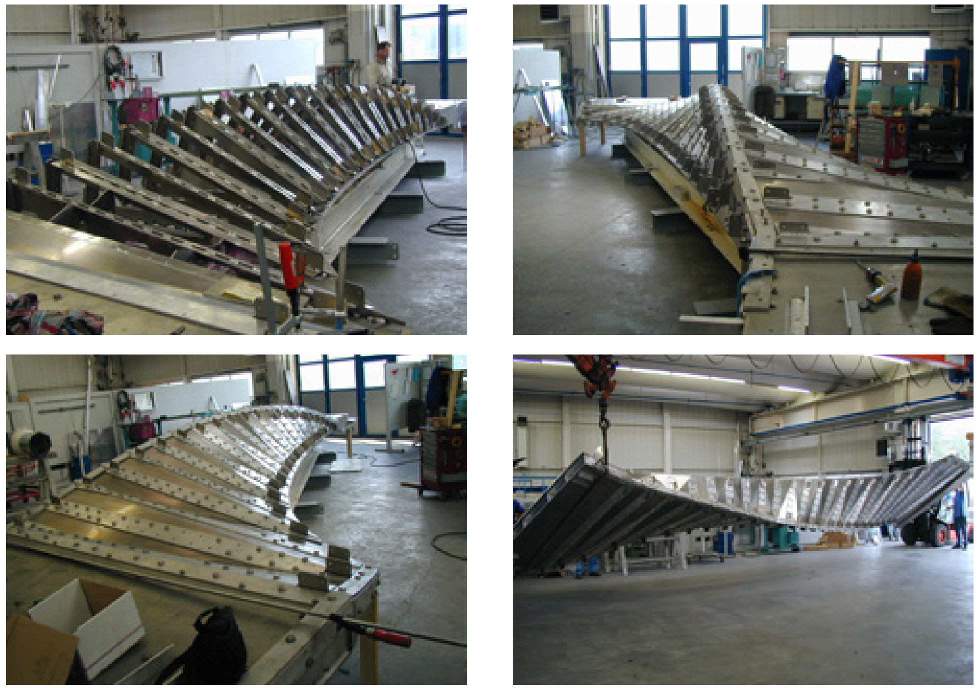


Fig 5.81 A WilkinsonEyre's plan of the Bridge of Aspirations

The realised design is composed of 23 aluminium frames, each rotated in space by 3.91°. The frames are linked together by a twisting aluminium box beam, which is only apparent during assembly. The bridge is articulated by the rotating aluminium frames and united by a glass skin that is translucent and clear. The translucent glass conceals the structure but more importantly provides privacy for the dancers from the street below. This gives way to clear glass that provides views out for those using the bridge. One way of reading this bridge is the interplay of two forms, each made of translucent and clear glass. Internally the aluminium frames are partially clad in oak, to accommodate the glass that is not parallel with the mullions and to accentuate the reading of the twisting geometry. Oak is also used to form the walking plane or floor.

The Bridge of Aspirations was totally prefabricated by GIG in its North London facility, which is more typically used for prefabricating unitised curtain walling. GIG is an Austrian company that fabricates aluminium systems in Austria. Thus, GIG has all the advantages of the controlled conditions of factory production, yet avoiding transporting large prefabricated assemblies across continental Europe and the Channel. The bridge was craned into position on a quiet Sunday morning with all of the people from WilkinsonEyre in attendance.

Fig 5.82 The assembly stages of the twisted aluminium spine beam of bridge at GIG's north London facility



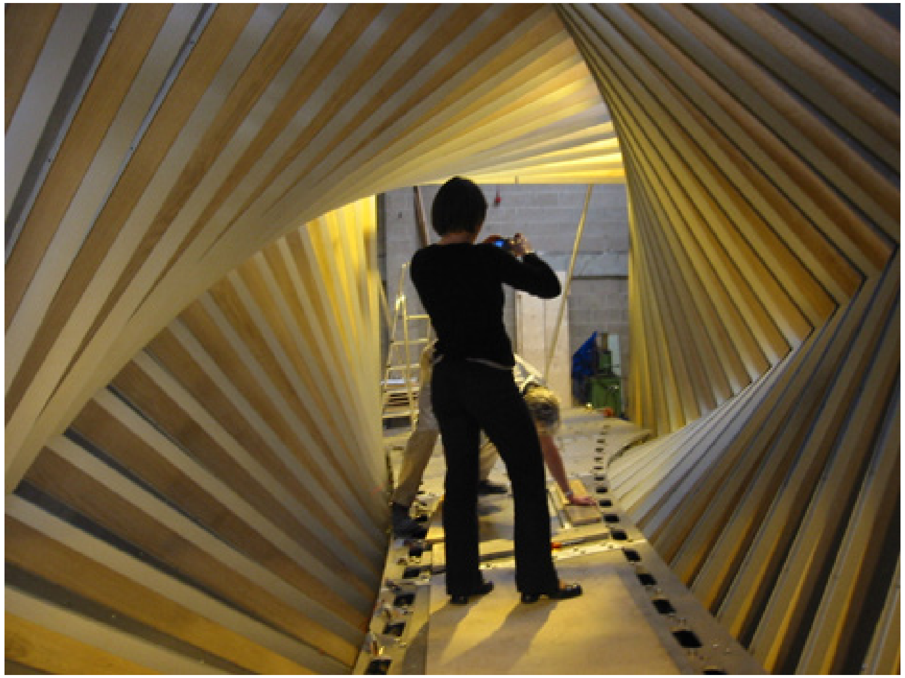


Fig 5.83 Offsite installation of the oak floor of the Bridge of Aspirations

Fig 5.84 Bridge of Aspirations was fully prefabricated by GIG

Fig 5.85 Bridge of Aspirations being trucked across London to Covent Garden

Fig 5.86 Under a road closure the bridge is craned into place

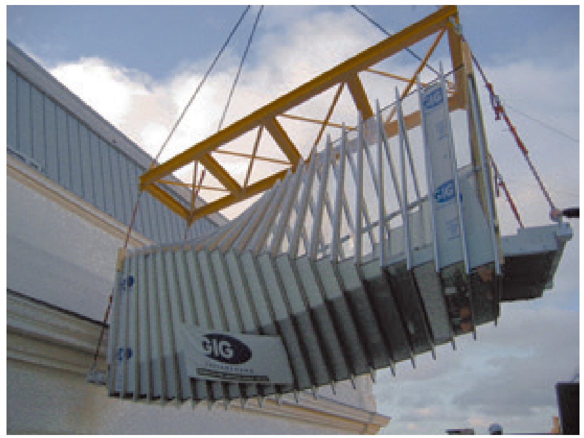


Fig 5.87 Note the steel strong frame keeps the temporary supports clear of the aluminium frames of the bridge

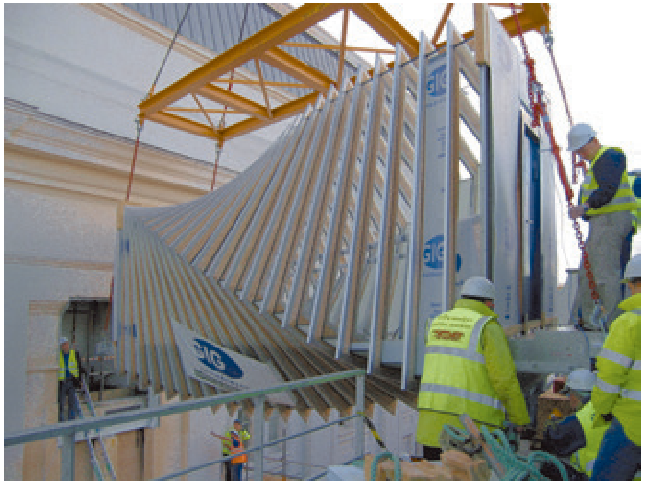


Fig 5.88 Carefully positioning the bridge to match the asymmetrical openings of the Royal Ballet School and the Royal Opera House

Fig 5.89 Note the precision of prefabricated assemblies as the bridge is eased into place

Jay Merick considers that 'the vortex-twist of the composite metal – timber frames forming the Bridge of Aspirations across London's Floral Street that expresses the practices' attention to detail most exquisitely.'[5] The bridge is literally a translation in space; however, it also serves as a metaphor of the movement of a dancer through space, an architectural overture of the performance in the Royal Opera House – just a few dance steps away across Floral Street.

Fig 5.90 Bridge of Aspirations crossing over Floral Street

Fig 5.91 [Overleaf] Royal Ballet School, Bridge of Aspirations designed by architect WilkinsonEyre

Westdork Bridge, Amsterdam, Netherlands: Architect MSVA Architects, 2003

This is a 5m wide and 48m long bridge over an Amsterdam canal for pedestrians and cyclists. The central span is a 16m single-leaf bascule to allow boats to pass. The bridge was designed by MSVA Architects and fabricated by Bayards, it was assembled in 2003.[6] The client for this bridge is the Amsterdam City Development Corporation, the lightweight all aluminium structure of this opening bridge facilities its day-to-day operation. Bayards actively promotes collaboration with architects in the design of bridges, using its experience in designing and fabricating prefabricated assemblies in aluminium since 1963. Bayards manufactures structural assemblies from aluminium on a bespoke basis using robust and reliable technologies. This can be contrasted with Sapa's standardised approach to the design of bridge decks, which is discussed below.

Fig 5.92 All aluminium Westdork Bridge designed by MSVA Architects, fabricated by Bayards

Fig 5.93 Westdork Bridge during twilight in Amsterdam

Fig 5.94 Westdork Bridge reveals that it is a 16m leaf bascule

Yanchep Bridge, Australia: Designer and Fabricator, Peter Maier Leichtbau GmbH, 2009

In the western Australian city of Wanneroo, the all aluminium Yanchep pedestrian bridge has been installed to protect the biodiversity of the beach dunes in an area of rapid urbanisation north of Perth. This bridge is 143m long and 2.5m wide, the aluminium is finished with silver anodising. It was fabricated by Peter Maier Leichtbau in Singen, Germany and installed by Landmark Products of Deception Bay, Queensland, Australia. Aluminium was primarily selected on the basis it would be maintenance free even in a costal environment and that the total cost of ownership would prove beneficial to the owner, the local authority, as is confirmed by the Canadian research cited on pages 438–439. However, the height of the bridge above the dunes has proved controversial with the residents of Wanneroo. In 2012, the State of Western Australia Administrative Tribunal ruled the City should lower the boardwalk from 5.5m at its highest point to 2.1m above the natural ground level. This work to lower and realign this bridge was carried out by R.W.E Robinson and Sons during 2014.[7] Yanchep Bridge is now a long term environmental and community asset on the coastline of Western Australia.

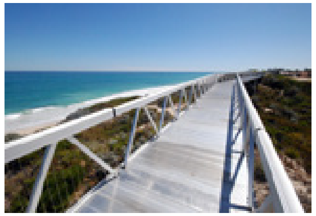


Fig 5.95 Aluminium deck of Yanchep Bridge, designed and fabricated by Peter Maier Leichtbau

Fig 5.96 All aluminium Yanchep Bridge, designed and fabricated by Peter Maier Leichtbau

Equestrian Park Bridge, Blainville, Québec: Designer and Fabricator, MAADI Group, 2012

This bridge was designed for use by pedestrians, horses and riders. It is an 18m single span all aluminium bridge with a clear width of 3m and a self-weight of almost 7 tonnes or 380 kg/m. It was fully prefabricated in Boucherville, Québec, by MAADI Group. It is an open truss with a gently curved profile fabricated from MIG welded square hollow section (SHS) aluminium extrusions in two sizes, 125mm and 150mm. This mill finished single span aluminium bridge rests on simple concrete abutments. It has an Ipe hardwood deck and kick plates with aluminium guardrails. The hardwood Ipe is often described as Brazilian Walnut.

Fig 5.97 Equestrian Park Bridge, an aluminium bridge with a hardwood deck, designed and fabricated by MAADI Group

Fig 5.98 Equestrian Park Bridge, Blainville, Québec

Oil Rig Pedestrian Bridge: Designer and Fabricator, MAADI Group, 2014

This all aluminium pedestrian bridge was designed and fabricated by MAADI Group. It spans 46.3m between two platforms and is a walk through box truss with a clear width of 1.2m. It has an aluminium grip span® deck, aluminium kick plates and guardrails. The self-weight of the bridge is only 13.7tonnes or 296 kg/m. The bridge is fabricated from welded 150mm and 200mm SHS aluminium extrusions, using a combination 5083-H321 and 6061-T6 alloys, all left mill finish. It will require very little maintenance, even in an exposed maritime location. Both MIG and TIG welding was used to fabricate this bridge. It was fully prefabricated in Boucherville, Québec, shipped to site in five 12.2m (40') shipping containers and installed as a single span element. MAADI Group produce a diversity of aluminium pedestrian bridges, typically based on welded fabrication. However, it has also developed weld free prefabricated aluminium bridges.

Fig 5.100 [right] 46.3m Oil Rig Pedestrian Bridge being craned into position, published with permission of the oil extraction company

Fig 5.99 46.3m Oil Rig Pedestrian Bridge linking two offshore platforms, published with permission of the oil extraction company

Deployable Military Bridge, Canada: Designer and Fabricator, MAADI Group, 2016

This prototype of a rapidly deployable military bridge for the Canadian armed forces has been designed and fabricated by MAADI Group.[8] Designed for pedestrian and light vehicles to over come obstacles in the battlefield, such as rivers and ravines. This bridge has an overall length of 18.3m to be able to span a maximum 16m, with a clear width of 1.5m. Eight to ten people can deploy the bridge in 80 minutes. The quick fit prefabricated assembly of aluminium components is locked off with stainless steel bolts, with reusable stainless steel split pins on stainless steel wire tethers. This military bridge is a development of MAADI Group's patented weld free civic pedestrian bridge range Make-A-Bridge®. It has a capability of being crossed by 127 soldiers if their weight is well distributed. The vertical frequency of this bridge is 5.8Hz, significantly greater than 3Hz required by AASHTO LRFD Code for the Design of Pedestrian Bridges (US 2009). The guidance to this code issued by Association of State Highway and Transport officials refers to the problems on the Millennium Bridge in London and states that the lateral frequency needs to be above 1.3Hz.[9] The bridge can also carry small vehicles, such as snowmobiles and quad bikes up to 500kg.[10]

Fig 5.101 A prototype of a rapidly deployable military bridge with a maximum span of 16m

The bridge is built up from modular aluminium components and the key detail of the trusses are cast aluminium tripods. The trusses are preassembled into four sections and then bolted together. The aluminium deck panels pivots on one tubular cross beam and clips onto the next one, the deck panels also interlock to help secure the complete bridge deck. Once the bridge has been assembled, typically it is launched into position from one bank. As soon as it is correctly located, each end of the bridge is jacked up and bearings are fixed in place. With training, all this can be achieved in 80 minutes, less time than a feature film. The bridge is operational and the obstacle has been overcome. The military version of MAADI Group Make-A-Bridge® is an exemplar of Design for Assembly (DfA) and Design for Disassembly (DfD) as discussed in *Aluminium Recyclability and Recycling*.[11] It is also an

Fig 5.102 Rapidly deployable military bridge on test by the Canadian Army

Fig 5.103 Inside a 6.1m container all the components of the prototype bridge

excellent example of the versatility of aluminium extrusions and casting, providing flexibility in design and realisation Alexandre de la Chevrotière, CEO of MAADI Group, considers that 'this product would not be possible without capability of aluminium extrusions'.[12]

The aluminium extrusions of the prototype rapidly deployable military bridge were fabricated from 6005A-T6 and 6061-T6 alloys, with the nodes cast in AA357-T6 alloy. The stainless steel bolts are coated Xylan® 1424 a fluroployemer that contains PTFE, providing corrosion protection and friction resistance. The bridge is polyester powder coated in Canadian Army Dark Oliver Green. The complete bridge only weighs 1970 kg or 69.9 kg/m^2, a direct equivalent to the average weight of a Canadian citizen per m^2, and at least half the dead weight of an equivalent steel bridge.[13]

Fig 5.105 Military personel using a rapidly deployable military bridge

Fig 5.104 A rapidly deployable bridge can carry small vehicles, such as snowmobiles and quad bikes up to 500kg

While this book is being produced, the 5e Combat Engineer Regiment of the Canadian Army is testing the prototype for sixth months including airlifting the bridge into remote locations by helicopter. This testing started on 18 January 2016. Prior to this, the prototype bridge was load and vibration tested by the Engineering Faculty of the University of Waterloo. This prototype is part of a research project led by MAADI Group, *Make-A-Bridge®*, funded by Centre québécois de recherche et de développement de l'aluminium (CQRDA), Qubec Aluminium Research Center, with the *Programme d'Innovation Construire au Canada* (PICC), *the Build in Canada Innovation Program* (BCIP) and *Programme d'aide à la recherche industrielle* (PARI), *Industrial Research Assistance Program* (IRAP).[14]

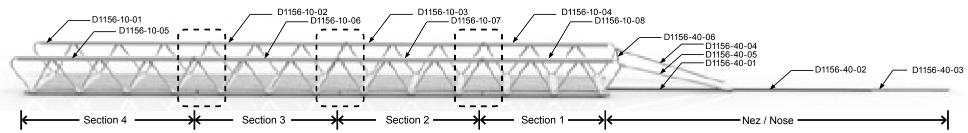


Fig 5.106 Elevation of the Deployable Military Bridge indicating sectional compnents

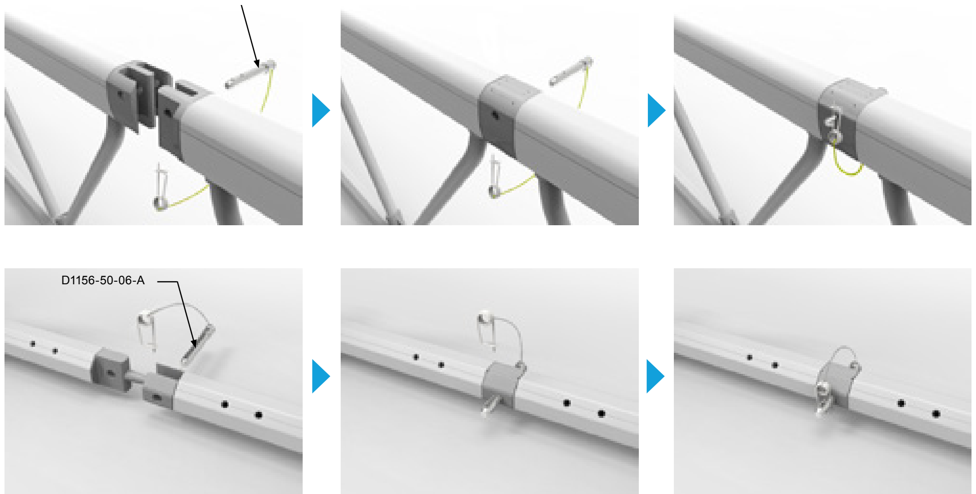
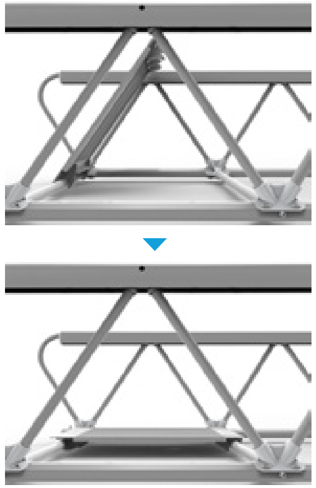


Fig 5.107 Section assembly of the Deployable Military Bridge



MAADI Group's Deployable Military Bridge is a development of its kit of parts approach to weld free civic footbridges, as demonstrated by its patented Make-A-Bridge® range. A silver anodised pedestrian footbridge from this range will be installed in Calgary, Alberta, Canada, during the spring of 2016.[15]

Fig 5.108 Decking assembly of the Deployable Military Bridge

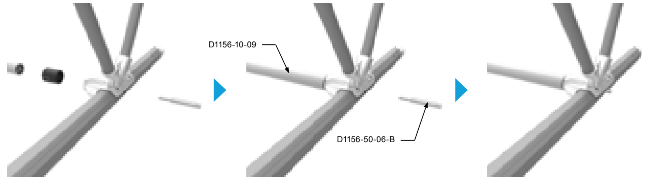


Fig 5.109 Truss assembly of the Deployable Military Bridge

Fig 5.110 A silver anodised Make-A-Bridge™ pedestrian footbridge at MAADI Groups factory awaiting installation in Calgary, Alberta

Tottnäs Bridge, Stockholms Län, Sweden, Sapa Bridge Deck System: Inventor Lars Svensson, 1989

In 1987, Sapa in Sweden developed a system of aluminium extrusions to form structural road bridge decks, targeted primarily at replacing failed wooden or concrete decks on existing bridges. To date it has completed almost 80 projects in Sweden and Norway. [16] The system was invented by Lars Svensson of Sapa. The system comes in two depths, 50mm extrusions to replace wooden decks and 100mm extrusions to replace concrete decks. The 50mm deep extrusions are 250mm wide and the 100mm deep extrusions are 300mm wide. In both cases the extrusions run transversely across the bridge supported by edge beams. Many extrusions are required to form a complete bridge deck. Although Sapa's factory in Finspäng is equipped with a friction stir welding machine capable of welding panels of extrusions up 14.5m long by 3m wide, at the date of publication, this resource is awaiting a bridge application.

A good example of the deployment of the 100mm deep Sapa aluminium bridge deck system is the Tottnäs Bridge. This multi-span bridge had its deck replaced in 1989, without the need to replace the foundations, the four piers or the abutments. This bridge, which is 55 km south of Stockholm, was inspected in 2014 by a group of specialists from AluQuebec and Aluminum Association of Canada (AAC) who found it to be robust and without any evidence of corrosion.[17]

The US Federal Highway Administration in its 2014 National Bridge Inventory identified that over 600,000 bridges in the USA are structurally deficient and thus there is an urgent need for bridge and bridge deck replacement.[18]

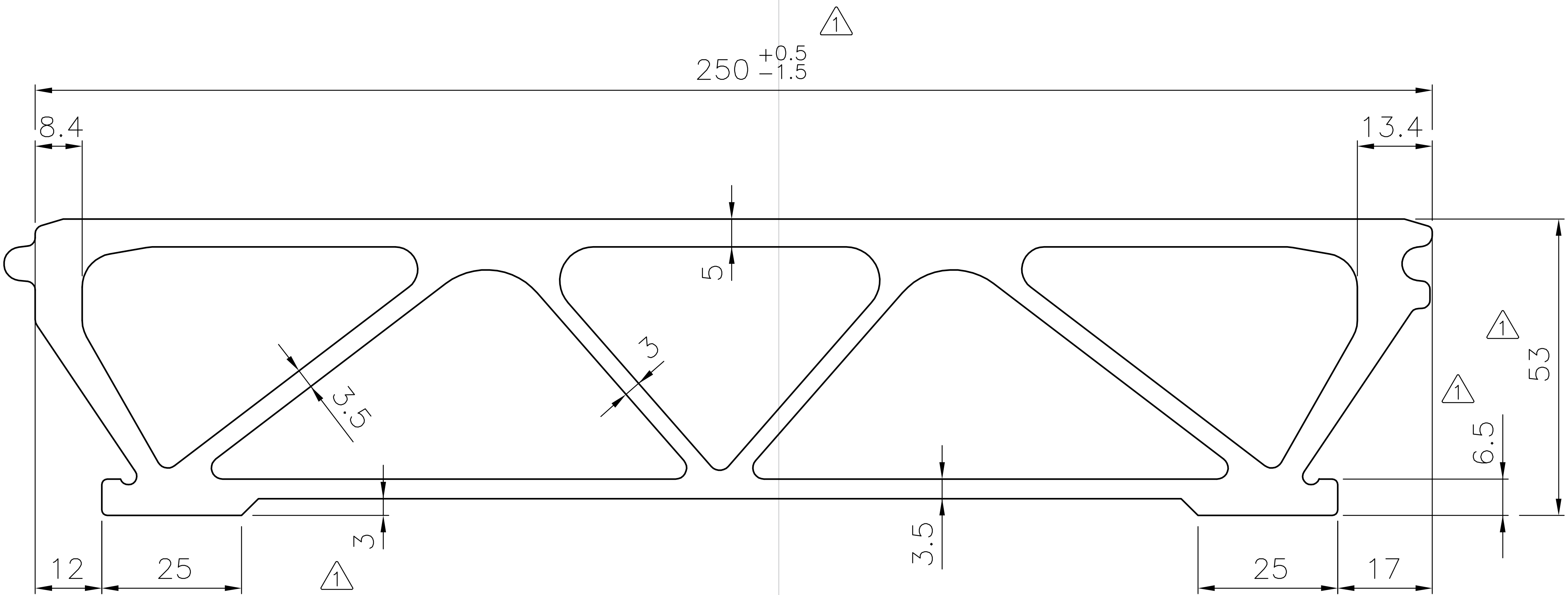


Fig 5.111 Sapa extruded aluminium bridge deck system: 50mm deep with extrusion 50mm × 250mm, 1:1, note all dimensions shown in mm

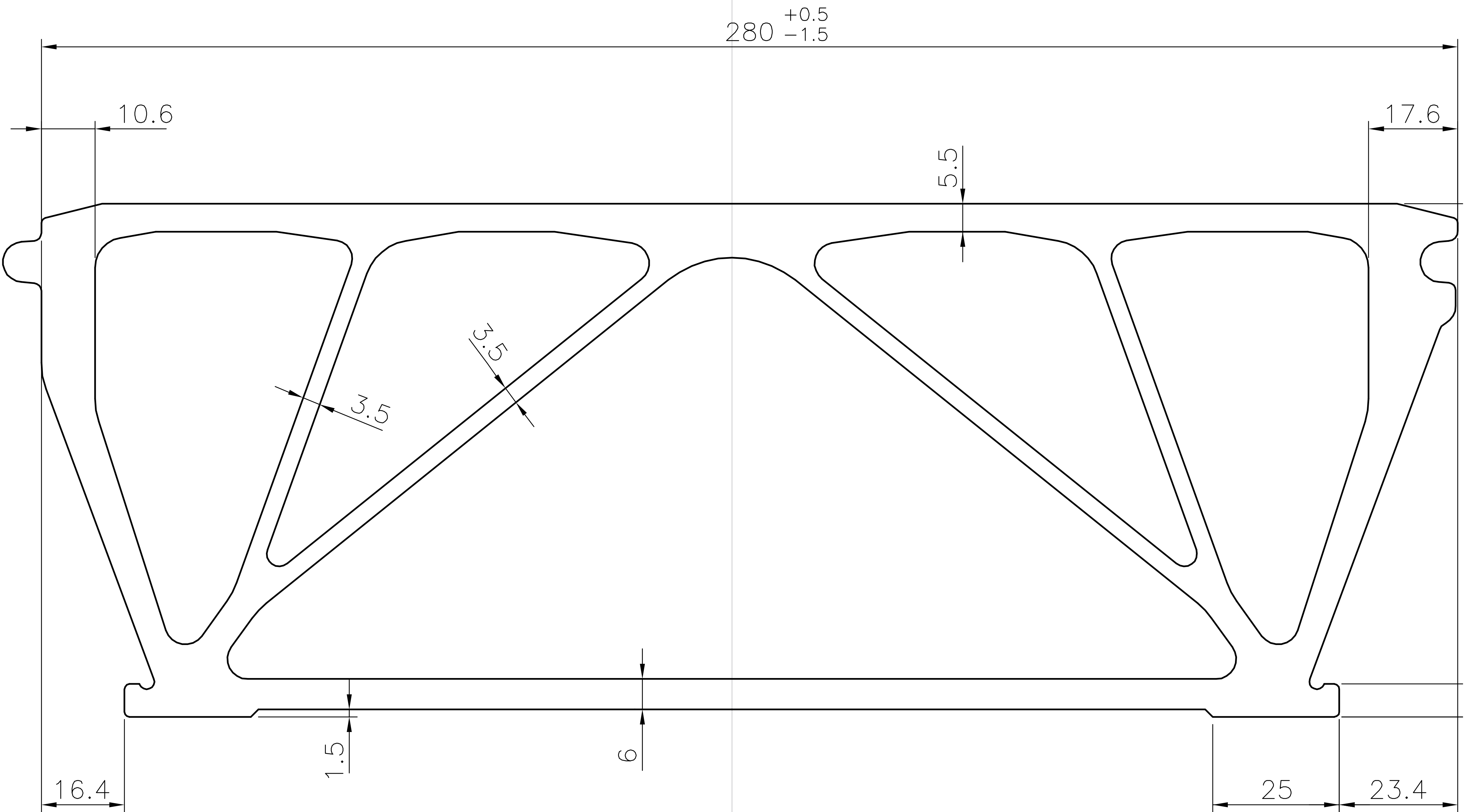


Fig 5.112 Sapa extruded aluminium bridge deck system: 100mm deep with extrusion 100mm × 250mm, 1:1, note all dimensions shown in mm

Forsmo Bridge, Vefsn, Norway: Design Team, Nordland County Roads Office and Hydro Aluminium Structures, 1995

Norway's first aluminium road bridge opened in Vefsn in September 1995. It was designed by Nordland County Roads Office and Hydro Aluminium Structures. It is 38.5m long and 7.4m wide, with two spans a little over 19m each, and a structural depth of 1.5m. It replaced a bridge from 1933 that was only 3.8m wide, which was proving very costly to maintain and needed extensive repairs when inspected in 1994. Thus the impetus to design a low maintenance aluminium structure. The bridge superstructure is formed from two aluminium box beams with inclined webs and transverse cross bracing at 3m centres. The box beams are stiffened with longitudinal web stiffeners that were welded to the outside of the beams for aesthetic reasons, breaking up the profile of the bridge structure. The deck is formed of aluminium extrusions, which are 250mm wide and 123.5mm high and in 8m lengths. The wearing surface is 50mm of asphalt on an epoxy/sand layer on the top surface of the deck extrusions. The deck and welded joints were extensively tested by the University of Trondheim (NTNU).

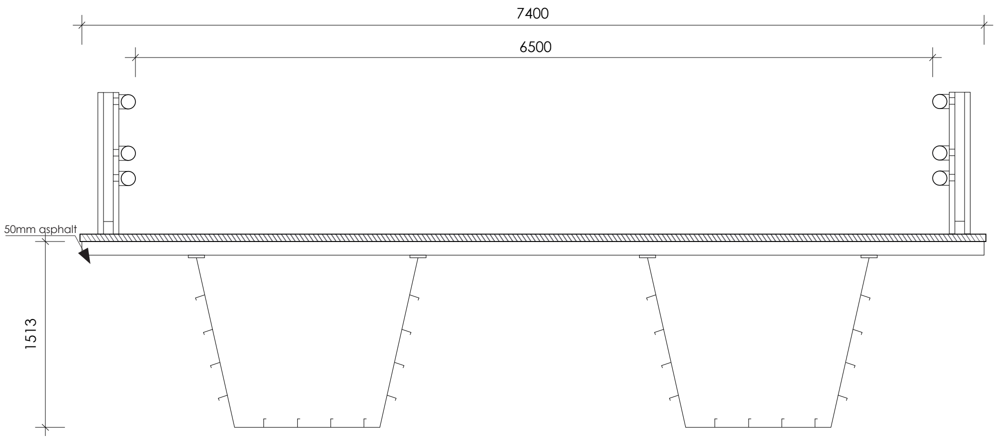


Fig 5.113 Typical cross section of Forsmo Bridge, it is constructed from aluminium except the asphalt road topping

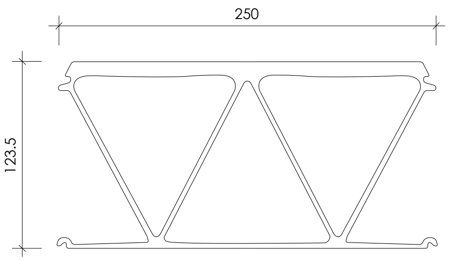


Fig 5.114 Section through an extruded aluminium section (scale 1:5) used to form the deck of extruded aluminium bridge deck system: typical bridge deck part long section

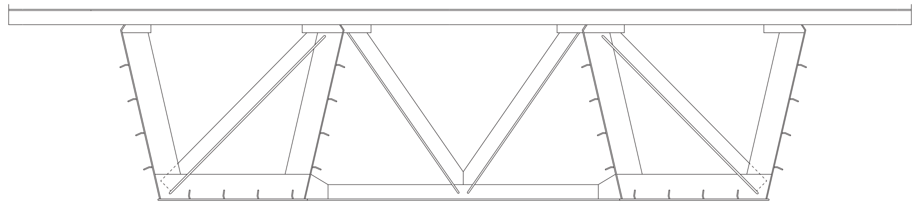


Fig 5.115 Cross section of Forsmo Bridge showing the cross bracing, which is at 3m centres, and detailed photograph of Forsmo Bridge

The welding of this aluminium bridge was undertaken by Lievre Sveis, specialists in welding aluminium, based on its experience of welding the living accommodation of offshore platforms in the North Sea Oil Field. The complete bridge that weighed 28.5 tonnes was transported by barge from Leirvik Sveis' workshop in Stord, and then transferred to lorry for the last 5km. It was then craned into position on new bases. The balustrade that also acts as a crash barrier was also fabricated from aluminium. To protect against bimetallic corrosion only stainless steel fixings were used for bolted details. The old bridge was demolished and the existing foundations extended, the lightness of the bridge meant that the existing foundations could be reused and the new bridge was installed within one week. Markey, Østlid and Solass observe 'the foundations did not have to be reinforced, only enlarged. This was due to the considerable reduction in dead weight obtained by using an aluminium superstructure. Neglecting the weight of the asphalt, the structure only weighs 100 kg/m^2.'[19]

On completion Forsmo Bridge was subjected to extensive monitoring and testing to evaluate the performance of the aluminium superstructure. This was initiated by the design team, which included Nordland County Roads Office, and carried out by three PhD students from NTNU under the guidance of the Norwegian Road Research Laboratory. The test regime included the measurement of temperature and strain, a static load test and a dynamic load test. The bridge was open to traffic during the 15-day testing period. Markey, Østlid and Solass report: 'To evaluate the importance of on the structure, strains and temperatures were measured over a prolonged period. Seven temperature gauges were installed at midspan: six on the aluminium structure and one for the exterior air temperature. Strain gauges were installed in nine locations on the structure (six rosette and three normal gauges). Five of the gauges [were] located in the same cross section as the temperature gauges.'[20] No correlation between temperature and strain was found.

The static load test involved the placement of two 20tonne lorries in the arrangements shown in Figure 5.116. The unloaded bridge was regularly measured during this five-hour test to check the zero measurement. For each of the six loading patterns, three sets of measurements were taken and in total 30 measurements were recorded.[21] 'There was a good coloration between the measured and calculated deflection and the maximum midspan deflection under lading patters A and B, was 10.2mm', observed Markey, Østlid and Solass.[22]

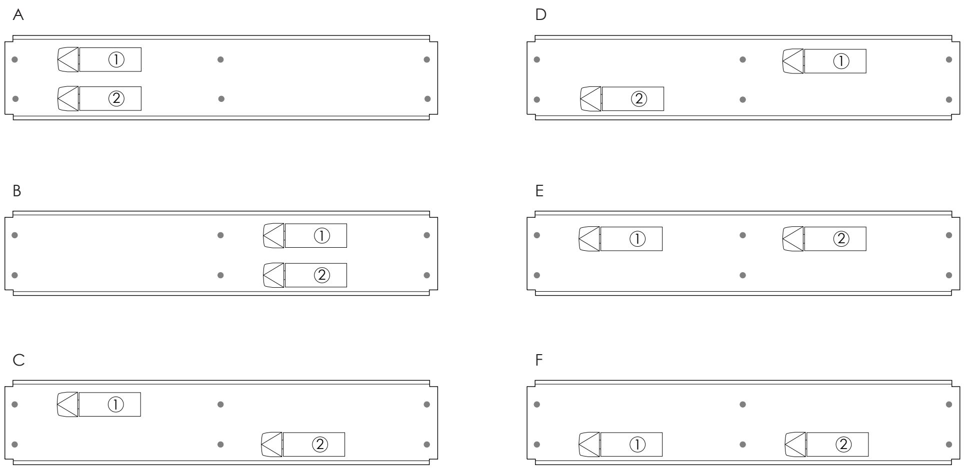


Fig 5.116 Arrangement of lorries for the load testing of Forsmo Bridge, each Lorry weighed 20 tonnes and each arrangement was repeated three times

Fig 5.117 Two lorries load testing Forsmo Bridge

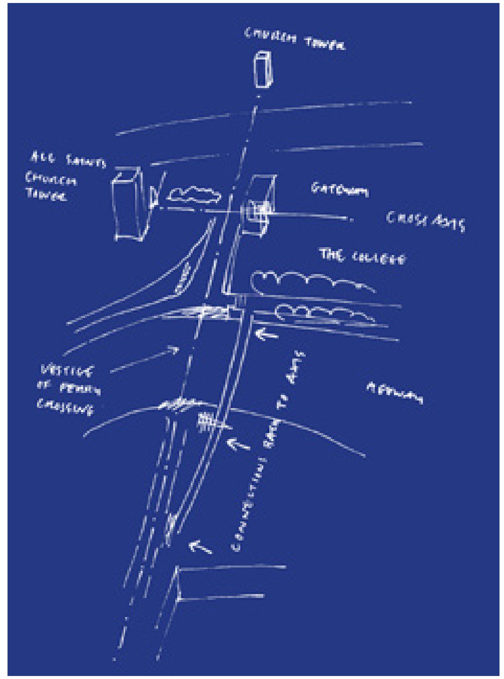
Forsmo Bridge is an exemplar of investment in design innovation, securing this with full scale post completion testing. The aluminium superstructure cost £250,000 and the total project including testing, widening approach roads and abutments, cost about £600,000 in 1995.[23] The bridge has now provided 20 years of service combined with low maintenance – see the research on the total cost of ownership of bridges on page 436–437.

Lockmeadow Footbridge, Maidstone, England: Architect WilkinsonEyre, 1999

The River Medway was the main trade artery and the reason for the growth of the county town of Maidstone in Kent, until the arrival of the railways in the mid-nineteenth century. Lockmeadow footbridge, designed by architect WilkinsonEyre with structural engineers Flint & Neill, has a structural aluminium deck that is only 300mm thick and spans 80m supported by cable stays from two masts at mid span that spring from the cutwater. The context of the bridge is Grade One listed buildings that date back to the fourteenth century. All located on the town side, the west bank of the River Medway, as shown in Figure 5.119, WilkinsonEyre's analysis of the context of the bridge to the north is the Archbishop's Palace and All Saints Church and to the south the Gateway, which is the remains of All Saints College. Lockmeadow footbridge gently curves on plan as it spans over to the opposite bank of the Medway. It spans beyond the spring points of its masts to allow the water meadow of the East bank to flood. The commission to design this footbridge was won in a competition by WilkinsonEyre in 1997 – the competition brief 'called for a design that was sensitive both to the location and to the modern idiom.' [24]

Fig 5.118 Lockmeadow Footbridge designed by WilkinsonEyre, viewed from the Medway

Fig 5.119 WilkinsonEyre's sketch analysing the context in Maidstone of Lockmeadow Footbridge



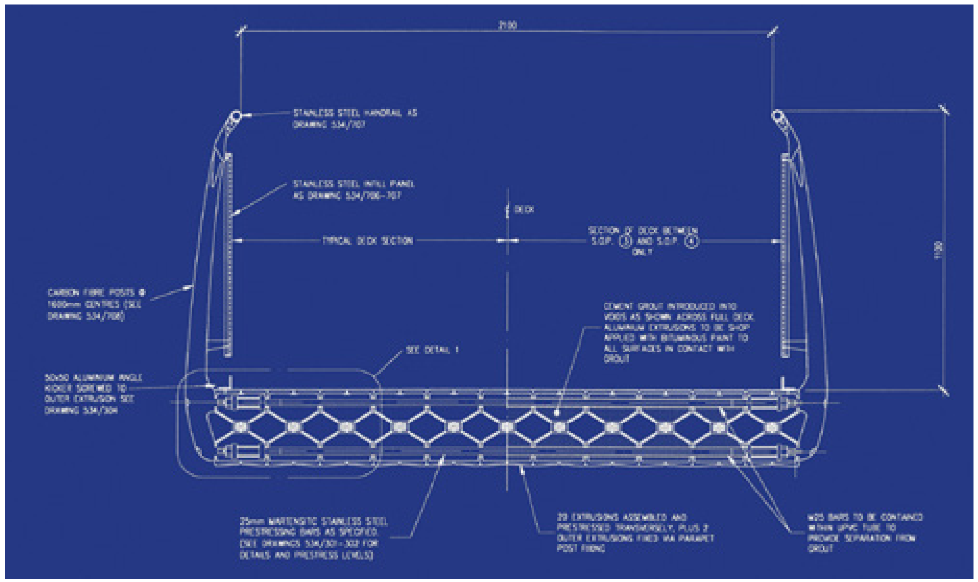


Fig 5.120 Cross section of Lockmeadow Footbridge showing the structural extruded aluminium deck

Jim Eyre reports that:

> Lockmeadow uses a bespoke aluminium extrusion in a very specific way. Flint + Neill, the structural engineers, and WilkinsonEyre took out a patent on the system. One advantage, other than the ability to 'laminate up' a curved plan, was that from the 300mm depth we could get quite long spans, some 16m provided there was continuity over the supports. This was because the whole deck acted compositely.[25]

WilkinsonEyre's design for this footbridge combines an economy of means that also minimises the visual intrusion of the bridge as it spans the Medway. The structural aluminium deck is made up of pairs of an open E-like extrusion. This extrusion is handable and balanced, meaning that only one die and one type of section is required to form both sides of the ridged cells, which are linked by solid aluminium central rectangular extrusions and aluminium flats in the top of the deck only. This assembly forms stiff structural cells by post tensioning in the transverse direction, from the penultimate extrusion of each side of the deck. The final extrusions form a clean edge to the aluminium deck as they are only fixed via the balustrade post fixings. Slipping the linear extrusion during assembly enables the gently curved plan to be achieved. The top surface of the E-like extrusions is ribbed to form a safe walking and cycling surface.

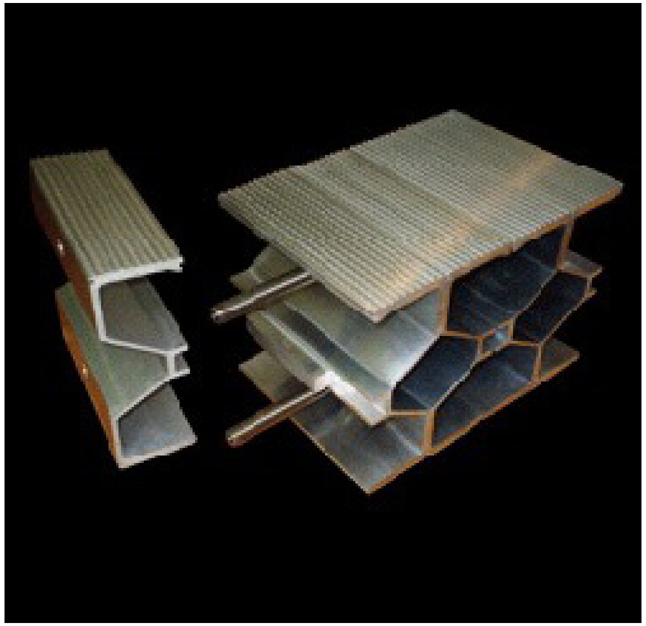


Fig 5.121 The structural aluminium deck of Lockmeadow Bridge is assembled from E-like aluminium extrusions

Fig 5.122 Stiff structural cells are formed by post tensioning – achieving a slender deck

Fig 5.123 The curved plan is achieved by slipping and gently curving the aluminium extrusion in a process of gradual lamination

The masts are formed from tapering open steel fabrications, using steel rods spaced by a pair of steel flats, topped with castings that pick up the cable stays. The original balustrade posts were fabricated from resin filled carbon fibre, however, due to problems of thermal cycling, they have been replaced by shapely steel flats, coated in micaceous iron oxide.[26] Lockmeadow Footbridge opened in 1999 and it achieves the architect's ambitions: 'Deck, parapet and cables combine to form a lightweight composition that stands in contrast to the mass of the medieval buildings'.[27]

Fig 5.124 Walking towards Maidstone town centre across Lockmeadow Footbridge

Fig 5.125 The Arhbishop's Palace viewed below Lockmeadow Footbridge

On inspection in 2015, this bridge was busy with people accessing the town centre of Maidstone and the architect's achievement was clear for all to appreciate as they crossed the River Medway.

Fig 5.126 Seven centuries of construction: All Saints Church viewed through Lockmeadow Footbridge

Millennium Bridge, London, England: Architect Foster + Partners with Engineer Arup, 2000 and 2002

In 1996 the London Borough of Southwark organised an open competition with the RIBA for the design of a new pedestrian footbridge linking Bankside Power Station, the future Tate Modern, and St Paul's Cathedral. The first new crossing of the Thames in central London for over 25 years, it formed part of the celebrations in the UK of the arrival of the twenty-first century. This competition was won by Foster + Partners in collaboration with Arup and sculptor Sir Anthony Caro, with a low slung suspension bridge entitled the Blade of Light. Foster + Partners placed the bridge on the axis of Peter's Hill, to focus the pedestrians on a clear view of St Paul's when crossing from the south bank of the River Thames.

The bridge is formed of three spans; 108m, 144m and 81m (travelling from the south to the north bank) with two concrete piers in the river. It has a total length of 325m and the aluminium deck is 4m wide, supported by a suspended steel superstructure. Two groups of four 120mm diameter suspension cables span bank to bank, with the cables below balustrade level to maximise views from the bridge deck. The design is mimetic of the Delaware Aqueduct; designed by John A. Roebling and completed in 1850, which is described as the oldest suspension bridge in North America. It comprises four spans with lengths ranging from 40 to 43m. It was constructed from masonry piers, cast iron saddles and iron suspension cables.

Fig 5.127 Millennium Bridge, London, Foster + Partners with engineers Arup, a new crossing of the River Thames in central London

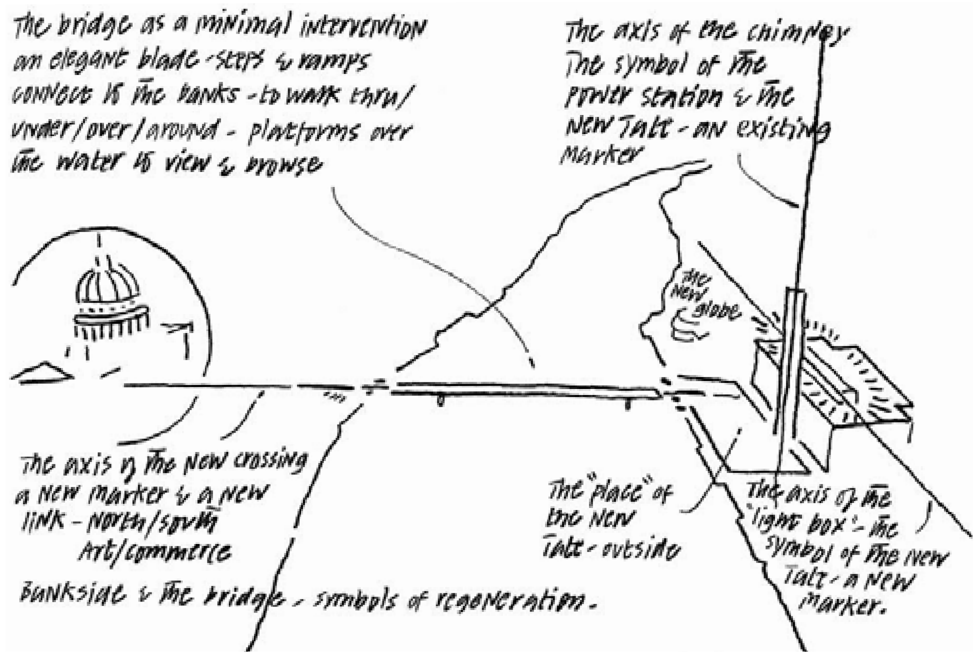


Fig 5.128 Foster + Partners' sketch of the Millennium Bridge, London, setting out the key design issues

Fig 5.129 Millennium Bridge, London, photographed 2015

'The bridge *gathers* to itself in *its own* way earth and sky, divinities and mortals.' Martin Heidegger

Fig 5.130 The low slung suspension cables of the Millennium Bridge, London, create an effortless openness to view and be viewed

On the Millennium Bridge, fabricated steel box sections form the transverse arms at 8m centres linking the suspension cable groups. Two steel circular hollow sections (CHS) form the edge of deck, spanning onto the transverse arms. The bridge deck comprises aluminium box sections that span between the CHS edge steels. Arup opted to detail the deck as an articulated structure, with sliding joints at regular intervals (16m centres) along the length of the bridge – deciding that a continuous deck would contribute little extra stiffness to the structure.[28] The articulated deck offered two clear advantages: it could be prefabricated in 16m 'chunks' and the overall depth kept to a minimum.[29] The walking surface is ribbed extruded aluminium deck sections, which run transversely with matching aluminium edge sections, as shown in Foster + Partners' section, Figure 5.131, and the detailed photograph Figure 5.133.

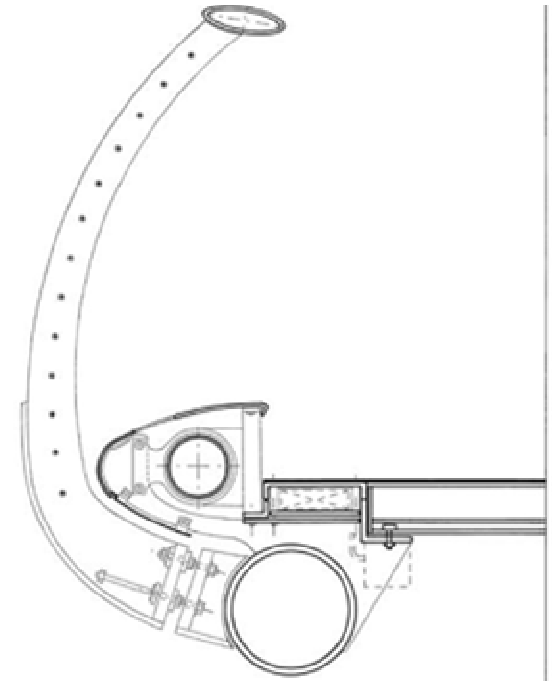


Fig 5.131 Foster + Partners' detail drawing of the Millennium Bridge, London balustated and floating aluminium bridge deck

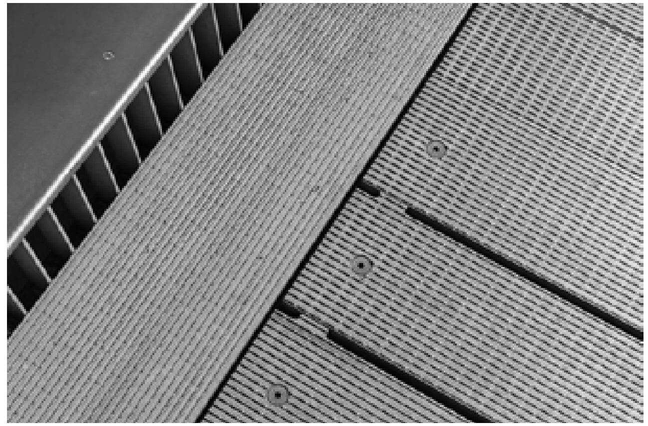


Fig 5.133 Detail of the ribbed aluminium deck of the Millennium Bridge, photographed 2015

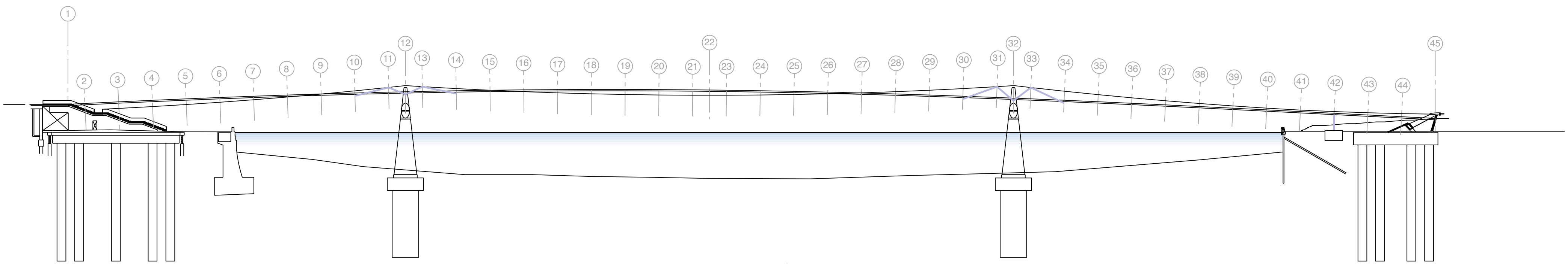


Fig 5.132 Foster + Partners' elevation of the Millennium Bridge, London looking downstream

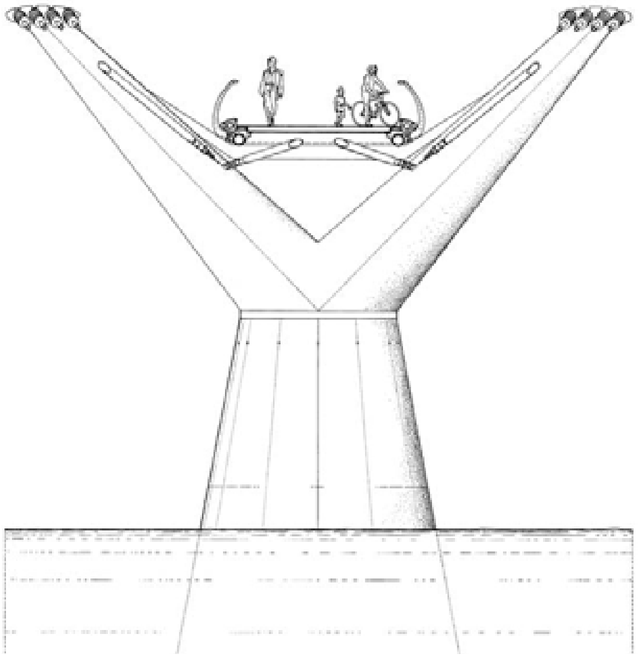


Fig 5.134 Foster + Partners' drawing of the Millennium Bridge, London adjacent to an in-situ concrete pier

Fig 5.135 Walking north Sir Christopher Wren's St Pauls Cathedral (1675–1710) is the focus of the axis of the Millennium Bridge

Main contractors Monberg & Thorsen with Sir Robert MacAlpine started the construction of the Millennium Bridge on 28 April 1998 and it opened to the public on Saturday 10 June 2000. The bridge cost £18.2m. In its first weekend, the Millennium Bridge had attracted many visitors. 'Soon after the crowd streamed on to London's Millennium Bridge on the day it opened, the bridge started to sway from side to side: many pedestrians fell spontaneously into step with the bridge's vibrations, inadvertently amplifying them.'[30] This strong lateral response of the Millennium Bridge was caused by resonance, however no excessive vertical vibrations were observed. Readers can see this phenomenon for themselves online, evidence that Arup used in resolving this problem.[31]

Fig 5.136 Since 2002 an estimated 45 million people have crossed the Thames via the Millennium Bridge

Arup's design process was thorough, including wind tunnel testing of 1:16 sectional models at RWDI's laboratories in Canada. Arup had designed the bridge for pedestrian excitation based on BS 5400 and had even tested the bridge with a few people in May 2000 – this appeared to confirm the design calculations. However, it was 'estimated that about '80,000 to 100,000 people crossed the bridge during the first day. Analysis of video footage showed a maximum of 2000 people on the deck at any one time, resulting in a maximum density of between 1.3 and 1.5 people per square metre', reported Arup in 2001.[32] On Sunday 11 June the numbers of people crossing the bridge was restricted. On Monday 12 June 2000 it was decided to close the bridge.

Should the large forces generated by synchronised lateral footfall have been anticipated by Arup? Joseph Paxton in 1851 had tested the timber floor units of the Crystal Palace by having soldiers march over them. The Albert Bridge, London, completed in 1873, has a sign stating that marching soldiers must break step whilst crossing. Similarly in circa 1860 a notice was erected on the twin-deck railway suspension bridge spanning the Niagara River at Niagara Falls, designed by J. Roebling and completed in 1854, which states:

> A fine of $50 to $100 will be imposed for marching over this bridge in rank and file or to music, or keeping regular step. Bodies of men or troops must be kept out of step when passing over this bridge. No musical band will be allowed to play while crossing except when seated in wagons or carriages.[33]

Following the closure of the Millennium Bridge, Arup set two primary research questions to inform the design of the retrofit:

1. To compare the dynamic properties of the built structure to the analytical predictions;
   and
2. To quantify the forces that were being exerted on the structure by the pedestrians.[34]

Arup would then use the findings of this research to design a retrofit installation that would reduce the movements of the bridge to acceptable levels.

Fig 5.137 The Millennium Bridge with Blackfriars Bridge in the background (prior to the construction of a railway station on the Blackfriars Bridge, 2008-2012)

Fig 5.138 The Millennium Bridge, London, architect Foster + Partners with engineers Arup

Fig 5.139 The Millennium Bridge at twilight

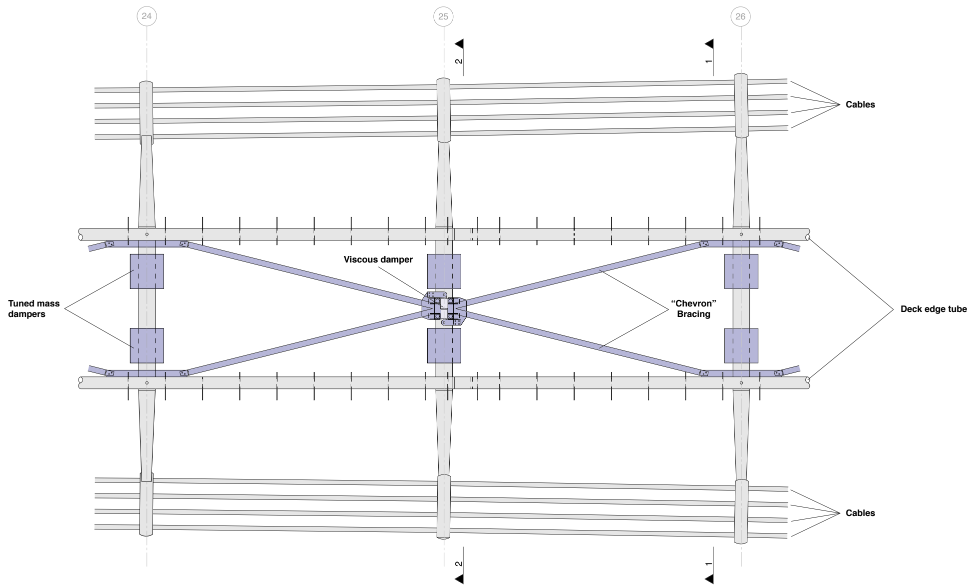
Arup's research revealed three previous examples of bridges demonstrating resonant excitation by crowds of people, movement was noted on: the north section of Auckland Harbour Road Bridge, New Zealand, completed in 1965, during a demonstration of about 4000 people in 1975; Groves Suspension Bridge, Chester, completed in 1923, during Jubilee celebrations in 1977; and Link Bridge from National Exhibition Centre to Railway Station, Birmingham, completed in 1978, during major events including rock concerts. Not one of these bridges had been the subject of significant research and analysis. However, one of Arup's conclusions from this programme of research was 'the same phenomenon could occur on any bridge with a lateral frequency below about 1.3Hz.' Furthermore Arup concluded:

> The movement of the Millennium Bridge was clearly caused by a substantial lateral loading effect, which had not been anticipated during design. The loading effect has been found to be due to the synchronisation of lateral footfall forces within a large crowd on the bridge. This arises because it is more comfortable for pedestrians to walk in synchronisation with the natural swaying of the bridge, even if the degree of swaying is initially very small. The pedestrians find this makes their interaction with the movement of the bridge more predictable and helps them maintain their lateral balance. This instinctive behaviour ensures that footfall forces are applied at the resonant frequency of the bridge, and with a phase such as to increase the motion of the bridge. As the amplitude of the motion increases, the lateral force imparted by individuals increases, as does the degree of correlation between individuals.[35]

A possible explanation for this phenomenon proposed by Arup is 'that pedestrians are less stable laterally than vertically, which leads to them being more sensitive to lateral vibration and to modify their walking patterns when they experience such vibration.'[36] Therefore, laboratory tests with pedestrians walking on moving platforms were carried out at Imperial College, London, and the University of Southampton. Arup set the design criterion as 2 people per m^2, based on the maximum density of people witnessed on the bridge on the day it opened - 1.5 people per m^2. Even though walking slows down in a crowd with a density of over 1.7 people per m^2.

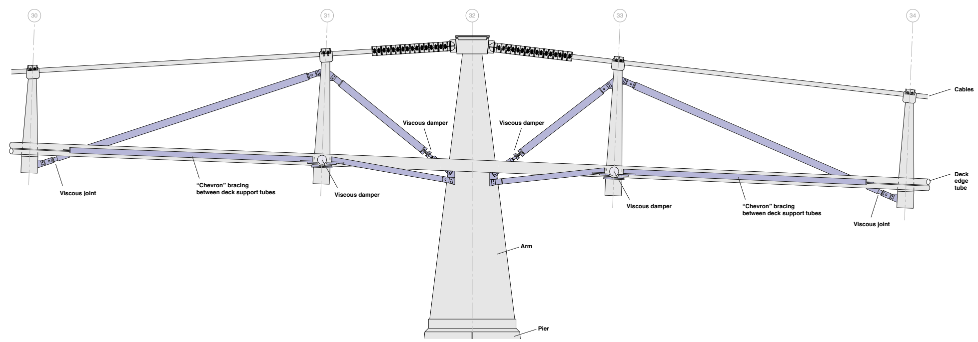
Having ruled out restricting the numbers of people using the bridge, two design options for the retrofit were identified: stiffening the structure to move all of its lateral frequencies out of range or increasing the damping of the bridge to reduce the resonant response.[37] Stiffening the structure was ruled out, as the remedial work would be extensive and expensive. Furthermore it would have had a dramatic impact on the visual characteristics of the bridge. Therefore a scheme was developed primarily using fluid-viscose dampers. The final scheme specified low friction fluid-viscose dampers, originally developed for NASA space satellites, and subject to a 35-year guarantee with no maintenance except painting periodically with the structural steelwork.[38] 37 fluid-viscose dampers were installed, primarily under the bridge deck, at 16m centres on every other transverse arm. In addition, where 'possible the viscous dampers are connected to fixed points such as the piers and the ground.'

Fig 5.140 Arup's plan of a typical 16m of the deck of the Millennium Bridge showing the viscous dampers and tuned mass dampers



Although no excessive vertical movements had been noted it was decided to include tuned mass dampers in the vertical plane, as this risk had been identified by some researchers. A total of 26 vertical tuned mass dampers, manufactured by Gerb Schwingungsisolierungen in Germany, were installed, and are guaranteed for 10 years to first maintenance, subject to biannual inspections. Cleveland Bridge UK won the tender for the remedial contract, work commenced at the beginning of May 2001 and completed by the end of that year. The remedial works cost £5million, increasing the capital cost of the Millennium Bridge to £23.2million.

Fig 5.142 Viscous dampers in plane between cables and deck at bridge piers



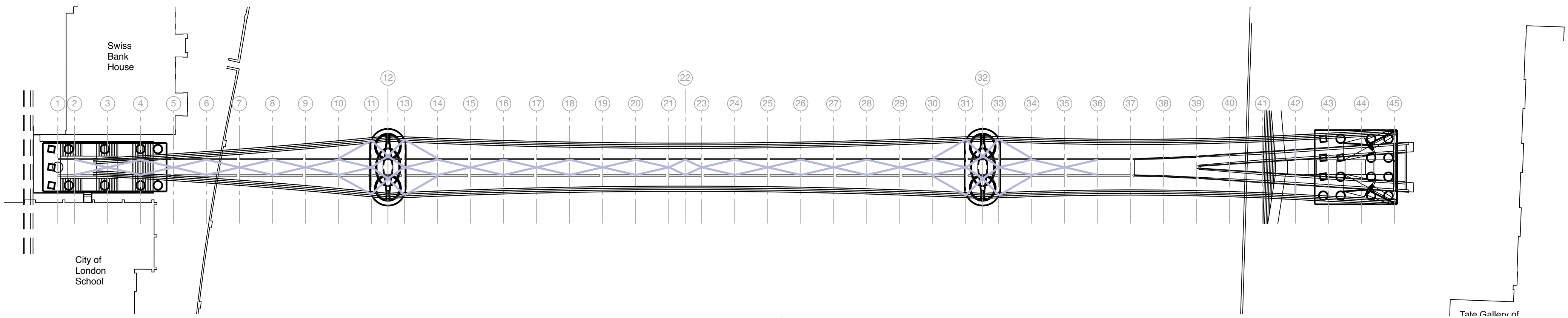


Fig 5.141 Arup's general arrangement drawing of the Millennium Bridge showing the viscous dampers

Fig 5.143 Crossing the Millennium Bridge, London, on a sunny autumn day in 2015

The author and design team of Ballingdon Bridge, described below, took part in the final mass pedestrian test on 30 January 2002, along with many other people working at or collaborating with Arup. This would have been like an enjoyable party on the bridge with many friends from the worlds of architecture and engineering, except that we had to march in step like soldiers. Many architects, engineers and even critics consider Arup and Foster + Partners response to the problems on the Millennium Bridge so professional it has enhanced their reputations.[39] The British Design Manual for Roads and Bridges (BD 37/01) now includes a clause on synchronous lateral excitation. The Millennium Bridge reopened on 22 February 2002 and it has been estimated that over 3.5 million people cross this bridge every year.

Fig 5.144 The Millennium Bridge a 'blade of light' reflecting from the aluminium deck, photographed 2015

Millennium Bridge, Gateshead, England: Architect WilkinsonEyre, 2001

This is a tale of two cities – Gateshead and Newcastle. In 1997 an international competition was organised by Gateshead Metropolitan Council for a new pedestrian and cycle bridge crossing the river Tyne linking Gateshead and Newcastle, yet allowing river traffic to pass. The bridge was seen as a key act of regeneration for this urban conurbation with a great industrial tradition. The competition was won by architect WilkinsonEyre working with engineer Gifford & Partners. The design of this inventive moving bridge was led by Jim Eyre. The arched form is reminiscent of Hulme Bridge in Manchester, completed in 1997. This was WilkinsonEyre's second completed bridge, the first was also won in competition. Both bridges take inspiration from Eero Saarinen's Gateway Arch in St Louis, USA (1964). The inventive design decision in the opening strategy for the Gateshead Millennium Bridge was to curve the bridge deck and the structural arch, thus when it is rotated into the open position, it remains a balanced assembly. In a movement that resembles the opening of an eyelid. Creating a simple and elegant opening bridge. It is an excellent example of the clarity of thought that an architect can bring to the design of bridges, expressed primarily by drawing. Jim Eyre reflected before the completion of the Gateshead Millennium Bridge: 'In bridge design, it is generally movement that is the most problematic. When a man-made structure mimics a life form by actually moving the result is often cumbersome. To capture the gracefulness of natural movement in an opening bridge is a serious challenge and I look forward to seeing the operation of the 'opening eye' at Gateshead where the whole structure is mobilised.'[40] The bridge clear spans the Tyne in 105m, yet the curved deck is 126m long to accommodate the changes in level and to match the geometry of the slender structural arch that rises 50m above the river, echoing the Tyne Bridge upstream.

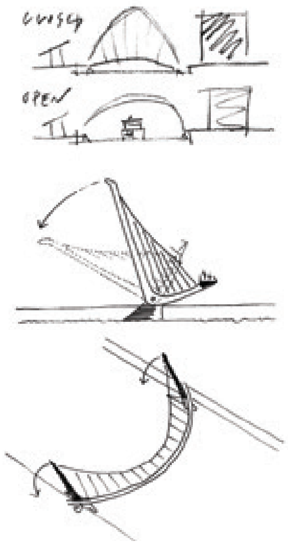


Fig 5.145 [above] Jim Eyre's sketches of the opening strategy of the Millennium Bridge, Gateshead

Fig 5.146 The Millennium Bridge, Gateshead, designed by WilkinsonEyre with Gifford & Partners

Fig 5.147 The Millennium Bridge, Gateshead, rotated into the open position

Jim Eyre's key thinking on this project was recorded in *Exploring Boundaries:* 'The site owes its presence to the array of historic bridges in close proximity.'[41] 'The short but memorable journey up the Tyne from Wallsend shipyards past the old cranes, seemingly defies the decline of an era of industrial might, evoking the new, forward-looking and optimistic spirit of the city.'[42] 'At each end the bridge rests on trunnion bearings, which are expressed to reveal the ability of the structure to rotate, powered by hydraulic rams'.[43] 'The practical constraints of the physical brief (no structure on the quays, the need to avoid an overly step gradient, were the bridge to cross in a straight line and a requirement for a limited 25m clearance) combined with the unwritten aspiration of the cultural civic brief… lead to such a specific design' for this bridge.[44]

Fig 5.148 The trunnion bearings at each end of the bridge are expressed to reveal its ability to open

The doubly curved steel structures of the parabolic arch and bridge deck were realised by Watson, using advances in welding and fabrication technologies developed in the late twentieth century. Both are stiffened by the curved geometry and are linked by 40mm stainless steel rods. It was fabricated in Bolton into transportable section and welded together at the famous Swan Hunter shipyard at Wallsend and transported upstream by barge. The total weight of the superstructure is 850 tonnes. The Gateshead Millennium Bridge opened on 17 September 2001.

Fig 5.149 The first boats sailing under the Millennium Bridge, Gateshead, on 17 September 2001

The curved deck of the bridge has two distinct zones, the inner deck is an epoxy coated walking surface on the structural steel deck beam for pedestrians, with an outer lightweight cantilevered aluminium deck which forms part of Sustrans [UK] national cycle network. This extruded aluminium grillage, which has a ribbed anti-slip surface was manufactured by Norton Aluminium Alloy Co. Peter Davey observes: 'The outer deck is for cyclists and has an aluminium grille surface intended to be safe and freely drained in all weathers; in some lights, when the bridge is rotated the aluminium becomes a shining semi-transparent arc leaping between the two cities.'[45]

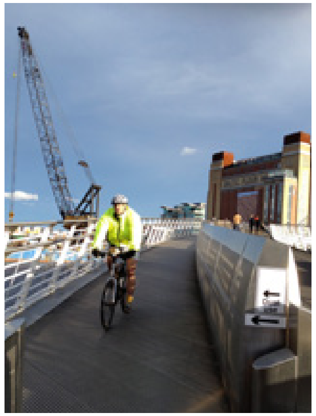


Fig 5.150 A cyclist crossing the Millennium Bridge, Gateshead in 2012

Jim Eyre observed that aluminium was used for the outer deck of the Gateshead Millennium Bridge for four reasons:

1. to reduce the weight on the extended cantilever;
2. the primary structure wasn't needed on the outer layer;
3. to enjoy the transparency; and
4. we liked the idea of creating a separate feel to the cycleway.[46]

The context of the Gateshead Millennium Bridge is formed by the quaysides and three earlier bridges across the Tyne. The High Level Bridge is double decked rail and road bridge, designed by Robert Stephenson and it was completed in 1849. William Armstrong's Swing Bridge is hydraulically operated and pivots about its centre point on plan to allow boats to pass. It opened to road traffic in 1876. The nearest is the Tyne Bridge, a through arch road bridge, designed by Mott, Hay and Anderson, was completed in 1928. The design and construction of the Gateshead Millennium Bridge is a dramatic design response to this context, it is both inventive and an act of cultural continuity.

Fig 5.151 The ribbed aluminium bridge deck of the cycle lane of the Millennium Bridge, Gateshead

Fig 5.152 The seperate zones for cyclists and pedestrians of the Millennium Bridge, Gateshead, evident but unusable as the bridge opens

Fig 5.153 The dramatically lit arc of the Millennium Bridge, Gateshead, bridge deck. WilkinsonEyre collaborated with Speirs + Major on the design of the lighting

The design excellence of the Gateshead Millennium Bridge was recognised in 2002, when WilkinsonEyre won the Stirling Prize from the Royal Institute of British Architects for the best work of architecture in the UK.

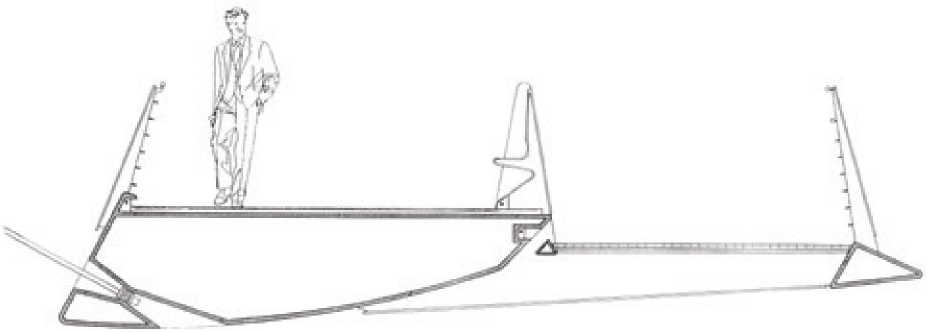


Fig 5.154 Wilkinson Eyre's drawing of a typical cross section of the deck of The Millennium Bridge, Gateshead

Fig 5.155 Detailed junction of the ribbed aluminium decking of the cycle zone and the edge plate

Fig 5.156 The Millennium Bridge, Gateshead, on opening day, 17 September 2001

Fig 5.157 The ceremonial opening of the Millennium Bridge on its first day. Opening of the bridge has become a spectacle for visitors and people of Gateshead and Newcastle

Fig 5.158 The Millennium Bridge, Gateshead, is set in the context of the earlier and famous bridges that cross the Tyne

Nichols Bridgeway, Chicago, Illinois, USA: Architect Renzo Piano Building Workshop, 2009

This bridge was designed by Renzo Piano Building Workshop in collaboration with executive architects Interactive Design Inc. of Chicago. Nichols Bridgeway is 190m long and 4.6m wide. It links Millennium Park with The Modern Wing of The Art Institute of Chicago, which was also designed by Renzo Piano Building Workshop. The steel structure of this bridge was 'chunked' into transportable sections, as shown in Figure 5.160, to facilitate its rapid installation during 2008. The aluminium deck was prefabricated in the Netherlands by Bayards in sections 4.6m wide and approximately 2.5m long, to enable the deck components to fit into a shipping container. The deck incorporates electrical heating to enable the bridge to remain safe in the harsh Chicago winters. In collaboration with the architects, Bayards also developed a durable anti-slip finish for the wearing surface of the aluminium deck.[47]

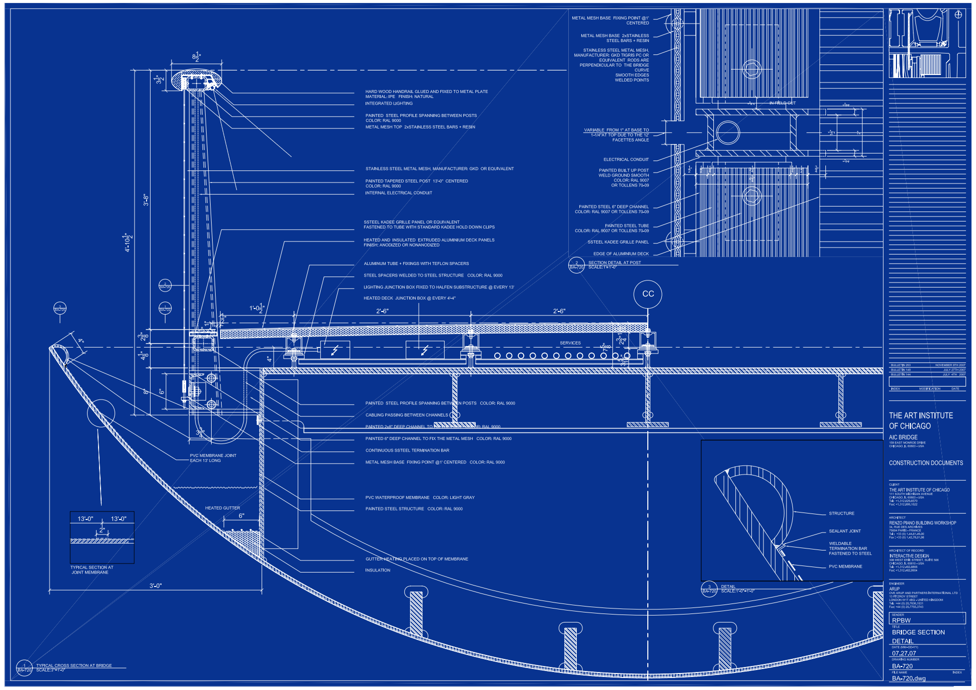


Fig 5.159 Renzo Piano Building Workshop's typical cross section drawing of Nichols Bridgeway

Fig 5.160 Transporting the large prefabricated sections of Nichols Bridgeway

Fig 5.161 The assembly of Nichols Bridgeway from large prefabricated elements

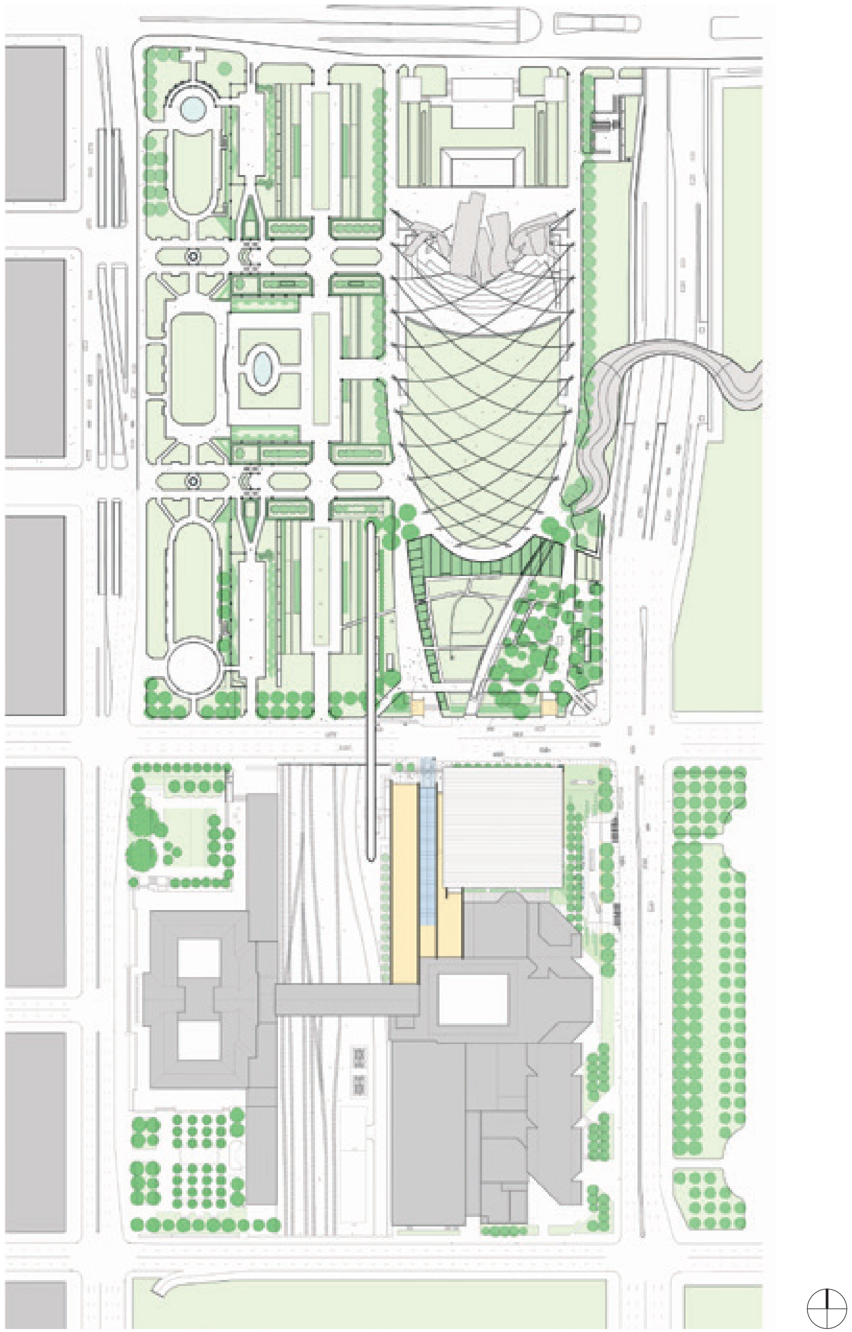


Fig 5.162 Site plan of Nichols Bridgeway showing how it links The Art Institute of Chicago with Millennium Park

Fig 5.163 Crossing Nichols Bridgeway at nighttime

Fig 5.164 Nichols Bridgeway integrates with The Modern Wing of The Art Institute of Chicago, which was also designed by Renzo Piano Building Workshop

Fig 5.165 Nichols Bridgeway crossing East Monroe Street to provide pedestrian access to The Modern Wing of The Art Institute of Chicago

Ballingdon Bridge, Suffolk, England: Architect Michael Stacey Architects, 2003

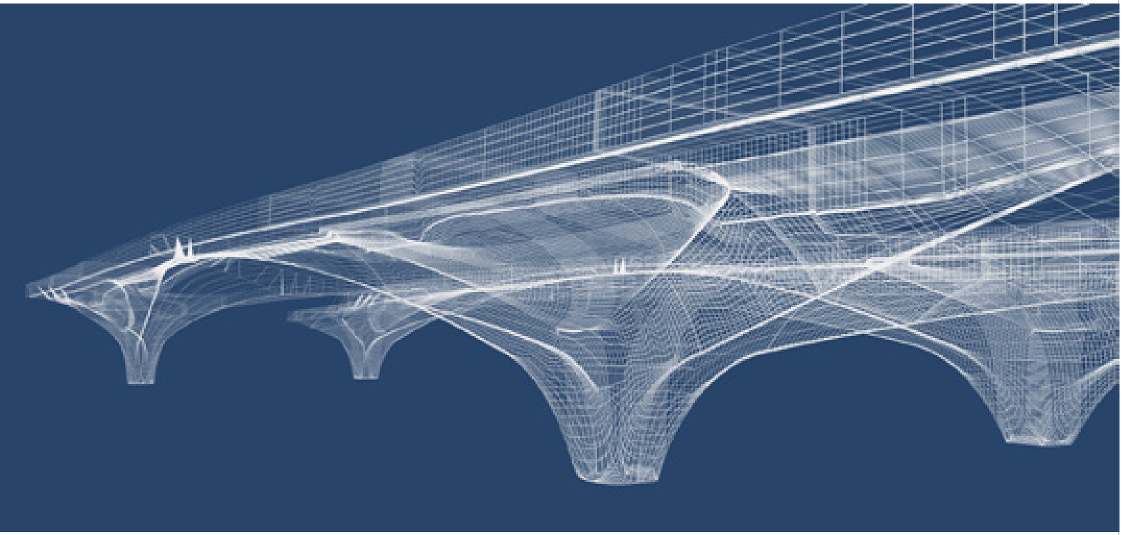
The setting of Ballingdon Bridge as it crosses the river Stour is a wonderful combination of a water meadow that surrounds Sudbury and the listed buildings that form the town and the village of Ballingdon, Figure 5.166. Completed in 2003, the new trunk road bridge is the first to be built in Britain with an architect leading the design team. The previous bridge, built in 1911, could not sustain 42 tonne articulated lorries (the maximum and norm in the EU) and its closure would have resulted in a 35-mile diversion from the A131. The RIBA competition for a new Ballingdon Bridge was the result of public protest against the design proposed by Suffolk Highway Engineers, the local people thought that their proposal was both ugly and disruptive – it would have taken 3 years to rebuild the bridge with the conventional engineering methods proposed.[48] Michael Stacey Architects won the limited competition to design Ballingdon Bridge in collaboration with structural engineers Arup and specialist lighting designers Evolution.[49] Thus Arup won its next bridge commission in the same week that the Millennium Bridge, which it has designed with Foster + Partners, closed on 12 June 2000, due excessive vibration resulting simply from pedestrian footfall, as discussed above.

Fig 5.166 Ballingdon Bridge viewed from the water meadows of Sudbury

The materials of the new bridge were carefully selected to respond to the local context and fulfil the performance requirements of a road bridge, including durability, which combine engineering, urban design and architecture. The material palette was discussed in detail with the planning officer, Ruth Stoakes. The primary structure of the bridge is formed from precast concrete, and the mix was selected to match the limestone of All Saints, a twelfth century Norman Church. This palette of materials also includes aluminium, stainless steel, granite and English oak. Even the aggregate within the tarmac of the roadway was agreed with the planning officer. The design of the new bridge is visually calm, respecting the historic context. The view over the bridge remains focused on All Saints Church and, in the other direction, on the seventeenth century timber-framed cottages of Ballingdon, as shown in the design sketches, Figures 5.167 and 5.168.

Fig 5.167 Michael Stacey Architects' sketch of the view down Ballingdon Street over Ballingdon Bridge with the view focused on twelfth century All Saints Church

Fig 5.168 Michael Stacey Architects' sketch of the view of Ballingdon Bridge from Sudbury, the architectural diversity resides in the seventh and nineteenth century terraced houses



However, the structure has a dynamically changing three-dimensional soffit. Designed using a research-based evolutionary technique, the bridge has an ever-changing and site-specific geometry, see Figure 5.169.[50] The new Ballingdon Bridge was delivered in partnership with Costain, overcoming a fascinating set of logistical constraints by collaboration, design and deep commitment to sustainability. The recycling of the existing bridge is set out in Towards Sustainable Cities Report 2: *Aluminium: Recycling and Recyclability*.[51]

By careful study of the construction and phasing of the bridge, and extensive prefabrication, disruption to Sudbury and Ballingdon was minimised, and two-way traffic on the Bridge was maximised during reconstruction. Ballingdon Bridge is an example of fast construction yet 'slow architecture', analogous to the slow food of the slow food movement. The bridge was rebuilt in 18 months and has a design life of 120 years. It is now possible to combine robust, rapidly deployable contemporary technology and the immutable qualities of architecture. Architecture made of fine ingredients designed to be purposeful, durable, savoured and enjoyed. Michael Stacey Architects sought to uphold the rich architectural traditions and construction quality of Suffolk. Sudbury was the home of Thomas Gainsborough and the landscape of the river Stour is set in John Constable country (Figure 5.173). The quality of design and the quality of thought embodied in this project represent key components for the creation of a built environment that will help to sustain human ecology.

Fig 5.169 Michael Stacey Architects' three dimensional digital model of Ballingdon Bridge – a common resource for the complete design team

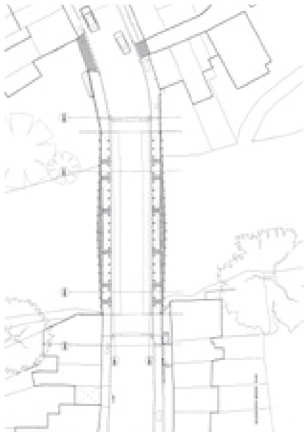


Fig 5.170 Plan of Ballingdon Bridge, the pavement formed of precast concrete and oak is enlarged at the centre of the bridge to place the priority of the design on the pedestrians who may stop to feed the ducks or simply enjoy the view

Fig 5.171 The balustrade of Ballingdon Bridge was designed to be visually open yet it is capable of stopping a 42 tonne track form falling into the river Stour

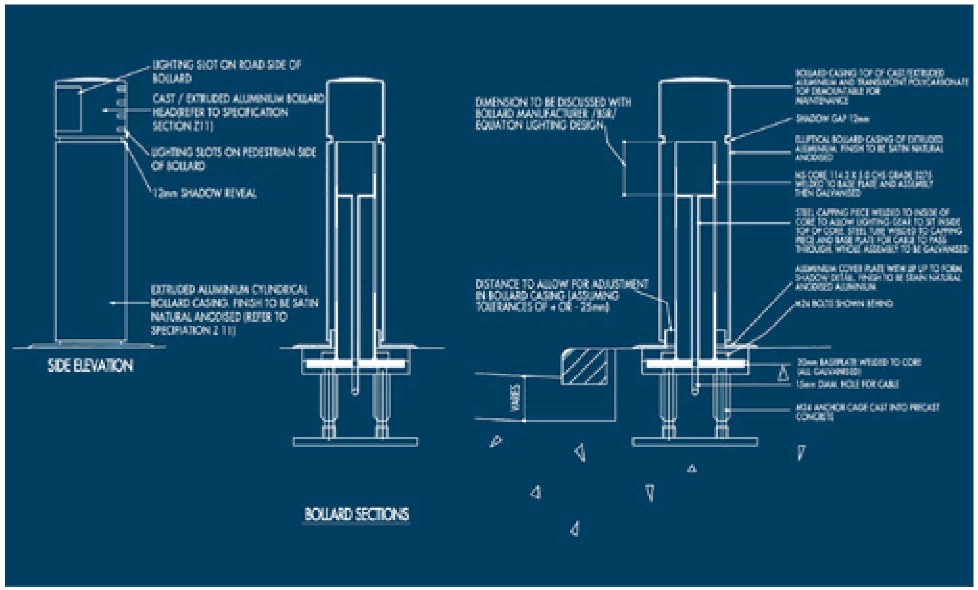


Fig 5.172 Michael Stacey Architects' working drawing of the waterject cut anodised aluminium bollards

Fig 5.173 Ballingdon Bridge set in SSCI of the river Stour. In a flood the bridge will hold back the flood-waters saving houses down stream

The balustrade was designed to be visually open so that the views of the landscape are as uninterrupted as possible. It is capable of arresting a 42tonne truck yet appears to be an elegant pedestrian handrail, its strength being achieved by a combination of stainless steel castings, stainless steel wires and two bespoke aluminium extrusions, as shown in Figures 5.174 and 5.175. The tensile strength of the aluminium is vital in stopping a truck from falling into the river. The illuminated bollards were designed for the project to avoid the need to use lampposts on the bridge. Cased in water jet cut anodised aluminium, the core of the bollards is a galvanised circular hollow steel section, which will stop cars from crossing the pavement, but shear off if hit by larger vehicles. The bollards were prototyped at one-to-one using white watercolour paper and discussed with the client on the earlier bridge. The top rail of the balustrade is a combination of extruded aluminium and English oak. This point of human contact is key to its design; to a pedestrian, the vehicular safety role of the balustrade is intended to be an unseen quality. The enlarged oak walkways create a generous provision for pedestrians to enjoy the views of the river and meadows. People enjoying the river and the urban spaces of Ballingdon and Sudbury are the priority within the design of this road bridge.

Fig 5.174 The centre of the deck and balustrade of Ballingdon Bridge

Fig 5.175 Visually open balustrade of Ballingdon Bridge

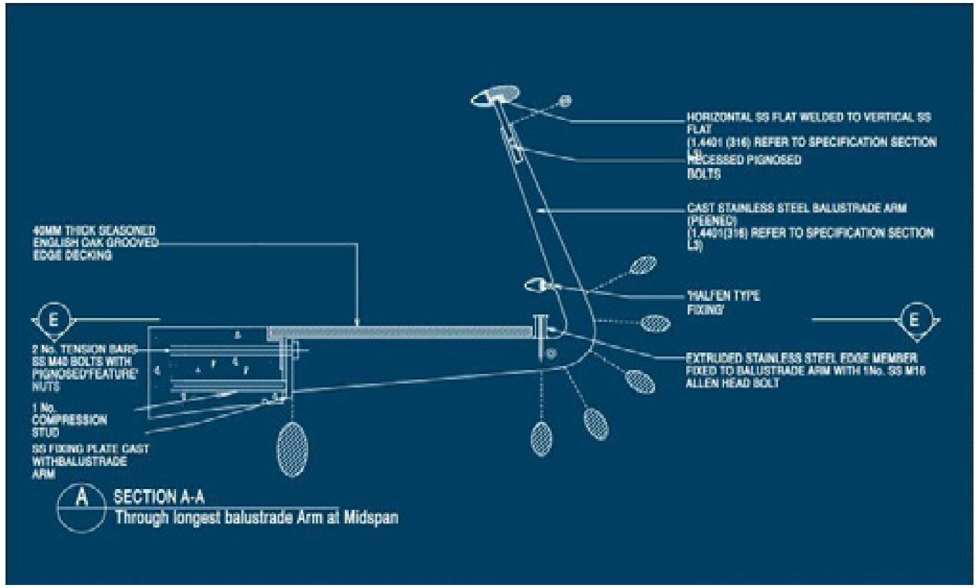


Fig 5.176 Michael Stacey Architects' working drawing of balustrade of Ballingdon Bridge, this safety system is a combination of stainless steel castings, stainless steel wires and two bespoke aluminium extrusions

Fig 5.177 Ballingdon Bridge at night, the illuminated bollards light the pavements and road thus avoiding the need for lampposts. The bridge itself is also lit on the upstream side only

Fig 5.178 Ballingdon Bridge designed by Michael Stacey Architects is an example of ‘fast construction’ yet ‘slow architecture’

Total Cost of Ownership of Bridges

One factor that has limited the uptake of aluminium in bridge construction has been the relatively high cost of aluminium when compared to steel or concrete (noting the variability of world commodity prices). However, as metals are sold by weight, the lightness of a well designed aluminium bridge may not have a higher first cost when compared to steel or concrete options. Increasingly infrastructure owners and design teams are using Life Cycle Assessments (LCA) to evaluate the full environmental impact of materials in a design proposal, as discussed in TSC Report 3: *Aluminium and Life Cycle Thinking*.[52] When evaluating the cost of a proposal, the total cost ownership (TOC) should be considered not just the first capital cost.

The TOC for a civil engineering project, for example a bridge, comprises:

- Acquisition – typically the purchase of land or assets included any cost related to remediation, if the site is brownfield or demolition and or disassembly of an obsolete bridge.
- Design and Construction – cost of the design, manufacture and assembly or construction of a new bridge, including planning and other approvals.
- Maintenance and Operation – maintenance costs are the annual expenses required to maintain the assets safety and functionality over its expected lifespan. Operational costs include, for example, the costs and revenue if the new bridge is to be operated as a toll bridge.
- End-of-Life – costs and revenues associated with the deconstruction, removal, recycling of materials, and site remediation.[53]

Professional fees need to be factored in each stage.

In 2012 Deloitte published *Life Cycle Analysis: Aluminium vs. Steel*, with input from MAADI Group and the Aluminum Association of Canada. This report presents the total cost of ownership [TCO] of pedestrian bridges in steel and aluminium using the methodology set out above, factoring an inflation and discount rate.[54] The full report considers two environments, urban and maritime. The three specifications for the corrosion protection of the mild-steel bridges were considered: two-coat paint system, three-coat paint system and hot dip galvanising. In all cases one aluminium specification was used, mill finish 6000 series and/or 5000 series alloys.[55] A single bridge span of 21.3m (70') with a width of 1.83m (6') was used. The aluminium option weighed 3.1 tonnes and the steel option 5 tonnes, thus the aluminium bridge was 38% lighter. An indicative life of 50 years was used for this comparative study.

Material	Characteristics
Steel – 2 coats	CSA G40.21 grade 350W (ASTM 50W), Standard commercial blast SSPC-SP-6, 2-layers 125µm Hi-Build Epoxy
Steel – 3 coats	CSA G40.21 grade 350W (ASTM 50W), Blast near white SSPC-SP-10, 1-layer 65µm Zinc Rich Epoxy, 1-layer 100µm Hi-Build Epoxy, 1-layer 50µm Polyurethane
Steel – hot-dip galvanized	CSA G40.21 grade 350W (ASTM 50W), Standards CSA G-164 and ASTM-123, 87µm thickness
Aluminum – Natural Finish	Aluminum natural finish, 6xxx and/or 5xxx alloys

Table 5.4 Comparative bridge specifications in the Deloitte TOC study

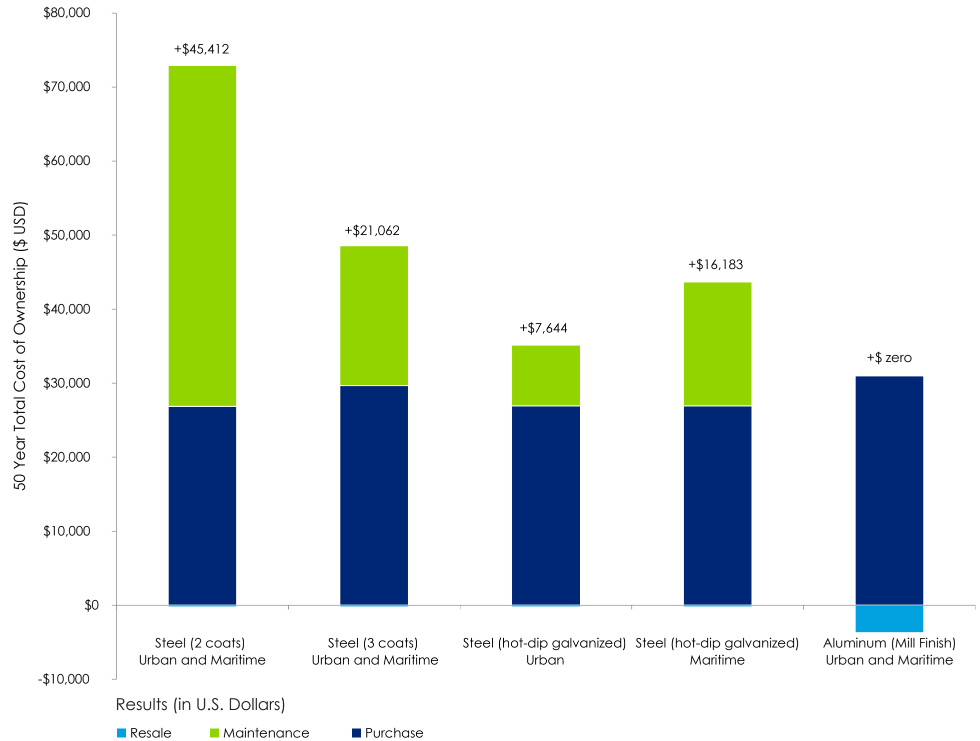


Fig 5.179 Comparison showing present value and total cost of ownership of 21.3m pedestrian bridges in urban and maritime setting over a 50-year timescale, using a 3% discount rate

The outcome of this analysis on the total cost of ownership of comparative pedestrian bridges showed that over a 50-year timescale an aluminium bridge in an urban environment is significantly more economical when compared to the steel options. An aluminium bridge in an urban environment becomes the better economic option after 33 years when compared to a galvanised steel bridge and only 21 years in a marine environment.[56] Thus studying the TOC in this case shows clear benefits in the specification and ownership of an aluminium pedestrian bridge. The recommendation of the TSC Research Team is to study the TOC of your proposed projects.

Staircases of Palazzo dei Congressi di Riccione, Rimini, Italy: Architect Gianni Ronchetti, 2008

The brief for the external stairs to serve the new Palazzo dei Congressi, which is located in the centre of the coastal town Riccione, required a high capacity to speed up the flow of the large number of people accessing the congress halls. Working with the architect Gianni Ronchetti, Bayards designed, fabricated and installed four staircases, which are airy, safe and attractive, serving the visitor to the Palazzo dei Congressi well.

The staircases were fabricated from 6005A T6 alloy, which was chosen instead of the slightly stronger 6082 T6 to ensure a better quality of anodising. The primary extruded aluminium section sizes used to fabricate the staircases are: 400 × 40mm flooring planks, 345 × 50mm step planks, 400 × 100mm lateral stair stringers, 400 × 200mm central stair stringer, 75 × 75mm handrail posts, and 100 × 20mm handrail top rail. During fabrication both MIG and TIG welding techniques were used. The finish is 20μm of silver anodising. The quality of this set of staircases was recognised by the European Aluminium Association awarding the project a European Aluminium Award in 2008.

The use of cast aluminium as the structure of a staircase designed by architect Julian Arendt with engineer Fluid Structures is illustrated in Towards Sustainable Cities Report 2: *Aluminium Recyclability and Recycling*.[57]

Fig 5.180 Palazzo dei Congressi di Riccione, designed by Gianni Ronchetti

Fig 5.181 Four staircases disgorge people from the Palazzo dei Congressi di Riccione

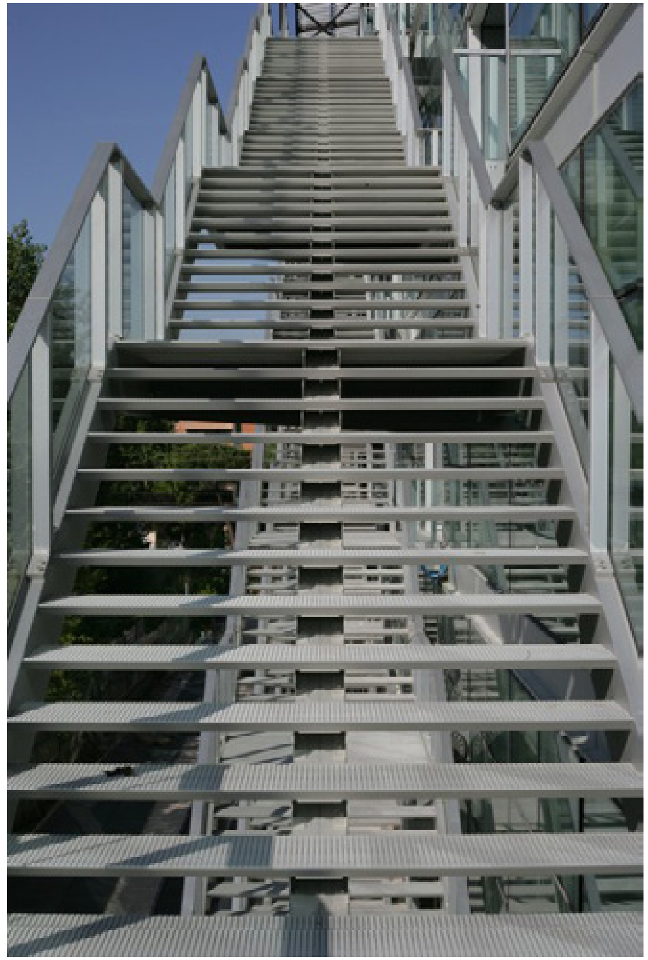


Fig 5.182 One of the aluminium staircases of the Palazzo dei Congressi di Riccione

Aluminium Staircase in Parc de la Rivière-Beauport, Québec, Canada: Designer and Fabricator, MAADI Group, 2015

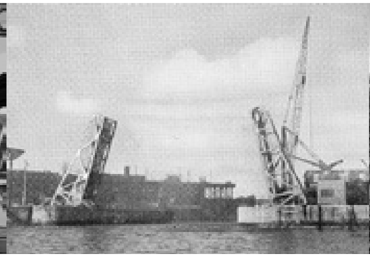
Descending 15m (50′) from the street into the park, this staircase, with its welded aluminium structure and timber deck was designed and fabricated by MAADI Group for the local government, Ville de Québec, who are the custodians of Parc de la Rivière-Beauport. This park is located around the river Beauport, which became a focus for the development of industry in Québec city in the eighteenth century. Traces of this early industry can still be found in the otherwise beautiful urban park. Aluminium was selected for the new staircase primarily for its durability and the minimal maintenance required beyond annual inspections. A combination of alloys were used in the assembly of this staircase 6061-T6, 3003-H14. A range of extruded sections were deployed including 50, 75 and 100mm SHS, 40 × 100 RHS and 40 × 40 L-sections, combined with 3mm plate and expanded mesh for the balustrade. All mill finish aluminium. Connections were predominately MIG welded.

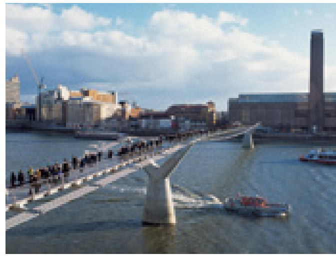
Fig 5.183 Aluminium Staircase descending 15m into Parc de la Rivière-Beauport

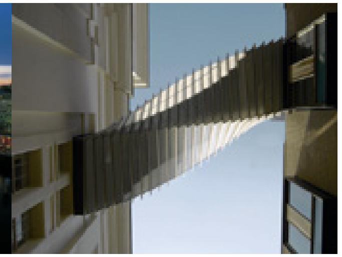
Fig 5.184 Timber treads and landing of the Aluminium Staircase in Parc de la Rivière-Beauport

Fig 5.185 A safe low maintenance route through the trees of Parc de la Rivière-Beauport

Timeline of Aluminium Bridges from the Jazz Age to the Digital Age





1933 — 2000

- **1933** Aluminium decking replaces the timber and steel decks of Smithfield Street Bridge, Pittsburgh, built in 1882
- **1946** First all-aluminium bridge, Grasse River Bridge, Massena, New York, spanning 30.5m
- **1948** World first aluminium bascule bridge: Hendon Dock Bridge, Sunderland is built by Head, Wrightson & Co of Stockton
- **1950** Arvida Bridge aluminium road bridge is still performing well today, spanning 88.4m
- **1953** Aluminium bascule bridge of Victoria Dock, Aberdeen, opened by the Queen Mother
- **1956** First aluminium road bridge in Europe: Schwansbell Bridge, spanning over the Datteln-Hamm Canal near Lünen, Germany, it is still in use today
- **1975** In France, three suspension bridges: Montmerle and Trevoux spanning the Saône river and Groslée on the Rhône river are restored using aluminium structural decks
- **1987** In Sweden, Sapa develop an extruded aluminium bridge deck system, inventor Lars Svensson
- **1989** Sapa aluminium bridge deck system installed on the Tottnäs Bridge, Stockholms Län, Sweden
- **1995** Norway's first aluminium road bridge opens in Vefsn, Norway
- **1996** Reynolds Metals Company install a new aluminium deck on the historic suspension bridge, Corbin Bridge, Pennsylvania, USA
- **1999** Lockmeadow Footbridge, Maidstone, a patented aluminium bridge deck designed and developed by WilkinsonEyre with engineer Flint & Neill
- **2000** Millennium Bridge, London, designed by Foster + Partners with engineer Arup
- **2001** Millennium Bridge, Gateshead, designed by WilkinsonEyre with engineer Gifford & Partners
- **2003** Bridge of Aspiration, London, designed by WilkinsonEyre with engineer Flint & Neill

Fig 5.186 Timeline of Aluminium Bridges form the Jazz Age to the Digital Age

Early Aluminium Bridges

The first use of aluminium in bridge construction is the replacement of deteriorated timber and steel decks of the 1882 Smithfield Street Bridge in Pittsburgh, USA, with aluminium decking in 1933. This is almost 40 years later than the first use of aluminium in architecture.[58] The deck was fabricated from 2014-T6 aluminium alloy and was in use until 1967, when the deck was replaced again with a 6061-T6 aluminium alloy deck. Due to very significant increases in road traffic volume, this deck was decommissioned in 1994, when the bridge was reconfigured to accommodate more lanes of traffic.[59] [60]

The earliest all aluminium bridge was built in Massena, New York State in 1946, the Grasse River Bridge had a 30.5m span fabricated from 2014-T6 alloy. It carried rail traffic serving an Aloca smelter.[61] Until 2008 Massena was also the location for General Motor plant, where aluminium engine components were cast.

The world's first two aluminium opening bascule bridges were built in the UK, serving the docks of Sunderland and Aberdeen. Hendon Dock aluminium bascule bridge, Sunderland, 1948, was built by Head, Wrightson & Co of Stockton who 'had started making mining engineering equipment out of aluminium alloys in the 1930s and they were awarded the contract by the River Wear Commissioners to build this bridge.'[62] This bridge was 37m long and 5.64m wide. This bridge has a curved toped truss girder of U-profile cords and I-profile verticals and diagonals, all connected by galvanised steel rivets. The bridge deck comprises a grid of I-profile cross beams, 900mm deep, with 10mm aluminium plate topped with an asphalt-wearing course. Below the railway tracks are two longitudinal beams both 600mm deep. The girders were fabricated from 6151 alloy and the deck from 2014A aluminium alloy, respectively. Siwosski observes that total weight of this bridge span is 40 per cent of an equivalent steel assembly.[63] This bridge was decommissioned and recycled in 1977.

Fig 5.187 Smithfield Street Bridge, Pittsburgh, completed in 1882 decking replaced with aluminium in 1933

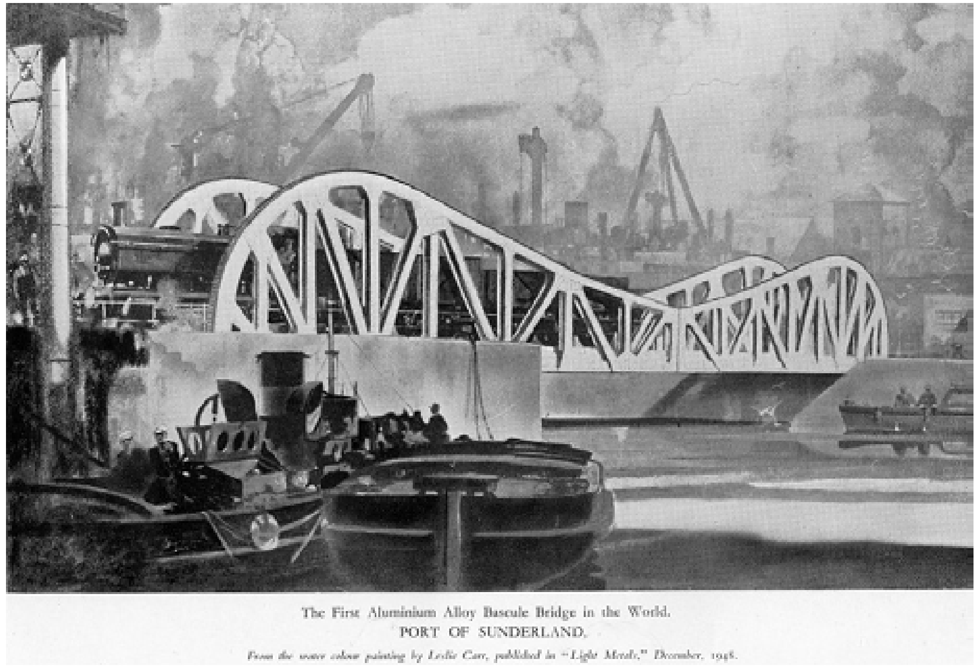


Fig 5.188 Repoduction of a water colour painting of the aluminium alloy bascule bridge at Hendon Dock, Sunderland by Leslie Carr, published in Light Metals, December 1948

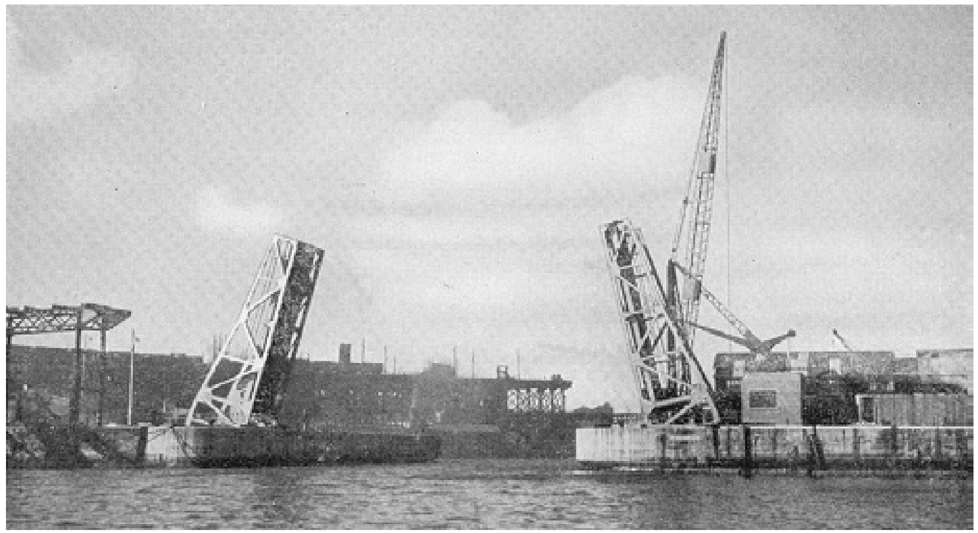
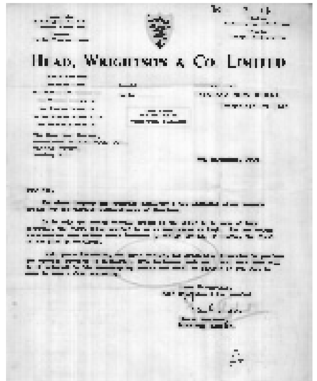


Fig 5.189 Aluminium alloy bascule bridge at the entrance to Hendon Dock, Sunderland, which opened in 1948

Fig 5.190 St Clements' Aluminium alloy bascule bridge of Victoria Dock in Aberdeen Harbour viewed from Waterloo Quay in 1970

Fig 5.191 The ceremonial opening of St Clements' Aluminium alloy bascule bridge by Queen Elizabeth, the Queen Mother, Aberdeen Harbour, 30 September 1953



HEAD, WRIGHTSON & CO. LIMITED

Fig 5.192 Scan of a letter by Frank Shepherd of Head, Wrightson & Co inviting British-Pathe to film the Queen Mother opening St Clements' Aluminium alloy bascule bridge

The second of these aluminium bascule bridges was assembled at Victoria Dock in Aberdeen, by Head, Wrightson & Co, to a similar specification, but it was only 30m long. Named St Clements' bridge, it was opened by the Queen Mother on 30 September 1953.[64] It is thought that neither bridge proved to be durable in the long term because of a poor understanding of bimetallic corrosion resulting from the use of unprotected steel fixings. St Clements' bridge was decommissioned and recycled in 1975.

Contemporary examples of bascule bridges built totally from aluminium include Helmond bridge built in 1999 and Riekerhavenburg bridge and Westdork Bridge both completed in 2003. These bridges in Amsterdam were fabricated by Bayards using extruded trapezoidal aluminium profiles. The lightweight yet stiff decks enable these bridges to achieve a low overall weight, which is beneficial installation and day-to-day opening.[65] Westdork bridge designed by MSVA Architects is featured on pages 368–369.

Arvida Bridge is a road bridge spanning the Saguenay River at Saguenay–Lac-Saint-Jean in Québec built of aluminium between 1948 and 1950. It is 10.4 m wide, 154m long and the primary arch spans 88.4m. This bridge, fabricated from 2024-T6 aluminium alloy, is still performing well having been refurbished during 2013 and 2014.

Fig 5.193 Arvida Bridge an all aluminium road bridge spanning the Saguenay River, 1950

Fig 5.194 Arvida Bridge is 154m long with a main aluminium arch spanning 88.4m

Fig 5.195 Arvida Bridge spanning the Saguenay River at Saguenay–Lac-Saint-Jean, Québec

Between 1946 and 1963, nine bridges were built from aluminium in North America, eight of which are still in service. This includes a bridge on Route 86 over the I-80 at Des Moines, Idaho, assembled in 1958 from 5083-H113 aluminium alloy and it is believed to be the first welded aluminium bridge, as it was prefabricated in four sections: two 21m spans weighing 9.5 tonnes and two 12m spans weighing 7.3tonnes, which were welded together to form four continuous spans. On which an in-situ concrete slab was cast separated by a coating of zinc rich primer on the top surface of the aluminium. It performed well for 35 years until it was replaced by a larger structure in 1993.[66]

The first aluminium road bridge in Europe that is still in use is the Schwansbell Bridge.[67] It was assembled in 1956 using AlMgSi1 alloy, which is equivalent to 6082 aluminium alloy, creating a 44.2m span over the Datteln-Hamm Canal near Lünen in the form of a Warren Truss and it is still in service today.[68] This bridge was prefabricated and transported to site by barge. [69] Walker and de la Chevrotière attribute the durability of this bridge to the quality of it's detailing, the components were joined with aluminium rivets, made out of the same alloy as the sections: 'A coating was applied between the overlapping plates to prevent crevice corrosion.'[70] Noting that 'minimal deterioration can be observed [on this bridge] after more than 50 years of service over a waterway, in a highly corrosive, industrial environment.'[71]

Role of Aluminium in Restoring Suspension Bridges

The high strength to weight ratio of aluminium has a key role to play in the restoration of early suspension bridges. In France, during 1975, three suspension bridges: Montmerle and Trevoux spanning the Saône river and Groslée on the Rhône river, have been restored using aluminium deck structures. The bridge at Montmerle, France, is a 190m suspension bridge comprising two spans of 80m. The timber and steel deck structure was replaced with an all aluminium truss suspended from the original pylons. The trusses are made up from U-profile chords, I-profile struts and bracing sections extruded in A-SGMT 6 aluminium alloy. Its deck is assembled from welded aluminium cross beams combined with welded aluminium panels, topped by 7mm bond resin wearing course. Groslée Bridge is the reconstruction of a 174m suspension bridge over the Rhône, originally built in 1912. The steel and timber deck structure was replaced with aluminium truss girders fabricated from extruded sections of 6082 R31 aluminium alloy that acts compositely with a 160mm concrete deck slab.[72]

A North American example of the uprating of a historic suspension bridge is Corbin Bridge, Huntington, Huntingdon County, Pennsylvania. This 98m (322´) span steel suspension bridge across the river Juniata was built in 1937 by Reading Steel Products Inc., using wire rope manufactured by Roebling and Son, Trenton, New Jersey. It replaces an earlier bridge that had been swept way on St Patrick's Day 1936. Corbin Bridge has only one lane and is 3.8m (12´ 6") wide. It was restricted to load capacity of 7 tons (6.35 metric tonnes), see Figure 5.197. In 1996, Reynolds Metals Company installed a new deck comprising 130mm extruded from 6063-T6 with transvers sections 250mm deep extruded from 6061-T6.[73] Enabling the steel suspension structure to be retained. The bridge was reopened with a capacity of 24 ton (21.8 tonnes). However, the clear height remains just over 4m (13'6") due to the first cross bar of the masts.

Fig 5.196 Corbin Suspension Bridge, Huntington, Pennsylvania, built in 1937

Real Ferdinando Bridge crossing the Garigliano River north of Naples is the oldest suspension bridge in Italy. It was designed by Luigi Giura in 1828 and built between 1831-32. The deck of this bridge was destroyed during World War II. This bridge was restored and reopened in 1998, using an aluminium bridge deck comprising 7020-T6 aluminium alloy for the longitudinal girders and 6060-T6 aluminium alloy for the transverse beams. The longitudinal girders are designed as a Vierendeel beam with the vertical components at the same centre as the suspension cable. The stone piers were consolidated, however, the lightweight of the aluminium deck is of vital importance in the restoration of this historically significant bridge.[74]

Fig 5.197 Wire rope anchorage detail of Corbin Suspension Bridge

Aluminium Bridges

The primary advantages of using aluminium in the construction of bridges are, it is:

- Lightweight, with a high strength to weight ratio, this is particularly important in opening bridges and the refurbishment of existing bridges.
- Durable, offering long-life with low maintenance, subject to appropriate alloy selection, detailing and finishing.
- Flexible in fabrication from the extrusion of large sections and highly developed welding techniques including friction stir welding.
- Rapidly installed, using large prefabricated components that can be readily transported and lifted in to place.

Furthermore, the total cost of ownership of all aluminium bridges can be beneficial. The case studies set out above evidence the benefits of specifying aluminium bridges in many parts of the world, with extant examples dating back over 65 years.

Fig 5.198 Aluminium Bridges from Arvida, 1950, via the Millennium, in London to 2016

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64 Film available from British Pathe http://www.britishpathe.com/video/aberdeen-queen-mother-opens-new-bridgewww.britishpathe.com/video/stills/aberdeen-queen-mother-opens-new-bridge (accessed December 2015).

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66 S. Walker & A. de la Chevrotière A., (2012), *Opportunities for the of Aluminum in Vehicular Bridge Construction*, Aluminum Association of Canada, Montreal, p.3.

67 The first all aluminium bridge in Europe was built in Szabadszallas, Hungary, in 1951. The superstructure is now exhibited in the Road Museum in Kiskoros, Hungary. See T. Siwowski, (2006) *Aluminium Bridges – Past, Present and Future,* Structural Engineering International, No.4 October, p. 288.

68 D. Kosteas, G. Albert G. and M. Meyer-Sternberg, (2010) *Evaluation of Aluminium Bridge Systems*, pp. 328-337, in J.E. Harding, P.Gerard & M. Ryall□, eds., *Bridge Management: Proceedings of the Third International Conference, CRC Press*

69 W. Mader, & A. Pieper, (2006) *Schwansbell Bridge celebrating 50th Birthday*, Structural Engineering International, Issue No.4, International Association for Bridge and Structural Engineering, Wokingham, pp. 356–359.

70 S. Walker & A. de la Chevrotière (2012), *Opportunities for the of Aluminum in Vehicular Bridge Construction*, Aluminum Association of Canada, Montreal, p.3.

71 Ibid.

72 T. Siwowski, (October 2006) *Aluminium Bridges – Past, Present and Future,* Structural Engineering International, No.4, p. 289.

73 D. Beaulieu, J. Internoscia and M. Hartlieb (2015), *Ponts et Passerelles en Aluminium: Rapport de visites et de rencontres en Suède, en Hollande et aux États-Unis*, April, AluQuébec and AAC, p. 49.

74 Mazzolani F.M., ed., (2003) *Aluminium Structural Design*, Springer, New York, pp. 79–85.

aluminium: flexible and light

light and strong: prefabricated

Aluminium Light and Strong: Prefabricated

Many of the aluminium bridges in the previous section of this chapter were prefabricated. This section focuses on the use of aluminium to form the primary structure of buildings that are also highly prefabricated, noting that the all-aluminium structure of the Comet Flight Test Hanger, completed in 1953, was also highly prefabricated, see pages 300–315. The primary advantages of prefabrication are:

- Speed of construction;
- Factory based quality control;
- Controlled condition of a sheltered factory environment;
- Minimisation of waste combined with short closed loop recycling of off cuts;
  and
- A better gender balance is often found in factories compared to building sites.

This section of Chapter 5 has three case studies in chronological order from 1999 to 2011.

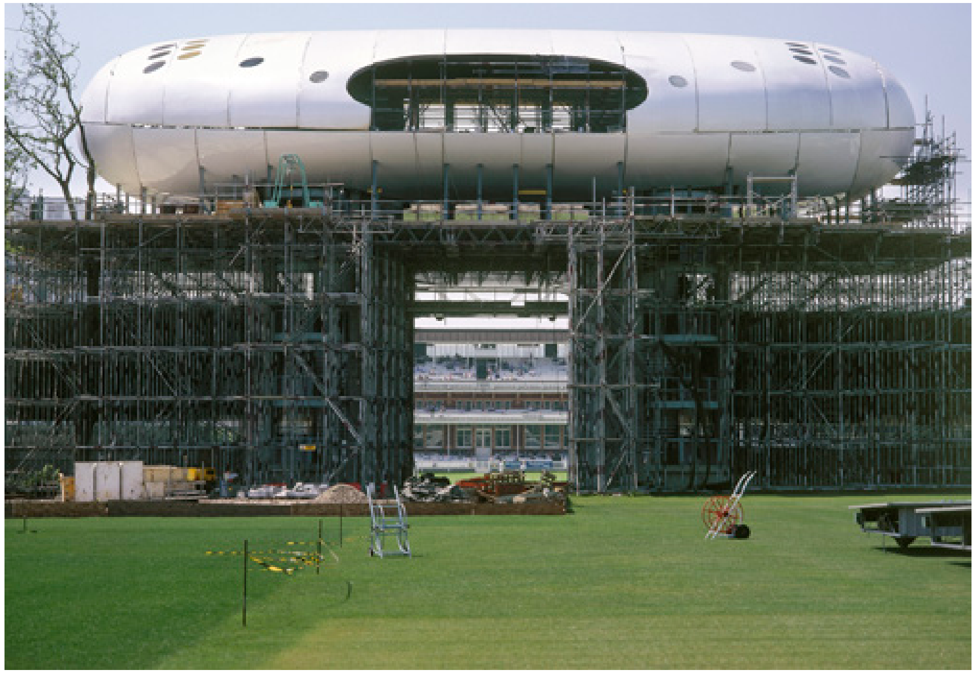


Fig 5.199 Lord's Media Centre under construction clearly showing the prefabricated aluminium components

Fig 5.200 The aluminium structure of Vague Formation Mobile Music Pavilion was prefabricated in large but easily craned chunks

Fig 5.201 The self supporting aluminium stair tower core was prefabricated in large chunks by Bayards

Lord's Media Centre, Lord's Cricket Ground, London, England: Architect Future Systems, 1999

Thomas Lord opened a cricket ground during 1787 at Dorset Fields, what is now Dorset Square, London. In 1809, due to rent increases in this central London location, near Marylebone Park (the future Regents Park), the Marylebone Cricket Club (MCC) moved to land on the Eyre Estates in St John Wood, which had once been hunting woods. MCC moved to the current site in 1814 due to the Regents Canal bisecting the second site of the ground, for which MCC received £4000 in compensation.[1]

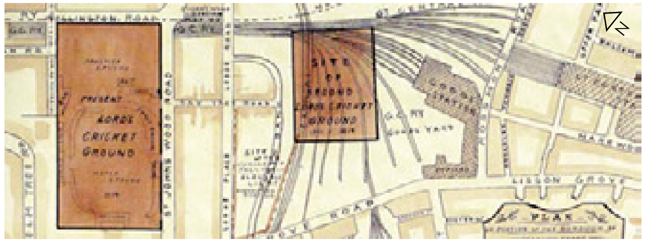


Fig 5.202 Nineteenth Century plan of Lord's Cricket Ground showing the location of the present ground and the second ground

By the mid twentieth century Lord's was a wonder ground to watch test cricket, however, architecturally it was characterised by the handsome faience clad Victorian pavilion designed by architect Thomas Verity and built in 1889 –1890. Starting with the Mount Stand by Michael Hopkins Architects completed in 1987. MCC becomes possibly one of the most unexpected patrons of cutting edge contemporary architecture. Deyan Sudic records in '1994, Peter Bell, an architect member of the Lord's Committee, came to Future Systems in search of some lateral thinking. He had a problem with sights screens, and the gap between two stands that he wanted to use to build more seats'.[2] Peter Bell was the architect who designed the Parsons House overcladding reviewed in TSC Report 1 *Aluminium and Durability* and referenced in this report on pages 266–267.[3]

Fig 5.203 Lord's Cricket Ground, St John Wood, London

MCC staged a competition for the new press box, which was won by Future Systems led by architect Jan Kaplicky with an audacious proposal for a 'glass-fronted white aluminium disk, raised on two legs' and hovering above the stands.[4]

Fig 5.204 Jan Kaplicky's sketch of the Lord's Media Centre

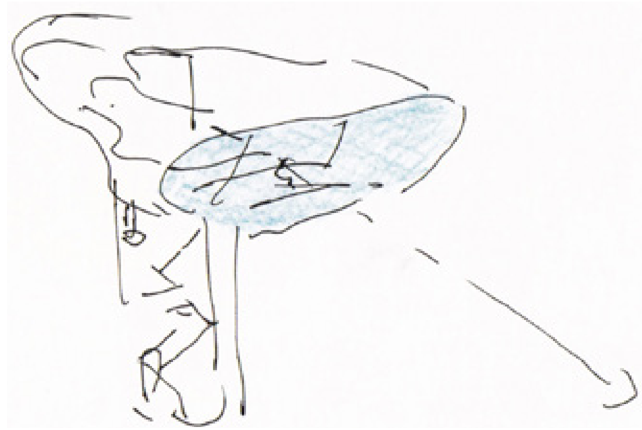


Fig 5.205 Lord's Media Centre, designed by Future Systems

Prefabrication was key to this project, as it had to be built outside the cricket season and thus not disturbing the programme of games at Lords. Kaplicky, who worked at Foster Associates, had a long held interest in new technology, often technology that had long roots but was being under used by the construction industry. The Lord's Media Centre offered the opportunity to explore and realise a monocoque aluminium structure. The scale of this cantilevered aluminium structure necessitated the use of internal stiffening ribs generating a semi-monocoque structure. Deyan Sudic records that during the design development process glass reinforced plastic (GRP) was considered, however, 'Future Systems were determined to use aluminium, conceptually a much more elegant material.'[5] Thickness of aluminium used to form the components or prefabricated 'chunks' of this semi-monocoque structure varies between 6mm and 18mm depending on the structural design of the shell.

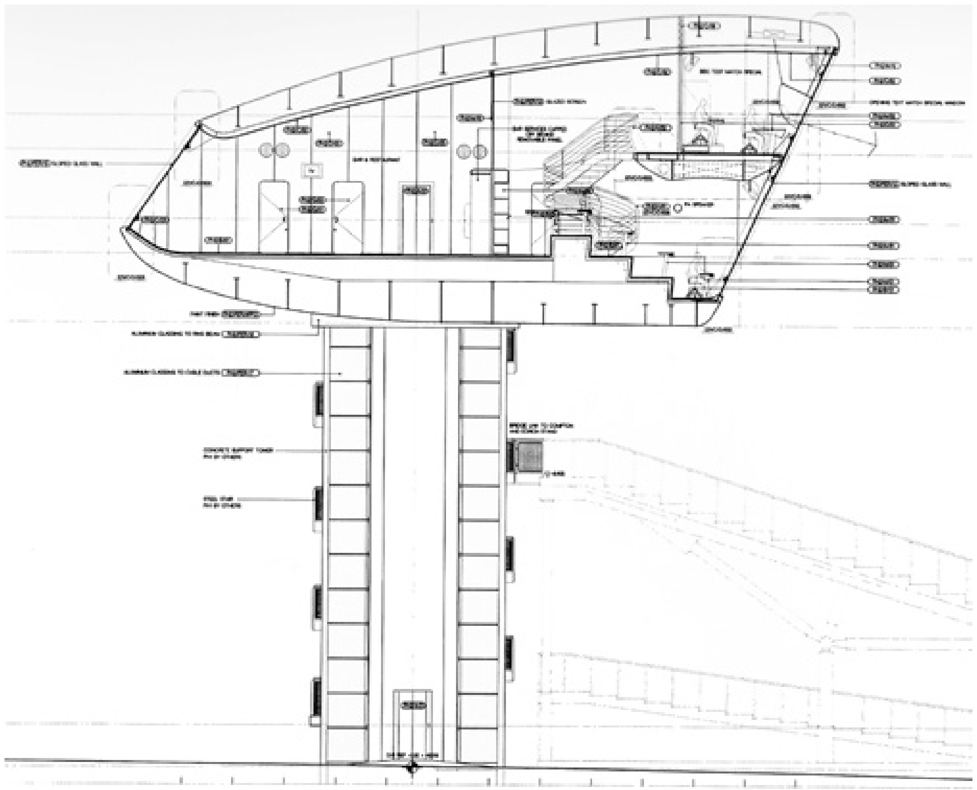


Fig 5.206 Future Systems' section through the Lord's Media Centre

Pendennis, a shipbuilder in Falmouth in Cornwall, England, was the key link with Future Systems, however the Lord's Media Centre was fabricated in the Netherlands by Bayards in its main hall in Nieuw-Lekkerland. The prefabricated components were then transported to site in London, temporarily supported and then site welded into a single shell. As discussed in Chapter 2, the welding of aluminium should no longer be considered difficult, although it is a highly skilled activity. By the early 1990s the techniques of welding developed in the factory or fabricating yard could be reliably applied to site conditions.[6] For example TIG welding can be carried out on site based aluminium components at a range of 200m from an appropriately equipped van. On completion of the welding of the semi-monocoque structure of the Lord's Media Centre a high performance white paint system was site applied. Completion of the project took two winters. The Lord's Media Centre has proved a great success providing uninterrupted sightlines for journalists and commentators in the comfort of air-

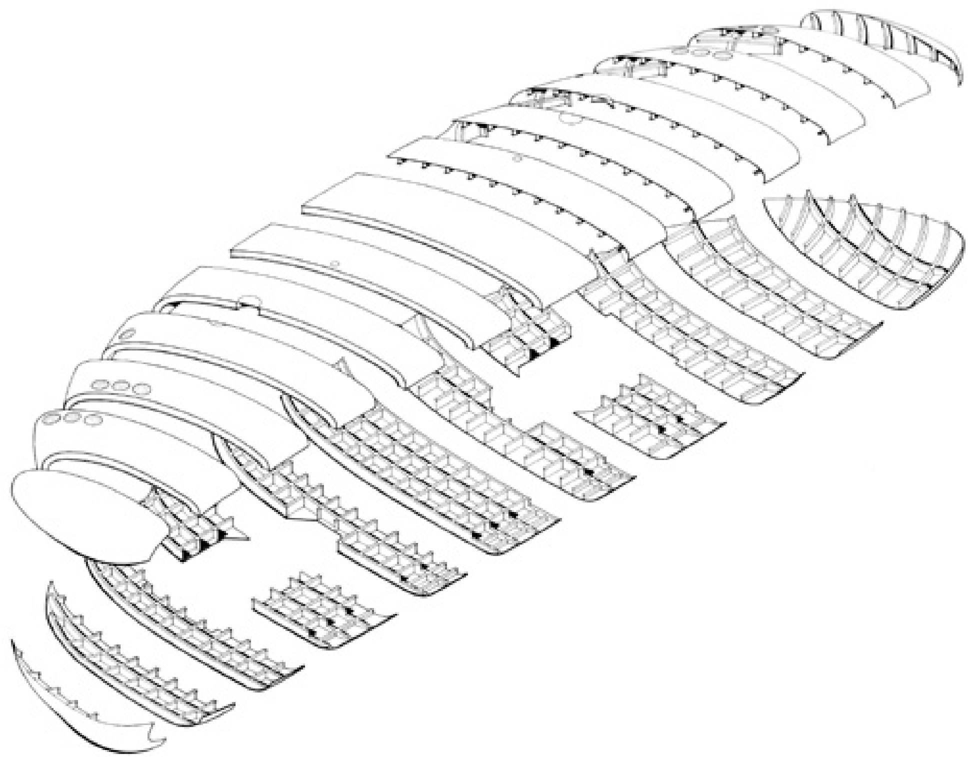


Fig 5.207 Future Systems' drawing of the element of the fabricated aluminium semi-monocoque structure and building fabric of Lord's Media Centre

conditioning. Deyan Sudic considers the white aluminium shell 'to hover above the ground, an enigmatic, ambiguous form, whose scale and form are initially hard to read'.[7] It both signals the presence of the Test venue and it 'has become a defining image of Lords, even though this last quality was never part of the brief.'[8]

In 1999 the Lord's Media Centre designed by Future Systems won the RIBA Stirling Prize, the highest honour available in UK architecture. Between the Pavilion and the Media Centre at Lords leys a field of dreams and over one hundred years of technological advancement in the potential for constructing architecture.

Fig 5.208 The aluminium semi-monocoque structure of Lord's Media Centre

Fig 5.209 The trial assembly of the Lord's Media Centre by Bayards in its main hall in Nieuw-Lekkerland

Fig 5.210 Lord's Media Centre, Marylebone Cricket Club, 1999

Barcelona Airport Traffic Control Tower, Barcelona, Spain: Architect Fairbanks Arquitectos with engineers M.E. & G.C. Giuliani, 2005

The capacity of Barcelona Airport has been significantly increased by the opening of a second terminal building and a third runway. This new capacity also necessitated the construction of a new Traffic Control Tower and the modernisation of air traffic control equipment. The new tower, designed by Bruce Fairbanks with engineers M.E. & G.C. Giuliani, is capable of handling 90 aeroplanes per hour.

Overall the tower is 62m high. The first element to be assembled was an octagonal 43m high self-supporting aluminium structure comprising: staircases, lifts and services. This core was prefabricated in large aluminium 'chunks' by Bayards, with bolted details to avoid site welding. To this the external hyperboloid concrete exoskeleton was fixed, without the need for scaffolding. The structure of the upper floors were assembled on the ground and then craned into position.[9]

Fig 5.211 Barcelona Airport Traffic Control Tower, architect Fairbanks Arquitectos with engineers M.E. & G.C. Giuliani, 2005

Fig 5.212 The self supporting aluminium stair tower core was prefabricated in large chunks by Bayards

Fig 5.213 The external concrete exoskeleton, aluminium stairtower and steel structure of the traffic control rooms

Vague Formation: a mobile Music Pavilion, multiple locations in Austria and Slovenia: Architect soma, 2011

This text describing the design and fabrication of Vague Formation, was primarily written by its architects Kristina Schinegger and Stefan Rutzinger of soma. It formed part of their essay *Adaptive Formation* in *Prototyping Architecture*.[10] It is reproduced here in edited form with their permission combined with additional commentary by the author.

The proposal for a mobile music pavilion by soma was chosen as the first prize-winner in an open, two-stage competition in October 2010. It was erected for the first time in the historic centre of Salzburg in March 2011 for a period of 3 months and housed the contemporary music festival Salzburg Biennale. Since then it has been assembled in the rural valley Krakautal, in Styria, Austria and in the inner centre of Maribor, Slovenia. At each location a different cultural activity inhabited the pavilion, the events showed a range from concerts, to exhibition, lectures, readings, installations or performances.

The structure can be divided into individual segments. By combining these in different ways or by reducing their number, it can adapt to its location. The removable interior membrane and the adjustable floor increases the flexibility of use. The pavilion's appearance is intended to provoke curiosity and invite visitors to encounter the unknown and unusual. It emphasises the understanding of art as a cultural process involving many participants within a discourse. This process does not reveal itself at first sight, but unfolds through engagement. The pavilion refers to a theme that is inherent to architecture as well as music – rule and variation. Its design process is based on simple repetitive elements, a set of rules for aggregation, and definition of the desired architectural effects. The single aluminium profiles with a uniform length produce an irregular, mass-like conglomerate that changes its appearance during the day, according to the different light conditions. The structure allows an ambivalent reading as single members and as a merging whole, depending on the distance it is viewed from. The speculative intention behind this obliteration of the pavilion's structure is to prevent any conventional notion or cliché of construction. Instead the ambiguous mass should invite visitors to come up with their own associations and interpretations.

Thanks to computation, complex structures employing disorder and randomness can be created and controlled. Although these irregular patterns are often applied to special building parts like façades, applications for load bearing structures are still an exception. Furthermore irregular complex structures are often based on highly individual components.[11] The bottom-up strategy

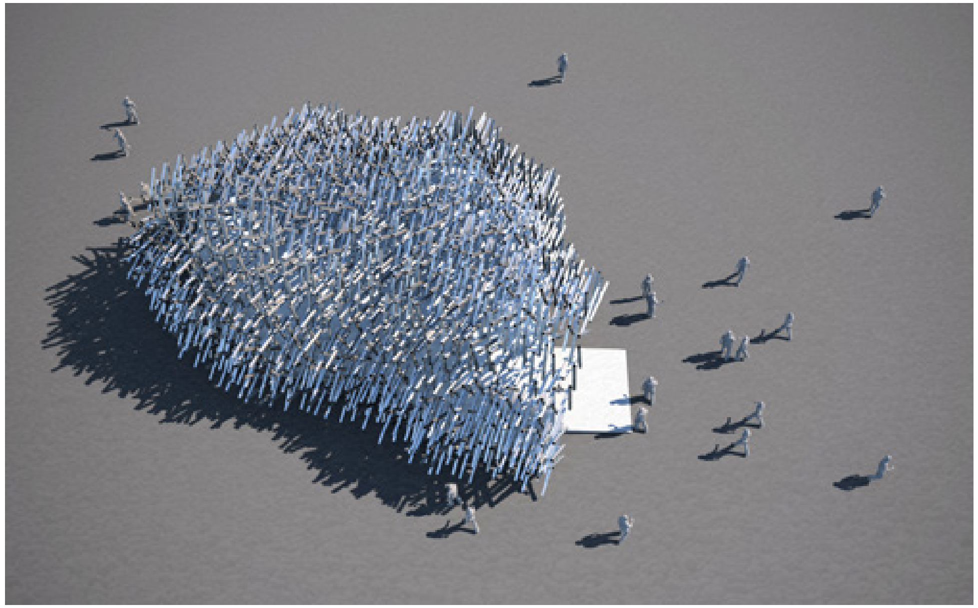


Fig 5.214 Soma digital model of Vague Formation

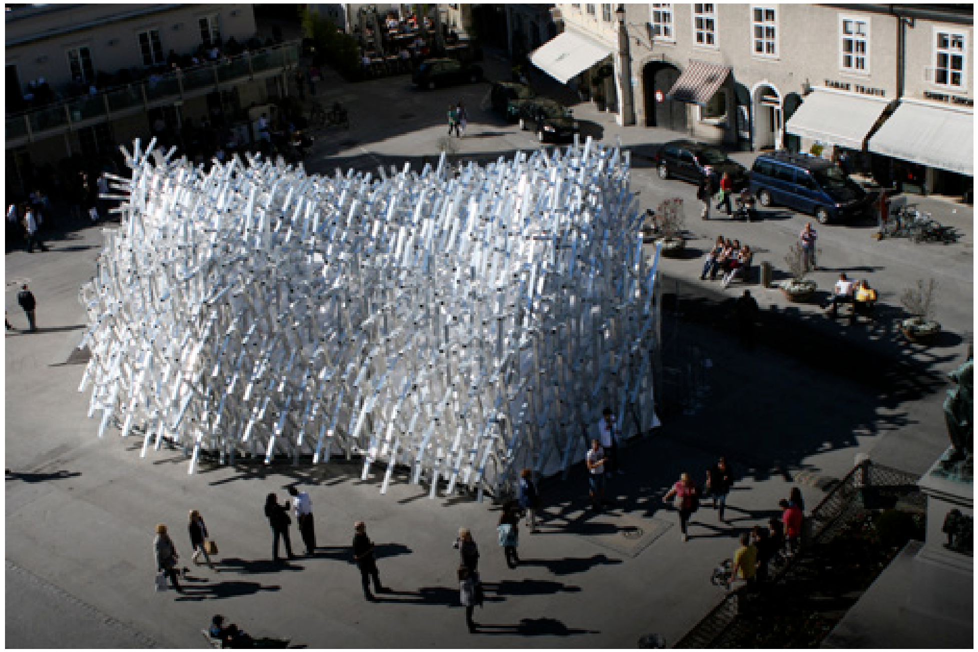


Fig 5.215 Vague Formation, a mobile music Music Pavilion in Salzburg, 2011

of the music pavilion is based on a repetitive linear base element that does not change shape. Furthermore the aluminium profile is cut from stock ware (6m length) to avoid leftover material. The overall structural system of the pavilion is divided into 5 individual sections to increase flexibility of use. Each section consists of 20 vertical construction layers with a spacing of 200mm, the start and end sections have fewer layers. On each layer intersection curves with the reference surface will host starting points for the structural members. The distribution of points and positioning of the structural members takes place within a range of randomised distances and angles but at the same time prevents intersections. The first layer of structure was successfully prototyped at the fabricators, Unterfurtner GmbH, as shown in Fig. 5.216.

Due to individual positioning of members along each section curve, projection intersections with neighbouring layers are generated. This process produces an interconnected structure. The structural optimisation by Bollinger Grohmann Schneider engineers takes the design rules into account but also considers working loads, amount of connection elements and the maximum

Fig 5.216 Welding the aluminium structure at Unterfurtner GmbH

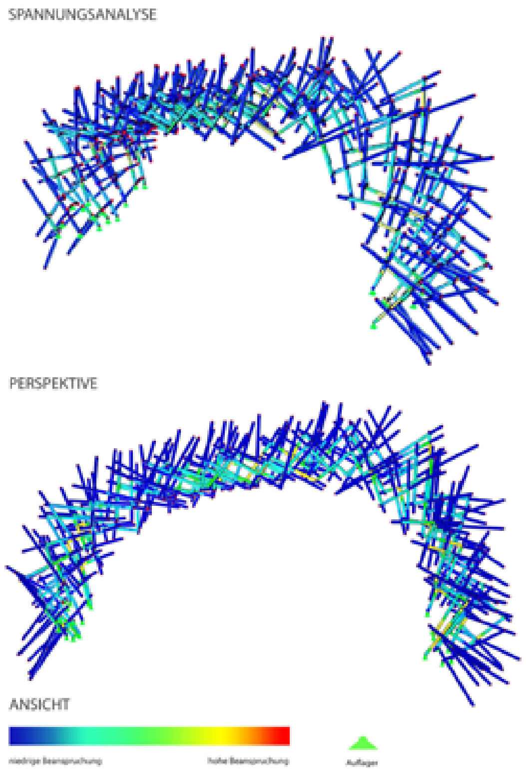


Fig 5.217 Sample images of the design team's parametric model of the structure of the Music pavilion

Fig 5.218 The structure is formed from standard extruded aluminium box sections linked by tubular aluminium sections

deflection of each segment. To evolve a structure Karamba[12] was applied within Grasshopper. Combined with a genetic algorithm the optimised solution was filtered out of the multiplicity of solutions through combination, selection and mutation over many generations. The elements are aligned iteratively and interact in a parallel way. By repetition of the same calculation step and with the feedback of the results, the system is incrementally evaluated until a certain target value is reached or the system converges to a threshold value. Multiplicity denotes the simultaneous and parallel observation and adjustment of the individual elements in a single step. The coactions of multiplicity and iteration result in the system's ability to adapt to a given task.

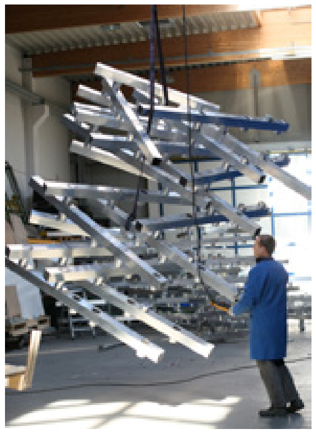


Fig 5.219 The aluminium structure was prefabricated in large but easily craned chuncks

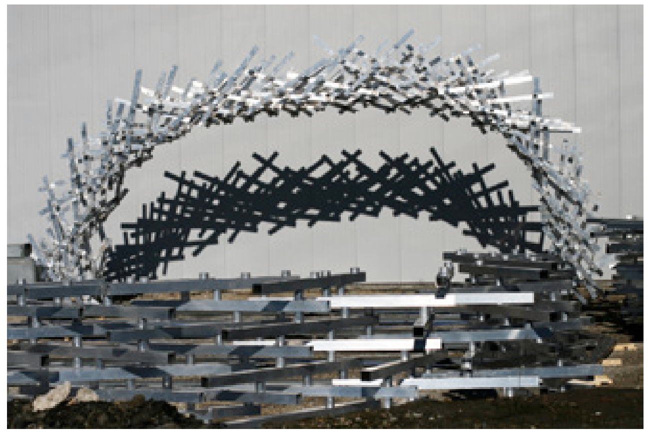


Fig 5.220 Prototype arch at Unterfurtner GmbH

Optimisation is here understood by Bollinger Grohmann Schneider Engineers as enhancing structural performance within architectural parameters and aesthetic intents given by the architect. In addition to structural aspects, the number of sections is minimised without losing the mass-like appearance. The parametric model, based on Grasshopper and Karamba, enabled the architects and the engineers to simultaneously design and evaluate the structure. This collaboration cannot be considered as a strictly parametric straightforward generation process, but is rather a back and forth negotiation between architectural aspiration, structural behaviour, buildability, logistics of assembly, and cost control. In the case of the music pavilion the design process is actuated by the set-up of rules and framing conditions that could be understood as the inherent logic of the emerging structure. 'On this modest project, costing 300,000 Euros' Michael Stacey's opinion is that 'parametric tools and specifically the Grasshopper plug in to Rhino has been used wisely.'[13]

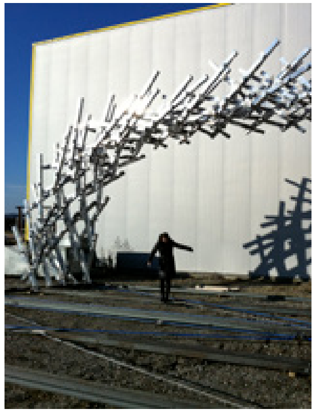


Fig 5.221 Prototype arch at Unterfurtner GmbH

Nevertheless, the experiential qualities of the design and its external expression remain a principal focus. The mass-like appearance aims at underlining the creative character of our perception, since our brains are constantly trying to distinguish figures and patterns within disorder. Rather than to produce forms or meanings, the ambiguous mass of the pavilion triggers visitors to come up with their own interpretations and associations. In this way the pavilion could be called performative, since it wants to engage visitors, not by being complicated or difficult, but by displaying the playfulness of complexity and creating a changing appearance that triggers visitors' curiosity.

Fig 5.222 An aggregated aluminium structure formed of standard extrusions

Fig 5.223 The aluminium exoskeleton of the music pavilion being assembled in Salzburg

Fig 5.224 Vague Formation Mobile Music Pavilion, Salzburg, 2011

This tendency towards the design of rules and display of inherent principles is also a shift from an interest in external form towards the inner logic or, as Stan Allen puts it, from object to field.[14] Form or figures do not disappear altogether, they rather appear in the eye of the beholder, and step out of a heterogeneous field as a local effect. 'What is intended here is a close attention to the production of difference at the local scale, even while maintaining a relative indifference to the form of the whole.'[15] Allen calls these fields 'systems of organisation capable of producing vortexes, peaks, and protuberances out of individual elements that are themselves regular or repetitive.' He highlights the 'suggestive formal possibilities' and the questioning of conventional top-down form controls. In his opinion fields also have the potential to provoke a re-addressing of use: 'More than a formal configuration, the field condition implies an architecture that admits change, accident, and improvisation.'[16] Following Stan Allen adaptability could be understood as a certain openness and experiential ambiguity in architecture that allows multiple readings and therefore multiple uses, that might be unplanned und unforeseen. At soma we advocate that this openness is not composed by the neutral and flexible, but the distinct and complex, the evocative and sensational, the multi-layered and fuzzy.

In 2012 the author reviewed Vague Formation mobile music pavilion for Architecture Today and the following is an edited extract.[17] The structure was designed parametrically, but the diversity of components often associated with freeform geometry was eschewed in favour of aggregating a standard component. Working with engineer Bollinger Grohmann Schneider, SOMA developed a bottom-up design strategy based on a repetitive element that does not change shape, yet creates a palette of spatial patterns depending on the rules of aggregation. The base component is a mill-finish aluminium box section extruded from a standard stock die. To facilitate transportation the structure of the pavilion is divided into five-arched segments that in turn are broken down into six sub-segments.

The architects did not want the construction to be read in a conventional manner – in contrast, for example, to Renzo Piano's traveling IBM exhibition pavilion from the early 1980s, which was formed from arched bays of polycarbonate and timber linked by elegant aluminium castings.[18] Rather, SOMA's 'speculative intention behind the 'obliteration' of the pavilion's structure is to prevent any conventional or cliché of 'construction'... the pavilion should appear to arbitrarily invite visitors to come up with their own interpretations.'[19]

The structure is prefabricated in segments with 20 vertical and parallel layers, spaced at 200mm centres, except for the rear segment, which has only 15 layers. The 95 layers or arches of the aluminium structure each span 10 metres. Each structural layer has a unique aggregated curvilinear geometry. The aluminium box

Fig 5.225 Preparing for a performance inside Vague Formation

extrusions are welded together with 90mm long circular aluminium extrusions, where layers of arches are bolted together during erection; 90mm long circular aluminium extrusions conceal the M10 stainless steel connecting bolts. Although the appearance of the aluminium structure is very diverse, the fixing method, whether bolted or welded, appears the same. The expression is based on aggregation rather than articulation of the detailing. The apparent complexity is underscored by the clarity of the fabrication. The exoskeleton of aluminium sections provides a dynamic pattern of shadows in the interior of the pavilion, which is revealed by the translucent membrane. The aggregated aluminium structure formed from standard aluminium extrusions generates a striking and delightful architecture both inside and outside; appropriately, this could be seen as a new example of architecture as frozen music.

Fig 5.226 Vague Formation in the historic centre of Salzburg

Notes

1 https://www.lords.org/history/lords-history/the-three-lords-grounds/ (accessed February 2016)
2 D. Sudjic (2006) *Future Systems*, Phaidon, London p. 187.
3 M. Stacey Ed., (2014), Aluminium and Durability: Towards Sustainable Cities, Cwningen Press, Llundain, second edition 2105, pp. 188–193.
4 D. Sudjic (2006) *Future Systems*, Phaidon, London p. 187.
5 Ibid, p. 188.
6 M. Stacey (2001) *Component Design*, Architectural Press, Oxford p.90.
7 D. Sudjic (2006) *Future Systems*, Phaidon, London p. 201.
8 Ibid.
9 www.fairbanksarquitectos.com/Twr_Barcelona.html (accessed February 2016)
10 K. Schinegger and S. Rutzinger *Adaptive Formations: Two Pavilions, One Adaptation and One Tower in M. Stacey (2013), Prototyping Architecture, Riverside Architectural Press*, Cambridge, pp. 80–83.
11 F. Scheurer, (2005) *Turning the design process downside-up – self-oranization in real-world architecture*, in Computer Aided Architectural Design Future 2005, ed. B.Martens, A. Brown,Wien: Springer, Wien, pp. 269-78.
12 http://twl.uni-ak.ac.at/karamba/ (accessed August 2013)
13 M Stacey, (June 2011) *Frozen Music*, Architecture Today, AT219, pp. 12–14.
14 Stan Allen (1997) *From Objects to Field*, in Architectural Design Vol 67, pp. 24–31.
15 Ibid.
16 Ibid.
17 M Stacey, (June 2011) *Frozen Music*, Architecture Today, AT219, pp. 12–14.
18 M. Stacey, (2015), *Aluminium Recyclability and Recycling: Towards Sustainable Cities*, Cwningen Press, Llundain, pp. 234–235.
19 S. Rutzinger, K.Schinegger, A.Hofmann and M.Heimrath, *Adaptive Design of a Music Pavilion* in F. Stacey and M. Stacey, eds., (2011), *Adaptive Architecture Conference Papers*, Building Centre, London.

Light and Slender

Windows are apparently simple, yet become surprisingly complex when providing a high performance including: good thermal insulation, natural ventilation, low **air infiltration rate** (draft proof), plentiful daylight, beneficial solar gains, security, and ease of user operation. Carefully designed glazing systems combine all of these issues, whilst providing a good energy balance. Windows are a familiar component of architecture for everyone and one of the first standardised building products – the timber London sash window was first produced in the eighteenth century.

The inherent complexity of windows is one of the reasons why TSC Report 3 *Aluminium and Life Cycle Thinking* selected window frames for a comparative life cycle assessment (LCA) of the use of aluminium, wood, aluminium-clad wood and PVCu to form this component of architecture.[1] In this study a reference size of 1.3 × 1.6m was used for all frame types, this is essential in a LCA study to make certain that the assessment is comparable across the four materials. However, this understates the potential of aluminium to support large areas of glass with slender stiff sections.

Fig 6.1 A diverse set of window selections in an exhibition by Rem Koolhaus at the Venice Bienalle, 2014

EN 14351-1 defines two sizes of windows – small windows under $2.3m^2$ in area, with a standard size of 1.23(±25%) × 1.48(±25%)m, and large windows as 1.48(±25%) × 2.18(±25%)m, with an overall area over $2.3m^2$. The size of window can significantly affect the thermal performance and light transmission due to the percentage of framing.

U-values

The measure of heat loss through the fabric of a building is described as a U-value, measured in W/m^2K. A low U-value represents a high level of insulation.

There are three important U-values to consider when evaluating the thermal performance of a window:

U_w (w = window): overall U-value of the window;

U_g (g = glazing): U-value of the glazing;

and

U_f (f = frame): U-value of the frame.[2]

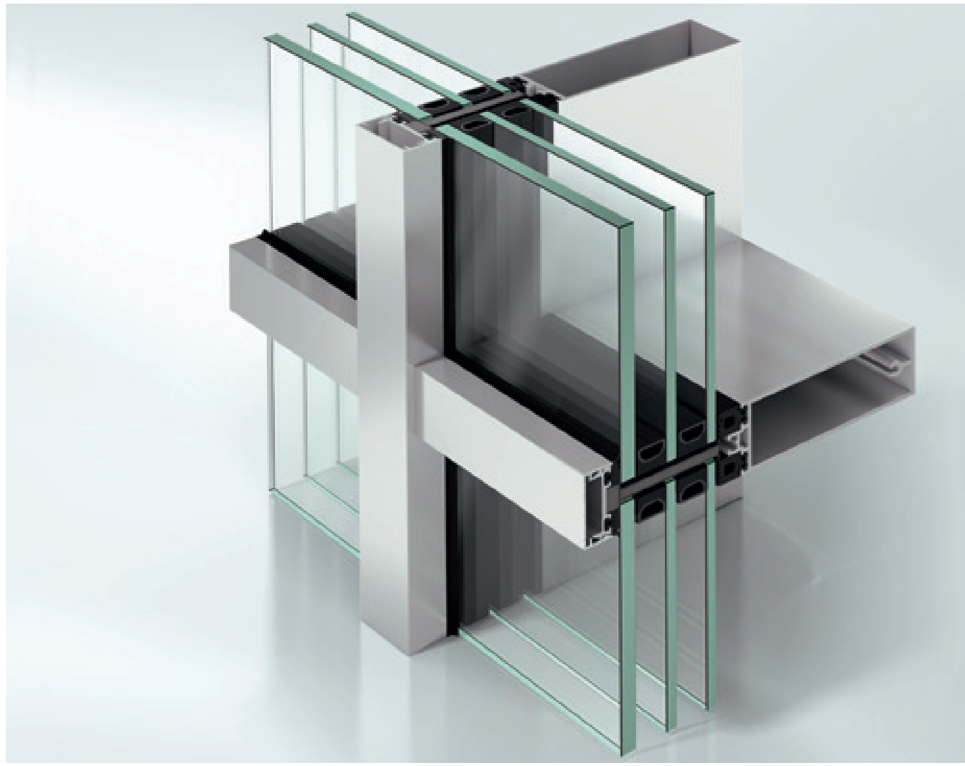


Fig 6.2 Schüco FWS 35 PD, triple glazed curtain walling

The heat transfer coefficient of the entire window U_w, is calculated in order to understand the overall assembly performance. This value incorporates the U-values for the glazing U_g and the frame U_f . The overall value U_w is influenced by the linear heat transfer coefficient of the frame and the glazing, and the sizes of the frame and the glazing.

The following formula is used to determine the U-value of the complete window U_w :

$$U_w = \frac{(A_g \; x \; U_g + \; A_f \; x \; U_f + l_g \; x \; \Psi_g)}{(A_g + \; A_f)}$$

Where:

U_g = heat transfer coefficient of the glazing;
U_f = heat transfer coefficient of the frame;
Ψ_g = linear heat transfer coefficient of the insulated glazing unit (IGU) edge seal;
A_g = total area of glazing;
A_f = total area of the frame;
$A_w = A_g + A_f$;
and
Lg = length of inside edge of frame profile (or visible periphery of the glass sheet). [3]

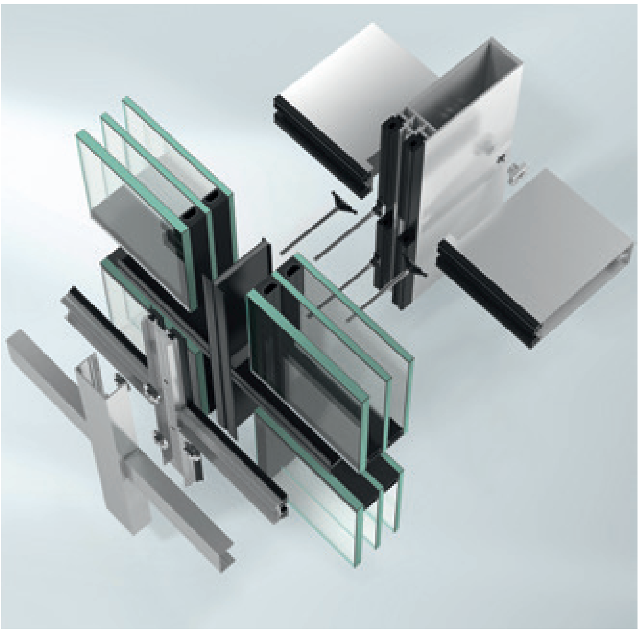


Fig 6.3 The components of the Schüco FWS 35 PD curtain walling system

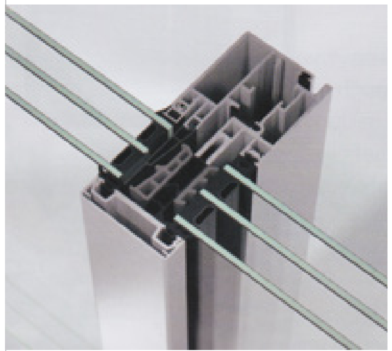


Fig 6.4 Schüco FWS 60 CV façade system with visually unobtrusive inward opening vents

U_w is the U-value of the complete window, which is highly dependent of the size of window specified and the proportion of framing. Therefore actual U-values should always be calculated, and the specifier should not just use the U-value of a standard window from the chosen system.

Schüco produces an extruded aluminium window system with a sight line or framing section that is only 60mm wide, the Schüco FWS 60 CV façade system includes inward opening vents that do not increase the sight lines, with no visible framing externally. This system uses glass-fibre-reinforced thermal isolators and provides U_{cw}-values down to 0.85 W/m^{2}K with a glazing U-value of 0.7 W/m^{2}K. Schüco observe 'the systems very narrow face width actually assists in improving its energy efficiency'.[4] U_{cw}-value is the overall U-value of a lightweight curtain walling in accordance with BS EN ISO 12631:2012, which follows a very similar procedure to that for the window, as set out previously.

Schüco has also developed a curtain walling system with even slimmer sight lines with a face width of only 35mm, which was launched in 2015. This pressure plate extruded aluminium curtain walling system can accommodate double and triple glazed units from 22mm to 50mm thick. The FWS 35PD system in its super insulated format is Passivhaus accredited with an U_{cw} of 0.79 W/m^{2}K.[5]

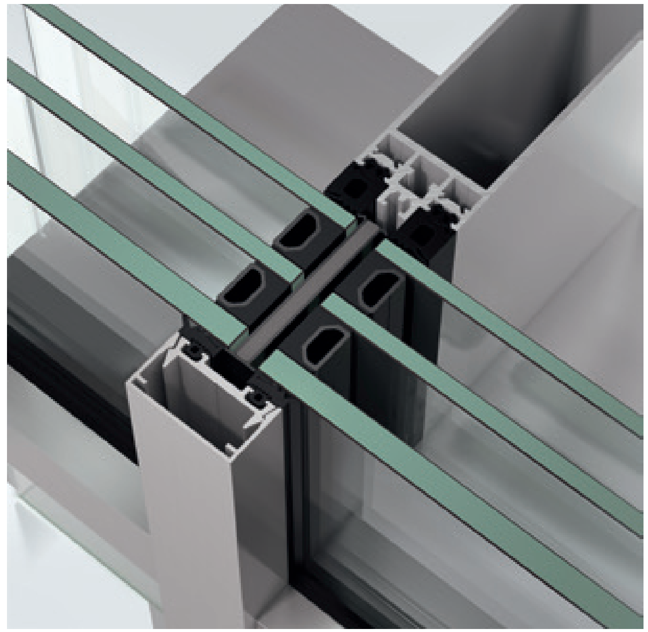


Fig 6.5 Detail of the Schüco FWS 35 PD curtain walling system

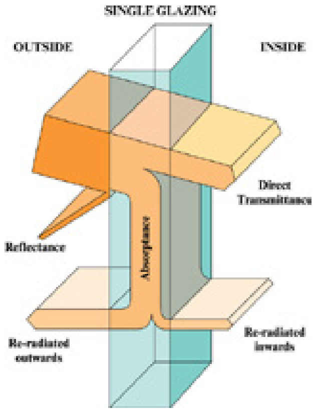
Beyond U-values

Energy efficiency in building fabric is not limited to achieving low U-values; it is also about balancing solar gains (**g-values**) and providing comfortable internal daylight levels, creating an energy balance. Achieving airtightness or a low air infiltration rate is also of vital importance; because once a building envelope is well insulated, unintended air changes can dominate the heat loss. This needs to be balanced by adequate ventilation to provide fresh air and to control condensation. A carefully resolved design that balances these criteria should be achieved to produce a satisfactory internal environment for building users, whilst minimising energy costs at the same time. [6]

The four main criteria that should be considered when assessing the energy balance of glazing are: thermal transmittance (U-value), solar gains (g-value), air infiltration rate, and cooling from ventilation. A window or glazed facade also provides daylight, expressed as light transmission factor (τ_v). A high light transmission value (**Lt-value**) is desirable to maximise daylight, but this should be balanced by controlling excessive solar gain in the cooling season. A g-value indicates the degree to which glazing blocks heat from sunlight and is expressed in a number between 0 and 1. The lower the g-value, the less heat is transmitted. The air infiltration rate is typically measured in $m^3/m^2/hr$. For g-value and light transmittance, it should be noted that these typically consider only the performance of the glazing. Hence for a window, it is preferable to consider the performance of the whole window by taking into account the frame fraction, with $g_w = g \times (Ag/Aw)$ and $LT_w = \tau_v \times (Ag/Aw)$.

Solar Gain

U-value regulations are now well established and understood, although only forming part of the key design considerations, however, g-values are relatively new to many specifiers and organisations. Solar gain is of particular importance in the regions relatively distant from the equator, where the sun is often at a low trajectory. Although solar gain can be beneficial in winter, as discussed in Chapter 3, the overall energy balance needs to be studied and preferably modelled, including the sizes and orientation of the glazing systems. Solar gain and light transmission are interdependent. Visible light, which can be seen and perceived by humans, is a very small part of the full electromagnetic spectrum, approximately only 3 per cent of this spectrum. The sun emits slightly more infrared than visible light, 52



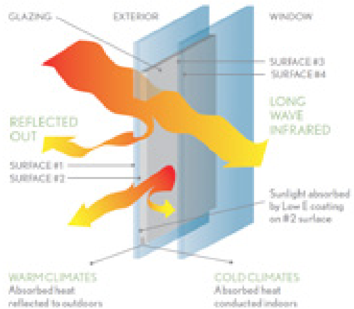


Fig 6.6 Comparative solar radiant heat diagrams for single glazing and an IGU incorporating a low-E coating on surface 2

compared to 48 per cent respectively. Visible light is absorbed and emitted by electrons in atoms moving from one energy level to another, and lies between the infrared and the ultraviolet wavelengths in the electromagnetic spectrum. Electromagnetic radiation [EmR] in the visible light region consists of quanta (called photons) between the invisible infrared, with longer wavelengths, and invisible ultraviolet, with shorter wavelengths. Above the range of visible light, ultraviolet light becomes invisible to humans mostly because it is absorbed by the tissue of the eye.

At the lower end of the visible light spectrum, EmR becomes invisible to humans because its photons no longer have enough individual energy to cause a lasting molecular change, a change in conformation, in the human retina. The aim for any energy efficient glazed facade system should be to achieve a good energy balance, minimising the solar gain, 780-2500nm infrared radiation, whilst transmitting as much visible light as possible, 400-780nm. In this regard, the role and design of solar shading is important, as reviewed in Chapter 3. A good energy balance within a façade will help to create a constant (within an agreed range) and comfortable interior temperature within the building, whilst minimising the need for artificial light. The thermal performance of 6mm single glazing is $5.7W/m^2K$, where as the U-value of a double glazed unit, comprising clear glass, typically 6mm glass with a 16mm cavity (6-16-6mm), is $2.7W/m^2K$. By adding a transparent sputtered metal low-emissivity coating to either surface 2 or 3 of a double glazed unit (6-16-6mm) the U-Value can be reduced to $1.4W/m^2K$. Low-emissivity coated glass (know simply as low–E glass) in an IGU reduces radiated heat loss from the interior, thus reducing the energy required for heating a space. Low-E glass will also absorb and reflect more of the incident solar energy, thus reducing the cooling load. There are two types of low-E coating – soft and hard, selection is primarily dependent on the climatic conditions of the proposed project. The development of low-E coatings began in the 1950s. The thermal performance of glazing can be further reduced by filling the cavity with a gas with lower a thermal conductivity, such as argon and the specification of triple glazing. Leading glass manufacturers including Pilkington, PPG, and Saint-Gobain provide detailed guidance on the performance of their product ranges.

Internal light levels

In the USA, day lighting is a well-proven and accepted part of building envelope design. The guidelines they use are based on an external luminance at ground level of 5000lux, which is equivalent to an overcast cloudy day. For an internal space to feel well lit, the average daylight factor should be 5 per cent or more. CIBSE LG10 states that an average daylight factor of 5 per cent or more will ensure that an interior looks substantially day lit. This equates to a light level of 250lux.[7] This may appear to be low but if this level is uniformly achieved from a large proportion of the external wall compared to a smaller more concentrated area such as a window, it will normally satisfy the requirements of BS 8206-2: 2008.

BS 8206-2 2008 highlights three ways that the provision of glazing contributes to the energy balance and the quality of an internal space:

- View – amenity;
- The enhancement of the overall appearance of interiors using direct sunlight and diffused daylight;
  and
- The use of daylight for visual tasks.

When designing the building envelope of a project the architecture needs to be viewed holistically, including the potential role of thermal mass in the internal structure, the longevity of the façade materials, and the balance of ensuring good daylight and light levels whilst protecting the occupants from unwanted solar gains in the cooling season. This approach can move the project's budget from primary energy consuming services, such as air conditioning into the architecture and the facades, enhancing rather than limiting the architectural expression and reducing the energy consumption and greenhouse gas emissions of the building over its lifetime. Often defined as a fabric-first approach to building design.

The required light transmission should be calculated alongside the energy balance of the façade. Designers of low energy facades need to balance all five critical factors; U-value, g-value, Lt-values, a low air infiltration rate and cooling by natural ventilation. Alongside the glass specification, the sight lines produced by the specified window frame is key to the percentage of glazing, and thus the amount of daylight entering through the façade. Figure 6.7 provides a visual comparison of currently specifiable window framing systems, organised not by material but by the relative slenderness of the framing system.

To provide an indication of sight lines and relative performance of aluminium window frames, the following is a comparison of four extruded aluminium thermally broken windows, using casement or tilt turn windows. In all cases the windows are double glazed with

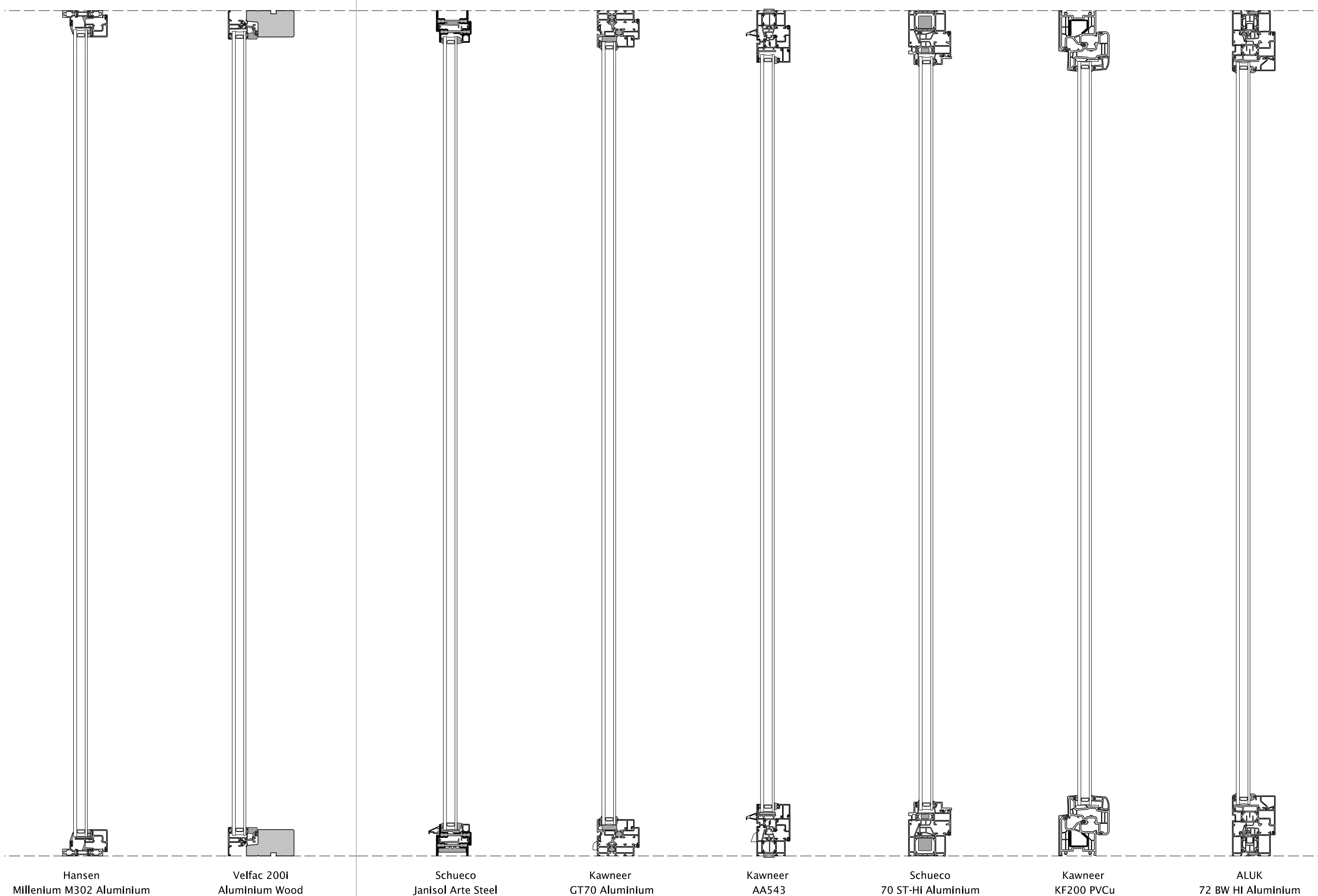


Fig 6.7 A visual comparison of currently specifiable window framing systems

6mm outer panes of Cool-Lite (SKN 174 I) – a low-E glass, 16mm cavity and 4mm inner pane of Planilux, both by Saint Gobain (6-16-4mm), with the cavity 90 per cent filled with argon.[8] The size of window used is 1.3 × 1.6m, as this is the reference size used in the LCA in TSC Report 3, *Aluminium And Life Cycle Thinking*.[9] This comparison of available window frames is provided as an indication of the options available to specifiers, and the author would encourage the reader to research potential window framing systems and seek early interaction with manufactures, many of whom will provide technical guidance and BIM objects for their window system.

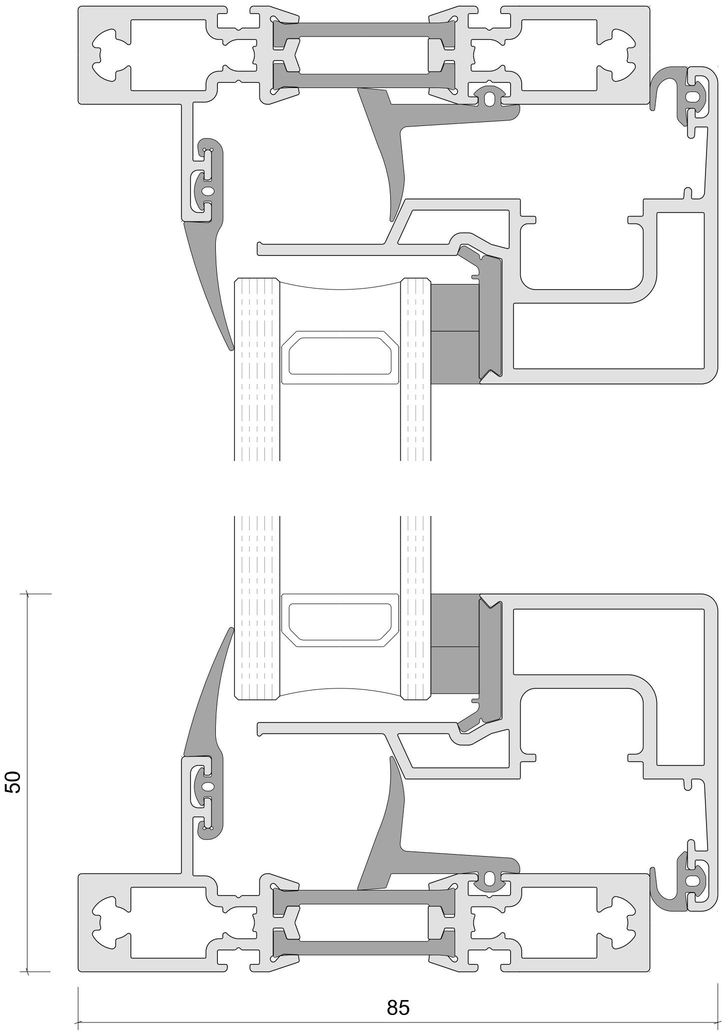
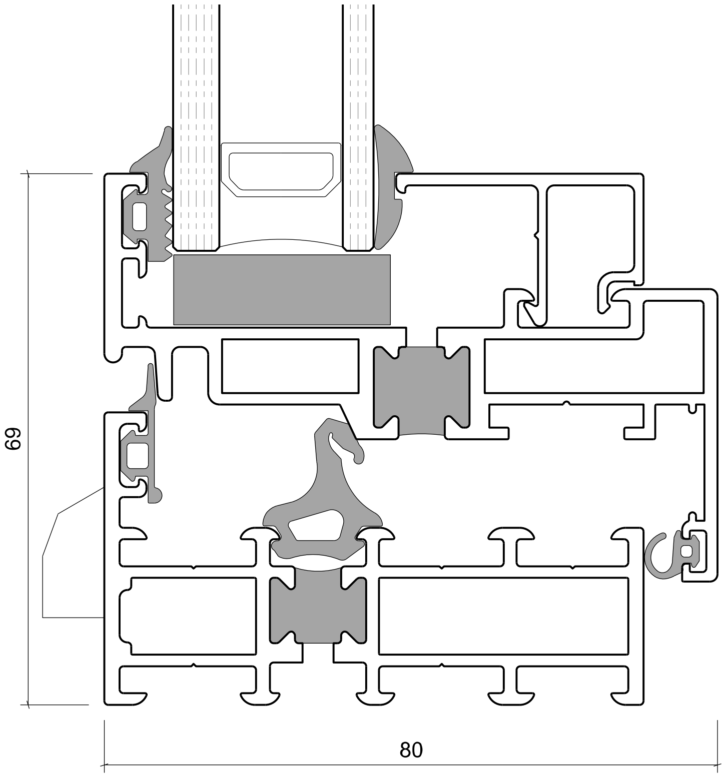
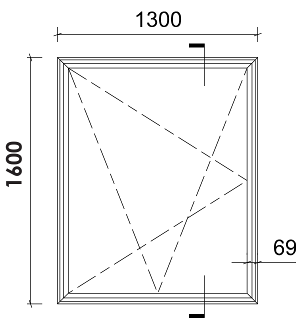


Fig. 6.8 Hansen Millenium aluminium casement

Hansen Millenium aluminium	
Frame Width (sight lines)	50mm
Frame Depth	85mm
U-value (double glazed)	1.4 W/m²K
Solar Factor (g-value)	0.41
% Glazed Area of 1.6 x1.3m opening	86 %

Fig. 6.9 [opposite] Hansen Millennium window, door and façade system

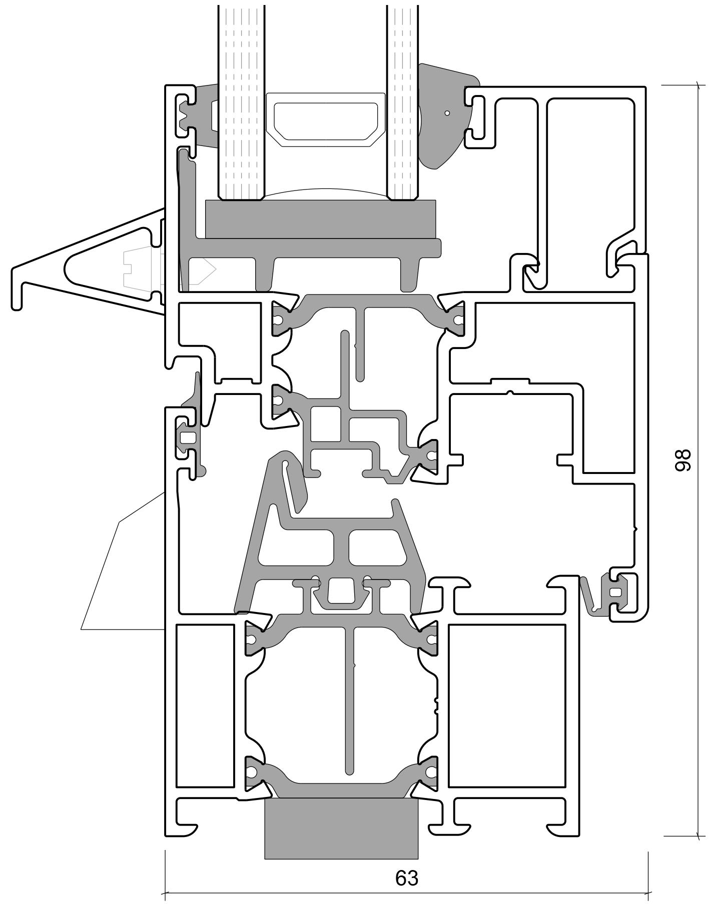




Kawneer GT70 aluminium renovation series tilt turn frame elevation. Opening size of 1.6x1.3m, scale 1:50

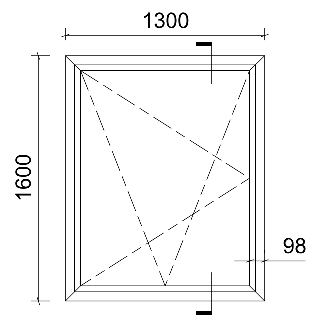
Kawneer GT70 Aluminium Renovation	
Frame Width (sight lines)	69mm
Frame Depth	85mm
U-value (double glazed)	1.5 W/m²K
Solar Factor (g-value)	0.41
% Glazed Area of 1.6 x1.3m opening	82 %

Fig. 6.10 Kawneer GT70 Aluminium renovation window

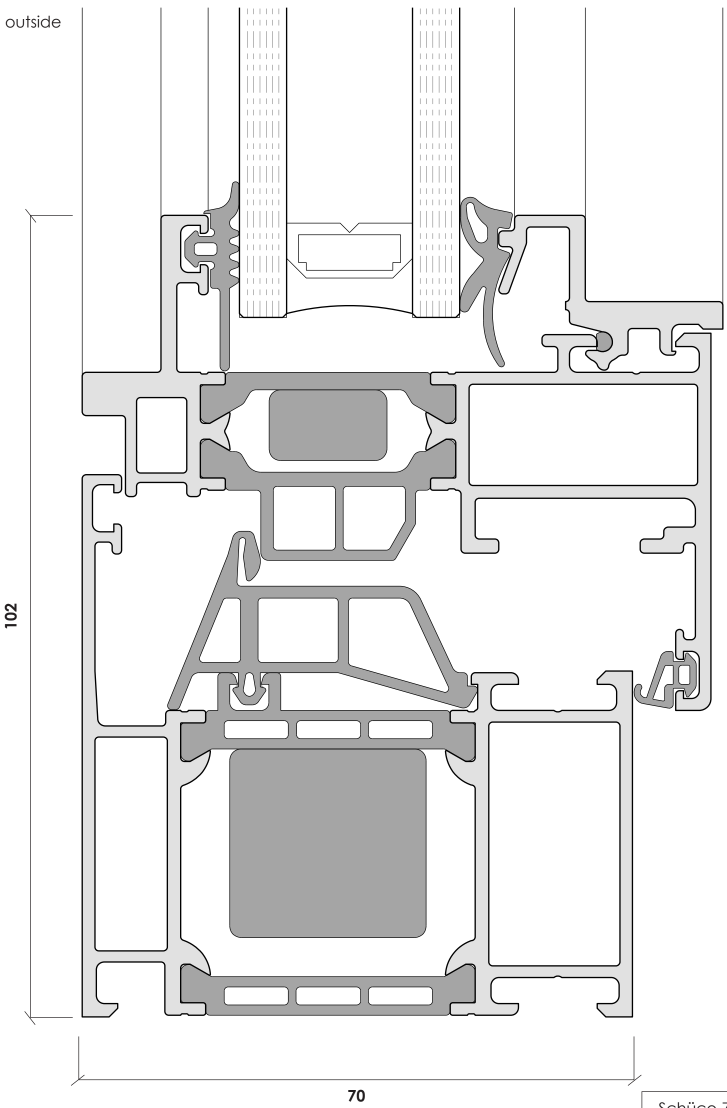


Kawneer AA543 Aluminium	
Frame Width (sight lines)	98 mm
Frame Depth	63 mm
U-value (double glazed)	1.6 W/m²K
Solar Factor (g-value)	0.41
% Glazed Area of 1.6 x1.3m opening	75%

Fig. 6.11 Kawneer AA543 tilt turn aluminium window



Kawneer AA543 Tilt Turn Aluminium Window frame elevation. Opening size of 1.6x1.3m. Scale 1:50



Schüco 70ST-Hi High Performance Alu.	
Frame Width (sight lines)	102 mm
Frame Depth	70 mm
U-value (double glazed)	1.4 W/m²K
Solar Factor (g-value)	0.41
% Glazed Area of 1.6 x1.3m opening	77 %

Fig. 6.12 Schüco 70ST-Hi aluminium tilt turn window

Part of the drive to inform the thermal performance of glazed façades has been consideration of the overall U-value, not just the performance of the double or tripled glazed unit, what was once known as the mid-pane U-value. Aluminium alone is highly conductive, as shown by its use in overhead electrical power lines and heat sinks. Therefore thermal breaks and insulation need to be detailed in aluminium curtain walling and windows, to lower the U_f. The past 40 years has witnessed the steady development of thermally efficient extruded aluminium windows frames, offering a frame U-value of 0.85 W/m²K, as demonstrated by the Schüco FWS 60 CV, discussed above. Another example is the PURe® extruded aluminium window system designed and manufactured by Senior Architectural Systems, which incorporates expanded polyurethane (PUR) thermal barriers and provides a U_w-value down to 0.71 W/m²K.

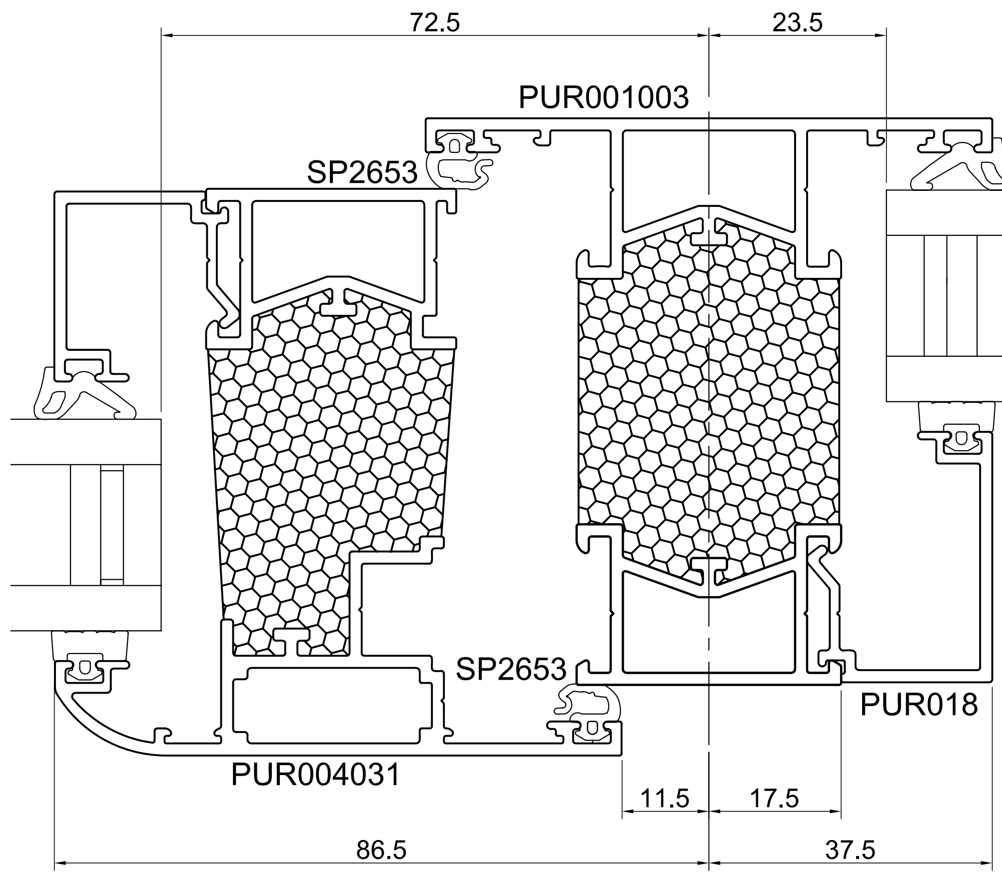


Fig. 6.13 Horizontal cross sections of a low U-value PURe extruded aluminium casement window mullion

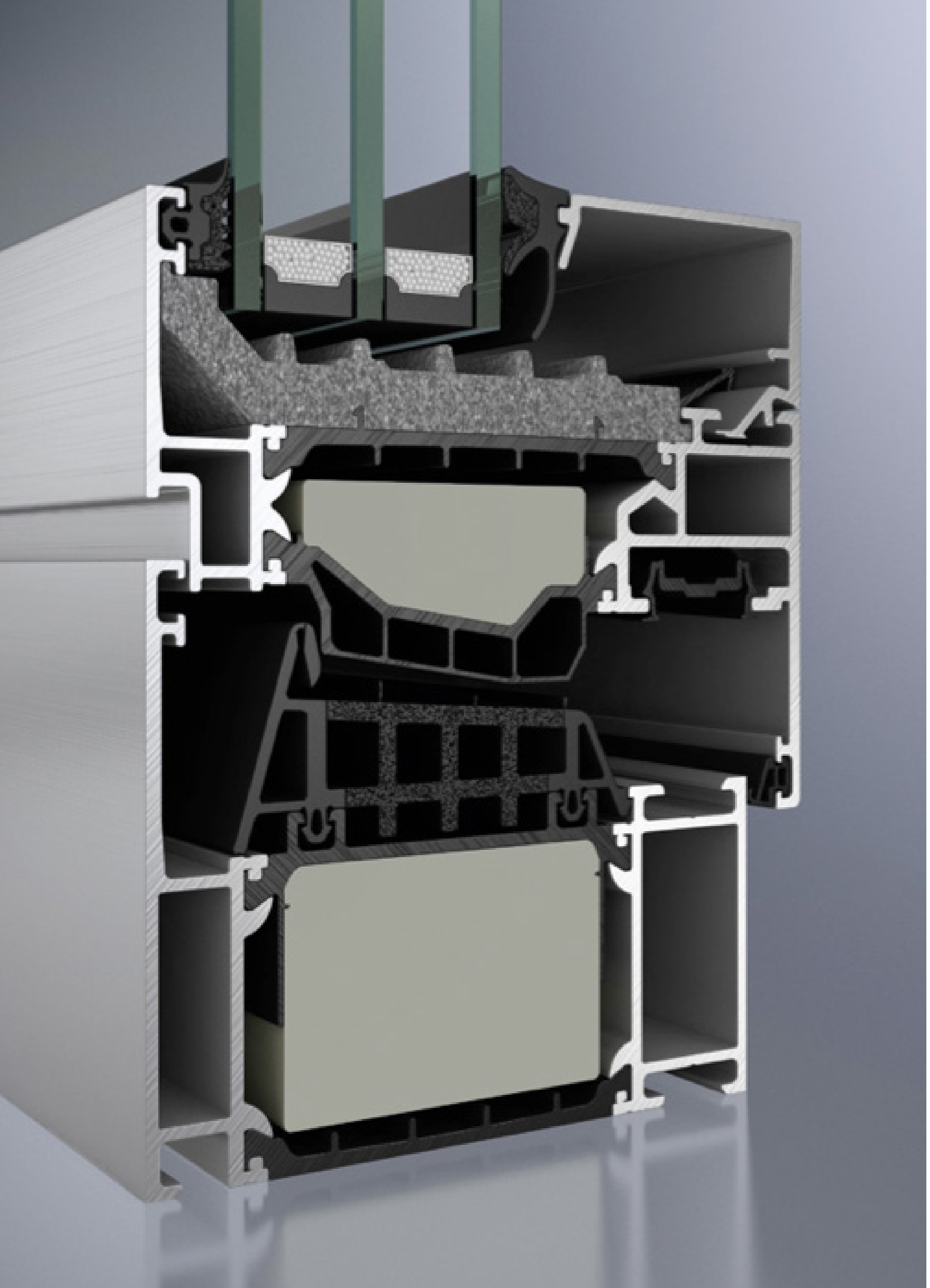


Fig. 6.14 Triple-glazed Schüco AWS 75SI thermally broken aluminium window

Once a building envelope is well insulated, the next key challenge is to control the air infiltration rate, as unwanted air changes will dominate the heat loss. Weather tests have long measured the air infiltration rate, weather resistance and stiffness of façade components, as discuss in TSC Report 1, *Aluminium and Durability*.[10] However, it was not until the mid 1990s that requesting and specifying the performative data on air infiltration rate became part of best practice. For windows and curtain walling this is typically measured in $m^3/m^2/hr$, for example the curtain walling of 240 Blackfriars Road by AHMM, reviewed in Chapter 7, achieves an air infiltration rate of 1.5 $m^3/m^2/hr$. The Passivhaus Standard takes a whole house approach to air infiltration by specifying the number of air changes per hour. It states an airtightness of 'a maximum of 0.6 air changes per hour at 50 Pascals pressure (ACH50), as verified with an onsite pressure test (in both pressurised and depressurised states).'[11]

Once an airtight building envelope is achieved it is essential to consider the number of air changes required for human inhabitation and the control of moisture in the internal environment, via trickle ventilators and the provision of operable windows, or mechanical air-to-air heat exchangers, which reclaim heat and the latent heat of evaporation from the exhaust air. Openable windows can be linked to a computer controlled Building Management Systems (BMS) and operated by stiff chain drives, which can be built into window transoms. This technique was pioneered on the Powergen Operational Headquarters, in Warwickshire, completed in 1994, designed by Bennetts Associates, with performance specification written by the author, which in collaboration with E. C. Harris included air infiltration rates for the aluminium windows and curtain walling. At night the BMS of the Powergen offices opens the windows to cool the exposed thermal mass of the concrete structure.[12] Many of the contemporary case studies in this report incorporate BMS as a key means of helping to achieve comfort conditions and a low energy performance.

Fig 6.15 Powergen Operational Headquarters, in Warwickshire, architect Bennetts Associates, 1994

Fixed Lights and Opaque Ventilators

One design strategy to minimise the slight lines of a glazing system, whilst providing natural ventilation operated by the occupants, is to combine the minimal sight lines of fixed glazing with opaque ventilators. This strategy was often used by Jean Prouvé, Le Corbusier and Louis I. Khan, primarily for its elemental clarity and the elegant simplicity of the fixed lights. Figure 6.16 shows the solid timber ventilators of the Margaret Esherick House, designed by Louis I. Khan and completed in 1962.

Fig 6.16 Margaret Esherick House, Chestnut Hill, Philadelphia, USA, architect Louis I. Khan, 1959-1962

In contemporary low energy architecture, architects are increasingly using the minimal simplicity of fixed double or triple glazing in thermally broken aluminium framing, combined with opaque insulated ventilators to provide natural ventilation. The insulated panels used to form the ventilators provide a lower U-value even than high performance triple glazing. The Engineering Building at Lancaster University and Cubbit House are two examples, as set out below.

The Engineering Building at Lancaster University, Lancashire, England, designed by John McAslan + Partners and completed early in 2015, at a capital cost of £8,400,000, is a taut and well considered engineering building that more than just accommodating the diverse functions of an engineering department – placing functions around a central atrium creating visual links between users. The plan is a creative slipping of three rectilinear volumes, sized for their primary function; with 12m clear-span labs, a 6m atrium and a 10.5m clear-span block containing labs and cellular office space.

Fig 6.17 The entrance of Lancaster University Engineering Building, architect John McAslan + Partners, 2015

Fig 6.18 The north façade of Lancaster University Engineering Building

A palette of self-finished materials compliments this clear spatial arrangement. This elegant building achieved BREEAM Outstanding by the integration of passive techniques, sectional geometry and orientation, combined with material selection, which included 50 per cent GGBS in the mix of the creamy coloured exposed in-situ concrete. In 2015 this project received a RIBA National Award.

Part of the elegance of Lancaster University Engineering Building is the use of fixed double glazed anodised curtain walling and windows with insulated opaque opening vents veiled by perforated anodised aluminium panels, set in a framework of yellow brick and creamy coloured precast concrete. Similar perforated anodised aluminium panels are used inside the atrium to accommodate acoustic insulation.

Fig 6.19 The façades of Lancaster University Engineering Building is a careful composition of glazing, perorated anodised aluminium, brick and precast concrete

Fig 6.20 [right] Detail of the perorated anodised aluminium panel veiling a ventilator

Cubitt House designed by Allford Hall Monaghan Morris (AHMM) is a six-storey housing block of ten apartments that forms part of the 240 Blackfriars Road project, completed in 2014, the office tower of which is described in Chapter 7. Cubitt House is located on the southern end of the site and is articulated as a separate block, yet maintains a related angular geometry. It is clad in dark-reddish brown almost black bricks, sourced from Germany, that form a common field of cladding, The double glazing is full height in each apartment, with simple and unobtrusive recessed detailing, made possible by an inward tilting opaque insulated panel that provides all natural ventilation – operated by the residents. When shut these ventilators read as part of the white internal walls or possibly an integrated cupboard.

Fig 6.21 [left] Cubitt House on Blackfriars Road designed by Allford Hall Monaghan Morris, 2014

Fig 6.22 An all-glazed corner window and opaque insulated ventilator inside an apartment of Cubitt House

The Eden Project, Biomes, Cornwall, England: Architect Grimshaw, 2001

In 1996, at a worked-out China Clay pit near St Austell, Cornwall, Tim Smit proposed the construction of an enclosure to grow plants to demonstrate ecology and biodiversity within a range of climates, from Mediterranean to tropical, like the Princess of Wales (Diana's) Pavilion at Kew Gardens, London, completed in 1987, but on a much larger scale. Grimshaw was a project partner and architect from a very early stage. At first Grimshaw with engineer Anthony Hunt worked 'entirely at-risk, since the Millennium Commission did not fund feasibility' studies, records Hugh Pearman.[13] Sir Nicholas Grimshaw observed: 'The project has held the office in thrall since the moment we got it. The brief was to build the largest plant enclosure in the world, but also to do this in the lightest and most ecological way possible.'[14]

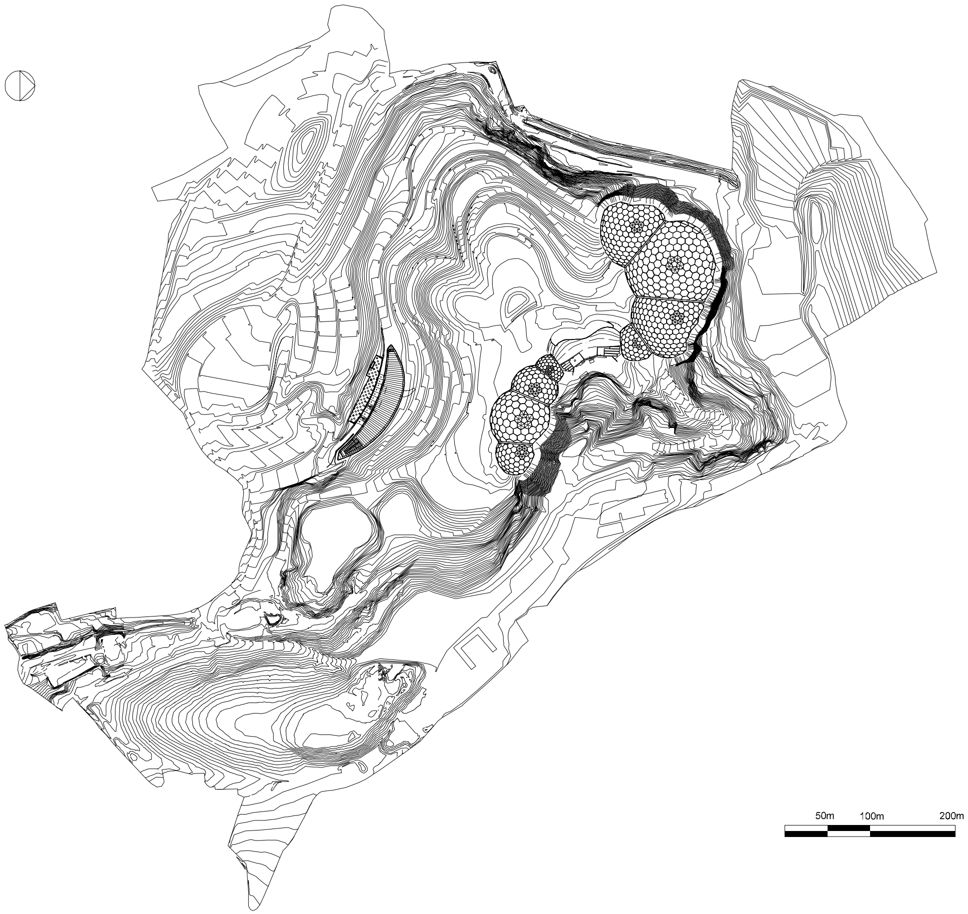


Fig 6.23 Site Plan of the Eden Project

Fig 6.24 The Eden Project Biomes designed by Grimshaw and completed in 2001

The initial designs resembled Waterloo International (1993) resting on the cliffs left by the extract of China Clay. This developed into a Buckminster Fuller inspired set of domes with a hexagonal geometry. Construction started early in 1999. Grimshaw described the biomes as 'a sequence of eight inter-linked geodesic transparent domes covering 2.2 hectares and encapsulating vast humid tropical and warm temperate regions.' [15] Observing the 'design of the biomes is an exercise in efficiency, both of space and of material. Structurally, each dome is a hex-tri-hex space frame reliant on two layers. The efficiency of the frame relies on the components of the geometric shapes: steel tubes and joints that are light, relatively small and easily transportable. The cladding panels are triple-layered pillows of high performance ETFE foil and environmentally efficient, with maximum surface area and minimum perimeter detailing.' [16]

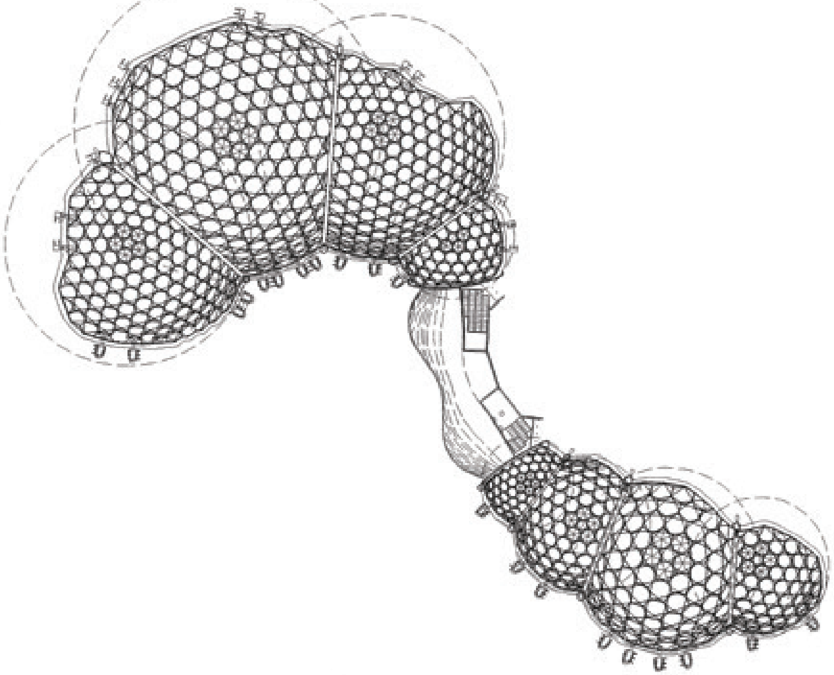


Fig 6.25 Plan of the eight intersecting Biomes of the Eden Project

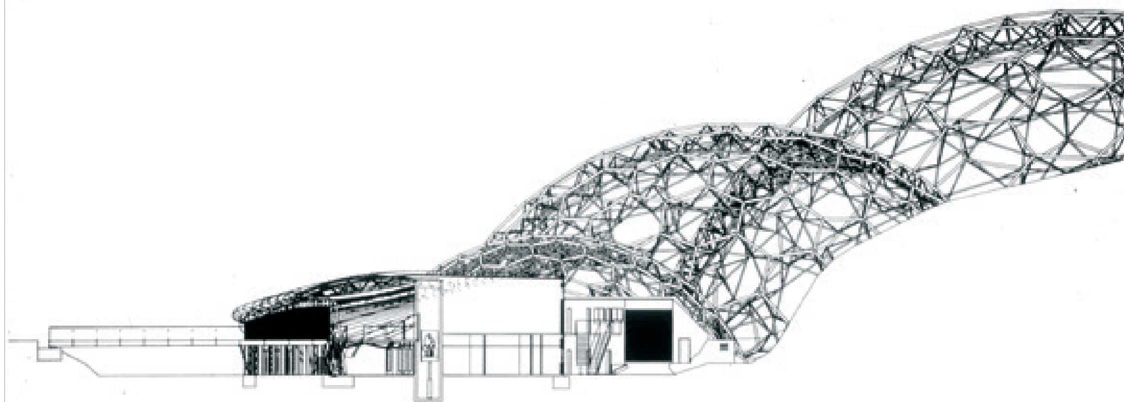


Fig 6.27 Section through the Eden Project Biomes

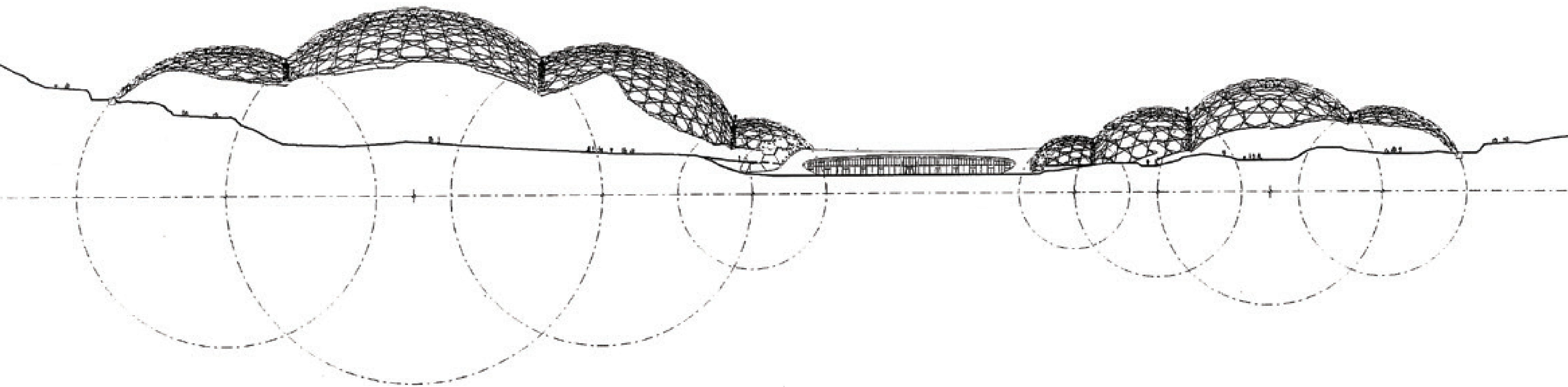


Fig 6.26 The geometric basis of the eight Biomes of the Eden Project

Fig 6.28 The rainforest Biome sheltered by the lightweight ETFE pillows

Fig 6.30 Openings in the façade provide ventilation, helping to control the internal environment

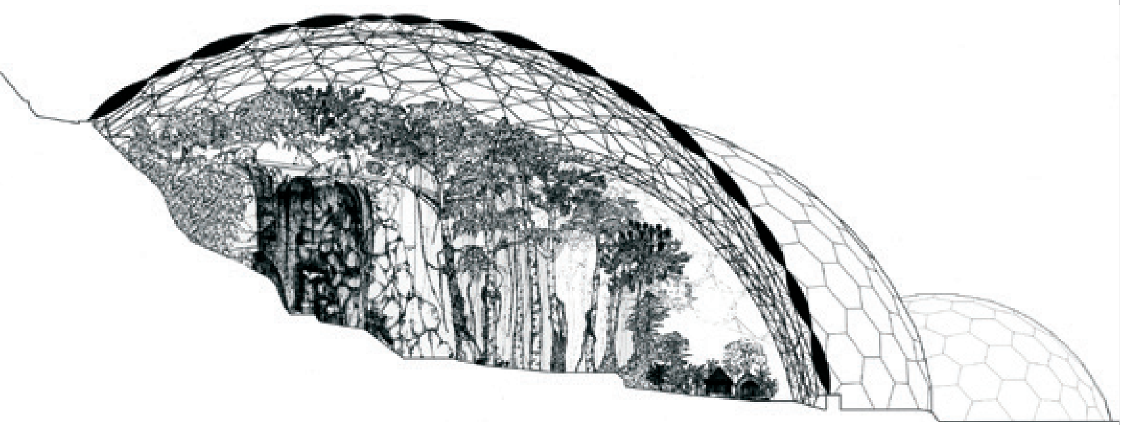


Fig 6.29 Section through a Biome

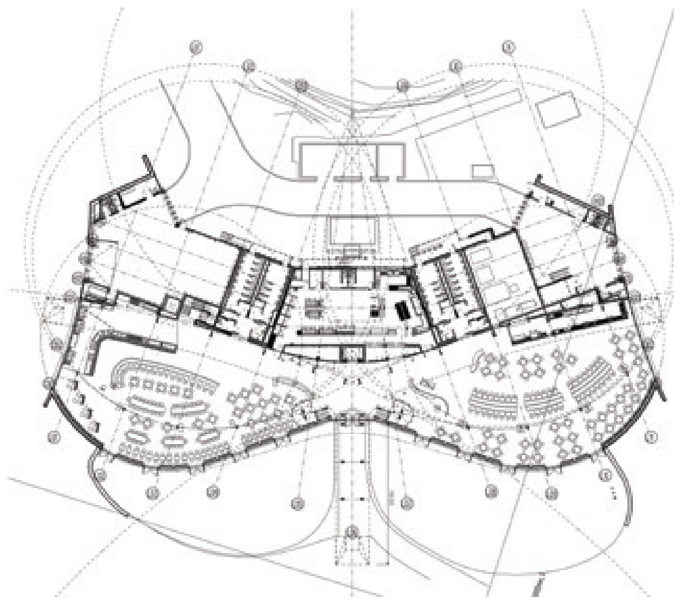


Fig 6.31 The 'heart' of the Eden Project

Fig 6.32 The nodes provide articulation to the building fabric with the ETFE providing light in during the day and views of the sky at night

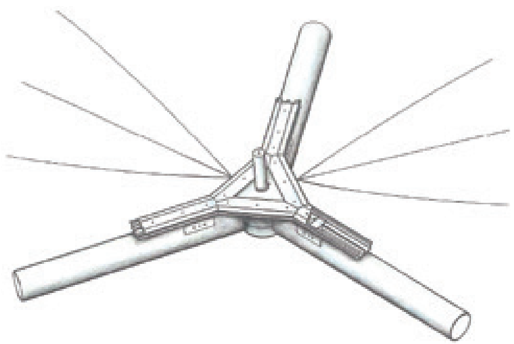


Fig 6.33 Node serving and supporting the ETFE inflated skin

Fig 6.34 The first ETFE pillow being installed on the aluminium hexagonal grid

The domes are based on 9-m hexagonal modules each with triple-layered inflated pillow of transparent ETFE foil, secured by aluminium extrusions. Hugh Pearman notes that 'the ETFE skin represents less than 1 per cent of the [mass] of equivalent glass.'[17] The combination of extruded aluminium sections securing and

Fig 6.35 The scale of the Eden Project Biomes is revealed by the abseilers

supporting inflated pillows of ETFE make the Eden Project Biomes an extreme example of light and slender architecture, minimising the materials needed to form an enclosure and maximising daylight.

At the centre of the plan is an earth-sheltered zone, which contains exhibitions, restaurant and services. The capital cost of the Eden Project was £53million in 2001. The Biomes officially opened on 17 March 2001 and received almost 2 million visitors in the first year. Eden is now one of the top three attractions in the UK, which charges for admission, and the second most visited destination outside London.[18]

Fig 6.36 The light and slender aluminium framing of the ETFE pillows and steel structure of the Eden Project provides expansive views of the night sky

'Work stops at sunset. Darkness falls over the building site. The sky is filled with stars. "There is the blueprint." they say' - Italo Calvino, Invisible Cities

Dún Laoghaire Rathdown Lexicon Library & Cultural Centre: Carr Cotter & Naessens Architects, 2014

The fabric of the town of Dún Laoghaire on Dublin Bay, the east coast of Eire, dates from the 1820s. You may know the town by its anglicised name – Dunleary. In the nineteenth century the town grew rapidly due to its large harbour, served by the first railway in Ireland, which opened in 1834.

Fig 6.37 Dún Laoghaire Rathdown Lexicon Library and Cultural Centre, designed by Carr Cotter & Naessens Architects, viewed from the harbour

Dún Laoghaire Rathdown Lexicon Library and Cultural Centre, designed by Carr Cotter & Naessens Architects, is located close to the town centre in an old quarry, from which the granite used to build the harbour's piers was extracted. The harbour was constructed between 1817 and 1859. The site of the drl Lexicon looks out onto this harbour across Queen Street. The quarry became a reservoir serving the steamships in the harbour. In 2007, Dún Laoghaire Rathdown County Council selected this site for a new library, cultural centre and enhanced public realm. During 2008, Carr Cotter & Naessens Architects, who are based in Cork, won the two-stage design competition organised by Royal Institute of Architects of Ireland (RIAI). Although controversial, the project survived the recession in Eire resulting from the global banking financial crisis. The Irish Times announced it's opening on 8 December 2014 with the headline 'Dún Laoghaire's controversial library quietly opens its doors'.[19] The local authority had prudently reserved funds for this new civic building. The capital cost of the dlr Lexicon was €29.5million (approximately £23million) in 2014.[20]

Fig 6.38 Carr Cotter & Naessens Architects' context sketch of the dlr Lexicon

The architects found the site to be a neglected pleasure garden encompassing a reservoir. They observed that 'Moran Park occupies a strategic location in Dún Laoghaire; it visibly demonstrates the natural fault line between the harbour and the town. The old park was dysfunctional; the abrupt changes in level and the walled-in reservoir reinforced the disconnection between the commercial precinct of the town and the harbour. The project was an opportunity to rebalance, and make the park a new centre of gravity that would reconnect these domains.'[21]

Creating a new public place anchored by a civic landmark, a multi-media library and cultural hub for the whole community. Carr Cotter & Naessens Architects observe; 'library design has evolved; contemporary libraries are seen as interactive knowledge hubs, a place for public assembly and exchange; this new design paradigm has informed the building design however at heart the building is concerned with universal qualities of space and light, a good public room.'[22]

Fig 6.39 Pedestrian route and entrance of dlr Lexicon

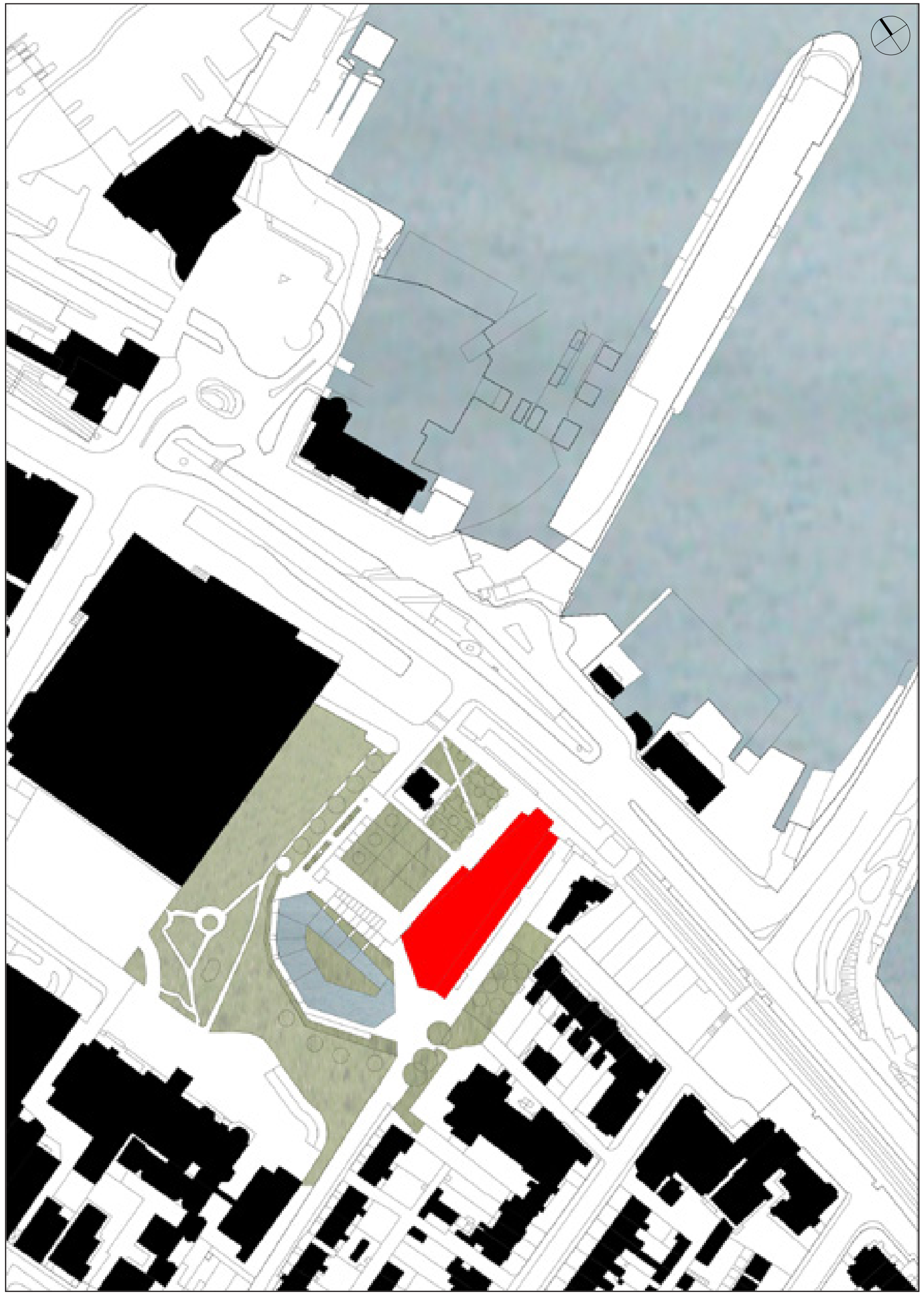
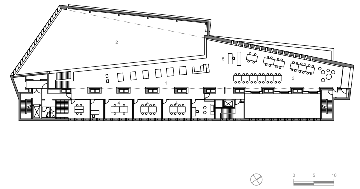
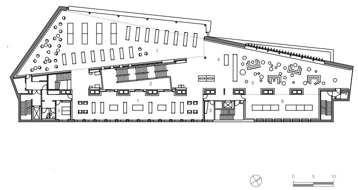


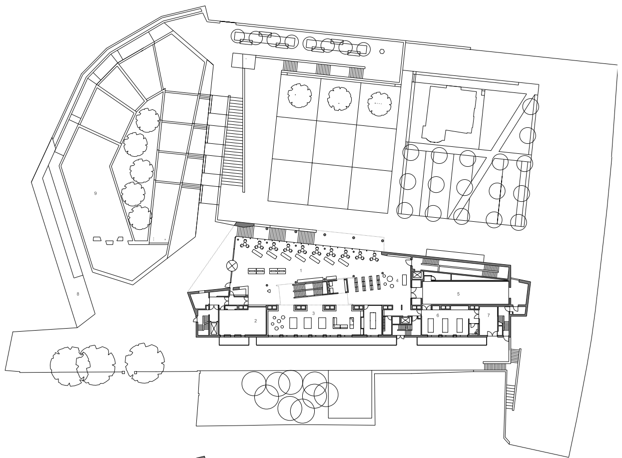
Fig 6.40 Site plan of the dlr Lexicon, nts



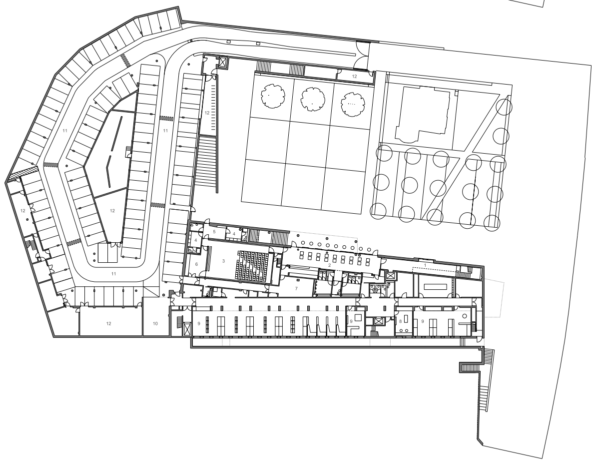
Level five:
1 Special collections
2 Void
3 Local studies
4 Community room
5 Information desk



Level four:
1 General lending
2 Void
3 Staff office
4 Information desk
5 Children's lending
6 Children's reading

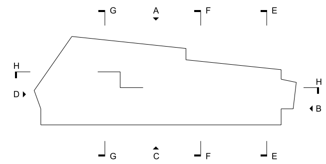


Level three:
1 Lobby
2 Book returns
3 Teenage space
4 Information desk
5 Gallery
6 Workshop
7 Store



Level One:
1 Entrance
2 Cafe & Ticket office
3 Auditorium
4 Dressing room
5 Green room
6 Backstage
7 Kitchen
8 Coffee room
9 Office
10 Loading bay

Fig 6.41 Carr Cotter & Naessens Architects' plans of the dlr Lexicon, showing levels one, three, four and five, nts



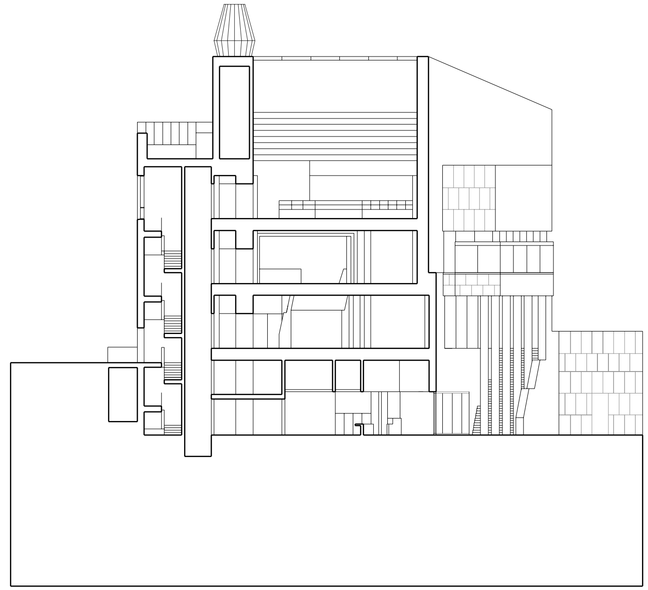


Fig 6.42 Carr Cotter & Naessens Architects' section F-F of the dlr Lexicon, nts, including plan showing section lines

The dlr Lexicon houses more than just a library, it encompasses a 100-seat theatre, art gallery, café, workshops and meeting spaces. On its opening, county librarian Maireád Owens noted 'the Lexicon embraces the modern concept of what a library should be, a key community space where all are welcome'.[23]

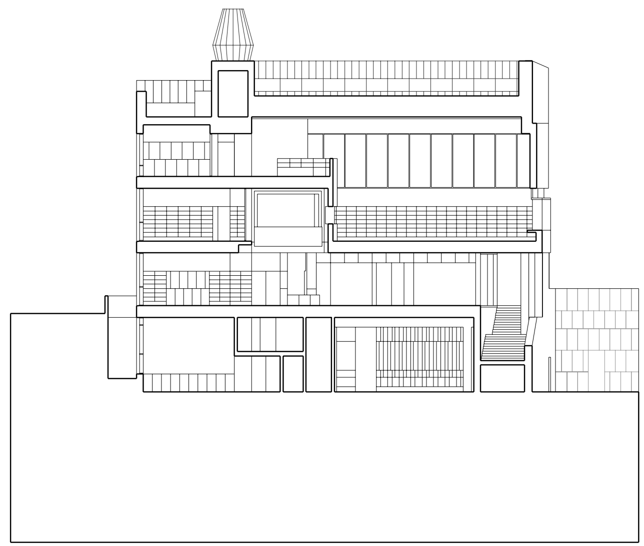


Fig 6.43 Carr Cotter & Naessens Architects' section G-G of the dlr Lexicon, nts

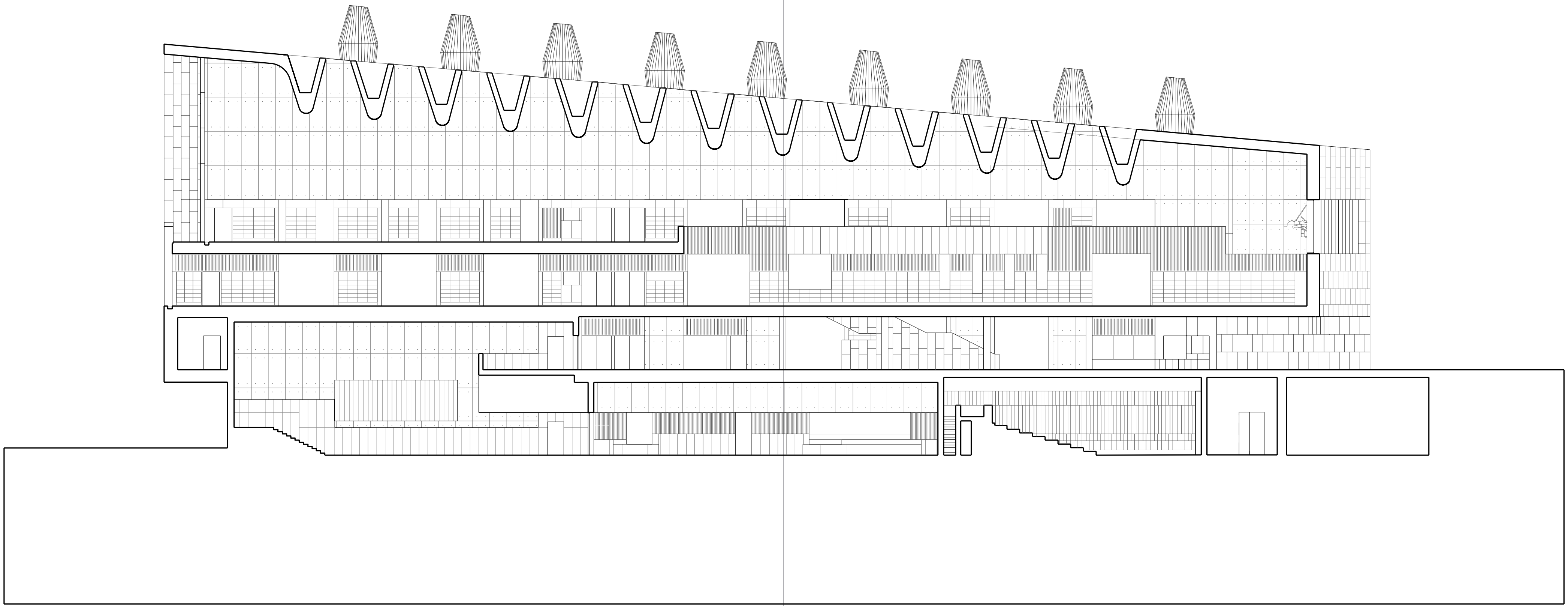


Fig 6.44 Carr Cotter & Naessens Architects' section H-H of the dlr Lexicon, nts

Carr Cotter & Naessens Architects combine the form, environmental tectonics and materials of the dlr Lexicon to articulate its civic role and internal life. The carefully considered palette of materials is spare and robust. The plan is structured by a row of concrete piers that become natural ventilation shafts that terminate in a series of roof cowls. This generates two volumes: the southern volume that houses the servant spaces is rectilinear, clad in brick, and continues the scale of Haigh Terrace; and the northern volume facing onto the park houses the public rooms of the library and cultural centre. This is clad in granite, as Dún Laoghaire is a granite town. However, no local quarries were large enough to fulfil this order, thus geologically identical granite was sourced from Galicia.

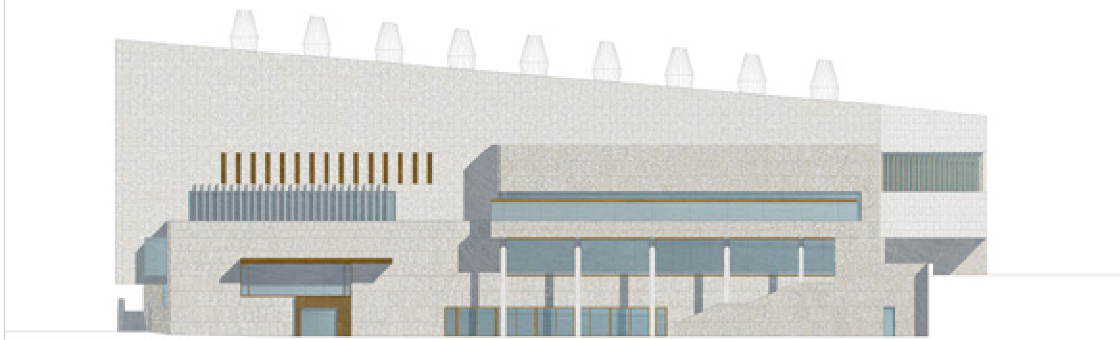
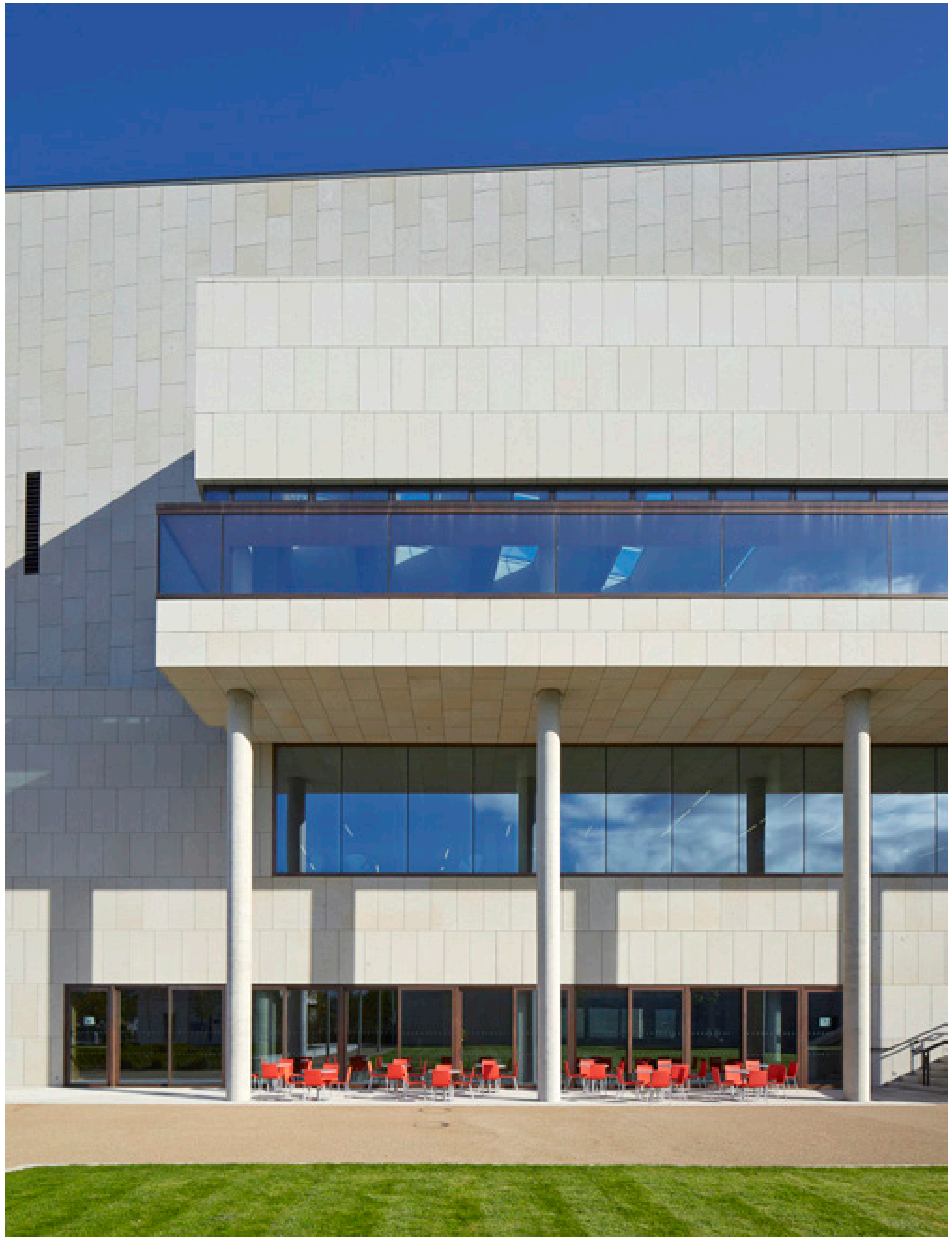


Fig 6.45 The granite clad north west façade of dlr Lexicon, nts

Fig 6.46 The Reading Room, shortly before occupation, looking south west

Services are carefully integrated and a biomass boiler, using timber from the local parks, powers the dlr Lexicon. The principle materials of the interior are a cream white fair-faced in-situ concrete and timber. The exposed 50 per cent ground granular blast slag (GGBS) based concrete provides thermal mass. All public spaces are naturally ventilated. The roof top cowls filter fresh air via house heat exchangers and heated or cooled air is supplied to the floor void for discharge at low level. Louvres located in the V-beam are linked to the Building Management System to exploit the stack effect. Project architect Lousie Cotter observes 'the building was conceived as a landmark with a minimum design life of 60 years for the components and 100 years for the structure'.[24] The materials selected are low maintenance, however, ease of maintenance has also been designed in to the project.

Fig 6.47 [opposite] The Reading Room, supported by piloti from the Café terraces



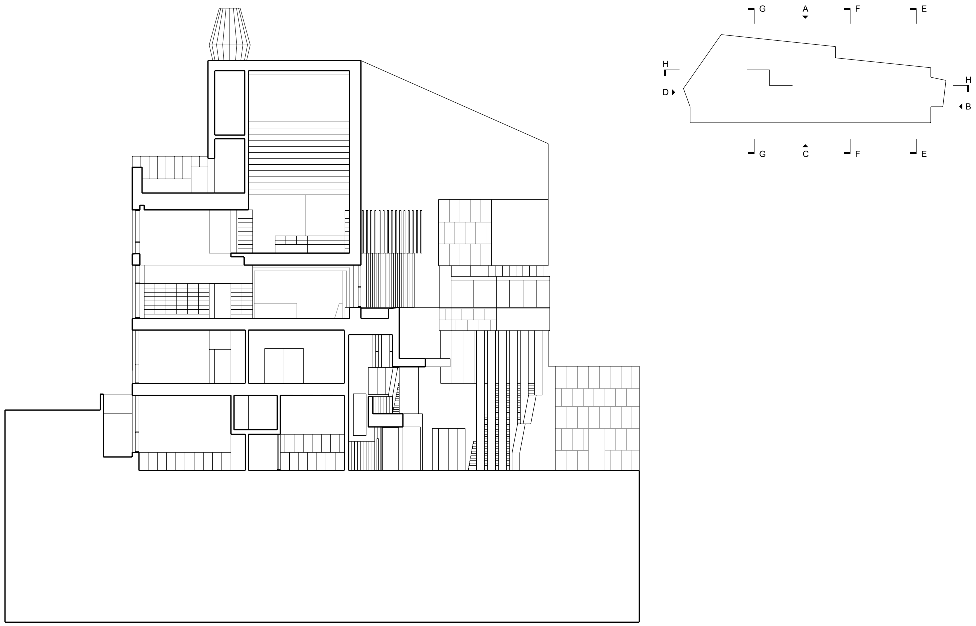
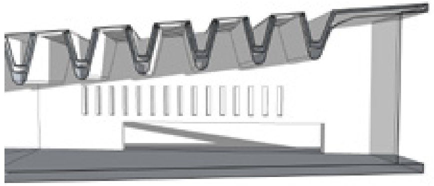


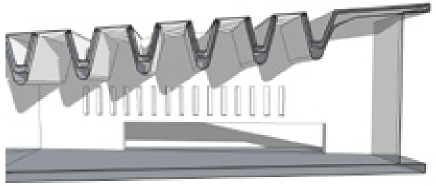
Fig 6.48 Carr Cotter & Naessens Architects' section E-E of the dlr Lexicon, nts

The change of level across the site of six meters is key to the design of this cultural centre, which can be entered at two levels. At the lower park level is the café/bar and theatre with library administration located behind these spaces. The park level is linked to the street level by internal and external staircases. Street level of the dlr Lexicon accommodates a lobby, book returns and a 'teenage space'. When the centre is closed the public realm remains linked by the generous external stairs. From the street level of the library the route turns around and the staircase is oriented with the roof that is also rising towards the seashore. The general lending library is located on level four, the 'piano nobile', with the childrens library, and an almost frameless the 'sea' window. The route culminates on the fifth floor and the local studies space, which benefits from the large scaled 'sea' window and its views of the harbour. This is the opposite of an Aldo Van Eych window scaled for the users. This window is a major civic gesture. Lousie Cotter notes that 'as people ascend the building it progressively gets quieter and more tranquil.[25]

Fig 6.49 The civic scale 'sea' window of the dlr Lexicon



20 March 8 am



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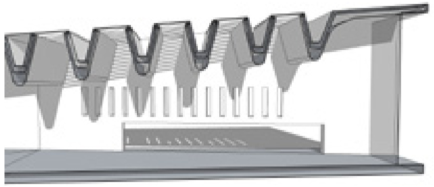
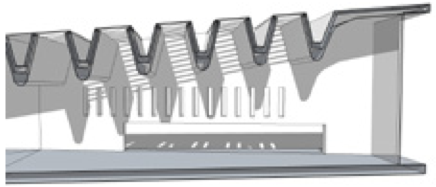
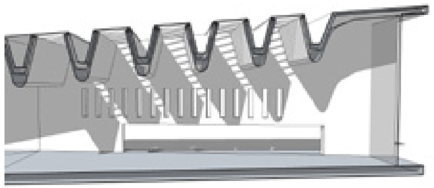


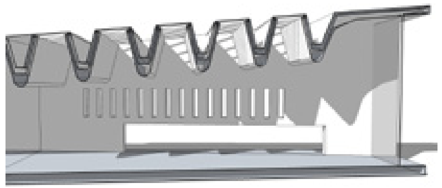
20 March 10 am



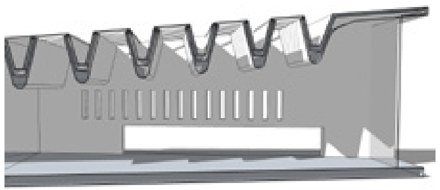
20 March 11 am



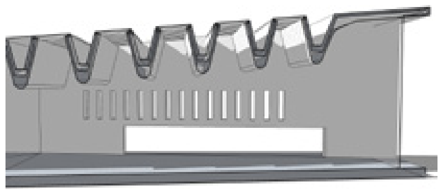
20 March 12 noon



20 March 1 pm



20 March 2 pm



20 March 3 pm

Fig 6.50 Carr Cotter & Naessens Architects' daylight studies of dlr Lexicon

Fig 6.51 Carr Cotter & Naessens Architects' long section through dlr Lexicon

Daylight is a key quality of the dlr Lexicon. Lousie Cotter observed 'significant design time was expended on working out optimum locations, orientations and specifications' of the windows and rooflights.[26] 'The daylight had to be calculated: we modelled the interior of the building, looking at where the sun can in at different times of the day and different times of the year because the windows are a really a critical part of the choreography of the building, it all about light and views really, and also space'.[27]

The top level, the fifth floor, houses the reference collection, local studies and a community meeting room, here the inclined roof of the dlr Lexicon is formed by V-shaped precast concrete beams. The rooflights are flush with the plane of the roof and made of Schüco FW50+ SG system – a high performance thermally insulated aluminium-framing system. Originally these rooflights had been on the inclined slope of the V-shaped beams, but when the architects modelled this arrangement the daylight was insufficient

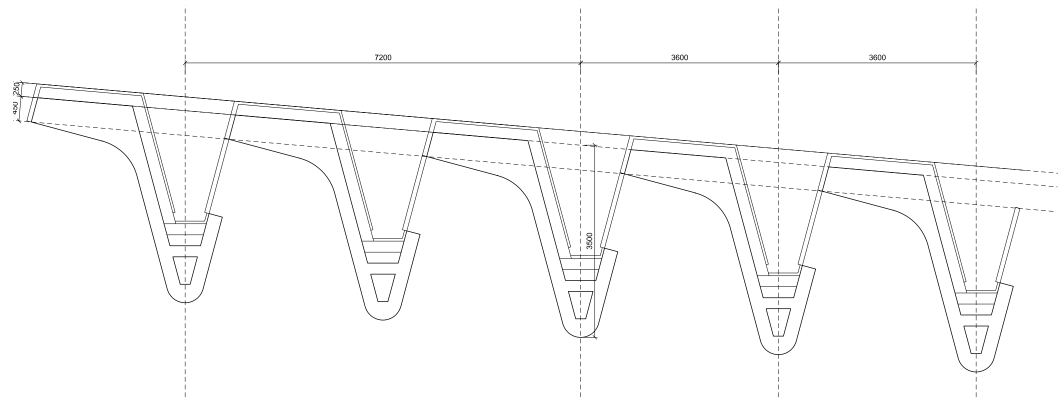


Fig 6.52 Rooflight detail of the dlr Lexicon, nts

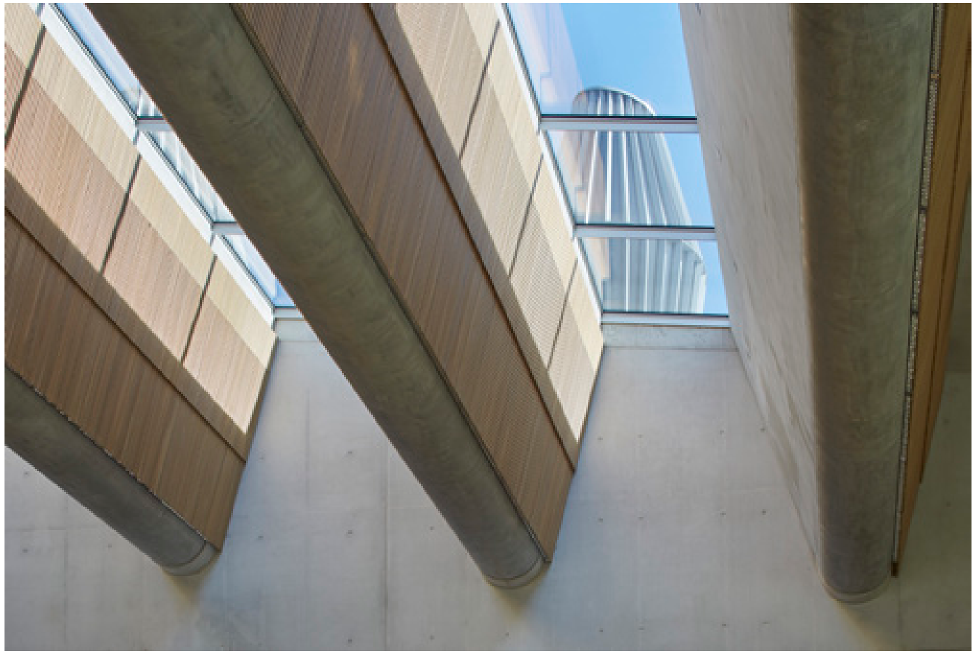


Fig 6.53 A roof cowl viewed through the rooflight glazing

and thus they made the rooflight flush with the roof to maximise the available daylight.[28] As well as daylight, passive solar design was a key consideration in the design of this building, to optimise the amount of energy that can be derived directly from the sun for winter heating, while minimising solar gain in summer to prevent overheating.

Carr Cotter & Naessens Architects prepared a very detailed performance specification for the glazing systems with input from façade consultants Billings Design Associates, founded by Sean Billings. The complete glazing package was won in tender by Schüco; predominately using its thermally efficient aluminium framed glazing systems. The scale of the major civic 'sea' window of the library necessitated the use of Schüco Jansen stainless steel sections.

Fig 6.54 Haigh Terrace elevation, bronze anodised aluminium louvres and window set in a façade of brick and stone

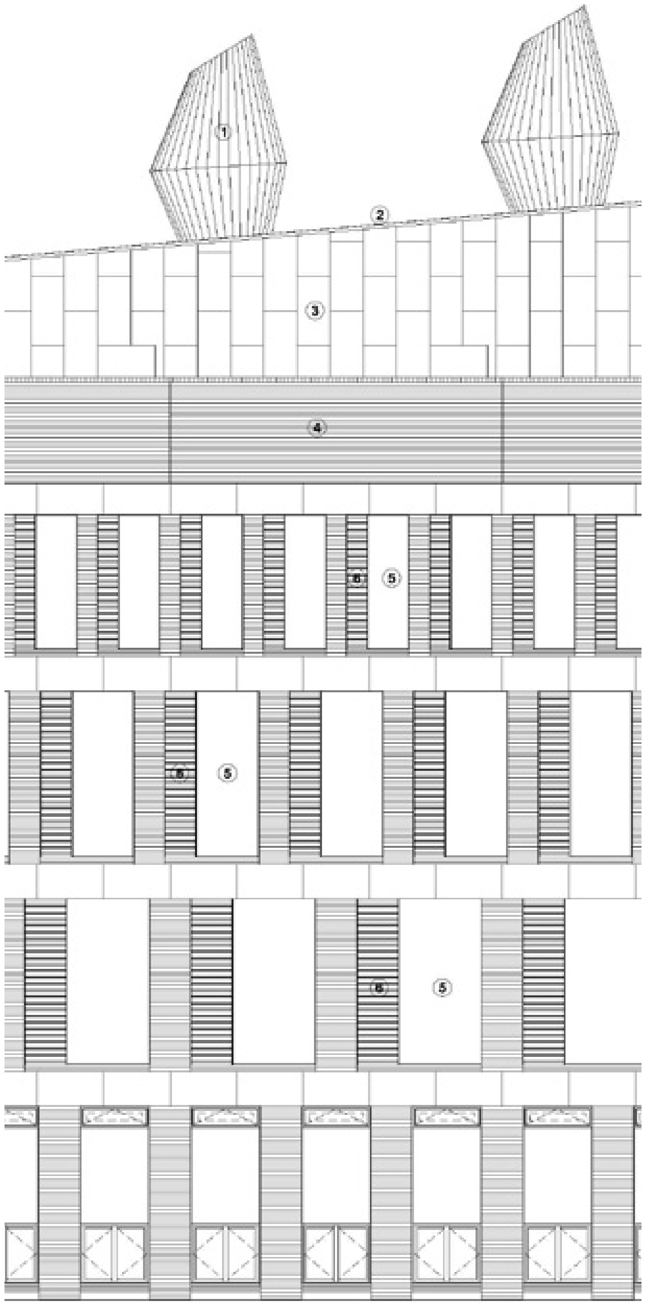


Fig 6.55 Carr Cotter & Naessens Architect's Haigh Terrace elevation, nts

1 Roof cowls
2 Zinc roofing
3 Stone cladding on support system
4 Brickwork cladding
5 Schueco FW50 + SG window system with inward opening sections
6 Bronze anodised aluminium louvres

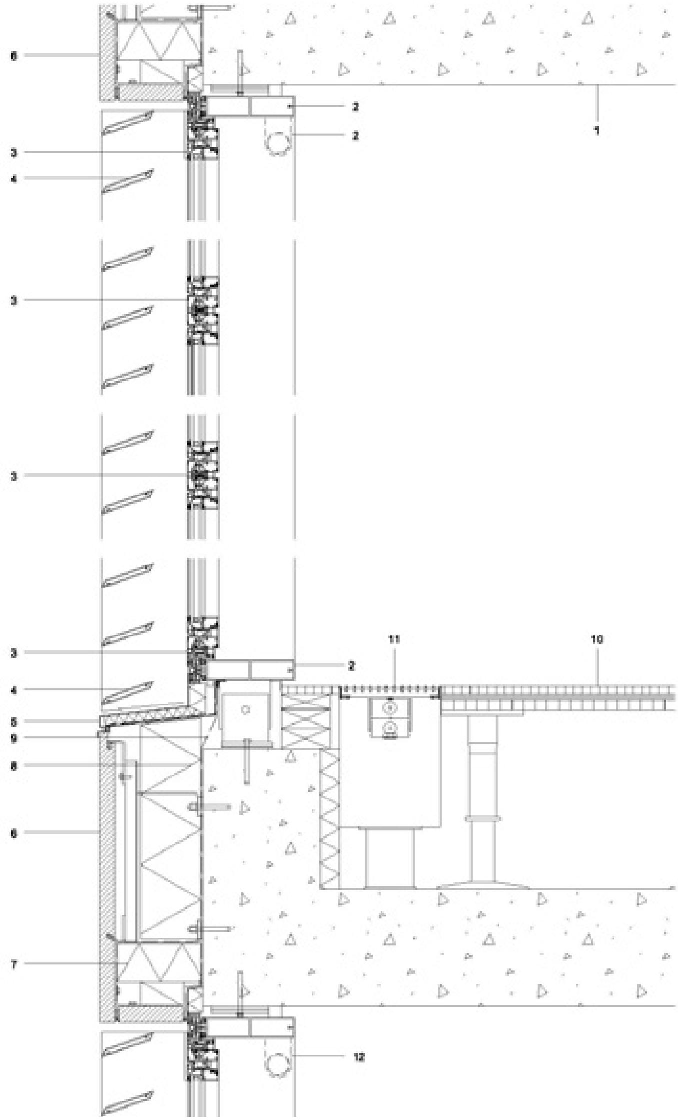


Fig 6.56 Carr Cotter & Naessens Architect's detailed elevation through the Haigh Terrace elevation

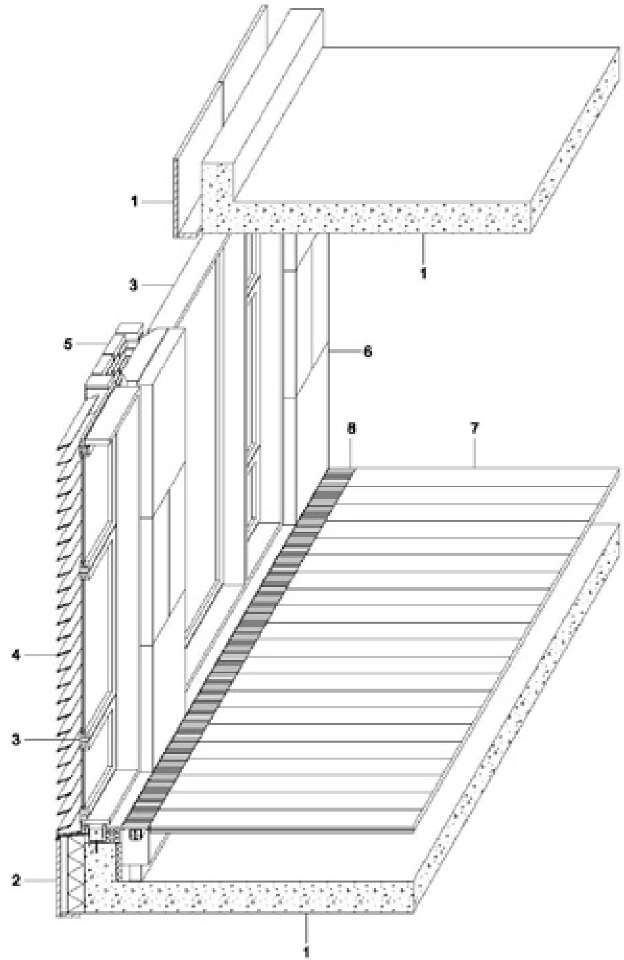
1 In-situ concrete structure, 2 Bronze anodised aluminium special extrusion transom and fixing brackets, 3 Schueco FW50 + SG window system with inward opening sections, 4 Bronze anodised aluminium louvres, 5 Bronze anodised aluminium cill, 6 Stone cladding on support system, 7 Fire stopping system, 8 Cavity insulation, 9 EPDM membrane, 10 Oak flooring, 11 Trench heater, 12 Roller blind

The south east façade responds to the scale of the houses in Haigh Terrace and is a considered composition of bronze anodised thermally broken aluminium windows and zones of bespoke bronze anodised brise soleil shading with inward opening bronze anodised aluminium windows, set in brickwork that is articulated by horizontal bands of stone.

Fig 6.57 Looking out towards Haigh Terrace

Fig 6.58 Carr Cotter & Naessens Architect's elevation drawing of the construction of Haigh Terrace

1 In-situ concrete structure
2 Stone cladding on support system
3 Schueco FW50 + SG window system with inward opening sections
4 Bronze anodised aluminium louvres
5 Brickwork cladding
6 Timber wall cladding
7 Oak flooring
8 Trench heater



Gary Boyd, writing in the Architects Journal, described dlr Lexicon as 'an extremely well-worked and considered architectural gesamtkunstwerk – erected in a period of specialisation, austerity, and economic optimisation – it evokes, in almost all of its spaces, an unquantifiable faith in architecture. For Dún Laoghaire and its indefinable hinterlands, it provides not only a library but a beacon for what public architecture can and should be.'[29]

Lousie Cotter is justifiably proud of the impact of the cultural centre 'with over 10,000 visitors a month … and library membership has increased by a third.'[30] Her practice has contributed to the creation of successful sustainable civic architecture for this Irish seaside town.

Fig 6.59 The General Lending Library of dlr Lexicon, designed by Carr Cotter & Naessens Architects

Notes

1 S. Carlisle, E. Friedlander & B. Faircloth (2015), *Aluminium and Life Cycle Thinking: Towards Sustainable Cities*, Cwningen Press, Llundain.
2 U-value calculation for windows, INOUTIC, www.inoutic.de/en/tips-on-window-purchase/saving-energy/u-value-for-windows/ (accessed September 2015).
3 This method is used in Germany (DIN standard) and is now adopted by ISO 10077(2000). As cited in H.Wang, *Thermal Transmittance (U-value) Assessment of Glazing Frame*, CWCT, University of Bath, available online at www.bath.ac.uk/cwct/cladding_org/fdp/paper17.pdf (accessed September 2015), p. 143. For additional information on u-value calculations and UK Building Regulations Part L see B. Anderson (2006), Conventions for U-value calculations, BRE, Scotland, available online at www.bre.co.uk/filelibrary/pdf/rpts/BR_443_(2006_Edition).pdf (accessed September 2015)Part L1 of the Building Regulations can be downloaded from www.planningportal.gov.uk/uploads/br/BR_PDF_ADL1_2002.pdf (accessed September 2015)
4 *The real beauty of the FWS 60 CV façade is what you don't see*, Schüco Partner 01, 2016, Schüco UK, Milton Keynes, p.16.
5 *New: uniquely slim FWS 35 PD façade is Passive House certified*, Schüco Partner 01, 2016, Schüco UK, Milton Keynes, p.12–13.
6 This section has benefited from input by Ron Fitch, Design Manager of Trimo and Justin Furness, Technical Director of CAB.
7 D. Mooney, *Why is Daylight design the Cinderella of Building Modelling*, www.cibse.org/getmedia/b2115002-15e6-4380-8871-541e44156102/Daylight-Design_The-Cinderella-of-Building-Simulation.pdf.aspx (accessed April 2016).
8 Saint Gobain Glass (2006) *Saint Gobain Glass Guide,* UK Edition, p.345
9 S. Carlisle, E. Friedlander & B. Faircloth (2015), *Aluminium and Life Cycle Thinking: Towards Sustainable Cities*, Cwningen Press, Llundain, p. 32.
10 M. Stacey ed., (2014), *Aluminium and Durability: Towards Sustainable Cities*, Cwningen Press, Llundain, second edition 2015.
11 www.passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm, (accessed April 2016).
12 The Powergen Operational Headquarters is discussed further in M. Stacey (2015), *Aluminium Recyclability and Recycling: Towards Sustainable Cities*, Cwningen Press, Llundain, pp. 203–204
13 H. Pearman (2000), *Equilibrium: The Work of Nicholas Grimshaw & Partners*, Phaidon, London, p.118.
14 N. Grimshaw cited by H. Pearman (2000), *Equilibrium: The Work of Nicholas Grimshaw & Partners*, Phaidon, London, p. 116.
15 http://grimshaw-architects.com/project/the-eden-project-the-biomes/ (accessed April 2016).
16 http://grimshaw-architects.com/project/the-eden-project-the-biomes/ (accessed April 2016).
17 H. Pearman (2000), *Equilibrium: The Work of Nicholas Grimshaw & Partners*, Phaidon, London, p.123.
18 http://grimshaw-architects.com/project/the-eden-project-the-biomes/ (accessed April 2016).
19 www.irishtimes.com/news/environment/dun-laoghaire-s-controversial-library-quietly-opens-its-doors-1.2030302 (accessed April 2016).
20 Check Partner p.8 29.5 euros
21 www.ccnarchitects.net/dlr-lexicon/(accessed April 2016).
22 Sourced from CC&N's unpublished description of DLR Lexicon.
23 www.irishtimes.com/news/environment/dun-laoghaire-s-controversial-library-quietly-opens-its-doors-1.2030302 (accessed April 2016).
24 *New Library and cultural centre is a game-changer for Irish seaside town*, Schüco Partner 01, 2016, Schüco UK, Milton Keynes, p.7.
25 Ibid, p.9.
26 Ibid.

27 Ibid.
28 Ibid.
29 G. Boyd (13 November 2014), Beacon of enlightenment: The Lexicon by Carr Cotter & Naessens, Architects Journal, pp. 48–57.
30 *New Library and cultural centre is a game-changer for Irish seaside town*, Schüco Partner 01, 2016, Schüco UK, Milton Keynes, p.11.

aluminium: flexible and light

Aluminium: Performative Façades

This chapter focuses on the role of aluminium in creating or supporting performative façades. The first example in the introduction to this chapter is the opaque panels of QbissAir, which uses the reflective quality of aluminium to help create a unitised walling system that provides a very low U-value without conventional insulation products. The introduction concludes with a brief comparison of the pioneering bespoke parametric design of 30 St Mary Axe by Foster + Partners (2004) and Schüco's parametric aluminium curtain walling system (2015).

This is followed by four case studies, two of which illustrate the performative benefits of double facades; Melvin J. and Claire Levine Hall by KieranTimberlake (2003) and iPADF, an integrated passive and active double facade system (2012), a prototype double façade with distributed services, researched and designed by Dr Aneel Kilaire working with The University of Nottingham Architecture and Tectonics Research Group. Following a case study of the well informed and highly resolved tectonics of 240 Blackfriars Road, London, (2014), by Allford Hall Monaghan Morris, with is crisply detailed unitised aluminium curtain walling. The chapter concludes with the remarkable i360 in Brighton, (2016), designed by Mark Barfield Architects, which uses expanded aluminium cladding to reduce vortex shedding on the this 160.5m tall and elegant tower.

Thus, this chapter incorporates further performative roles for aluminium in the delivery of sustainable architecture and infrastructure or emphasises qualities apparent in earlier chapters. However, the importance of a holistic and collaborative approach to the design and realisation architecture in the twenty first century remains a key theme throughout.

QbissAir is a unitised total wall system designed to maximise the internal floor space of a building by being up to three times thinner than traditional façades, developed by Trimo of Slovenia and launched in 2011. It comprises opaque, translucent and transparent modules, which are designed to self-span between the floor slabs of a building. Each module consists of an inner and outer skin that incorporates internal insulation chambers of still air. The system is designed to be installed from inside the building, eliminating the need for external access. QbissAir is a modular façade system, which demonstrates how the science of thermodynamics can be used to produce a highly insulated product with low g-values and minimum air leakage, whilst maintaining a minimal wall thickness. In other words, it elegantly provides a high performance and low carbon building fabric.[1]

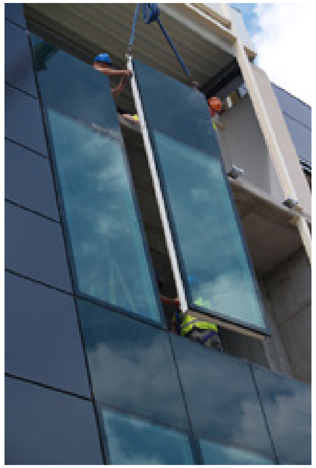


Fig 7.1 QbissAir modular façade system is fixed from inside the building

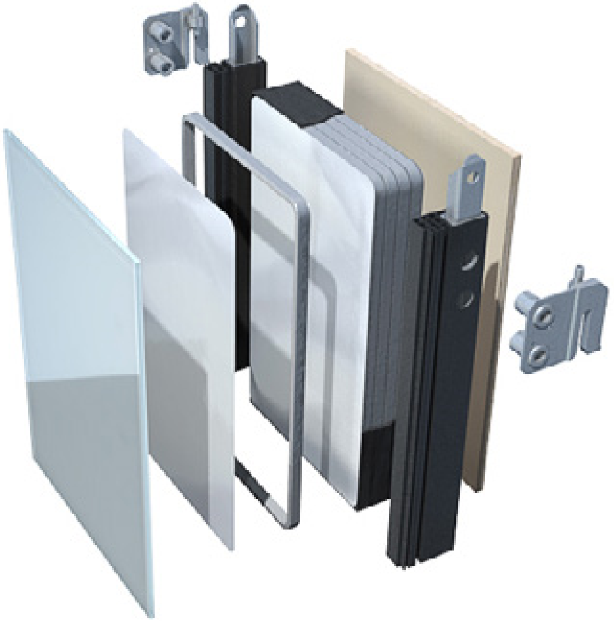


Fig 7.2 Digital model of the layered construction of an opaque panel in QbissAir façade system

Fig 7.3 QbissAir unitised façade system including an opening light

Fig 7.4 Load testing of a QbissAir façade panel

A key feature of the design of QbissAir is its excellent thermal performance, which is achieved by controlling the thermodynamics of the system rather than using solid insulation materials. QbissAir is a range of clear, translucent and opaque modules of identical thickness, which can be installed from inside the building. A QbissAir glazed façade can achieve a U-value of 0.35w/m^{2}k and a G-value of 0.1 at an overall thickness of 133mm. Acoustic performance averages 45db and air tightness is 1.2 m^3/m^2/hr @50 Pa.

QbissAir opaque façade panels can achieve a U-value of 0.19w/m^{2}k, at an overall thickness of 133mm. It is the reflective quality of aluminium in the form of foil layers that is key to this performance. 'By using thermodynamics, the development team engineered a solution of internal chambers that reflect radiation, minimise conduction and limit heat transmission. Aluminium foil chambers are used for opaque modules and low-E coated glass is used for clear modules, which also contains inert low conductive gases, such as argon' observed Ron Fitch, Design Manger of Trimo.[2]

Also unique to the system is the incorporation of structural members within the modules, eliminating the requirement for a secondary support structure such as a curtain wall. The external skin is normally glass [enamelled, translucent or transparent] but a range of alternative materials and finishes are also available. The system is manufactured using structural glazing technology, therefore no external frames or caps are necessary. QbissAir is offered internally framed by either extruded polymer profiles or extruded aluminium profiles. When installed, QbissAir provides a flush internal and external face with no intermediate mullions or transoms. The joints between modules are sealed with 20mm recessed gaskets.

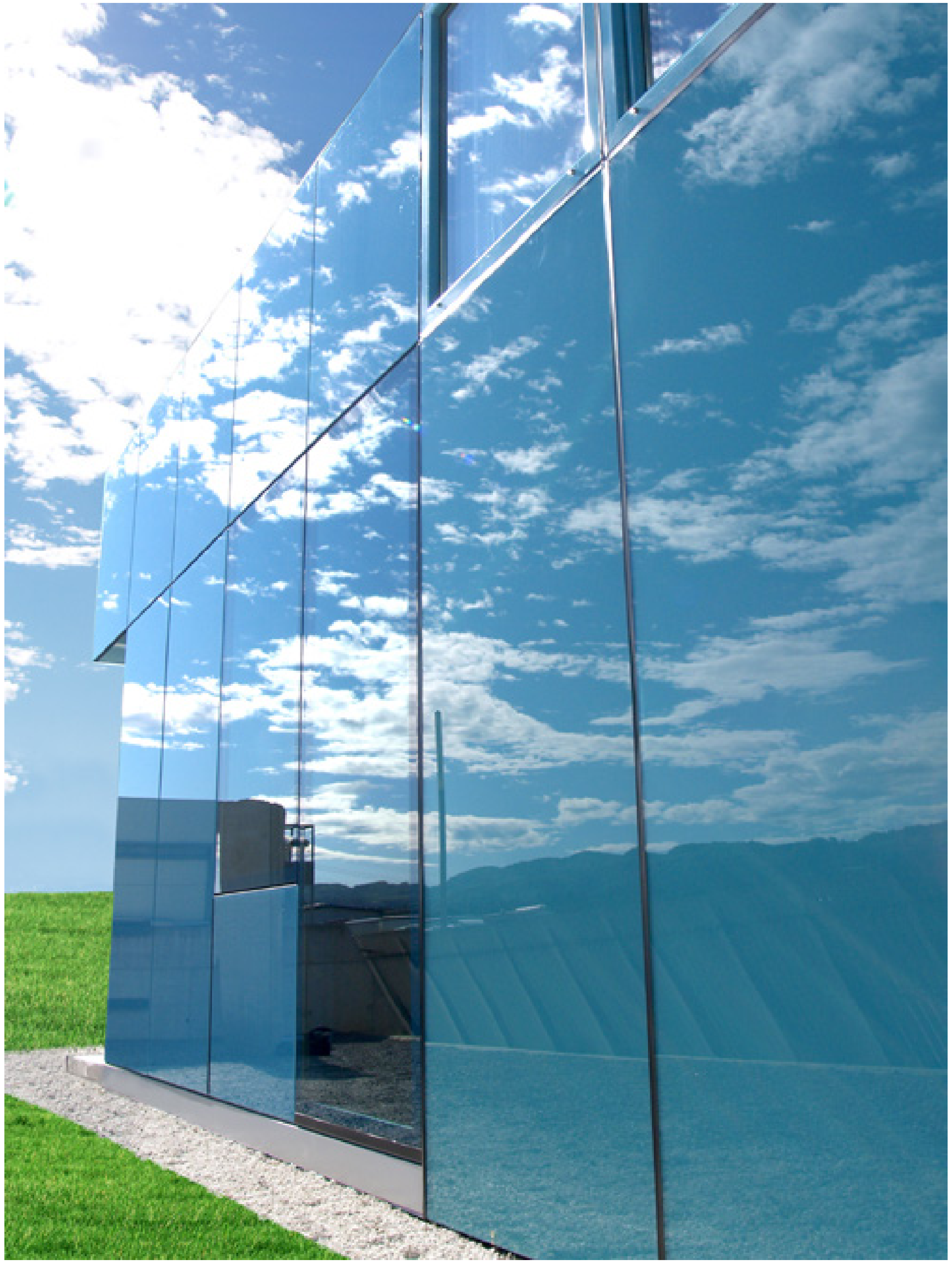


Fig 7.5 QbissAir unitised cladding system

The first decade of the twentieth first century witnessed the rapid adoption of parametrically designed architecture and building façades. 30 St Mary Axe, London, is a 180m tall, environmentally progressive, office building designed by Foster + Partners, completed in 2004. It is one of the first parametrically designed tall buildings in the world, based on geometry generated by seven tangents rotated through 360°, which results in a gently tapering aerodynamic form. Characteristically of Norman Foster it is also an excellent example of investment in early and experimental design. The development of the parametric modelling benefited from the extended planning approval process on a 'controversial' site: the Baltic Exchange was the location of an IRA bomb in 1992.[3]

Although parametrically designed, based on seven carefully chosen tangents, 30 St Mary Axe is a conventionally layered construction, from the planning envelope within which the building could be constructed that is just outside the aluminium curtain walling to the diagrid steel structure. It is clad in 5500 glass panels, which vary dimensionally at each level. One of the aspects of 30 St Mary Axe that remains remarkable is that the doubly curved geometry is delivered by a combination of triangular and diamond shaped panels, thus greatly reducing the cutting and framing required. This is a double façade comprising an outer double glazed unit supported by an aluminium curtain walling, a ventilated cavity incorporating solar control blinds and an inner layer of single glazing. Foster + Partners designed the cavity to act 'as buffer zones to reduce the need for additional heating and cooling and are ventilated by exhaust air which is drawn from the offices.'[4] The distinctive spiral bands of grey glazing articulate the internal atria.

30 St Mary Axe is a pioneering, collaborative and bespoke parametric design. Just over 10 years later at Bau 2015, Schüco launched a parametric aluminium curtain walling system combining a high degree of geometric freedom and certainties offered by a well-tested product.[5] Schüco present this system as a risk free route to realising a parametrically designed façade. Many factors can feed into the planning of a façade's geometry, for example; 'guided views, optimised daylight conditions, sound reduction or protection against unwanted sunlight.'[6]

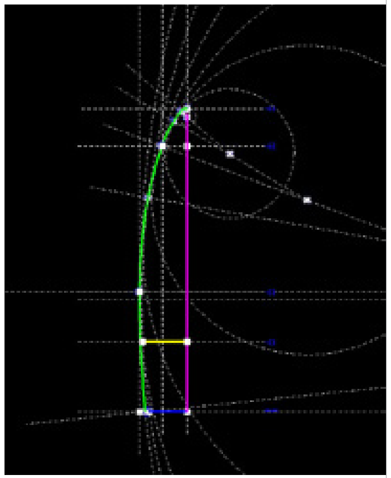


Fig 7.6 Seven tangents parametrically define the geometry of 30 St Mary Axe, architect Foster + Partners

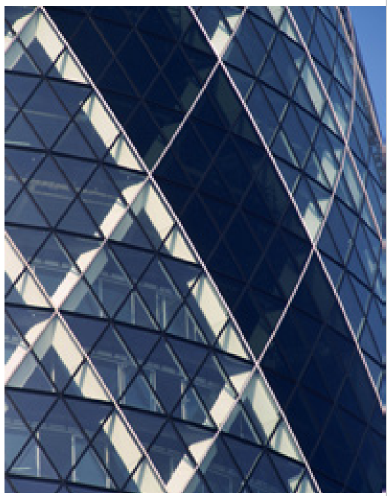


Fig 7.7 The openable double glazing of 30 St Mary Axe, is defined by the dark grey tinted glass, architect Foster + Partners

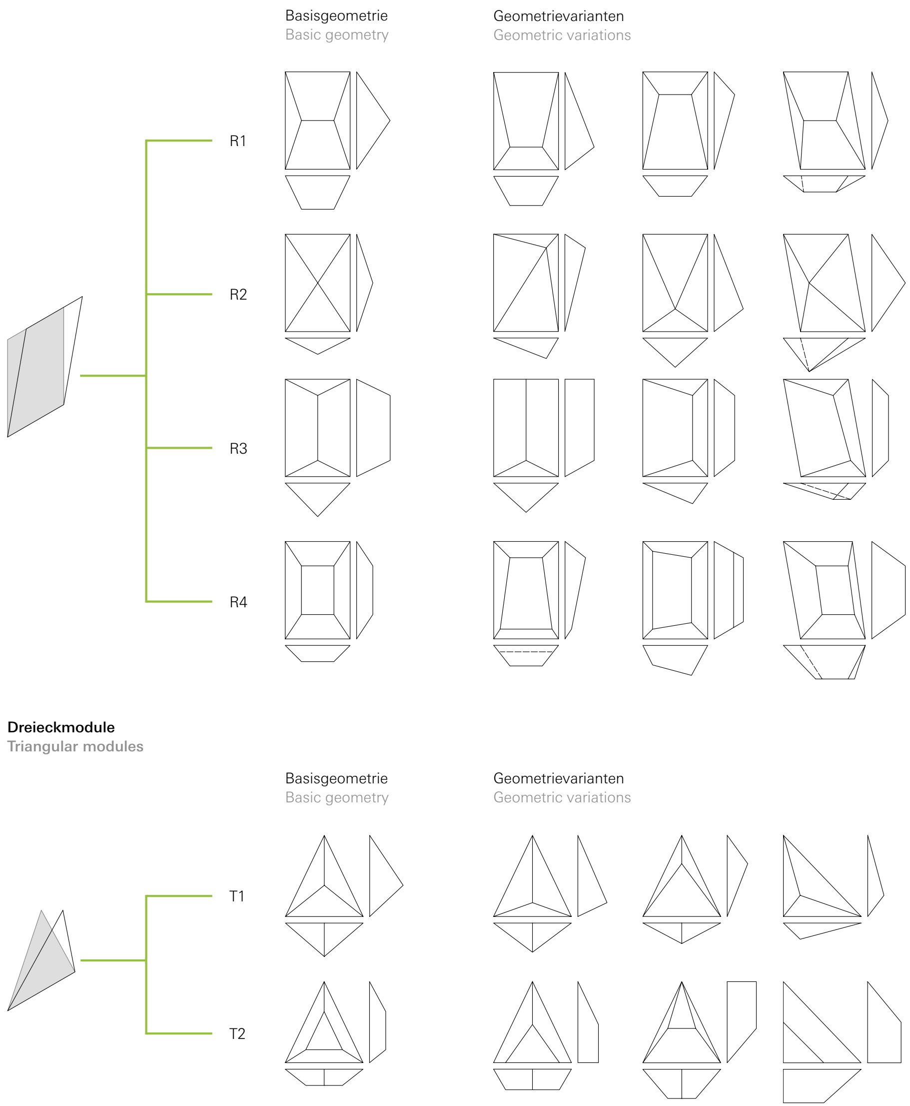


Fig 7.8 The Schüco Parametric Façade System is based on a hierarchy of six basic modules, which can be positioned, edited and combined freely

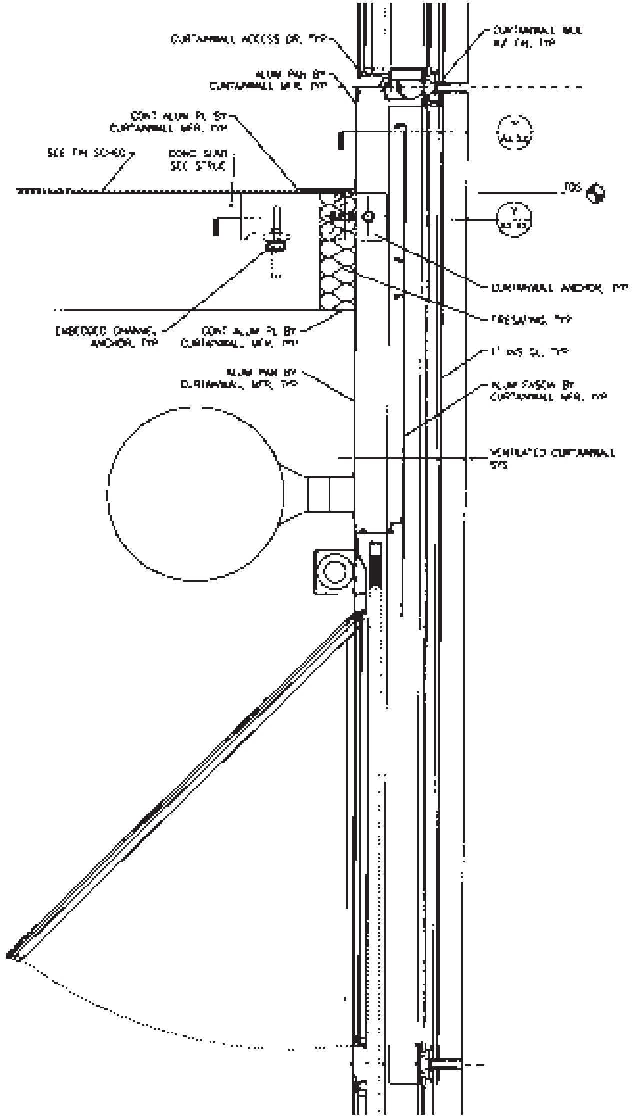
Melvin J. and Claire Levine Hall, Philadelphia, USA KieranTimberlake, 2003

The University of Pennsylvania's Melvin J. and Claire Levine Hall establishes a forward-looking character for the School of Engineering and Applied Science, while remaining sensitive to its historic context.[7] Located on a former parking lot Levine Hall stiches together two existing university buildings, Towne Building, architect Cope and Stewardson, 1906, and the Graduate Research Wing, architect Geddes Brecher Qualls Cunningham, 1967, forming a central courtyard and common entrance for the School of Engineering and Applied Science, via Chancellor Walk off 34th Street. The building comprises six floors, with the possibility of adding a seventh floor, housing offices laboratories and meeting space for the Department of Computer and Information Science and a 150-seat auditorium. Levine Hall was designed by KieranTimberlake to maximise long-term flexibility and has a 4.27m (14') floor to ceiling height.

Fig 7.9 Melvin J. and Claire Levine Hall, designed by KieranTimberlake, the first use of an active double façade in the USA

The footprint and massing respond to adjacent buildings, with particular attention to scale and fenestration. The building is articulated as a glazed pavilion presenting luminous, transparent façades to the campus.[8] This strategy allows daylight to be maximised on a dense, urban site, and provides visual interconnections between the life of the campus and life within the building.

Fig 7.10 KieranTimberlake's section through the aluminium framed active double façade of Melvin J. and Claire Levine Hall



Fátima Olivieri of KieranTimberlake reflecting on the design and life of the project in 2014:

> 'A present-day view of Levine Hall from Chancellor Walk makes clear that the building met more than its programmatic requirements; it also set the tone for further development of the precinct. In line with Penn's tradition of internal pedestrian walks, Chancellor Street, once a city street and later a service corridor, has transformed into a pedestrian path terminating at Levine Hall's glass façade, enriching the passage between 34th and 33rd streets with a series of interior and exterior public rooms. The walk is now a hub of activity, with students passing to and from class, gathering on benches, and studying on sunny days. Students from different departments use the lobby of Levine as a cut-through, and meetings, bake sales, and study groups take place there throughout the day.'[9]

The west and main façade of Levine Hall incorporates a pressure-equalised and ventilated aluminium curtain wall system, which provides maximum views and day lighting with substantial energy efficiency and interior comfort. Key components of the ventilated system are a double glazed, pressure-equalized unit on the exterior, a single glazed unit on the interior, with air continuously ventilated through the cavity between them. Blinds are house in the ventilated cavity and are fully adjustable allowing for shading or visibility. Housed in the cavity the blinds should require very little maintenance.

Fig 7.11– Fig 7.13 Permasteelisa installing the unitised double façade of Melvin J. and Claire Levine Hall

This active double wall was developed by close collaboration between KieranTimberlake and façade specialists Permasteelisa and delivered as bespoke unitised factory glazed aluminium-framed units to rapidly and precisely deliver the façade. It is the first use of an active double glass façade in the USA. KieranTimberlake's design intent has been achieved: 'The use of ventilated curtain walling technology allows the use of large expanses of glazed exterior wall surfaces, providing abundant natural light an views, while providing interior comfort and modest energy consumption.'[10]

Fig 7.14 Melvin J. and Claire Levine Hall, viewed from Chancellor Walk

Prototype Double Façade - iPADF, Nottingham, England: Research, Design and Fabrication, Dr Aneel Kilare, 2012

Double skin facades, as seen in the St Georges Wallasey (1961), Levine Hall (2003) and SIEEB (2006) case studies offer a route to the creation of low energy, low carbon architecture, whilst improving the comfort condition of the occupants.[11] The specific typologies studied by Aneel Kilaire in his thesis research were medium to high-rise office or mixed use buildings, in urban locations. The challenge addressed in this research is the integration of services into a double façade to enhance its performance as an environmental filter. Thus reducing the energy requirements and operational carbon emissions, reducing the plant area required and lowering the floor-to-floor height required. Whilst increasing constructional quality by prefabrication, beyond just the unitised façade. Furthermore creating a positive aesthetic, providing visual amenity and comfort for the occupants. A vital element of this research is the importance of the well-being and productivity of the workers in contemporary offices to the success of their organisation.

This challenge was addressed by research, design and production of a full-scale prototype double façade. Following background research and consultation, the design strategy adopted was first to implement all possible passive options for environmental control and then integrate active techniques as necessary, which resulted in an Integrated Passive and Active Double Facade system (iPADF). The project's overall aim is to provide a specifiable product with a range of design options for the UK and northern European office market. iPADF involved the research, design and development a product range that could be deployed in the construction of sustainable cities. The route to achieving this was collaboration with key participants of the construction industry supply chain. The iPADF prototype was developed as part of a CASE PhD funded by United Kingdom ESPRC and Buro Happold and the Architecture and Tectonics Research Group of The University of Nottingham.[12]

The basic elements of the iPADF system are: a unitised aluminium curtain walling comprising an outer skin of low-E double glazing, air cavity with operable and retractable blinds, openable single glazed internal skin, with an overall façade depth 300mm. The integrated services include: a reversible air-source heat pump, refrigeration unit and active chilled beam.

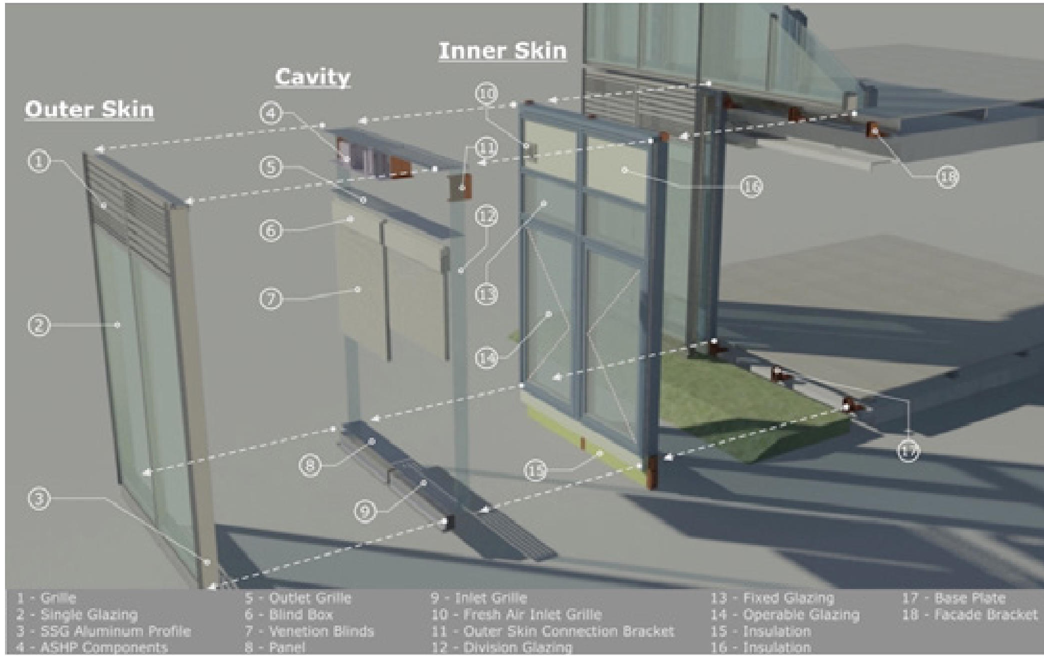


Fig 7.15 The principle components of the iPADF prototype

Natural ventilation is provided on a storey by storey basis with aluminium louvres at slab level, at a low level to ensure outside air is brought in which has not had a chance to heat up in the cavity, with exhaust below the next slab or ceiling level. The internal skin is openable for ventilation as well as maintenance. To prove the effectiveness of this opening configuration computational fluid dynamic (CFD) simulations were carried out, which confirmed the concept. The heating and cooling is provided by a reversible air-source heat pump, which provides 3-4kW of heating or cooling for every 1kW of electricity. This is linked to an active chilled ceiling beam and backed up by a trench heater (although this item may prove unnecessary). The distributed approach to the services enables the zonal control by occupants and or a Building Management System.

The full size prototype was developed and fabricated in collaboration with Schüco, Crown Aluminium and Frenger Systems. The prototype had a dimensionally coordinated width of 2400mm and a height of 3100mm responding to the floor-to-floor dimension identified. To build the prototype, on a tight research budget, where possible off-the shelf products were specified and adapted as necessary. An existing Schüco unitised curtain walling system was used, which accessed the development and testing already carried out by this systems house. The major change was the use of an inner and outer mullion, as shown in Figure 7.16. A further iteration of the design of iPADF would optimise the quantity of aluminium used, as the roles of the two mullions are not identical and could be replaced by a single thermally broken aluminium extrusion

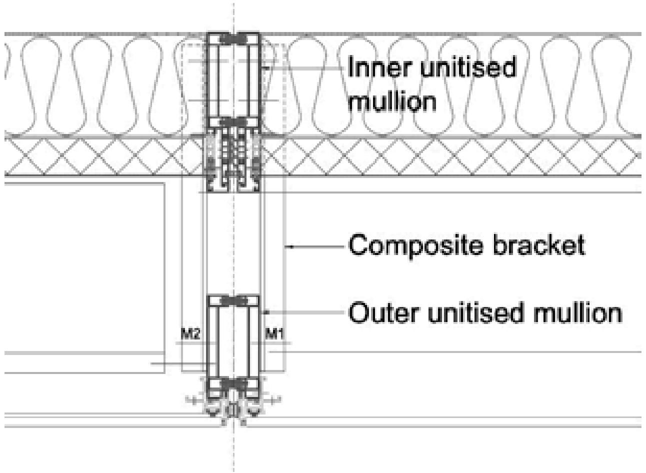


Fig 7.16 Horizontal section of the iPADF prototype showing the double mullions

The prefabrication of the unitised aluminium framed double façade was developed with the fabricators Crown Aluminium, and its Managing Director Roger Philips in particular. Aneel Kilaire, following training with Schüco and under the guidance of Crown Aluminium, undertook the fabrication himself – a rare example of learning by doing as part of a PhD Thesis. The overall aim of iPADF is to fully prefabricate the curtain walling and the integrated services, for the prototype, the air source heat pump and refrigeration unit were a plug in module and the active beam was a declared component in the room, which could be integrated with LED lighting.

Addition of cleats

Adding frame members

Completed inner frame

Assembly of outer frame

Completed outer frame

Fig 7.17 The fabrication of the iPADF prototype at Crown Aluminium by Aneel Kilaire

The prototype was assembled and tested at The University of Nottingham. The iPADF was tested and evaluated in terms of the comfort, weather and aesthetic performance. This testing predominantly focused on airflow and the performance of the services components, however, a Centre for Window and Cladding Technology (CWCT) on site weather test was also performed. As part of the research, feedback on the prototype was sought from quantity surveyors, architects, students and maintenance engineers. The responses included that the depth of the double skin at 300mm, was considered comparable with a well-insulated wall and therefore would not affect the gross to floor area ratio of a project. An even greater level of design integration was the response of many viewers to generate a specifiable product, noting they were inspecting the first prototype.

The evaluation of the iPADF prototype revealed that the integrated and distributed services would save almost 50 per cent of the plan area needed for mechanical and electrical services. The omission of a ceiling void provides a saving of façade area of over 12 per cent – an additional floor in a 25m high office building, which can be scaled up as required. In essence achieving more, while using fewer resources. The energy intensity of the iPADF system is calculated as 2.25kWh/m² representing an energy saving of 92.5 per cent when compared to centralised plant.

One of the potential barriers to the adoption of systems such as iPAF is the need to break down barriers between specialist subcontractors with mechanical & electrical and façade specialists working together, which is already happening in the field of the integration of photovoltaics into façades.

The iPADF has been successfully progressed to 'proof of concept' stage. It has integrated the functions of heating, cooling and fresh air in both a passive and active way to avoid the need for centralised plant and enable greater space efficiencies. Enhanced occupant comfort for inner-city medium to high-rise offices has been provided by giving occupants maximised external views, daylight, natural ventilation and improved thermal control. The energy and carbon dioxide emissions have been reduced by providing natural ventilation, a dynamic skin, reduced distribution losses, improved zonal control and low carbon heating, cooling and fresh air supply and delivery.

The success of the iPADF project in part led to the construction of a Prototyping Hall in the Energy Technologies Building on the Jubilee Campus of The University of Nottingham. Named the Wolfson Prototyping Hall, when it opened in the autumn of 2012. This 400m² facility has a clear height of 9m. It has been designed to enable the full scale testing of façades and other building elements, with a further 200m² of external hard standing for real time weather and daylight tests.

Fig 7.18 The Prototyping Architecture Exhibition on the opening day of the Wolfson Prototyping Hall

240 Blackfriars Road, London, England: Architect Allford Hall Monaghan Morris, 2014

This recent contribution to the cityscape of London is a 20-storey crystalline commercial volume and a smaller six-storey masonry clad residential block. Haydn Thomas of Allford Hall Monaghan Morris (AHMM) describes how '240 Blackfriars Road defines the skyline at a pivotal junction of road, rail and river at the south end of Blackfriars Bridge.'[13] It provides over 21,132m^2 of high-quality workspace above ground-level retail units and a new public realm, together with ten residential units in the adjoining brick clad six-storey volume, at a capital cost of £70million. This mixed-use scheme replaced a collection of low-rise unprepossessing and dilapidated light industry and office premises on the Blackfriars Road.

The design development of the crisp crystalline form of 240 Blackfriars Road was undertaken by AHMM beginning in 2005, having gone through a number of iterations, the final 20-storey design is a response to the context and key sightlines including

Fig 7.19 240 Blackfriars Road, London, Architect, Allford Hall Monaghan Morris, viewed looking north down Blackfriars Road

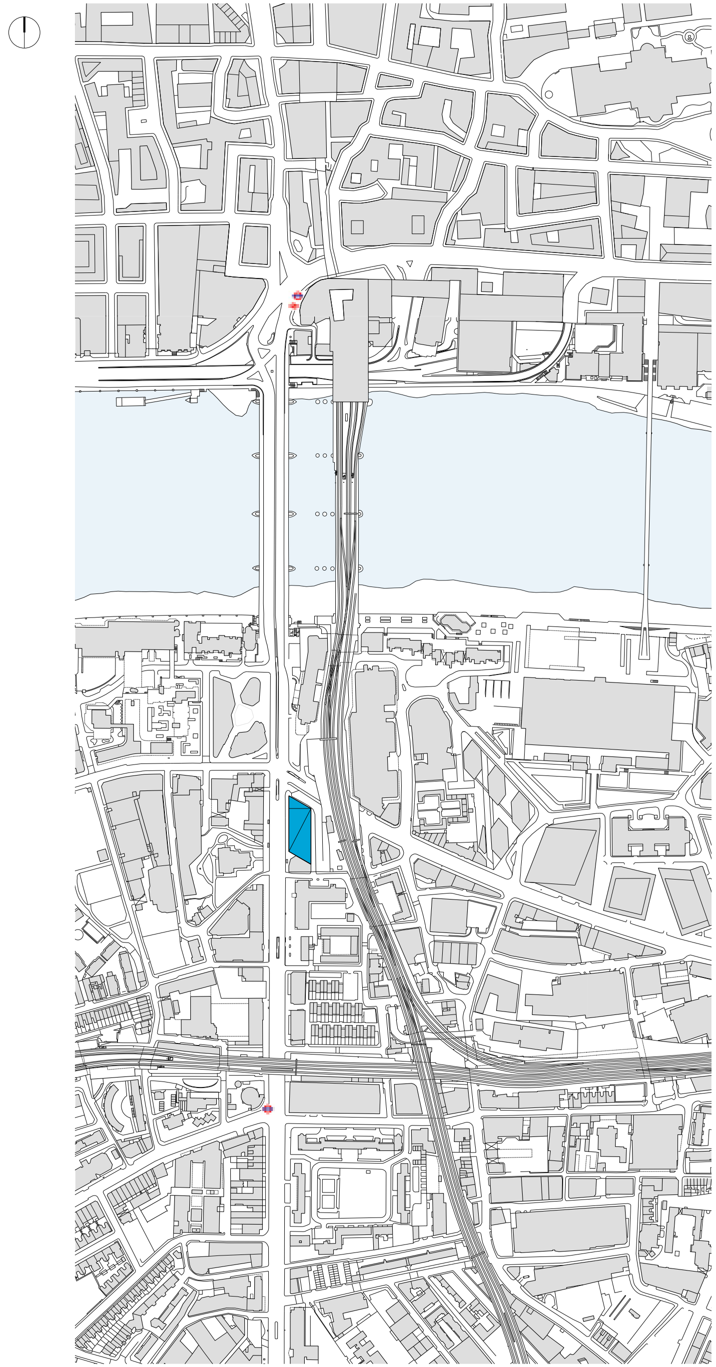


Fig 7.20 240 Blackfriars Road, Site Plan, nts

St Pauls Cathedral, yet achieving occupancy levels above the British Council for Offices norm. The plan form is very efficient with the servant spaces of; lifts, service voids, escapes stairs and washrooms, all located as a single block, occupying most of the east façade. Above the central entrance atrium the offices form generous spaces that can be open plan from the south to the north façades. The building is topped by a triple height 'sky-room', behind which is the plant room.[14]

AHMM describe the form as being 'inspired by the strength of natural geological forms, the basic 90m tall trapezoidal extrusion is cut four times to respond to its context: to the south to minimise the impact to Ludgate House; diagonally to the north to orientate the building towards the river and city; at street level to add generosity to the public realm; and across the roof to create a reflective triple-height 'sky-room'.'[15] The 90m high office tower of 240 Blackfriars Road, completed in 2014, is a crisp and elegant contribution to the central London skyline and cityscape.

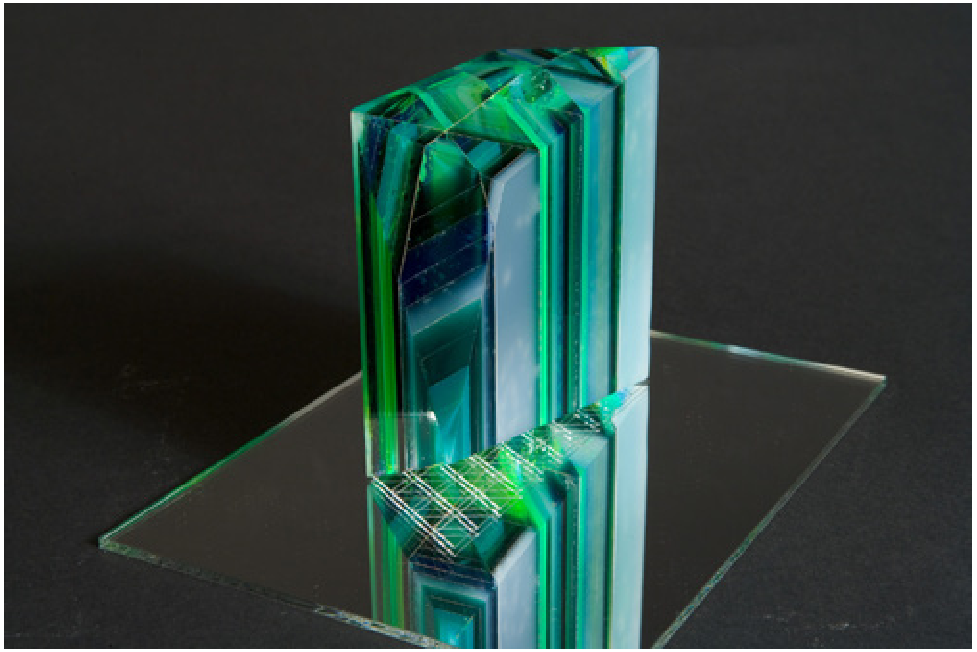


Fig 7.21 AHMM's design development model of 240 Blackfriars Road

For the top floor of 240 Blackfriars Road, AHMM inventively resolve one of the recurrent dilemmas in the design of tall buildings – where to house the plant room? Mechanically the efficient location is the top of the building making the access to free air for exhausts and flues very simple and direct.

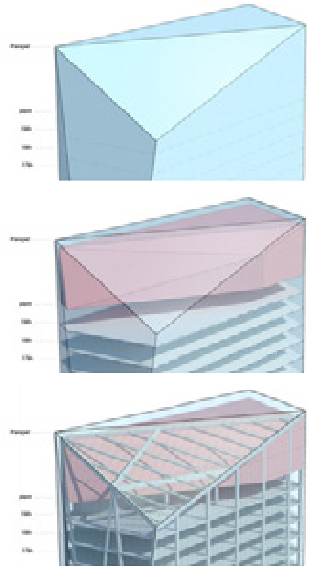


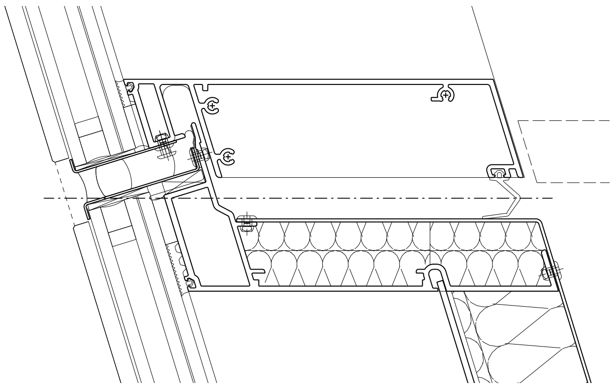
Fig 7.22 AHMM's diagrammatic drawings for the 19^{th} floor: sky-room, plant and building envelope

Yet typically this is the most attractive and valuable space created in this form of architecture. Following the language of sculptural cutting of the form of 240 Blackfriars Road, AHMM divided the 19^{th} floor in two, the north and west side of the plan is the triple height sky-room, which is a function room, a celebratory 'town-hall' space with sweeping views across London. The east and south part of the plan is the plant room. On the roof of the plant room is a 9kW photovoltaic array comprising 40 panels.

240 Blackfriars Road is predominately a concrete framed structure that utilises post tension concrete slabs, only 275mm thick, combined with low profile raised floor, and chilled ceiling with LED lights, in a 350mm service zone to achieve an efficient floor-to-floor height, which created an additional one and half floors when compared to a conventional steel frame. The design and coordination of the project was delivered by the use of a Building Information Model (BIM) from RIBA (2013) Plan of Work Stage 4 (Technical Design). AHMM extensively used prefabrication to 'minimise site waste, increase quality and reduce the construction programme on site. These items included the unitised curtain cladding system, washroom fit out components and three storey high mechanical riser installations.'[16]

This office building is completely clad in high performance argon filled double glazed units, predominately in the form of silicone bonded unitised aluminium curtain walling providing a flush outer surface and crisply detailed edges – delivering the desired crystalline form. The unitised aluminium curtain walling is set out on 1.5m grid. Solar control is achieved via 'pinstripe' fritting and a solar control layer on surface 3. On the sloping north façade, which is visible from the Thames, the fritting is omitted to maximise daylight and views of the city. Throughout the building envelope only glass-to-glass junctions are used contributing to the tectonic crispness of the project. With the exception of the corner-to-corner junctions arising from the projects crystalline form, here black anodised aluminium extrusions were introduced to provide edge protection whilst retaining the sharpness of form and detail. The aluminium extrusions of the curtain walling and roof glazing are the largely unseen helping 'hands' of the building envelope. Other aluminium components include the internal shadow boxes at slab level and the aluminium louvres to the plant room at the top of the east elevation. The rainscreen glazing to service cores on the east façade has an additional 80 per cent dark grey frit to the inner face of the glazed unit to maintain visual consistency throughout the curtain walling.

Whereas the aluminium framed curtain walling is fully unitised to facilitate precision and speed of erection. The roof glazing was installed as a 'stick' system to accommodate deflections and to ensure drainage continuity. In the sky-room the glazing sections are supported by bespoke steelwork and fixed via silver anodised brackets with countersunk stainless steel bolts. AHMM considered this component to be key and a highly visual part of the roof assembly. To enhance the solar control of the roof glazing, a 45 per cent chrome frit is used to reduce glare while maximising daylight and views of the sky above.



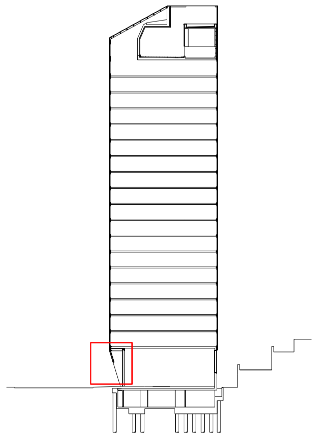


Fig 7.23 Detail of 240 Blackfriars Road showing the high performance argon filled double glazed units and silicone bonded unitised aluminium curtain walling

The air leakage rate through the façades was limited to $1.5M^3/m^2/hr$. This combined with a U_{cw}-value of $1.4W/m^2K$, effective solar control and other measures, some of which are listed above, created a good energy balance in the building fabric of 240 Blackfriars Road. This achieved a 28 per cent improvement on England and Wales Building Regulation Part L 2010 and achieved an Excellent rating under BREEAM 2011.[17]

The building envelope was fabricated and installed by Scheldebouw, who worked closely with AHMM via a process of mock-ups and prototypes in its factory in The Netherlands. This included the design development of a discreet fail-safe mechanical restraint system for the sloping silicone bonded aluminium framed curtain walling.

240 Blackfriars Road is an excellent example of a twenty first century project for a 'commercial client', Great Ropemaker Partnership (with Great Portland Estates leading the development on behalf of their joint venture partner), which the architect and design team have thought through in considerable detail and at every level, including: the crisp aluminium framed curtain walling, well informed design of the concrete elements to the tectonic of the internal fit out.

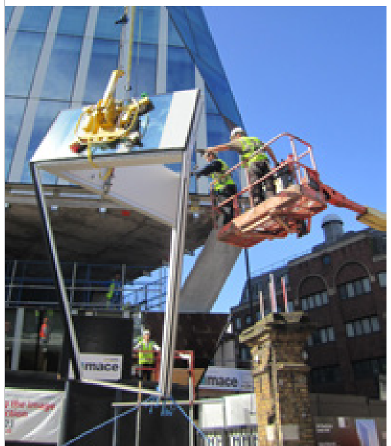


Fig 7.24 Installation of the unitised aluminium curtain walling of 240 Blackfriars Road fabricated by Scheldebouw

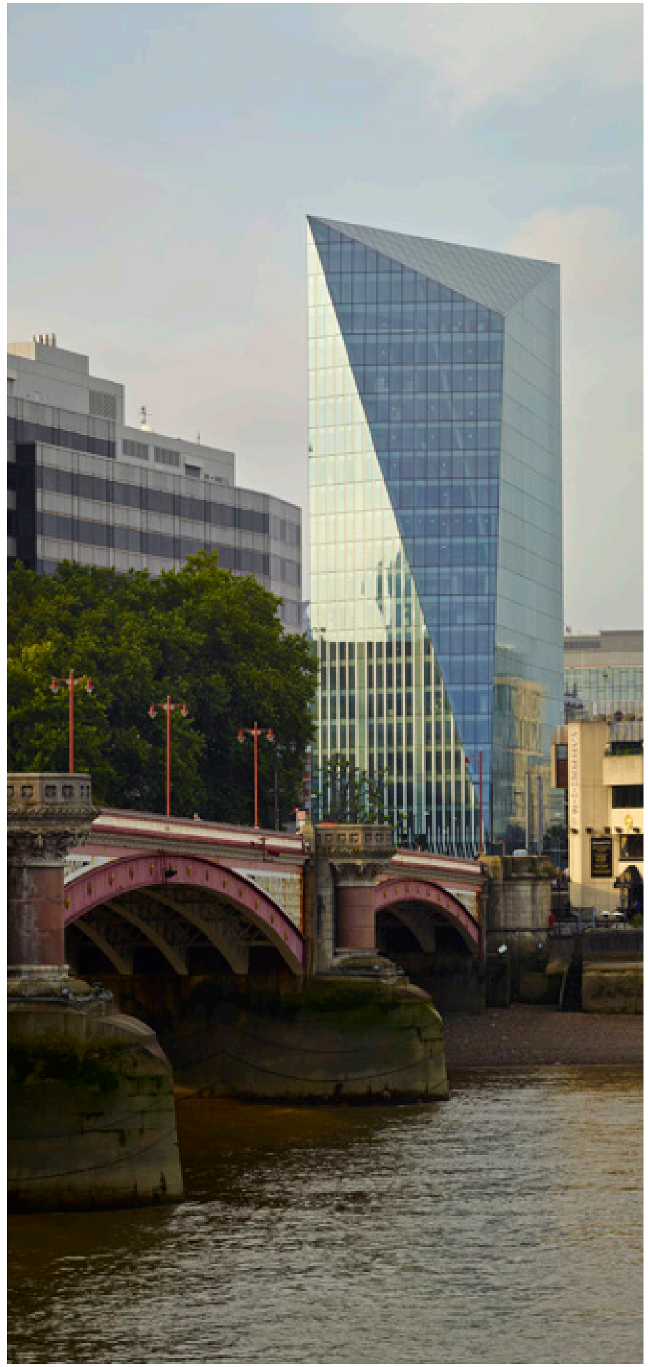


Fig 7.25 The north façade of 240 Blackfriars Road is clear glazed to maximised daylight and views of the City of London

British Airways i360, Brighton, England: Architect Marks Barfield Architects, 2016

In Brighton on 4 August 2016 the first 'flight' of the British Airways i360 took off. Designed by Julia Barfield and David Marks, architects of the London Eye (2000), it is a vertical pier located at the entrance to Brighton's old West Pier, which opened in 1866, fell into disrepair in 1975, and burnt down in 2003.[18] It follows on from the London Eye, which they invented and designed as a temporary celebration of the millennium. The London Eye is a 132m high Ferris wheel with 32 pods, completed in 2000, is now a permanent landmark on London's skyline, visited by over 4 million people annually.

Although the i360 shares design 'DNA' with the London Eye, it has been tailored to work successfully as a regional attraction within a seaside city. Brighton and Hove has a population of over 280,000 people, with about 10 million tourists visiting the city annually.[19] The i360 is a vertical cable car with a single pod that has a capacity of 200 people. It has been designed as a venue, a destination and a symbol of renewal.

Fig 7.26 The British Airways i360 located on site of the entrance to the old West Pier, Brighton

Fig 7.27 Marks Barfield Architects' vision of the British Airways i360

The i360 tower is 162.4280m high, measured from the Ordnance Survey Datum, and only 3.9m in diameter. It is officially the slimmest tall tower in the world, with a width to height aspect ratio of 1 to 40.[20] To reduce vortex shedding on this elegantly slender tower Marks Barfield Architects has clad it in expanded anodised aluminium.

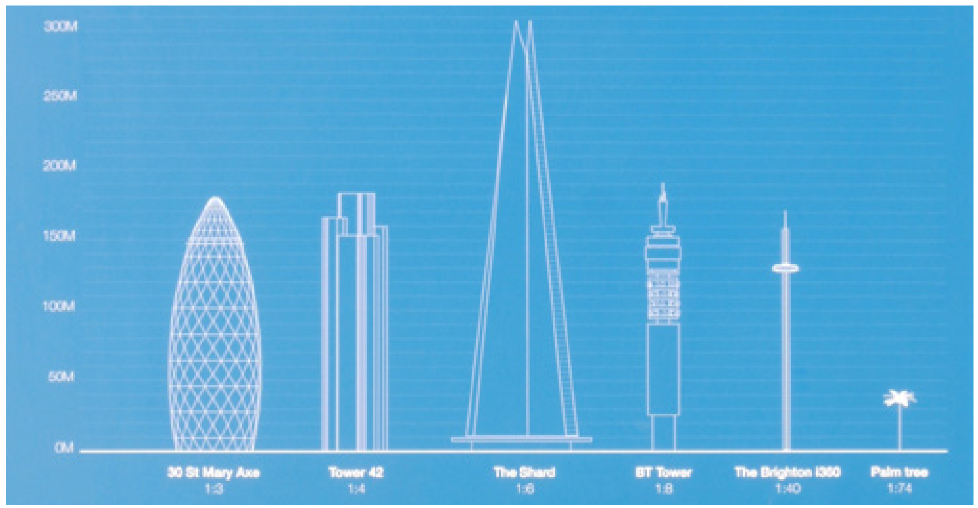


Fig 7.28 Marks Barfield Architects' comparative analysis of aspect ratio of key tall buildings in London with the i360

During a flight in the i360, up to 200 people rise 138m above the Brighton seaside in a glazed doughnut like pod. This description does not do justice to the elegance of the pod designed by Marks Barfield Architects in collaboration with POMA and the only way to fully appreciate the collective experience of rising gracefully above the townscape and seashore of Brighton is to ride the i360.

Marks Barfield Architects, who conceived and designed the i360, and remain a financial stakeholder in the project, had to wait out the recession arising form the global financial banking crisis for work to start on site in the summer of 2014 – despite the project receiving planning permission in 2006. The construction cost of the i360 on completion was £37million.[21] To deliver the i360, Marks Barfield Architects in essence reassembled the core team from the London Eye, Hollandia for the prefabricated steelwork and the POMA for the pod. David Marks described Hollandia as a world leader of prefabrication in steel, following an inspection of Maeslantkering storm surge barrage at the Hook of Holland, as part of the process of Hollandia's selection to fabricate the steelwork of the London Eye.[22]

The engineer of the i360 is John Roberts (BA i360's chief engineer). The in-situ concrete foundations of the i360 are 3m deep and 25m square to support the vertical cantilever of the tower. This steel tower was prefabricated by Hollandia in it's works at Krimpen aan den IJssel, the Netherlands. The high-grade steel was roll formed by Sif and then welded into vertical tubular sections known as cans, which are coated in zinc rich primer and three layers of marine specification paint.

The tower is formed of 17 steel cans, which are a combination of 6 and 12m high, and were progressively jacked into place. Each can was installed at the bottom, with the preceding cans being hydraulically jacked up. The steel in the tower weighs about 30tonnes, and was bolted together using 1336 stainless steel bolts.

Once prefabricated by Hollandia, the cans were sailed to Brighton by barge and beached on a specially prepared landing area on the foreshore at the site of the old West Pier. All the cans were fully prepared to receive the expanded aluminium cladding, with cladding rails already in place. The top two cans were installed fully clad. The tower was then clad from the top down.

Fig 7.29 Before the foundations of the i360 could be formed, a major sewer had to be diverted

Fig 7.30 Steel cans fabricated by Hollandia

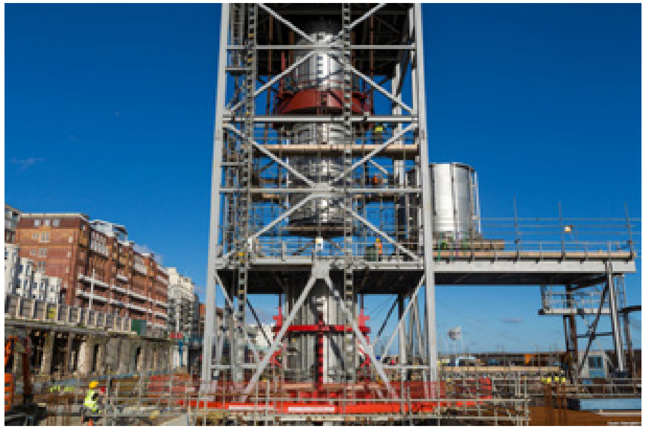


Fig 7.31 The jacking process of assembling the tower of the i360

The single pod is counterbalanced by a weight inside the tower, which is slightly lighter than the pod itself. A cable draws down the counter weight and the pod rises. On the return journey to the ground, 50 per cent of the energy used is harvested by regenerative motors. With the cable passing over a pulley wheel at the top, the i360 is a distant echo of the coalmine pitheads that were once commonplace in many parts of the British landscape, until the 1980s.

The glass pod fabricated by POMA in France, has the feel of a Dan Dare spaceship or flying saucer, an elegant observation deck, which one can walk around and enjoy the full 360° panorama. 18 m in diameter, the geometry of the pod is an oblate ellipsoid, an ellipse rotated through 360° about its minor access, with a cylindrical hole through its centre. The pod is supported by a red painted steel chassis comprising: four masts, a large ring beam supporting the floor structure of the pod and a smaller I-section top ring beam, which picks up the internal structure of the pod. Each of the four masts are linked to the counterweight inside the tower by a high tensile steel cable, which are located behind the expanded anodised aluminium cladding. The masts are equipped with a set of spring loaded guide wheels that run on the steel structure of the tower. The pod is structured and clad in 24 radial segments. The lower ring beam picks up the cantilevered steel floor structure, the glass is supported by 48 polyester powder coated steel sections, which span from the floor to the upper ring beam. These sections, or ribs, taper towards the top and are elegantly lighted by extended circular cut-outs. For precision, and to speed up assembly, the doubly curved glazed units are unitised with independent steel framing. The tapered ribs are bolted together inside the pod. The red chassis structure is only glimpsed through the inner cylindrical glazing of the pod, which will allow the travel or flight up and down to be calibrated via the visible passage of the 2m-high cladding panels. The floor void houses all the heating, ventilation and air conditioning (HVAC), audio-visual and safety systems of the pod, powered via two bus bars on the tower next to the east and west guide ways.

The pod is glazed in doubly-curved, double-laminated double glazing. The outer surface of the glass incorporates a permanent self-cleaning treatment (the pods of the London Eye are only single glazed). The double glazed units, which comprise a laminated outer pane, a sealed air gap and laminated inner pane, were produced in Italy by Sunglass, using bespoke and patented moulds. As the glass is heated in the moulding process it can be considered to be heat strengthened, but not toughened.

Fig 7.32 The Pod of the i360, photographed April 2016

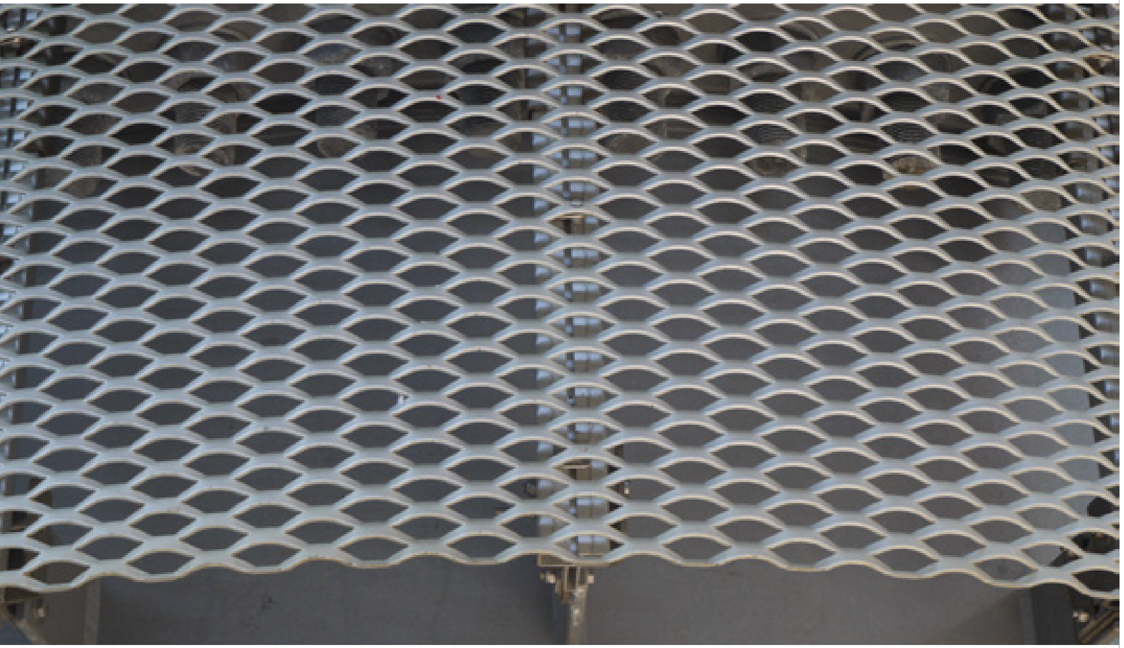
However, the size and details of each pane had to be predetermined, as it is not possible to cut or drill this type of glass after moulding.

The soffit of the pod is also glazed in 24 segments. Here the outer pane of glass has been fully mirrored on surface two. Ian Crockford, Project Leader for Marks Barfield Architects, described "the spectacular iris like effect of watching the pod ascend the tower from the entrance deck level, created by this curved mirrored surface."[23]

On completion of the glazing of the pod on site in Brighton, 14 January 2016, Julia Barfield observed: 'This is an extremely important moment for us. The pod is completed and it looks stunning. The fluid form of the glass sits beautifully in its beachfront setting and the mirrored underside will cast reflections of the naturally shifting shapes of the sea and sky.'[24] David Marks commented: 'It is incredibly exciting to see the pod finally take shape on the tower. The team from POMA have done a remarkable job, both in terms of the craftsmanship of the handmade pod as well their skilful and swift assembly.'[25]

Fig 7.33 Inside the i360 pod during construction, photographed April 2016

The two-storey podium building and the its central circular void are both clad in clear glazed silver anodised aluminium curtain walling installed by Fill Metalbau, using aluminium I-beam mullions. The two original ticket booth of the West Pier have been faithfully reconstructed with a cast iron outer skin; cast by the Swan Foundry of Banbury. A visitor to the i360 enters at the level of the seaside promenade and having risen and returned from 138m, leaves the pod at lower ground level, effectively the top of the beach. This space will house a brasserie, cafe, tearooms, exhibition, kids soft play zone and shop, some of which will spill out on to the beach.



The tower is clad in 5mm thick expanded aluminium, which is finished in 25μm silver anodising in accordance with BS 3987:1991. Expanded with the 'Bilbao' pattern from a bespoke aluminium grade 151EX sheet, which combines good ductility for expanding and anodises well. This was supplied to the Expanded Metal Company by James & Taylor who coordinated the cladding, which was installed by Hollandia. The expanded aluminium cladding panels were roll formed to the desired radius and are 2m high with a radial panel width of 3.2m. The anodised aluminium panels, with periodic cleaning, should prove durable for the complete design life of this project, despite the marine location. Although each large format expanded sheet is light enough to be readily carried by four people, weighing approximately 10kg/m^2, almost 20tonnes of aluminium were used to clad the i360, covering an area of just over 2000m^2.[26] One advantage of working with expanded metal to create façade panels is that there are no off cuts produced when processing the sheet material, unlike perforating sheet metal with a punch tool.

Fig 7.34 The 'Bilbao' pattern anodised expanded aluminium cladding of the i360 Tower

Fig 7.35 The expanded aluminium sheet being manufactured in Hartlepool

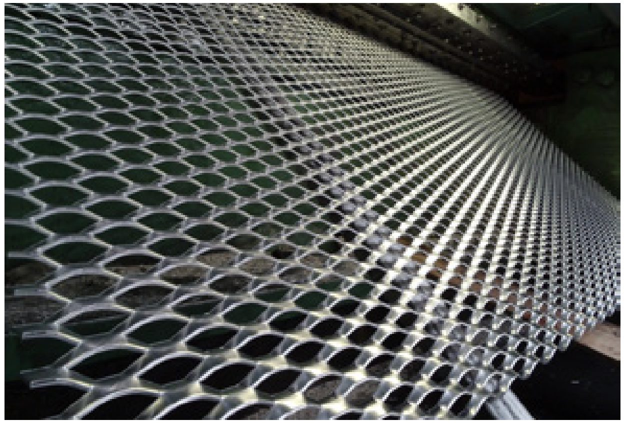


Fig 7.36 Mill finish expanded aluminium sheet during manafature by Expanded Metal Company in Hartlepool

Fig 7.37 Each sheet of expanded aluminium is light enough to be easily carried by four people

The fixing detail of this cladding is shown on site at the base of the tower in Figure 7.38. The anodised expanded aluminium cladding is supported by hollow tee section aluminium extrusions, which incorporate a fixing channel. These cladding rails are fixed back to the steel tower via rowlock like u-shaped steel fabrications, which are bolted to cleats welded to the tower. The potential for bimetallic corrosion, between the aluminium cladding rail and the steel subassembly, is avoided by polymeric isolators.

All structures have a natural vibration frequency, which is a product of its slenderness ratio and the stiffness of the structure. The i360 tower has three modes of oscillation, which are the three lowest natural frequencies of vibration this tower will respond to. The starting point to eliminate the risk of wind-induced vibration was the specification of the expanded aluminium cladding to minimise vortex shedding.

Ian Crockford described 'the expanded aluminium cladding is a key part of the damping strategy, the surface roughness and air flowing through the cladding disrupts the wind speed thus minimising the vortex shedding on the leeside.'[27] The design team did not consider it necessary to wind tunnel test the cladding, based on the expert advice of Professor Max Irvine from Sydney, Australia, on the minimisation of vibration risks on the extremely slender tower. The tower is also fitted with three types of liquid filled dampers, each tuned to one of the vibration modes. The dampers were fabricated in New South Wales and were fitted in the steel cans in the Netherlands and the pod in France. In total over 50 dampers have been fitted to the tower, with a further eight located in the pod.

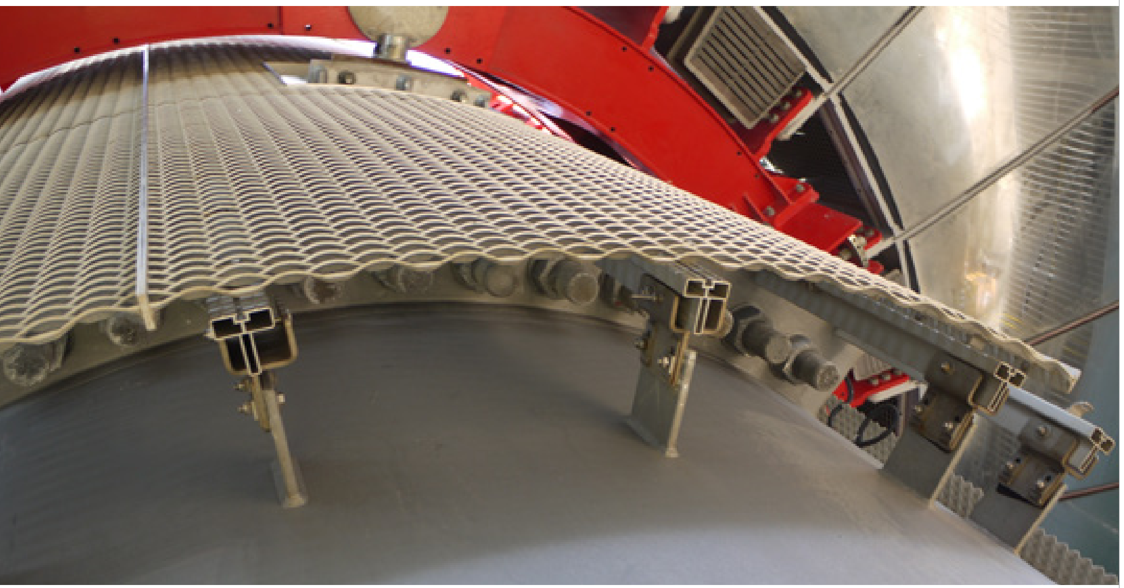


Fig 7.38 The anodised expanded aluminium cladding at the base of the tower

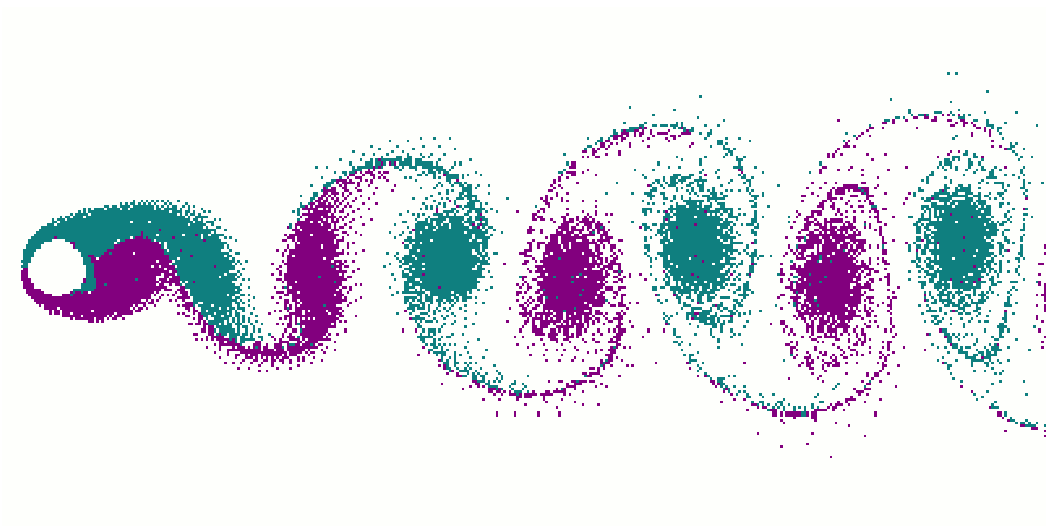


Fig 7.39 Vortex shedding caused by a circular object subjected to wind flow like i360 Tower

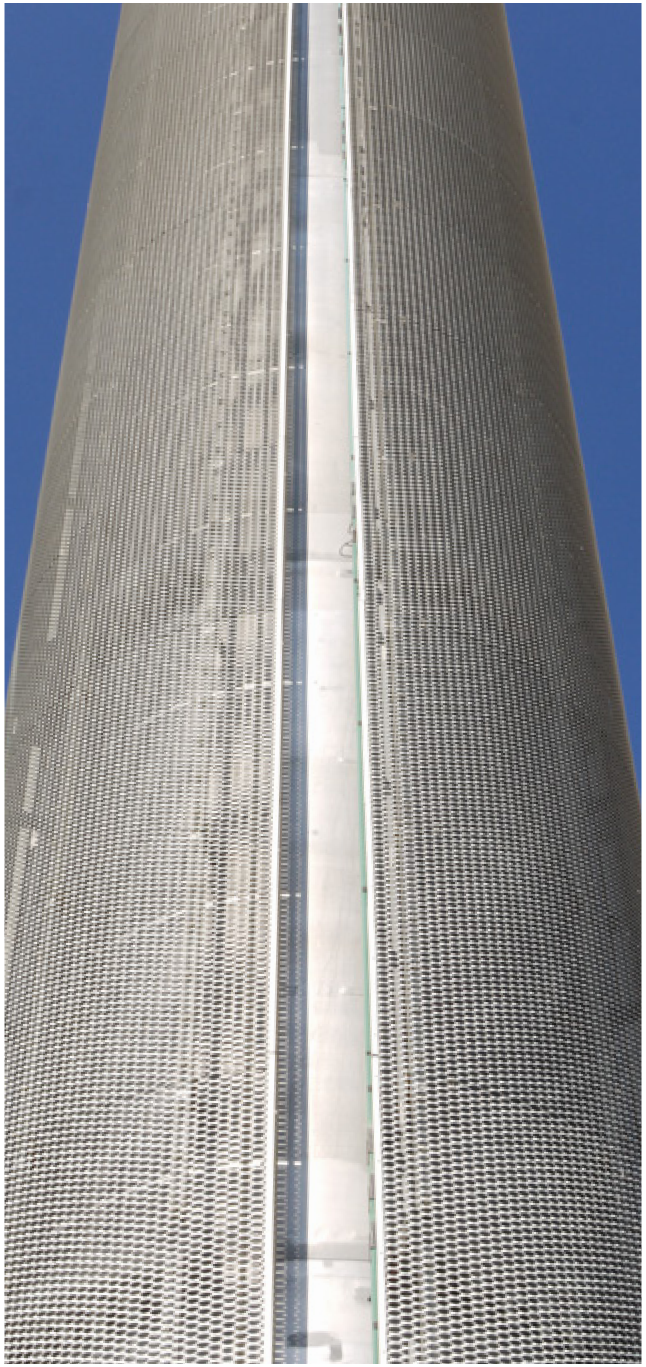


Fig 7.40 The expanded aluminium minimises the vortex shedding and thus limits the possibility of vibration in the i360 tower

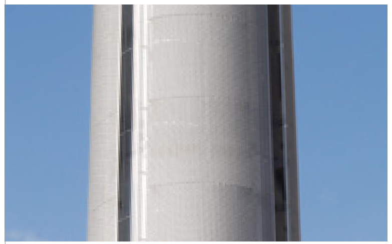


Fig 7.41 Gaps for the four masts of the pod where it climbs the tower delineate the anodised expanded aluminium cladding and further emphasising the slenderness of the tower

Aluminium was selected for the cladding in competition with grade 316 stainless steel, the role of the cladding is described by Ian Crockford as 'a transparent veil combined with its performative function'.[28] The expanded panels with their many edges and the coastal location convinced Marks Barfield Architects that anodised aluminium was the better option. Knowing that the cladding will need to be washed on a regular basis, the tower is crowned by a circular rail to support abseilers.

The gaps for the four masts of the pod, where it climbs the tower, delineated the anodised expanded aluminium cladding and further emphasise the slenderness of the tower. The anodised expanded aluminium cladding creates a gentle visual softness to this monumental tower. Like Stirling and Gowan's Leicester Engineering Department Tower (1963) the scale of the i360 is difficult to discern, except this time it is taller than many views suggest. Perhaps this will enhance the experience of riding in the British Airways i360.

Fig 7.42 The spectacular iris like effect of watching the pod ascend the i360 tower

Fig 7.43 The i360 Tower viewed from the Brighton foreshore

Notes

1 M. Stacey (2013), *Prototyping Architecture*, Riverside Architectural Press, Cambridge. pp. 223–225.

2 R. Fitch, (2011) *A Short History of Building Fabric and Architecture* in *Adaptive Architecture*, M. Stacey and F. Stacey, eds., Building Centre Trust, London (DVD only).

3 10 April 1992 see: http://news.bbc.co.uk/1/shared/spl/hi/pop_ups/07/magazine_baltic_exchange_bombing/html/1.stm (accessed April 2016).

4 *30 St Mary Axe* (pdf) accessed April 2016, via www.fosterandpartners.com/news/archive/2004/04/30-st-mary-axe-london/

5 *Home, Work, Life*, www.schueco.de/bau2015/special/files/Messebroschuere_BAU_2015_low.pdf (accessed April 2016).

6 *Schüco Parametric System* (pdf), p.7, downloaded April 2016, via www.schueco.com, registartion may prove necessary.

7 http://greenbuilding.world-aluminium.org/en/benefits/efficient/melvin-j-and-claire-levine-hall.html (accessed March 2015)

8 S. Kieran, J. Timberlake and K. Wallick (2011), *KieranTimberlake: Inquiry*, Rizzoli Internal Publications, New York p. 235.

9 http://kierantimberlake.com/post/view/269 (accessed March 2016).

10 KieranTimberlake's Project Data Sheet for Melvin J. and Claire Levine Hall supplied to the author in 2009.

11 For St George's, Wallasey (1961) see pp. 214–217, Levine Hall (2003) see pp. 552–555, and SIEEB (2006) see pp. 602–609.

12 PhD supervisor Professor Michael Stacey, advisors Facade Engineer Claudia Farabegoli formally of Buro Happold, Tony McLaughlin of Buro Happold; industrial partners Crown Aluminium, Schüco UK, Solaglas, Fiberline Composites and Frenger Systems.

13 Haydn Thomas of AHMM speaking, as one of the 16 architects who contributed to the *CAB Thames Journey*, 1 October 2105, recorded by the author.

14 Allford Hall Monaghan Morris, *240 Blackfriars Road Supporting Information* (pdf), supplied to the author September 2015.

15 Ibid.

16 Ibid.

17 Data provide by Haydn Thomas, Project Architect at AHMM, U-values for other elements on this project: inclined overhead roof panels, U_{cw}-value 1.8W/m²K, and Rainscreen panels, U_{w}-value 0.3W/m²K.

18 www.westpier.co.uk (accessed April 2016).

19 The Economic Impact of Tourism Brighton & Hove 2012 (accessed April 2016).

20 Guinness World Record verified on 26 January 2016, http://britishairwaysi360.com/latest-news/blog/british-airways-i360-worlds-most-slender-tower/ and www.guinnessworldrecords.com/world-records/401534-most-slender-tower (accessed April 2016). Data updated by Ian Crockford in conversation with the author.

21 Data supplied by MarkBarfiled Architects to the author, September 2016, noting that this construction cost does not includes fees, interest and other related project costs.

22 S. Rose (2007), *Eye: The story behind the London Eye*, Black Dog Publishing, London, p. 98.

23 Ian Crockford in conversation with the author on site in Brighton 13 April 2016.

24 http://britishairwaysi360.com/latest-news/blog/british-airways-i360-pod-is-completed/ (accessed April 2016).

25 Ibid.

26 Data supplied by James & Taylor via Marks Barfield architects, May 2016.

27 http://britishairwaysi360.com/latest-news/blog/british-airways-i360-pod-is-completed/ (accessed April 2016).

28 Ibid.

Aluminium: Servant of Sustainability

Throughout this report the contribution of aluminium in creating sustainable cities, architecture and infrastructure is demonstrated by quantified case studies that serve humankind well. Many of the projects, such as the overcladding of Guy's Hospital, are examples of low carbon architecture; in this particular case the pay back period of its embodied carbon is under 13 years. Other case studies demonstrate the durability and long-term service of aluminium-based projects. This chapter focuses on the role of aluminium in delivering and integrating renewable energy into architecture and infrastructure. Aluminium is the first choice material for the support of photovoltaic panels as demonstrated in the three case studies, with a related large-scale infrastructure example, set out below.

In Europe a photovoltaic panel will generate enough energy to offset the embodied energy of its manufacture in about one and half years to two and half years, largely dependent whether specified in southern or northern Europe respectively. Remaining efficiently operational for the subsequent 30 years, if washed on a seasonal basis.[1] However, there appears to be a clear need for more research into the long-term durability of photovoltaic panels, especially when integrated into a facade system. Therefore, disassembly and replacement should be designed in from the outset in a photovoltaic installation.

A good product based example of aluminium, as a servant of sustainability, is Bauder's Biosolar roofing system, which combines a complete roof of photovoltaic panels with extensive vegetation, whilst maximising the output of the photovoltaic panels. This system comprises a moulded polymer base to which a framework of aluminium extrusions is fixed, that in turn supports a photovoltaic panel above the roof, at the optimum angle for generating solar electricity. The system is ballasted by the growing medium and extensive vegetation. Typically no fixings are required, thus avoiding the complications of fixing details through a waterproof roofing membrane, thus minimising cost and risks of leaking. This makes the Biosolar roof system cost effective and typically it can be retrofitted to existing roofs without any need for structural modifications.

In common with all vegetative or green roof systems, the waterproof membrane is protected from the harmful effects of the Ultra Violet spectrum of sunshine. Furthermore, the presence of the photovoltaic panels increases the biodiversity of the green roof, encouraging plants to grow that need shade and shelter, as well as those that enjoy sunshine. This product is a rare 'both-and' assembly that results in positive synergies between biodiversity and generating renewable energy.

The electrical output of the polycrystalline photovoltaic panels are increased by the cooling effect of the vegetation and the water retained in the substrate, aided by the free passage of air below the panels. Research undertaken by Bauder in Germany shows that the panels should generate 6 per cent more electricity.[2]

Collectively, humankind has the means of cost effectively creating low carbon, carbon neutral and energy positive architecture, which both tackles the risk of climate change and mitigates the risks of increased summertime temperatures. Aluminium can appropriately be described as a good servant of sustainability.

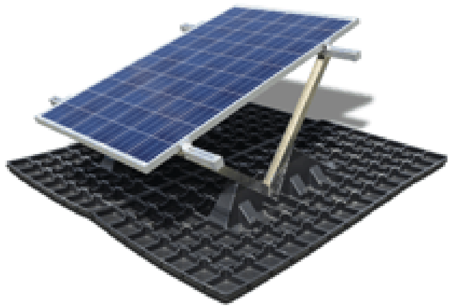


Fig 8.1 The primary components of Bauder's Biosolar roofing system - moulded polymer base, extruded aluminium framework supporting a photovoltaic panel

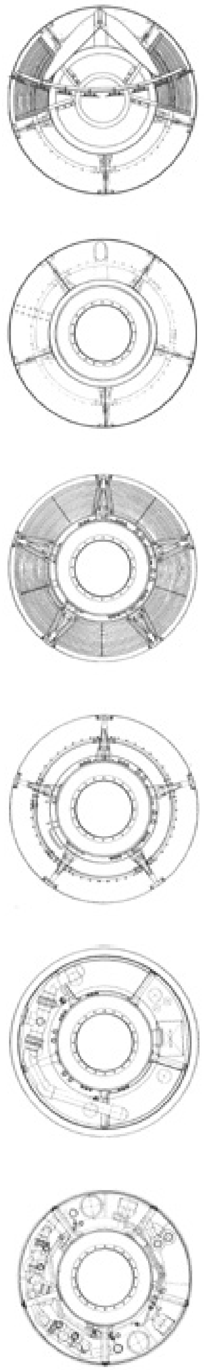
Fig 8.2 The photovoltaic panels are held above the extensive vegetation

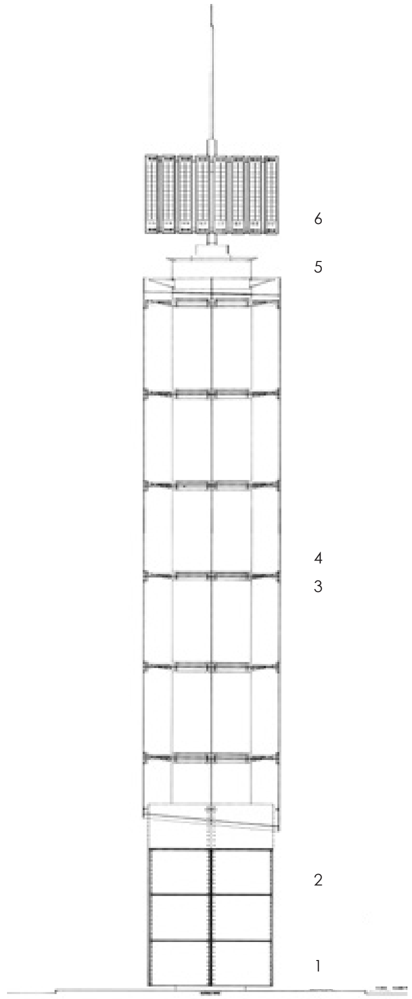
Fig 8.3 Bauder's Biosolar: a both-and product, solar electricity and biodiversity

Thames Water Tower, London, England: Architect Brookes Stacey Randall Fursdon, 1995

Designed as a striking contribution to the urban landscape of London, this inventive tower of glass, stainless steel and aluminium is a prototype for an environmentally responsible and responsive building. It was built to house a surge pipe on Thames Water's drinking water ring main; an unseen marvel of hydro engineering serving all of London. The tower was designed by Brookes Stacey Randall Fursdon, in collaboration with students of the Royal College of Art, Damian O'Sullivan and Tania Doufa. The tower celebrates an otherwise invisible engineering achievement, with an amplified electronic barometer in the centre of Holland Park Roundabout, London.[3] The 15m-high tower has a base housing the services, a smooth column of glass, and a capital formed by the solar array. Blue water appears to rise up the tower, layer by layer, in response to climatic conditions and then fall again in times of low air pressure. 'The approach to the design of the structure and enclosure is one of increasing sophistication as it rises up to the tower to the solar vane', observed the Editors of ViA Arquitectura.[4] Who continue: 'The Thames Tower is a working model of a responsive building. In the design of the tower the architects sought to detail the complete assembly in such a way that the play of light is encouraged as it strikes and penetrates not only the glass and water but also the polished surfaces and components within the tower to create a visually poetic effect'.[5]

Fig 8.4 Thames Water Tower, designed by Brookes Stacey Randall Fursdon





1 The 'engine room' in the clad base
2 Services in the clad base
3 Water spray system
4 Typical plan with castings and access decking
5 Toughened glass roof with aluminium mast
6 Solar vane and access decking

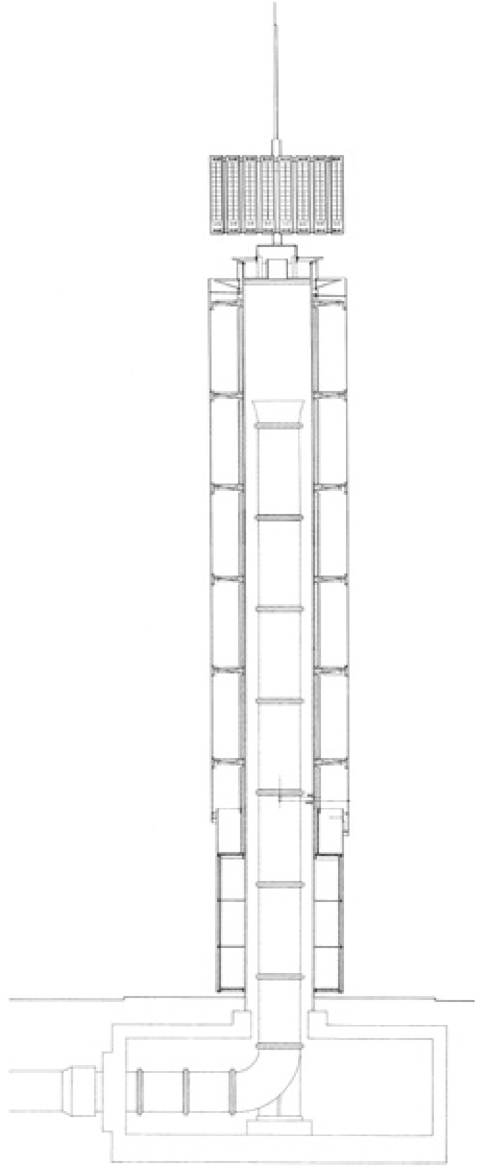


Fig 8.5 [left] Brookes Stacey Randall Fursdon's plans of Thames Water Tower, which are typically at 2m intervals

Fig 8.6 [above left] Thames Water Tower, elevation

Fig 8.7 [above] Thames Water Tower, section, showing the surge pipe

Fig 8.8 Brookes Stacey Randall Fursdon's initial perspective sketch of Thames Water Tower

Fig 8.9 The precise curved toughened glass cylinder of the Thames Water Tower crowned by a polycrystaline solar array

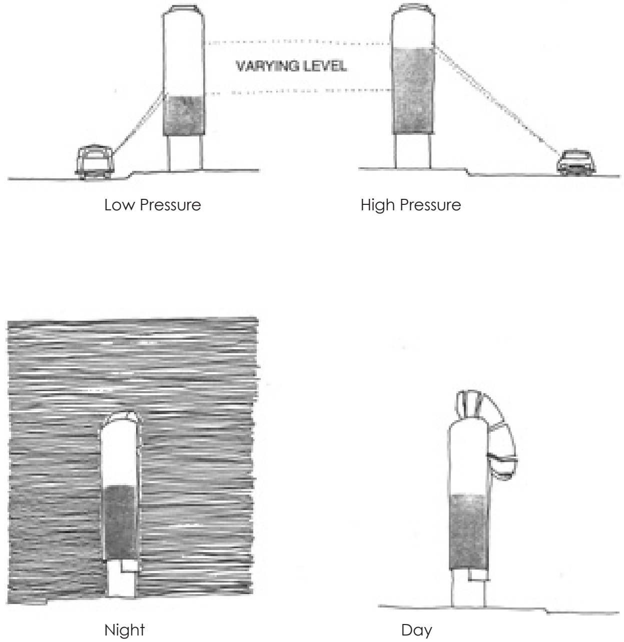


Fig 8.10 Thames Water Tower, sketches of effective communication

Fig 8.11 Shepherd's Bush roundabout at dusk

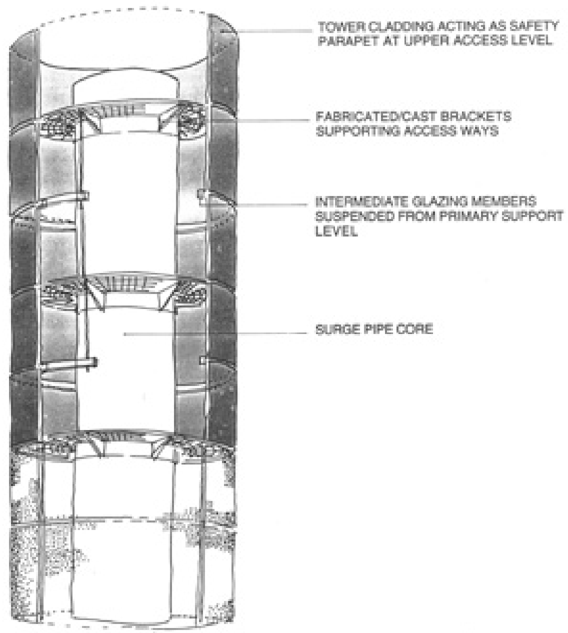


Fig 8.12 Thames Water Tower, initial structural design

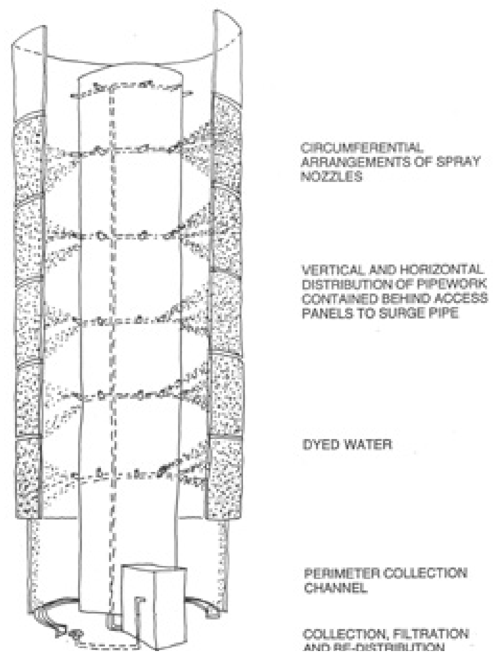


Fig 8.13 Thames Water Tower, initial design of the sprayed water system

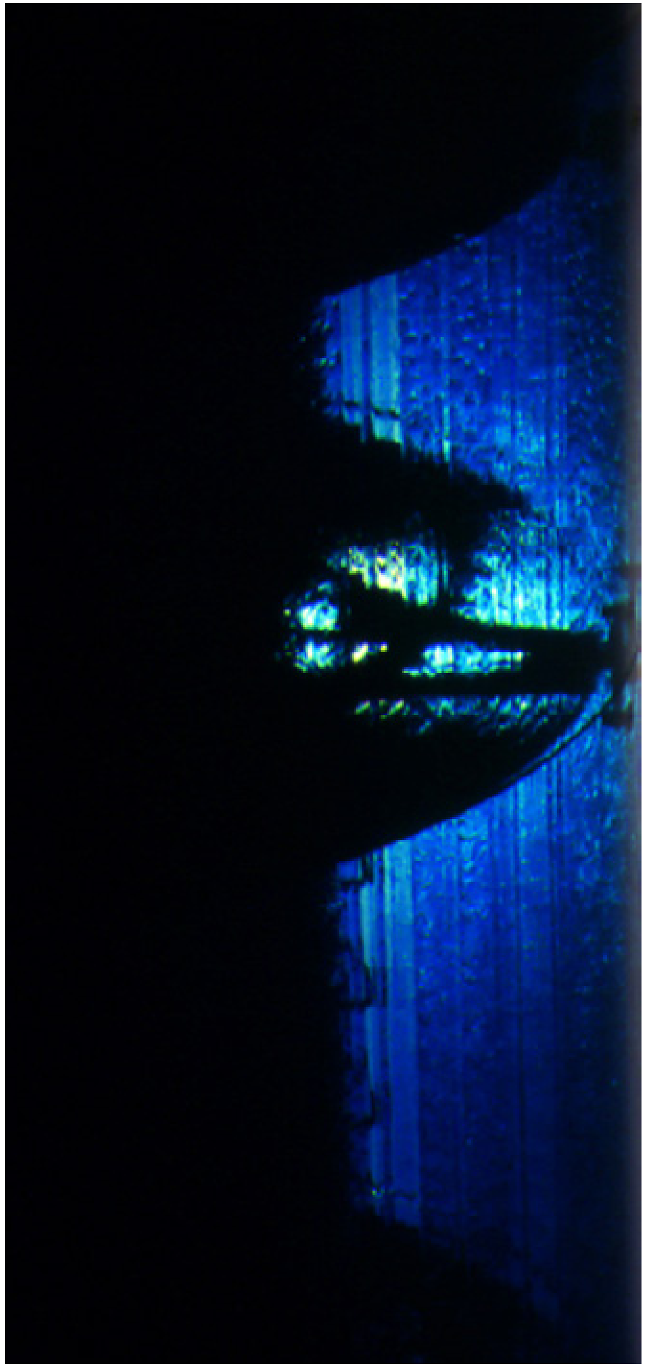
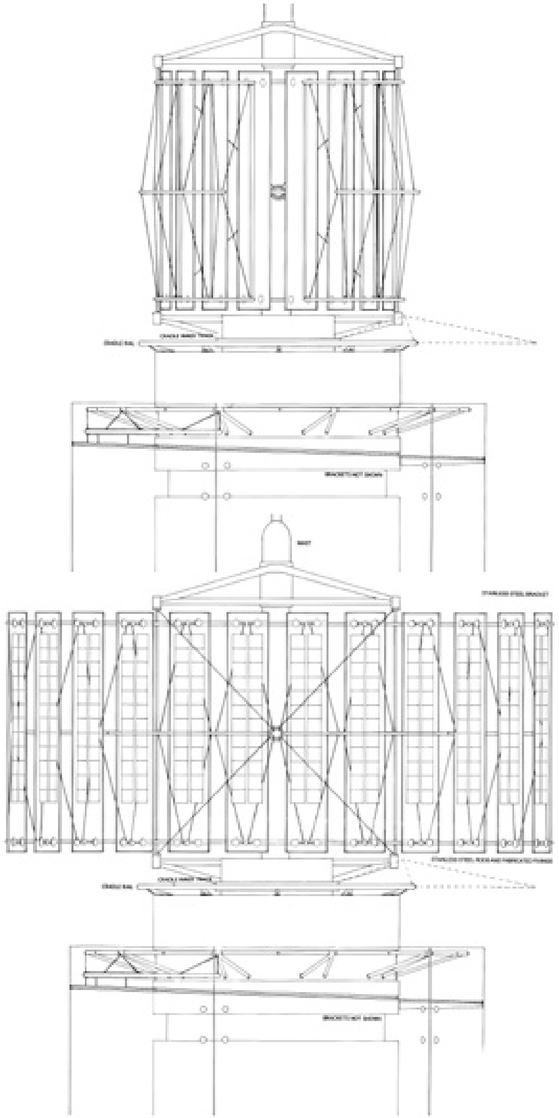


Fig 8.14 The sprayed dyed blue water inside the Thames Water Tower

The project was realised through the research and application of new technologies. The tower is clad with sophisticated, purpose-designed suspended glazing supported by bespoke stainless steel sand castings. All water is fully recycled within the tower. The Thames Water Tower was built by main contactor J. Murphy, for a capital cost of £500,000, using a non-adversarial partnering contact, New Engineering Contract, Option 3.

Fig 8.15 [below left] Brookes Stacey Randall Fursdon's tender drawing showing an automated solar vane open and closed

Fig 8.16 [below] Tender elevation drawing showing closed solar vane



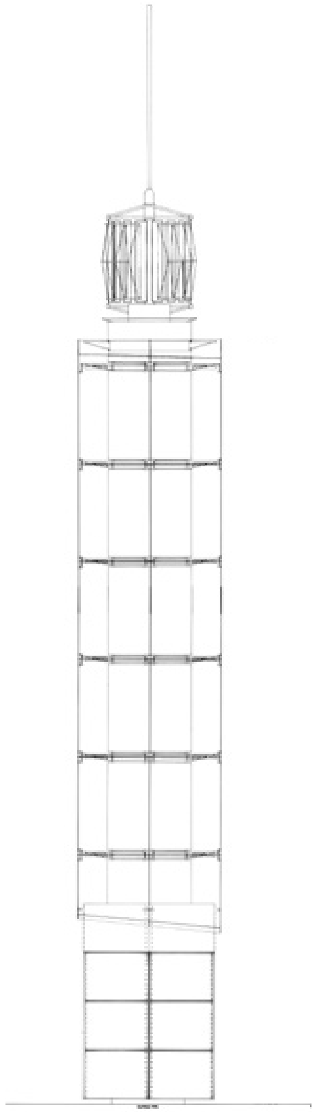
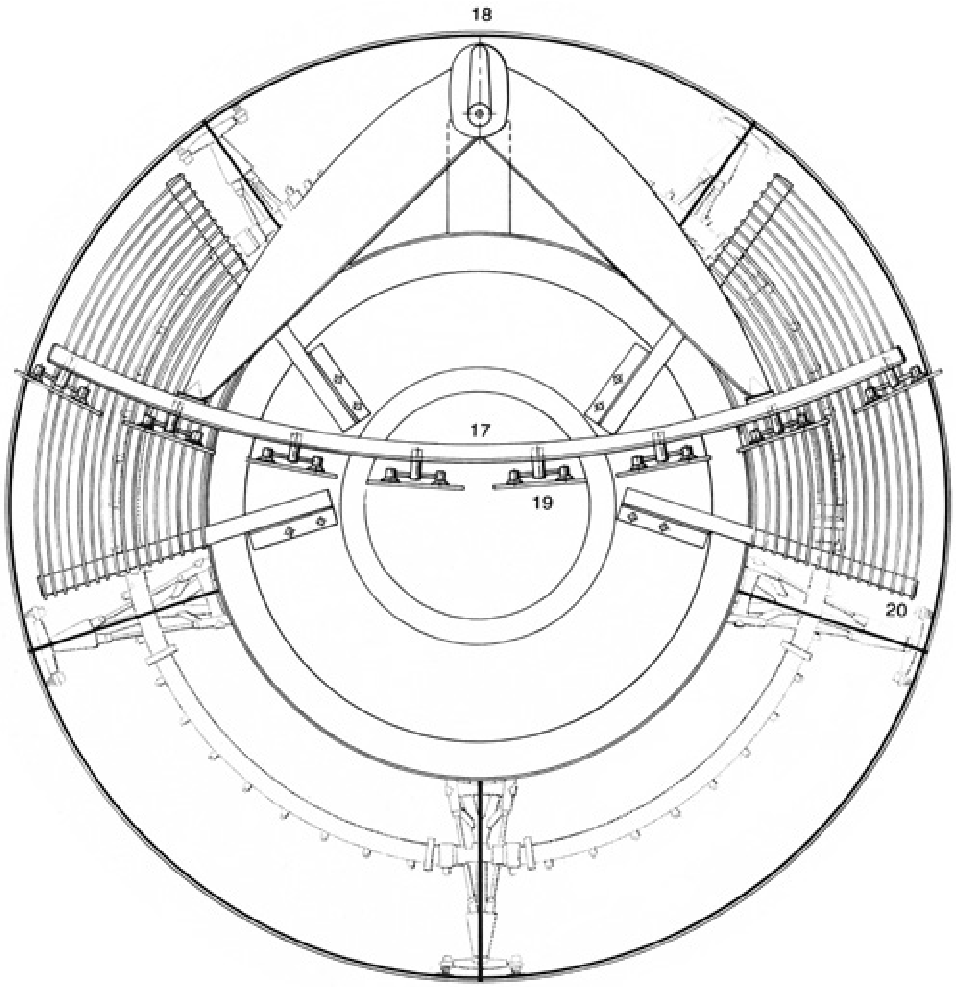


Fig 8.17 As-built plan of the fixed solar vane, aluminium mast and support structure with access deck and glass roof below



The polycrystalline solar cells of the vane assembly generate energy to power the barometer's pumps. The solar cells are supported by an elliptical aluminium extrusion that is refabricated and welded to form a curve in elevation. Aluminium arms reach out top and bottom to support the solar cells. The assembly was fabricated by Proctor Masts, who typically fabricate yacht masts. The aluminium is finished in 25µm of dark grey anodising to BS 3987:1991 by LTH Anodisers, now part of United Anodisers. The solar array is topped by a lighting conductor. Building Magazine observed 'aluminium was used as it offered advantages of ease of fabrication and a high strength-to-weight ratio',[6] quoting the author 'the mast was designed and specified to utilise the characteristics of durability and potential malleability inherent in aluminium extrusions'.[7]

The Thames Water Tower was tendered with a solar vane that automatically opened for daylight hours and closed at night when it was not functioning. This design option had to be dropped due to the tight timescale of the project, in line with the completion of the Thames Water Drinking Water Ring Main, and not due to cost constraints. Thus, although a specialist subcontractor responded to the architect's inquiry eventually, Brookes Stacey Randall Furdson had to design the fixed solar vane that tops the tower in order to meet the completion date.

It was the first public building in London to be powered by photovoltaic. The Thames Water Tower demonstrates engineering excellence and contributes to London's public realm. It received a RIBA Award and the judges stated 'such is the inspirational nature of the tower that the panel felt its qualities transcended the question, is it sculpture or architecture?'[8]

Fig 8.18 Maintenance is an essential part of sustainability

Fig 8.19 Thames Water Tower solar vane in moon light

Fig 8.20 On the Queen Elizabeth II reservoir at Walton-on-Thames, England, Thames Water has built a 'solar farm' of 23,000 photovoltaic panels, with a 6.3MW peak output, generating 5.8million kW per year – enough to power about 1,800 homes, using a Japanese system. It was completed in March 2016

Co-operative Insurance Society (CIS) Tower, Manchester, England: Architect G. S. Hays with Gordon Tait, 1962, Overcladding by Arup, 2005

Construction began in 1959 and was completed in October 1962, at 122m the CIS Tower was the United Kingdom's tallest building. Built as an expression of the progressive approach of Co-operative movement, it still houses the Co-operative Banking Group. It was designed by G. S. Hay Chief, Architect of the Co-operative Wholesale Society, with Gordon Tait of Sir John Burnett, Tait & Partners. The office tower is 118m tall, with 26 storeys, and accommodates 2500 Co-operative insurance workers, consolidated from disparate buildings in Manchester. The project cost £4 million in 1962.

The CIS Tower was listed Grade II in November 1995 by English Heritage (now Historic England).[9] This listing states ''it has a strikingly elegant and sophisticated design inspired by Skidmore, Owings & Merrill's Inland Steel Building in Chicago (1956-8), which together with its imposing scale and massing, is highly successful in conveying, as originally intended, the status and prestige of the CIS and the wider Co-operative movement, and the strength of the financial community within Manchester'.[10] This listing also observes that both named architects designed other building in England, which are now listed.

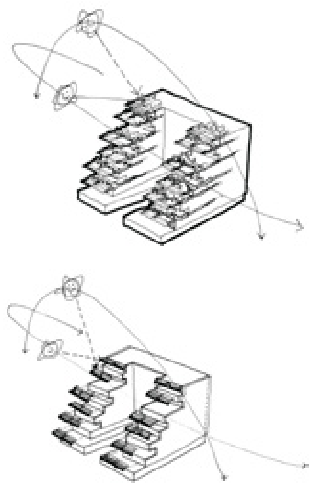
The design of the tower was inspired by the work of Skidmore Owings & Merrill and in particular a visit by the client, Robert Dinnage, and the architects to the Inland Steel Building in Chicago. The crisp composition of the CIS Tower comprises a 26-storey office tower, 28-storey service tower and 5-storey podium. The office tower is steel framed and clad in a clear glazed curtain walling, with articulated I-section anodised aluminium mullions and black vitreous enamel spandrel panels. The materials were selected to resist the highly polluted atmosphere of 1960s predominately industrial Manchester. The articulated service tower houses 28 storeys and is 122m high, clad entirely in 14 million one centimetre square grey Italian mosaic tiles (or tesserae), which started to fall off shortly after the completion of the building, due to adhesion failure and lack of expansion joints in the concrete substrate.

In 2005 the service tower was overclad with photovoltaic panels manufactured by Sharp Electronics and supplied by Solar Century, under the design direction of Arup. At the time it was the largest building-integrated solar array in Europe, generating over 180,000kWh of electricity annually. The removal of the mosaic tiles and the installation of the photovoltaic panels and 24 roof based wind turbines cost £5.5 million in 2005. It was formally switched on by Prime Minister Tony Blair on 3 November 2005 and immediately started to feed into the UK national grid, thus generating an estimated annual saving of over 100 tonnes of CO_2 emissions. Solar Century worked with Plusswall to design an aluminium framing system to integrate the installation of the 7,244 photovoltaic panels, which generate electricity and protect the tower's building fabric from the weather. This project demonstrates the potential for cost effective and environmentally responsible refurbishment of dilapidated existing buildings.

Fig 8.21 CIS Tower, Manchester, England, 1962, overclad with photovoltaic panels in 2005, photographed by Adrian Toon (a2n) in 2016

Sino-Italian Ecological & Energy Efficient Building (SIEEB), Beijing, China: Architect Mario Cucinella Architects, 2006

Beijing's Sino-Italian Ecological & Energy Efficient Building (SIEEB) is the result of a co-operation between Italy and China. It represents a platform to develop bilateral long-term collaboration in the fields of energy and environment and showcases the potential for reducing CO_2 emissions from the building sector in China.[11] The SIEEB is located on the Tsinghua University campus, Beijing, and was designed by Mario Cucinella Architects and the Politecnico di Milano. It houses a Sino-Italian education, training and research centre for environmental protection and energy conservation. It has a floor area of 20,000m^2 in ten visible storeys and two basement levels. Overall it is 40m high. The public part of the programme is housed on the ground floor and the first basement, including a 200-seat auditorium, main hall and exhibition spaces. The lowest basement level is car parking.



The offices and laboratories are located on the upper nine floors in a u-shape plan, which progressively and symmetrically steps back to allow the sun to penetrate the heart of the plan, which is a landscaped courtyard. The stepped south façades are

Fig 8.22 SIEEB, Beijing, China, designed by Mario Cucinella Architects

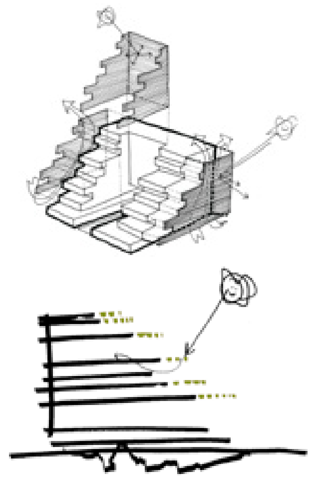


Fig 8.23 [left and above] Mario Cucinella Architects' sketches of inviting daylight into the SIEEB, yet providing solar shading

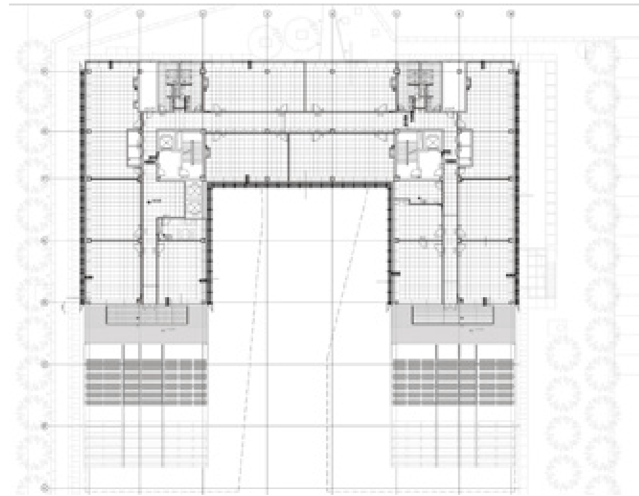


Fig 8.24 SIEEB level 5 Plan: Offices and Laboratories

further enlivened by cantilevered structural elements on which photovoltaic panels are mounted, extending to the south providing shade to the terraces and curtain walling. These assemblies carry 95 photovoltaic panels on each side of the courtyard, with a total nominal peak power of 19.95KWp. This building optimises the production of solar energy in winter and solar protection in summer.

This project is the result of an integrated design process with collaboration between architects, consultants and researchers, a key issue in the design of green buildings. The underlying philosophy combines sustainable design principles and state of the art technologies to create a building that responds to its climatic and architectural context. The design uses both active and passive strategies, through the building's shape and architecture of its envelope, to control the external environment in order to optimise the comfort and conditions of its internal environment. The building design has been assessed through a series of tests and computer simulations of its performance in relation to its possible shape, orientation, envelope and technological systems to find a balance between energy efficiency targets, minimal CO_2 emissions, a functional layout and the image of a contemporary building. The SIEEB building takes shape from an analysis of the site and of the climatic conditions of the city of Beijing.

The aluminium curtain walling system is a vital component in delivering this holistic architecture. The building is closed and well insulated on the northern side that faces the cold winter winds and is more transparent and open towards the south. On the east and west sides, light and direct sun are controlled by a double skin facade that filters solar gain and optimises the penetration of daylight into the office spaces. As shown in Figure 8.25 this includes bouncing daylight deeper into the office by the use of aluminium light shelves. Artificial lighting in these offices can be controlled both electronically and manually. The double façades facing the courtyard are shaded by laminated glass louvers comprising an 8mm outer pane with PVB interlayer and a 6mm inner pane. The inner skin of the double façade is an aluminium based curtain walling with 8-16-8mm double-glazing units providing a U-value of 1.4W/m^{2}K. The curtain walling systems were fabricated by Permasteelisa and the photovoltaic panels were manufactured by Enitecnologie.

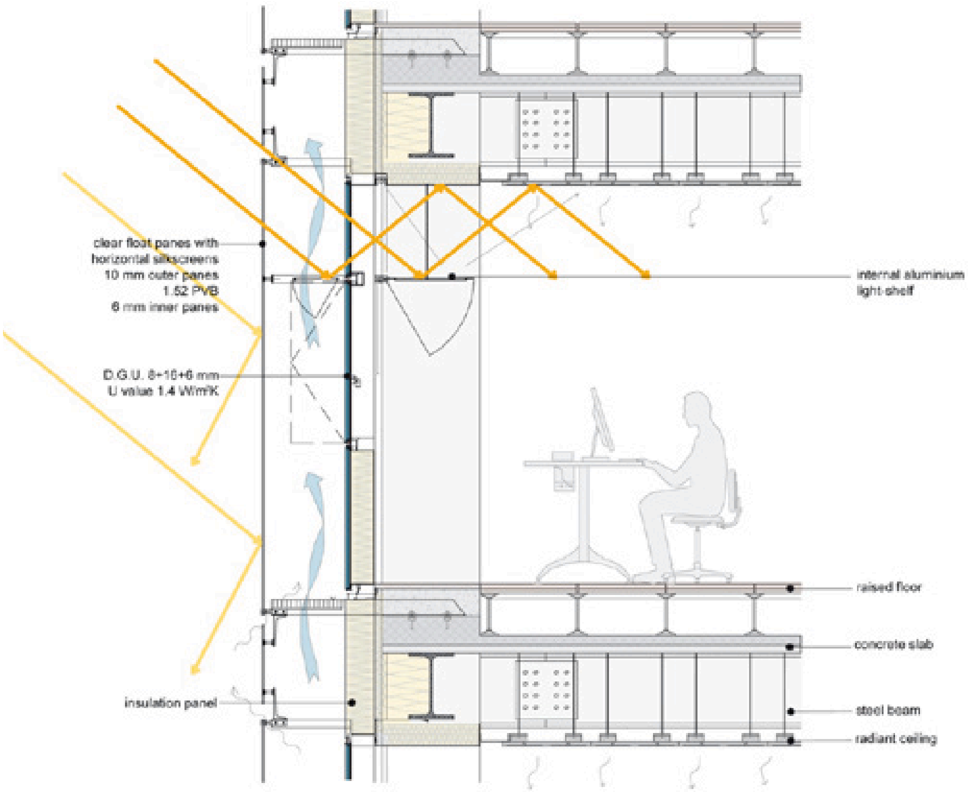


Fig 8.25 Section through the double façade of the east and west elevations

The envelope components, made of extruded aluminium, as well as the control systems and the other technologies are an expression of the most up-to-date Italian production methods, within the framework of a design philosophy in which proven components are integrated into innovative systems of:

- Resource-use minimisation, including construction materials and water;
- Minimisation of environmental impact in both the construction and in-use stages;
- Intelligent control during operation and maintenance;
- Photovoltaic with a combined heat and power system;
- Improved air quality;
- Environmentally sound and durable materials;
- Water recycling and re-use.

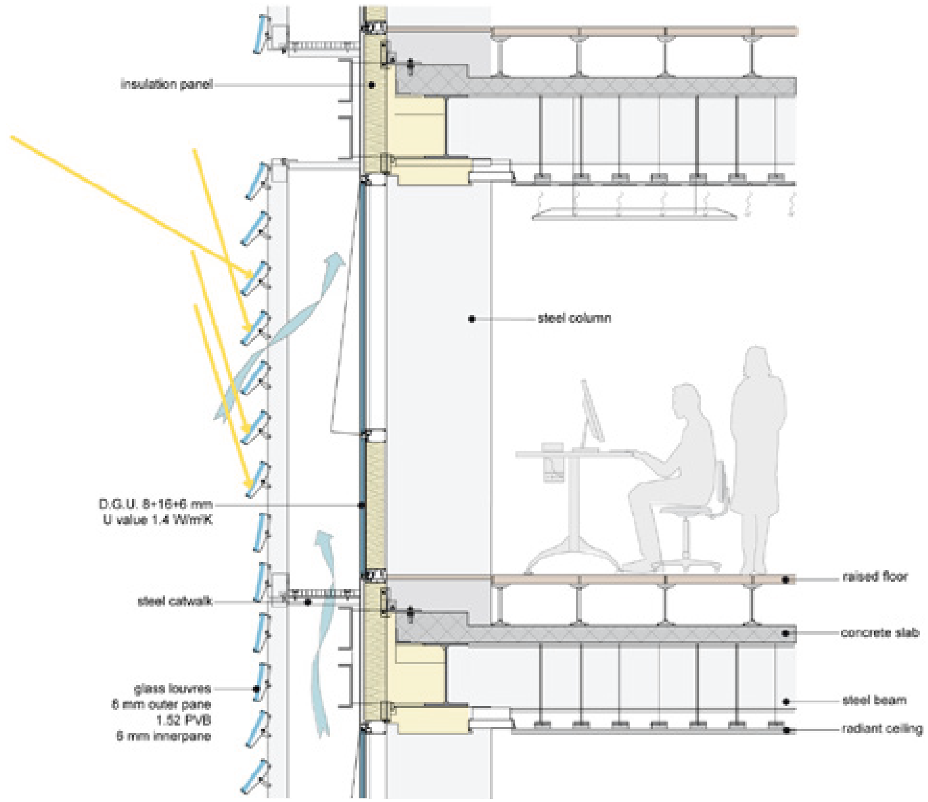


Fig 8.26 Section through the double façade of the courtyard elevations

Fig 8.27 The courtyard is richly planted with bamboos

The centre of the plan is a courtyard garden generously planted with bamboos and surrounded by water. The two-storey opening in the north façade and the open form of the building ensures this is visible from the surrounding streets, inviting the general public into this environmental institute.

The use of a combined heat and power plant in conjunction with the photovoltaic panels enables SIEEB to sell energy back to the grid in Beijing. Mario Cucinella Architects seeks to reduce the carbon footprint of all the projects it designs. Mario Cucinella attributes 17 per cent of the carbon savings to technology and 36 per cent to the design of the architecture.[12]

Fig 8.28 The photovoltaic panels also shade the south façades and terraces

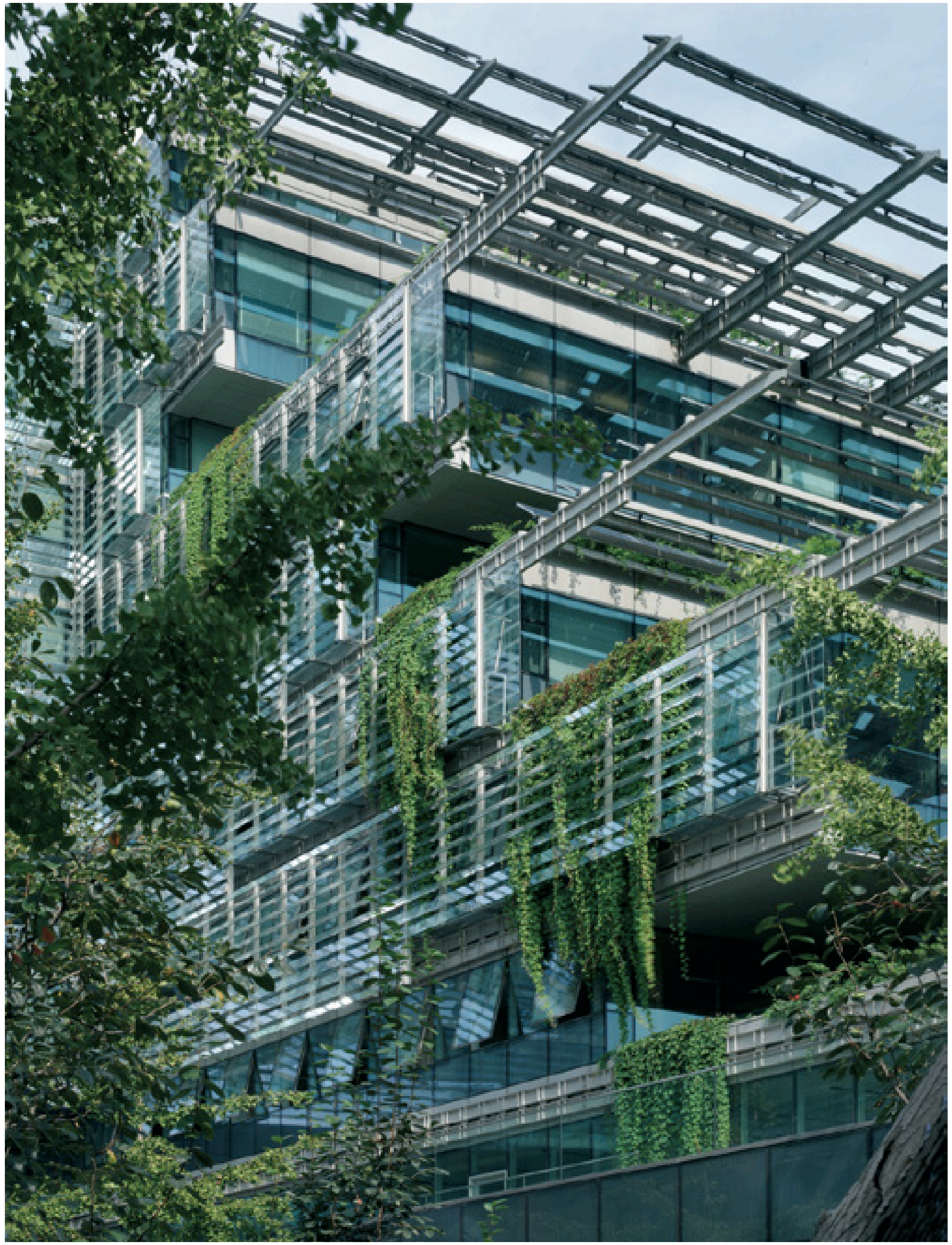


Fig 8.29 SIEEB is a green building, combining biodiversity and power generation

Fig 8.30 SIEEB, Beijnig, China

The Nottingham House, London, Madrid and Nottingham: Designed & Built by Faculty & Students of the School of Architecture, The University of Nottingham, 2010

The University of Nottingham's entry into the 2010 Solar Decathlon Europe competition - the Nottingham House, is a prototype of a zero carbon affordable starter home that can be constructed throughout Europe.[13][14] The research aims included the realisation of a fully prefabricated house providing a comfortable and domestic environment that would have little or no running costs. Thus, simultaneously tackling fuel poverty, eliminating the need for winter fuel payments whilst protecting against over heating in summer, which can be equally injurious to human health and well-being. Underscoring this was a wider societal goal of tackling global warming and reducing our dependence on fossil fuels, seeking to contribute to achieving the carbon reduction of the Stern Review, 2006.[15] However, the design aim of the Nottingham House was firmly focused on domesticity, with technology as a servant of this homely environment. The plan form can be used

Fig 8.31 The Nottingham House at Rio Parque, Madrid

to create two storey terrace housing and courtyard housing depending on the climatic situation, local traditions and culture. This is based on the placement of the L-shaped plan. The Nottingham House is a prototype for a housing system that is adaptable both culturally and technically so that it can be used throughout Europe. In essence, this means that the Nottingham House is pre-adapted to the risk of elevated temperature ranges in the summers of Northern Europe, as predicted by some climate models, later in the twenty first century.

The Nottingham House was Britain's only entry into the 2010 Solar Decathlon Competition. This was the first time the competition was staged in Europe having been initiated in America in 2002. The design process started in the form of a competition within the Masters and Diploma (RIBA Part 2) design research studio ZCARS (Zero Carbon Architecture Research Studio), led by Michael Stacey with Swinal Samant and Lucelia Rodrigues, with input from Brian Ford and Mark Gillott. The strict spatial requirements of the competition were included in the ZCAR studio brief, as shown in Figure 8.32, alongside wider issues related to zero carbon housing. The ten tasks of the Solar Decathlon Competition are: Architecture, Engineering, Market Viability, Communications, Comfort, Appliances, Hot Water, Lighting, Energy Balance, Getting Around, thus, the title a Solar Decathlon.

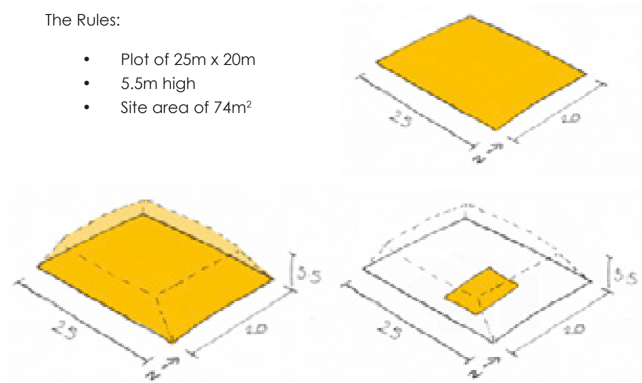


Fig 8.32 The strict spatial requirements of the Solar Decathlon Competition, 2010

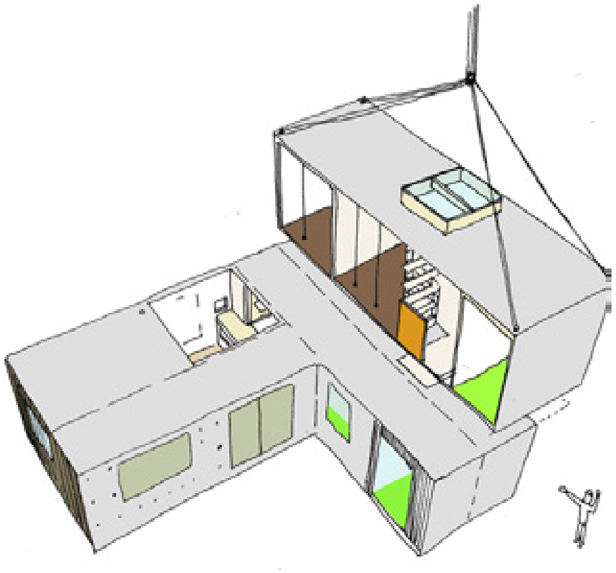


Fig 8.33 Rachel Lee, Chris Dalton and Ben Hopkins' sketches of the Nottingham House - modular construction

The students researched the issues influencing the proposed houses collectively from the demographics of European households through to how to achieve super insulation and comfort in all seasons. In particular, they studied and modelled the climate of middle England and the significantly hotter and generally dryer

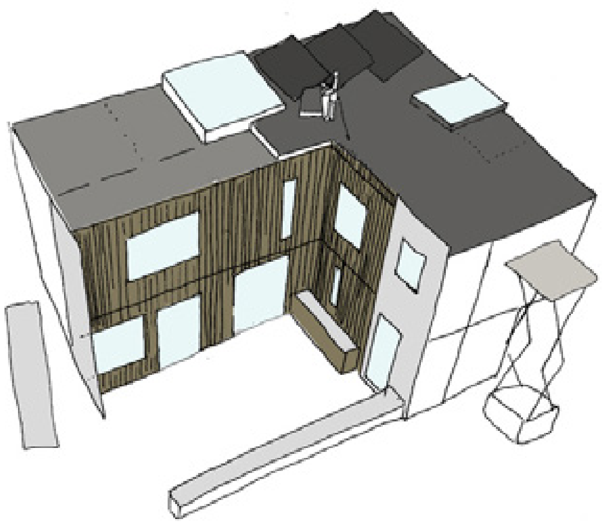


Fig 8.34 Rachel Lee, Chris Dalton and Ben Hopkins' sketches of the Nottingham House - the home nearly complete

climate of Madrid, in central Spain. Environmental and tectonic strategies were provided to all students by the authors. It is at this stage that the use of passive downdraught evaporative cooling (PDEC), was proposed to cool the house in Madrid, based on previous collaborative EU funded research into this innovative technique, coordinated at the University of Nottingham.[16] In essence, nesting a prototype cooling system within a prototypical house. The ZCARS competition brief also specified prefabrication to minimise waste and to deliver quality in a short construction timescale. The energy targets were set as both Code for Sustainable Homes Level Six and Passivhaus Accreditation.

The ZCARS students competed in teams, typically of three. This internal competition was won with a design authored by Rachel Lee, Chris Dalton and Ben Hopkins; they tested the design as a group of houses in the Meadows Nottingham, Figure 8.35. The spatial arrangement of the winning proposal spoke of homely starter housing. On arrival at the Nottingham House one notices that entry to the front door is sheltered by the first floor above.

Fig 8.35 Testing the Nottingham House design on a site in the Meadows, Nottingham

Passing through the draft lobby – essential to minimise unwanted air changes - there is daylight and views to the courtyard. Turning left, observing that the house has been designed to Lifetime Homes Standards for accessibility, one enters the house passing the downstairs toilet, which also accommodates hot water storage created by the rooftop solar thermal panel. Passing the stair to the first floor you can either directly enter the kitchen or proceed to the dining room and onto the living room. The corner of the living room is glazed, providing ample daylight and views to both the courtyard and landscape or streetscape beyond.

On returning to the dining room one becomes aware that this is a double height space. This is the heart of the house both socially and environmentally. In essence it is a mini-atrium providing spatial and communication opportunities to the house as well as stack ventilation. At the top of this space, below the openable aluminium framed double glazed roof light, is the PDEC system. In hot dry climates, as found in southern Europe, the house is cooled by a PDEC system, developed by Professor Brian Ford in collaboration with the Spanish company Ingeniatrics-Frialia. The core of this technique is adiabatic cooling from finely misted water linked to a gull wind roof light operated by electrical actuators. The tiny water jet nozzles were developed by Ingeniatrics-Frialia and the system was designed and tested by the University of Nottingham.[17] The performance of the PDEC combined with the relative thermal mass of this lightweight yet very well insulated home proved very successful when tested in Madrid, despite the frequent visitors inherent in this public competition.[18]

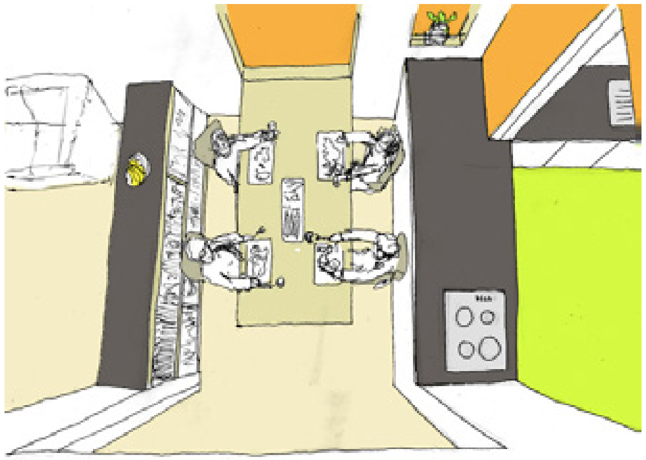


Fig 8.36 Sketch of the dining space - the heart of this home

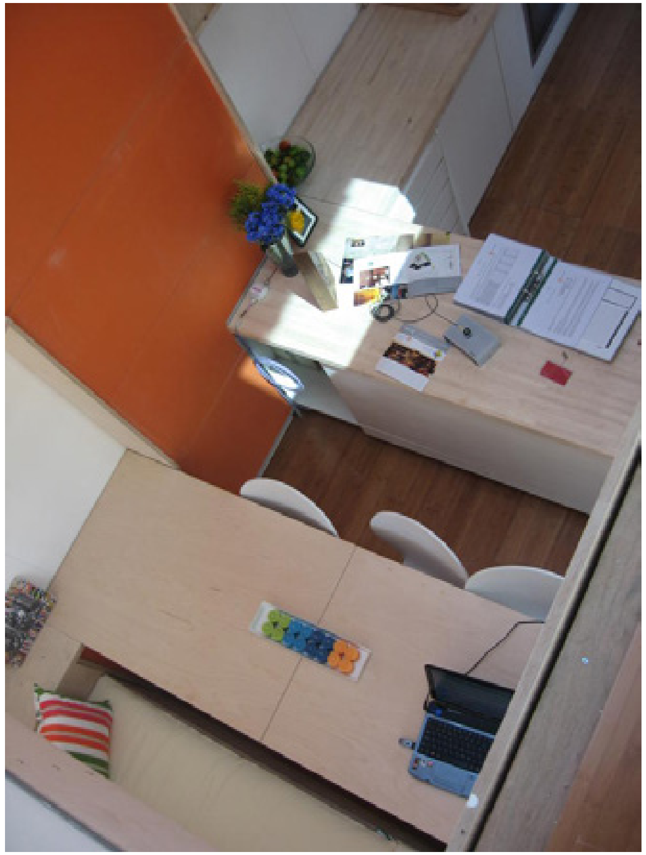


Fig 8.37 Dining space and kitchen counter viewed from the first floor

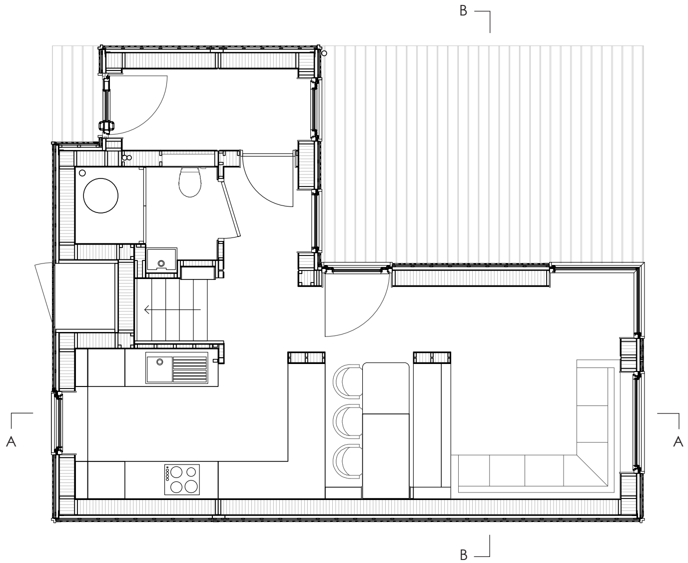


Fig 8.38 Nottingham House, ground floor plan

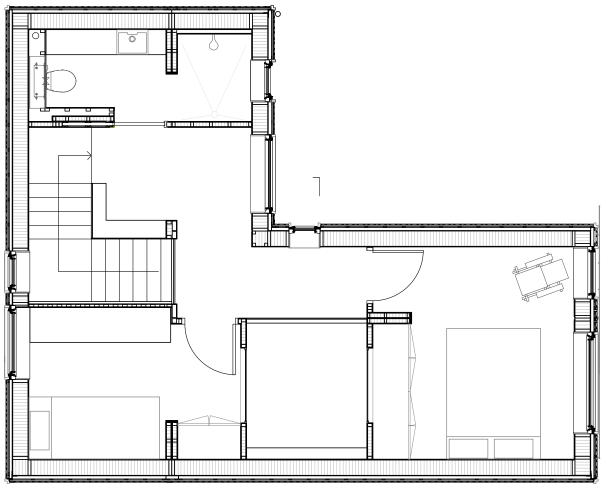


Fig 8.39 Nottingham House, first floor plan

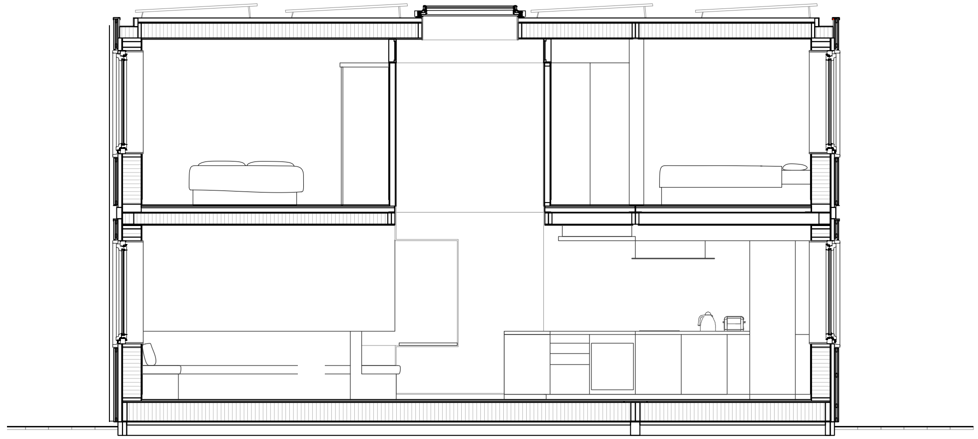


Fig 8.40 Nottingham House, section AA

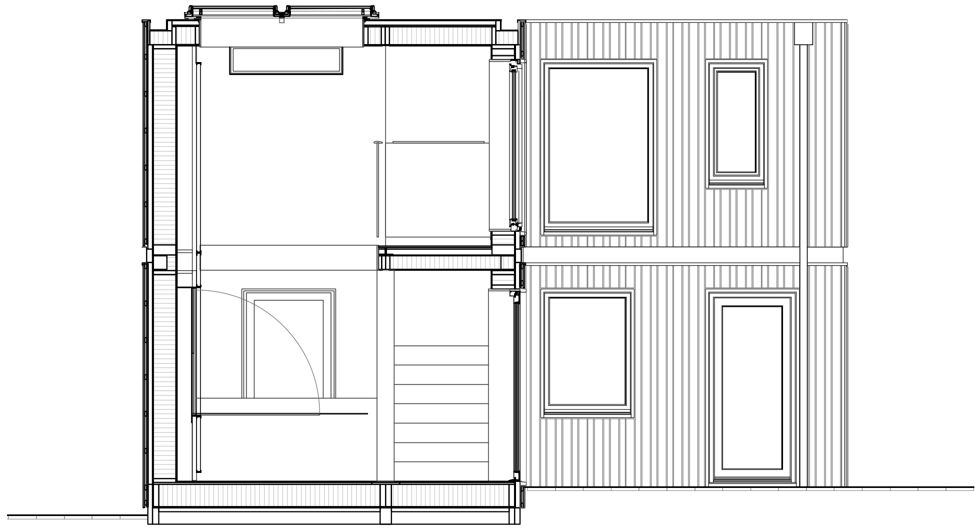


Fig 8.41 Nottingham House, section BB

The kitchen is open to the dining room and is a modest and well appointed fitted kitchen, not unlike a twenty first century update of the fitted kitchens of AIROH post Second World War aluminium prefabs.[19]

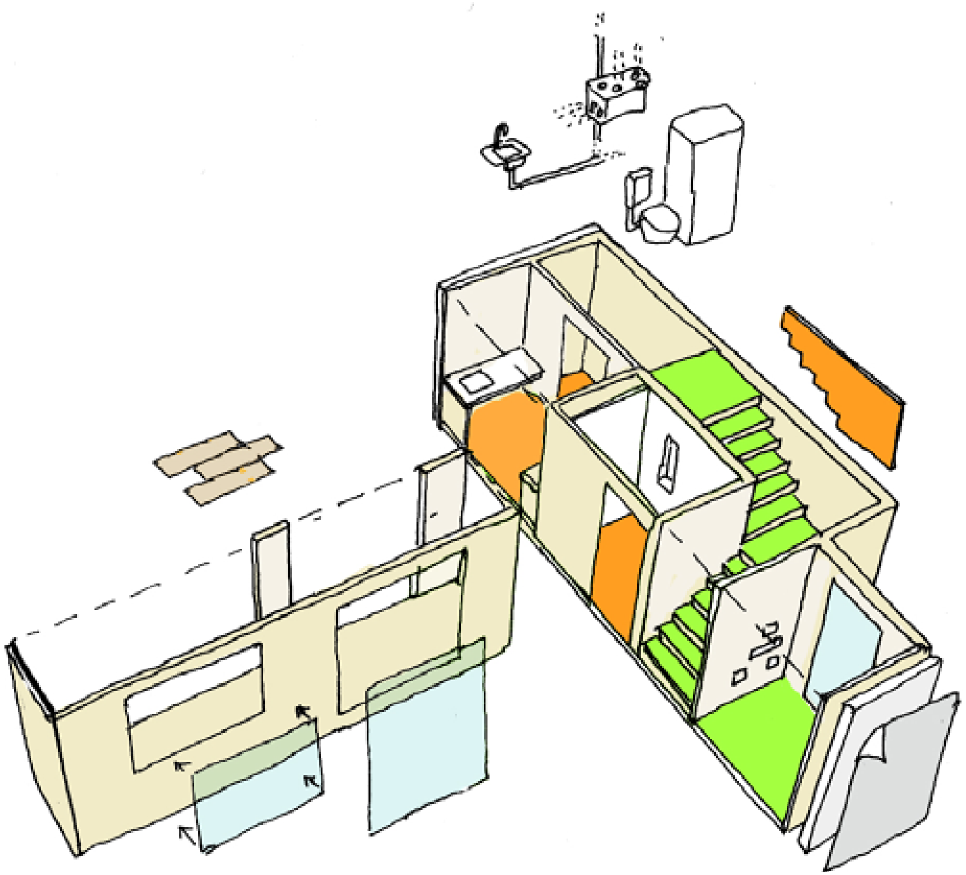


Fig 8.42 The module that primarily contains the kitchen, No 1, is the most highly serviced module, incorporating the majority of services of the house

In the corner of the kitchen is a whole house heat recovery system, which remained exposed in the Solar Decathlon Competition for didactic reasons, Figure 8.42. The kitchen ceiling is a little lower to accommodate ducting primarily in the kitchen, which is formed by bringing together Modules 1 and 4. Fair face birch ply is used to delineate the spaces of the home. Ecophon, in a blood orange red, highlights the dining room wall and the staircase wall respectively, both vertical elements in the house design, whilst providing acoustic absorbency. All other surfaces are hard including the bamboo floor. Bamboo was selected as it is fast growing and renewable. Stepping out to the courtyard here we find the homeowners are growing their own fruit and vegetables. The growing of edible plants was an important sub-theme of the Nottingham House, further contributing to reducing the carbon footprint of the family.

The floor area of the house is only 187m^2. A compact home in many ways reminiscent of a home designed by Sverre Fehn, except a hearth and a fireplace are missing.[20] The excellence of the students' design was recognised in a RIBA East Midlands Low Carbon Award, 2009, awarded before fabrication had commenced.

The Nottingham House was designed from the outset as a fully prefabricated assembly. Thus the maximum transportable size was an important design constraint, however this was not allowed to dominate the internal domesticity. The house modules were fabricated and assembled by architecture students and staff at the University of Nottingham, coordinated by Mark Gillott. The primary sponsor of materials and components was Saint Gobain and its subsidiaries in the UK, without whom the project would not have been realised.

Fig 8.43 The whole house heat recovery system is left exposed in the kitchen

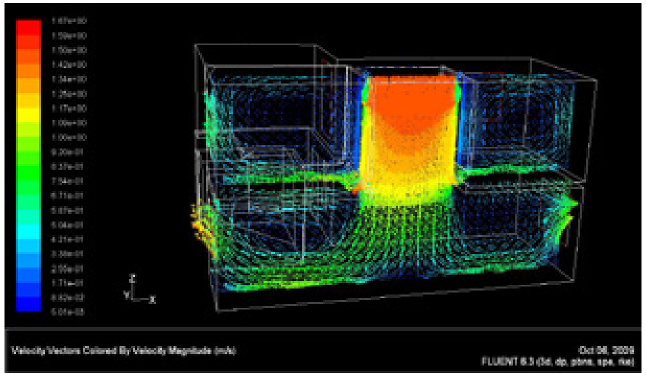


Fig 8.44 Computer fluid dynamic model of the cooling by PEDC of the Nottingham House

Fig 8.45 PEDC spray system in operation below the rooflights of the Nottingham House

The final design comprised eight volumetric modules that were transported fully glazed with all services installed and fully finished internally, for final assembly on site in Madrid by a team of students and staff. The ground floor Module 1, which primarily forms the kitchen, is the most intensively serviced. The only services in most other modules are power and lighting, except where Module 5 & 6 come together to create the shower room. The modules are all open on one side and only form the enclosure of the house when all eight modules are in place.

Aluminium plays a vital role in the assembly of the Nottingham House, in part, based on the author's more than 30-year experience from research and practice in the use of aluminium in component based construction.[21] Stock aluminium angles have been used to create contemporary interpretations of skirting boards and architraves. Stock aluminium angles and channels also support structural glass balustrades. It is surprising that stock aluminium sections are still predominately sold in the UK in imperial sizes, suggesting that some of the dies are over 40 years old. Brackets made of three stock aluminium angles, expertly welded by Faculty of Engineering technicians, support the corners of the ThermoWood timber cladding; the idea that aluminium is difficult to weld is 'history' as discussed in Chapter Two. Although the aluminium is conductive, it is only 3mm thick. The essence of this detail is to minimise the material in the insulation zone bridging between the structure and the cladding.

Fig 8.46 Assembling the modules of the Nottingham House in the former Carlton Television Studio

The windows of the house are triple glazed achieving a U-value of 0.5Wm^2/K provided by 36mm thick units, comprising three layers of 4mm toughened glass with low emissivity coatings on surfaces three and five, combined with 90 per cent Krypton filled cavities. The window profiles are a combination of timber with insulated inserts, pultruded thermal breaks and polyester powder coated aluminium outer sections, manufactured in Germany by Hermann Gutmann Werke but fabricated in Derbyshire. On completion the windows, equipped with triple glazed low emissivity glazing units, proved to be very heavy. The largest window for the living room on the ground floor required three people to carry and install it. Apart from the fact that these window sections are bulky, they potentially represent the material future of architecture, with each material playing a distinct role; the timber safely in the warm dry interior capturing CO_2, the insulation ensuring that the low U-value is achieved, the pultrusion stops thermal loss through the frame and the aluminium retains the triple glazing and provides a guaranteed low maintenance finish via polyester powder coating.[22] TSC Report 3 provides a life cycle analysis of window framing comparing aluminium, aluminium clad wood, wood and PVCu – interestingly, in the long-term study the all aluminium window frames offered the best overall environmental performance.[23] All the external aluminium sections, including the window sections on the Nottingham House, are polyester powder coated a warm grey colour, Ral 7022. The house is completed by aluminium rainwater hoppers and downpipes, supplied by Marley Alutec, and press braked 3mm aluminium copings and flashings, manufactured by Crown Aluminium and polyester powder coated by Birmingham Powder Coaters.

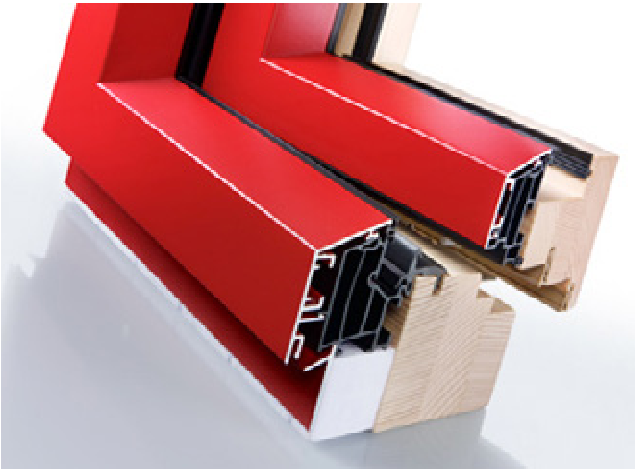


Fig 8.47 Aluminium timber triple glazed windows manufactured by Hermann Gutmann Werke.

Fig 8.48 Suppliers and sponsors of the Nottingham House

The high-performance photovoltaic panels were assembled on the roof using standard Schüco aluminium extrusions, as shown in Figure 8.50. The unseasonal rain in Madrid collected on the flat roof – it was not laid to falls due to competition height restrictions – and as it slowly evaporated, it increased the performance of the solar panels and helped to keep the house cool.

In Madrid, despite torrential rain that flooded our site, the Nottingham House was assembled in 11 days. What was billed as a new public park over a newly sunken urban highway, adjacent to the Palacia Real on the banks of the Rio Manzanares and designed by West 8, on arrival proved to be an un-landscaped building site, which soon became very muddy. After the competition the house was disassembled ready for transportation back to England in 2 days. Today the Nottingham House, following its reassembly, makes a permanent contribution to University Park, Nottingham and housing people from the School of Architecture.

Fig 8.49 The Nottingham House in Madrid, 2010 during the Solar Decathlon Competition

Fig 8.50 Fixing the photovoltaic panels in the rain of Madrid

The Nottingham House is a situated domestic ecology that fulfils Feenberg's recommendation to design to create appropriatable technology.[24] Almost nothing is more important in peoples' lives than their home and home life. In the twenty first century we have the technology and knowledge to construct a much higher standard of housing, which delights and serves humanity well.

Notes

1 Fraunhofer ISE (11 March 20160, *Photovoltaics Report*, Fraunhofer Institute for Solar Energy Systems, ISE, Freiburg.

2 www.bauder.co.uk/renewables/biosolar-system (accessed March 2016)

3 Michael Stacey founding partner at Brookes Stacey Randall Fursdon, 1987, set up Michael Stacey Architects in 2004.

4 M. Plannelles Herrero and A Mengul Muñoz, (December 2001), *Agua – Water* Via Arquitectura, 10.V-2, p. 49.

5 Ibid.

6 *The Shapemakers Award – Thames Water Tower*, Building Magazine, 23 June 1995, p. 42.

7 Ibid.

8 Cited by P Gruner, *Best building prize for blue water tower,* Evening Standard, 28 September 1995, p. 16.

9 Co-Operative Insurance Society (CIS) Building, Miller Street, Manchester, Listing Number 1270494, accessed via www.historicengland.org.uk/listing/the-list/list-entry/1270494 (April 16).

10 Ibid.

11 This text is based on information supplied directly by Mario Cucinella Architects and it also forms the basis of the text of this case study in *The Future Builds with Aluminium*, http://greenbuilding.world-aluminium.org/home.html

12 www.mcarchitects.it/sostenibilita (ac.cessed March 2016)

13 This text is edited from B. Ford and M.Stacey (2013) *The Nottingham House: Responsive Adaptation and Domestic Ecology* in M. Stacey, *Prototyping Architecture*, , Riverside Architectural Press, Cambridge, pp. 126–143.

14 Nottingham HOUSE (Home Optimising the Use of Solar Energy)

15 Robert Stern - The Economics of Climate Change: The Stern Review, 2007, Cambridge University Press. The Stern Review was published by the UK Government in 2006, this reference provides the paperback book of this review, as a stable source.

16 For more information on *Passive Downdraft Evaporative Cooling* see *Prototyping Architecture*, M. Stacey, *Prototyping Architecture*, , Riverside Architectural Press, Cambridge, pp. 124–143.

17 Ibid, and B. Ford, R. Schiano-Phan and E. Francis, (2010) *The Architecture & Engineering of Downdraught Cooling: A Design Sourcebook*, PHDC Press, London.

18 B. Ford, R. Wilson, Mark Gillot, Omar Ibraheem and J. Saimeron (2012), *Passive downdraught evaporative cooling: performance in a prototype house*, Building Research & Information 40(3) Routledge, London, pp 290 – 304.

19 AIROH [Aircraft Industries Research Organisation on Housing], 1948, re-assembled at Museum of Welsh Life - St Fagan's, near Cardiff. For more information please see M. Stacey, ed., (2014) *Aluminium and Durability,* Cwningen Press, second edition 2015, pp. 44-45.

20 P. Fjeld, *Sverre Fehn: The Pattern of Thoughts*, Monacelli Press, 2009 or I. Helsing Almaas, [Ed.] *Sverre Fehn: Projects and reflections*, Arkitektur N., 2009.

21 Future Builds with Aluminium, Case Studies curated and written by Michael Stacey see http://greenbuilding.world-aluminium.org/en/home.html

22 40 year guarantees are available on Super Durable grades of Polyester Powder Coating, underwritten by extensive testing as discussed in M. Stacey, ed., (2014), *Aluminium and Durability: Towards Sustainable Cities*, Cwningen Press, Llundain, second edition 2015.

23 S. Carlisle, E. Friedlander & B. Faircloth (2015), *Aluminium and Life Cycle Thinking: Towards Sustainable Cities*, Cwningen Press, Llundain

24 Andrew Feenberg, *Questioning Technology*, Routledge, 1999

Economical

This chapter focuses on the affordability of aluminium as a means of providing long-term durability in contemporary architecture. Focussing primarily on aluminium in sheet form, as roofing and cladding systems. The economics of the specification of aluminium is also evident in many other chapters, for example; in the delivery of curtain walling or shelving systems, as discussed in Chapter 2, and in the total cost of ownership of footbridges, discussed on pages 438–439. The long-term durability and successful service of aluminium – including roofs – is reviewed in TSC Report 1, *Aluminium and Durability*, with exemplars being inspected and tested – dating back to San Gioacchino in Rome, 1897, which is now almost 120 years old and it is still performing well. Furthermore, the earliest aluminium standing seam roof in Europe, the Nuremberg Congress Hall, 1968, is now approaching 50 years of service.[1]

Fig 9.1 Aerial view of Kalzip's profiled aluminium standing seam roof of the Nuremberg Congress Hall, installed in 1968

Fig 9.2 The mill-finish aluminium dome of San Gioacchino, Rome, 1897

The high strength to weight ratio of aluminium alloys is of vital importance to the design of roofing and cladding systems – with benefits such as; minimising transport cost, facilitating mechanical handling or the potential of installation by hand. In the majority of examples, the ability of aluminium to readily adopt or be formed into single curvature or double curvature components is key to the realisation of five out of six case studies, which have been set out chronologically. It is noticeable in this chapter that all the projects are of a large scale; from a train shed, via stadia to exhibition and mixed-use projects. However, this technology remains accessible to all architects whatever the scale of his or her project.

Fig 9.3 Aluminium can economically and efficiently clad projects, such as the 2012 Olympic Velodrome by Hopkins Architects

Fig 9.4 Riveting the aluminium cladding of the Dome of Discovery at the Festival of Britain, architect Ralph Tubbs, 1951

Stratford Market Depot, London, England: Architect WilkinsonEyre, 1996

Now twenty years old Stratford Market Depot, the train shed for the Jubilee Line extension at the eastern end of the line, was the key break through project for WilkinsonEyre, which fulfilled the intellectual promise shown in Chris Wilkinson's book *Supersheds*, published in 1991.[2]

Stratford Market Depot is a supershed, 100m wide and 190m long, which forms a parallelogram in plan, in part to avoid the archaeological remains of Strafford Abbey at the southern end of the site. Stratford Market Depot accommodates 11 train lines; three lines accommodate the Heavy Lifting Shop, the central five lines – General Maintenance and three lines – Cleaning. Ancillary accommodation is arranged in three blocks to the western side of the Depot with the Control Building articulated on the opposite corner. The steel structure is a diagrid of trusses 9m long and 2.4m deep. The two lines of trusses are at 60° generating parallelogram bays. This diagrid is picked up by tree-like columns in bays of 18 × 40m, creating an 8m clear height above the track level. The Depot has generous eves on all elevations, not just where the trains enter on northern elevation. Chris Wilkinson and Jim Eyre decided to erect the structure first 'followed by the roof deck and finishes, in order to provide a dry area to cast the concrete floor slab below.'[3]

Fig 9.5 North east façade of Stratford Market Depot, designed by WilkinsonEyre

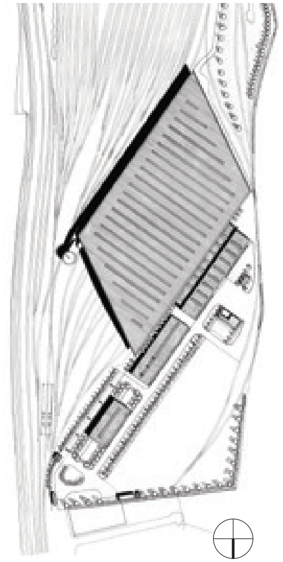


Fig 9.6 Plan of Stratford Market Depot, nts

The roof is clad in a Kalzip dual alloy mill-finish aluminium standing seam roof in continuous sheets that are gently curved, thus avoiding internal gutters. This train shed is generously day lit by rooflights throughout, which run broadly east-west in response to the structural grid below. The specialist installer of the aluminium standing seam roof was Prater Ltd.

Fig 9.7 The expansive aluminium standing seam roof of Stratford Market Depot

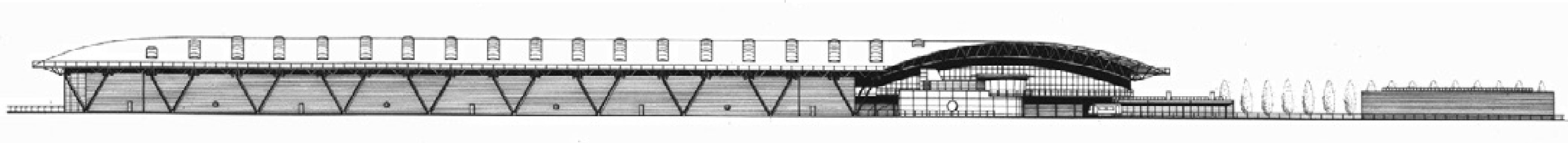


Fig 9.8 WilkinsonEyre's elevation of Stratford Market Depot

Fig 9.9 A Jubilee line train being serviced inside Stratford Market Depot

The southwest wall of the Depot is clad in Kalwall to provide thermal performance and to diffuse direct sunlight thus avoiding glare, (for more information on Kalwall, see page 244). This is a cost effective and hard working industrial building delivered with an elegant economy of means. Colin Amery suggests 'it will be a pleasure to use while having all the dignity of a modern cathedral'.[4] The Depot, completed in April 1996, was conceived and delivered as a high-quality work of contemporary architecture, in keeping with all of the stations of the Jubilee Line.

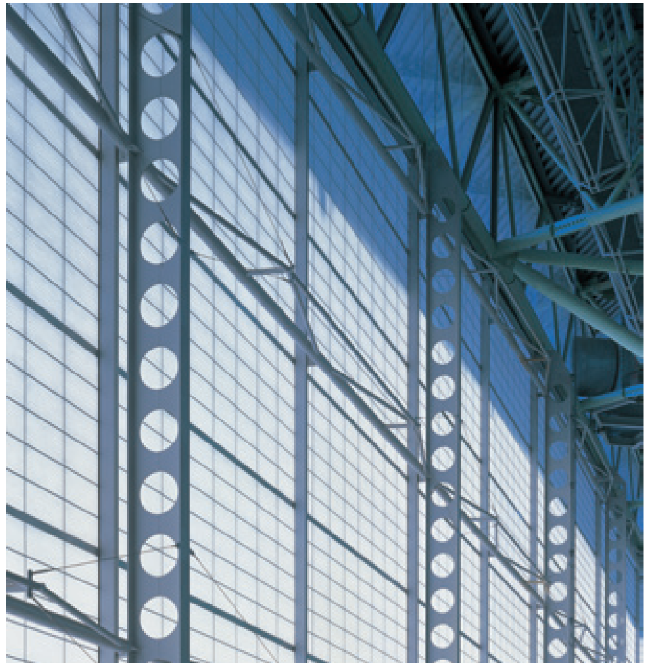


Fig 9.10 The south west façade of the Depot is clad with Kalwall

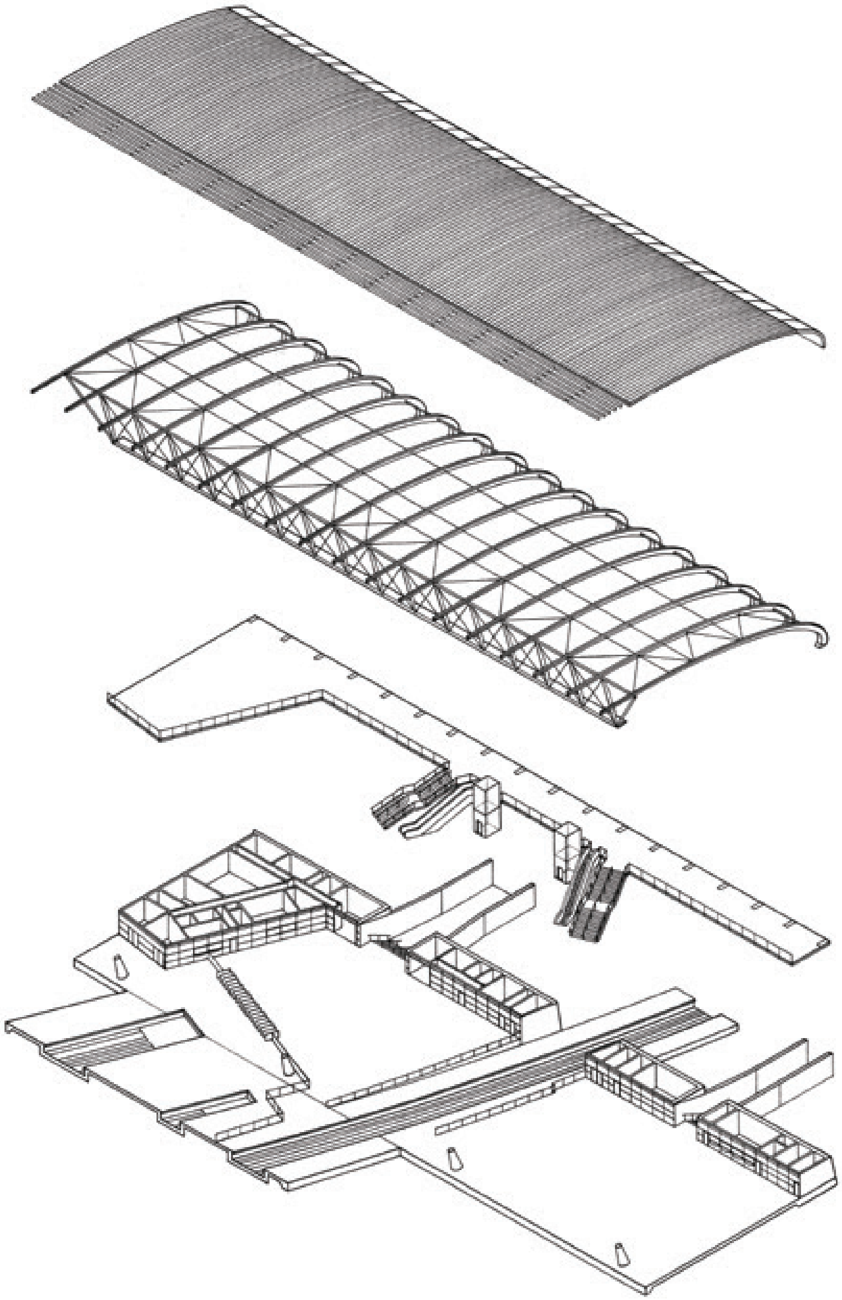


Fig 9.11 The primary elements of Stratford Jubilee line station, architect WilkinsonEyre, 1999

WilkinsonEyre went on to design Stratford Jubilee line station, which is also clad with an aluminium seam roof. The design of the Jubilee Line extension was led by Roland Paoletti and it opened to the public in 1999. The excellence of this public architecture and infrastructure was a key factor in London winning the 2012 Olympic bid in 2005. Stratford Jubilee line station served as a major gateway during the 2012 London Olympics.

Fig 9.12 North west elevation of Stratford Jubilee line station

Fig 9.13 South façade of Stratford Jubilee line station

2012 Olympic Velodrome, London, England: Architect Hopkins, 2011

Three of the watchwords for the design and procurement of the London 2012 Olympics were responsible sourcing and legacy. At one stage it appeared that the Olympic Delivery Authority (ODA) did not understand the environmental credentials of aluminium and that it can be readily sourced responsibly. Furthermore that it can be part of a re-use strategy or recycled, or better still offer long term durability in a legacy mode of continued use. The UK aluminium industry worked hard to secure the role of this light metal in the delivery of 2012 Olympics.

The 2012 Olympic Velodrome, designed by Hopkins Architects, is probably the best example of a venue tuned for Olympic success, with nine new World and Olympic Records with a further two Olympic Records, combined with a future use that was in place before the Olympics, as the Lea Valley Velopark. Richard Arnold, the ODA project sponsor of the Velodrome, observed in 2007 following Hopkins Architects' appointment, 'we spent the first four months focusing on the masterplan of the VeloPark, during which, while the facilities stayed the same, we actually increased the overall site area over that identified in the brief.'[5] Following extensive consultation with future user groups and with the legacy secure, only then did Hopkins Architects with its fellow consultants focus on the design of the Velodrome itself. The elegant simplicity of Hopkins Architects' Velodrome design delivered a world-class arena seating 6000 spectators for a capital cost of £90million. Following the 2012 Olympics the Velodrome and its site were converted into a VeloPark at a cost of only £4million. In contrast the main Olympic Stadium, designed by Populous, is currently being converted to a football (soccer) stadium as a retrofit. This was part of the initial brief for the main stadium, which cost £486 million in 2012.[6] The cost of the conversion, which has also been designed by Populous, is a further £272million.[7]

Fig 9.14 The 2012 Olympic Velodrome viewed across the Queen Elizabeth Olympic Park

Fig 9.15 2012 Olympic Park under construction

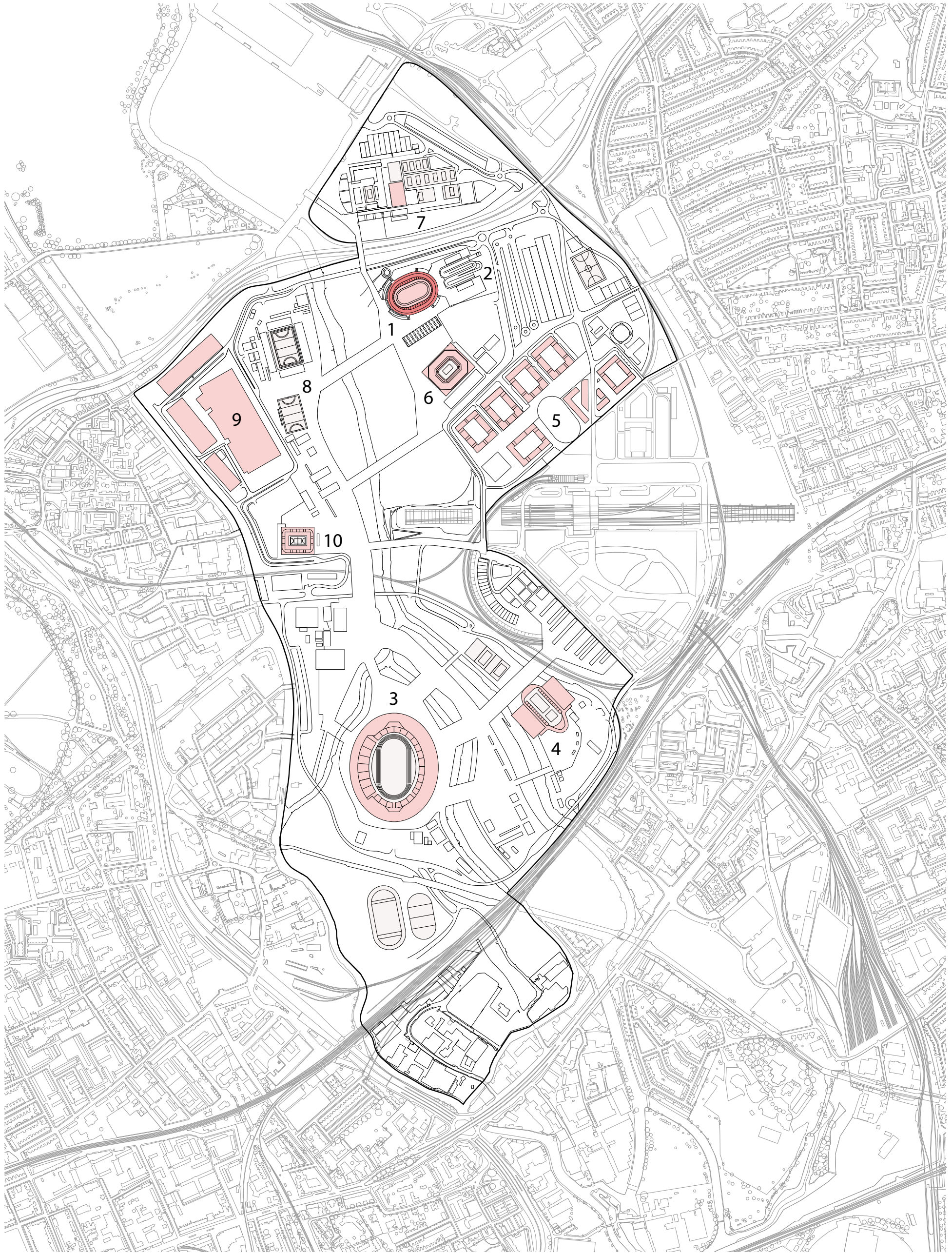


Fig 9.16 [left] 2012 Olympic Park Site Plan, nts:
1 Velodrome
2 BMX Track
3 Olympic Stadium
4 Aquatics Centre
5 Athletes' Village
6 Basketball Arena
7 Eton Manor
8 Hockey
9 Media Centre
10 Handball Arena

Hopkins Architects, working with engineers Expedition, won the competition to design the 2012 Olympic Velodrome from a shortlist that included architects without direct experience of designing velodromes. Chair of the judges Nicholas Serota, Director of Tate, recalls that:

> The Hopkins Architects team impressed from the earliest stages of the competition. Their personal engagement with the cycling community gave them an understanding of the needs of the prime users of the building. The clarity of their initial concept of a civic building with a lean structure, elevated above the park and lit by natural light, was informed by their knowledge. It has survived the design and construction process by virtue of the skill, determination and sensitivity of the whole design team.[8]

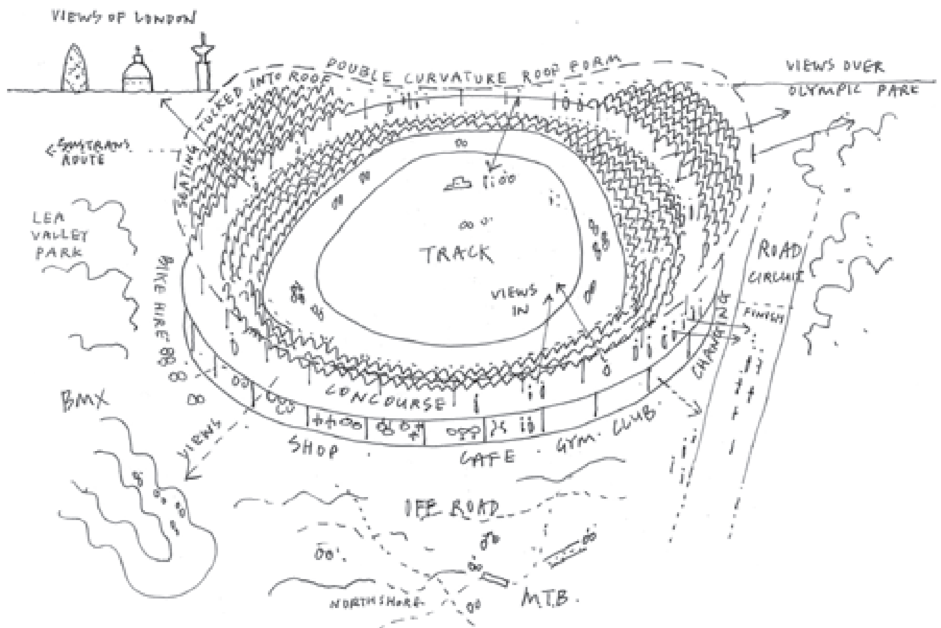


Fig 9.17 Hopkins Architects' initial design sketch of the 2012 Olympic Velodrome

Hopkins Architects observe of this project:

> 'The Olympic Delivery Authority set a number of sustainability and material targets; through careful consideration and integration of the architecture, structure and building services the design has met or exceeded these requirements. Work started on site in February 2009 and was completed ahead of programme and on budget in January 2011.'[9]

The design and delivery of the 2012 Olympic Velodrome is an excellent example of close collaboration within the design team and with the main contractor ISG, the specialist subcontractors and the complete supply chain. It was delivered using a non-adversarial partnering form of contract, a New Engineering Contract: Option 3.

Ghent Veledrome, designed by architect M.J. Tréfois and completed in 1964, uses a 67m clear span aluminium roof structure, see pages 316–319 in Chapter 2. Whereas the 2012 Olympic Velodrome deploys a steel cable net structure, which is a tension only system that generates the saddle form that characterises this building.

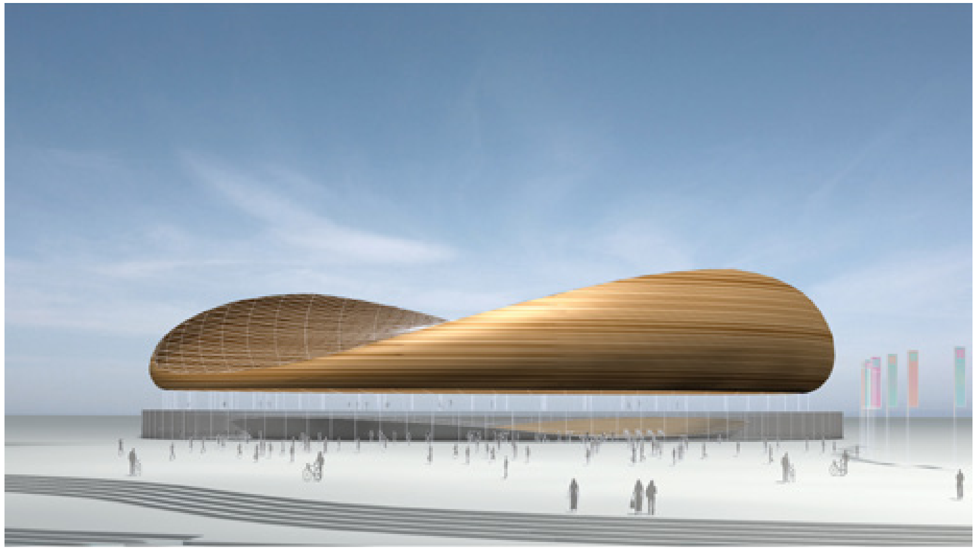


Fig 9.18 Competition model of Hopkins Architects' proposed 2012 Olympic Velodrome

Fig 9.19 2012 Olympic Velodrome, photographed in January 2013, during the minor works to prepare it for long term community use

Fig 9.20 Inside the Velodrome, itself, no changes were required, photographed January 2013

Hopkins Architects' design for the Velodrome is not directly mimetic of bicycles, however, it does takes inspiration from the design of bicycles with all of the components of the building being expressed, combined with a refined level of integration. Mike Taylor, an architect and partner at Hopkins Architects observed: 'Whereas the design of the bicycle has evolved through numerous evolutionary steps, we had one hit at the Velodrome.'[10] Noting that it 'could not have been designed and built without the latest 3D computer modelling techniques.'[11] Furthermore that the design process began with sketches: 'Perhaps surprisingly for such complex building, nearly every aspect started life as a sketch by hand on paper.'[12] He observing the importance of cross-disciplinary collaboration in achieving such a highly integrated design, he stated the need to retain a clear 'a philosophical and aesthetic vision' of the project.[13] Revealing his clarity of vision during the design process, 'the Velodrome sets out to reconcile ambitious engineering and technology with more architectural concerns of form, proportion and composition.'[14]

Chris Wise founder of Expedition Engineering describes how a 'striking, doubly curved roof shape evolved as the form which would best answer the stadium's needs. The saddle-shaped roof 'shrink wraps' the building around the track, minimising the interior volume and in turn reducing heating and cooling requirements'.[15]

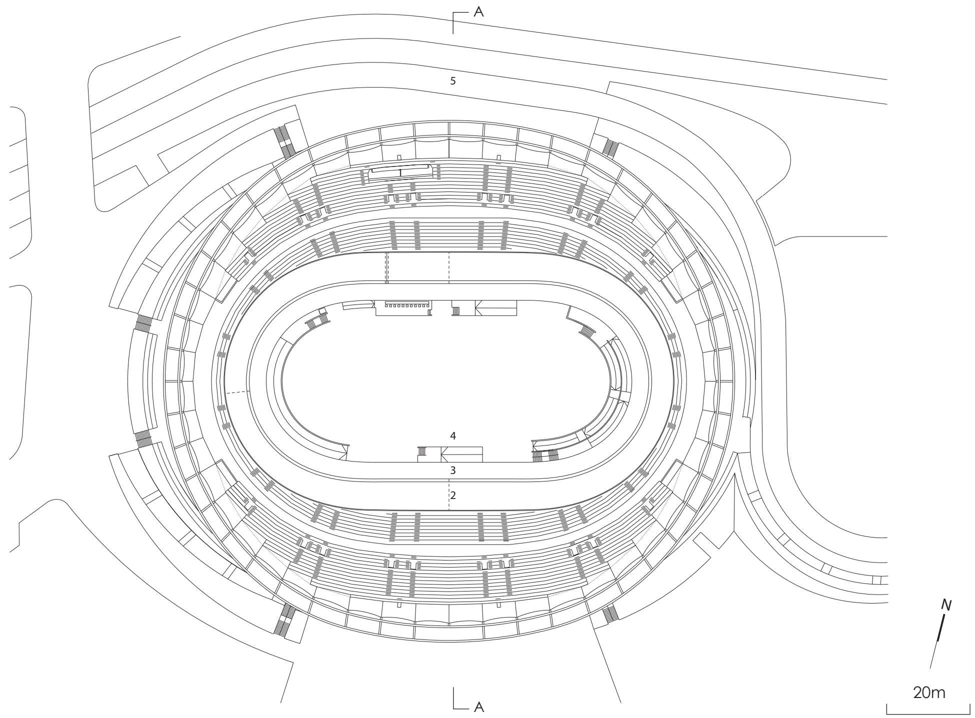


Fig 9.21 2012 Olympic Velodrome, Upper Tier Plan:

1 Timing/scoring zone
2 Track
3 Safety zone
4 Infield
5 Legacy road circuit

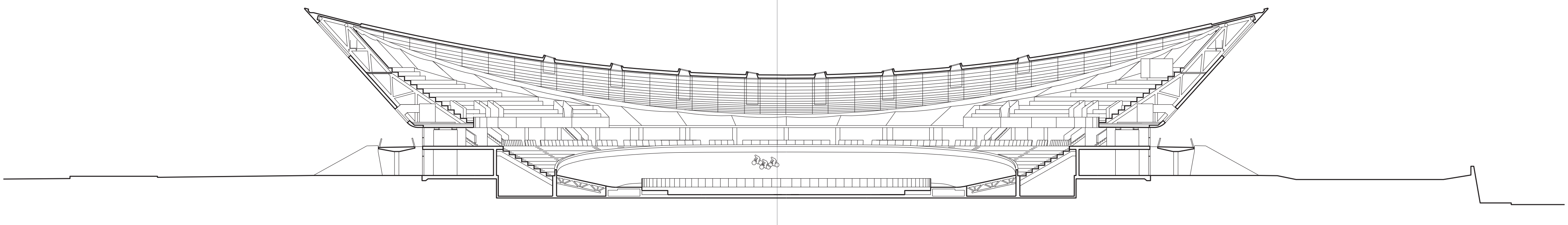


Fig 9.22 2012 Olympic Velodrome section A-A

The cable net comprises pairs of 36mm diameter spiral strand steel cable set out primarily on a 3.6m grid. The cables running north-south resist gravity and have their high points on the ring truss, those running east-west resist wind uplift in this lightweight roof connected to the roof truss at its low sweep. The cables are locked together with forged steel nodes, which also carry 'receiver brackets' that start the roof build up. The design eschews a large ring beam that would have been visually heavy and added significantly to the amount of steel required. Following careful design iterations the forces from the cable net were resolved via the steel frame of the upper setting rack and into the concrete structure below, see Figure 9.23.

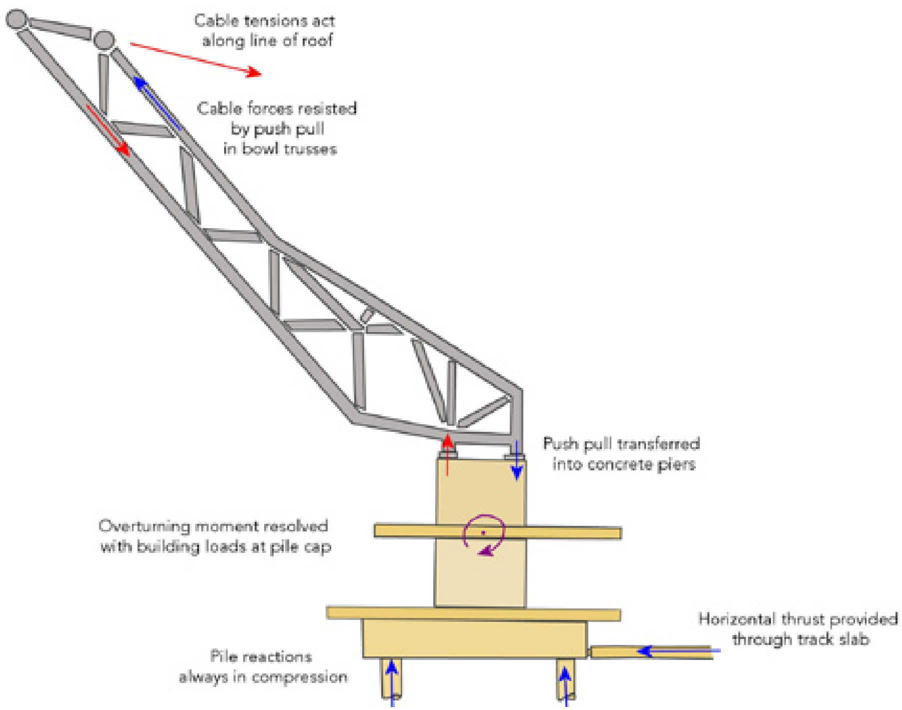
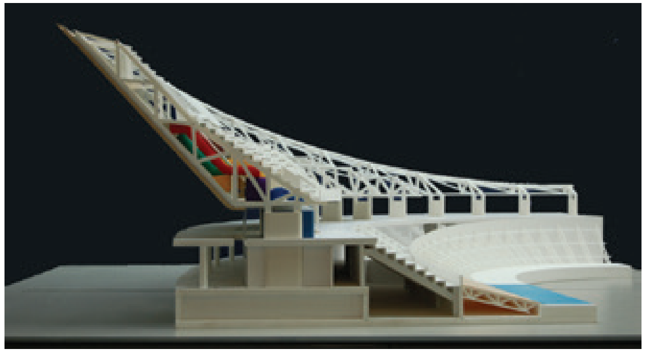


Fig 9.23 Diagram of the principal structural load paths in the Velodrome's steel trusses and piled concrete foundations

Fig 9.24 Study model of the integration of structure, seating and track



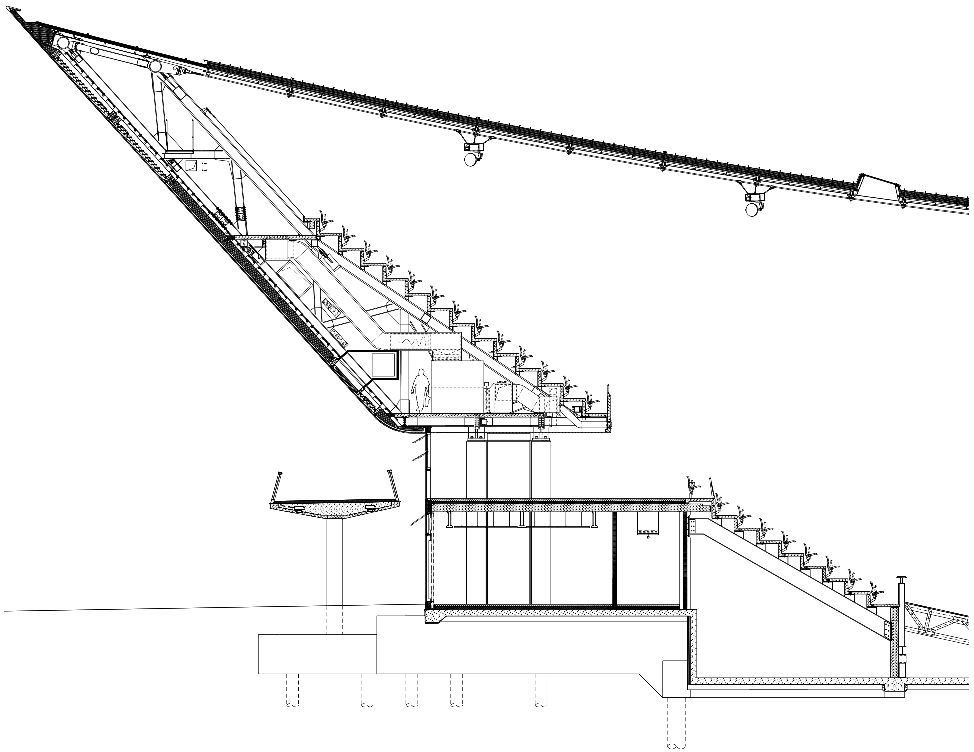


Fig 9.25 Detailed cross section through the Velodrome's seating

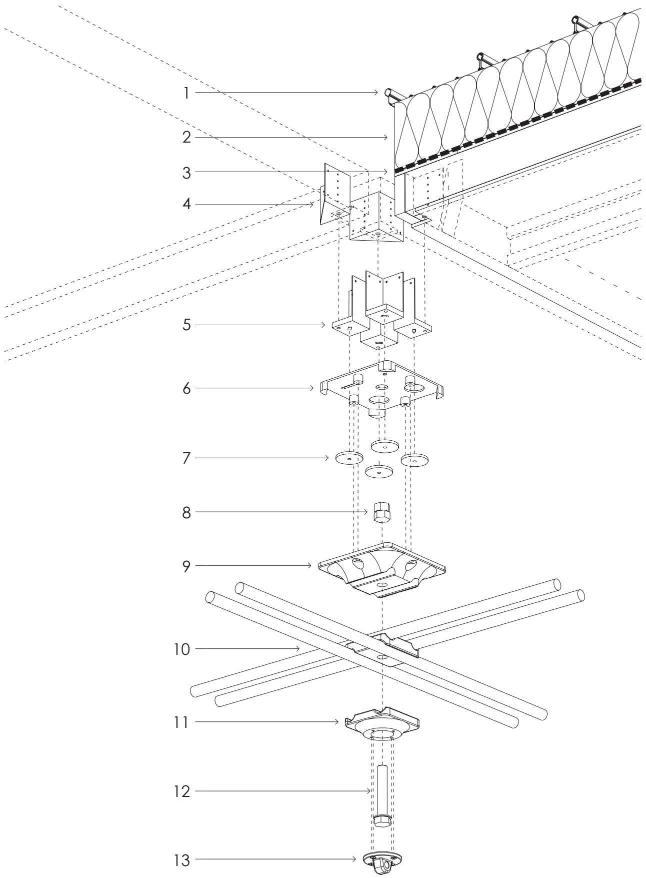


Fig 9.26 Node detail:

1. Aluminium standing seam roof
2. 300mm insulation providing overall U-value of 0.15 W/m²K
3. Vapour barrier
4. Timber roof cassette with birch-faced plywood soffit incorporating steel corner brackets
5. Fabricated steel powder-coated receiver brackets with PTFE coating to underside
6. Fabricated steel powder-coated connection plate with PTFE coating to top. Combination of fixed, slotted and oversized holes varies with location
7. Steel powder-coated washers
8. Nut
9. Galvanised forged steel top cable clamp
10. Galvanised forged steel middle cable clamp with paired 36mm diameter cables at 120mm centres
11. Galvanised forged steel bottom cable clamp
12. Bolt through cable clamp assembly
13. Galvanised forged steel coverplate with connection for lighting containment

Timber cassette panels were placed on 'receiver brackets', with a temporary waterproof layer, on the nominal 3.6m grid. There are about 1000 standard panels and approximately 100 non-standard. All are carefully detailed to allow for movement in the cable net and to constrain this in particular directions. A vapour check layer was laid onto the temporary waterproof layer followed by 300mm of insulation and then a Kalzip dual alloy mill-finish aluminium standing seam roof. The thermally efficient Kalzip clip fixing detail for the standing seam roof is attached to the timber cassette panels. These roll formed aluminium roof panels are up to 130m long, in single sheets, and the standing seams run east-west. The specialist installer of the aluminium standing seam roof was Prater Ltd. [16] With a roof area of 1.4ha or 14,000 m² the case for design

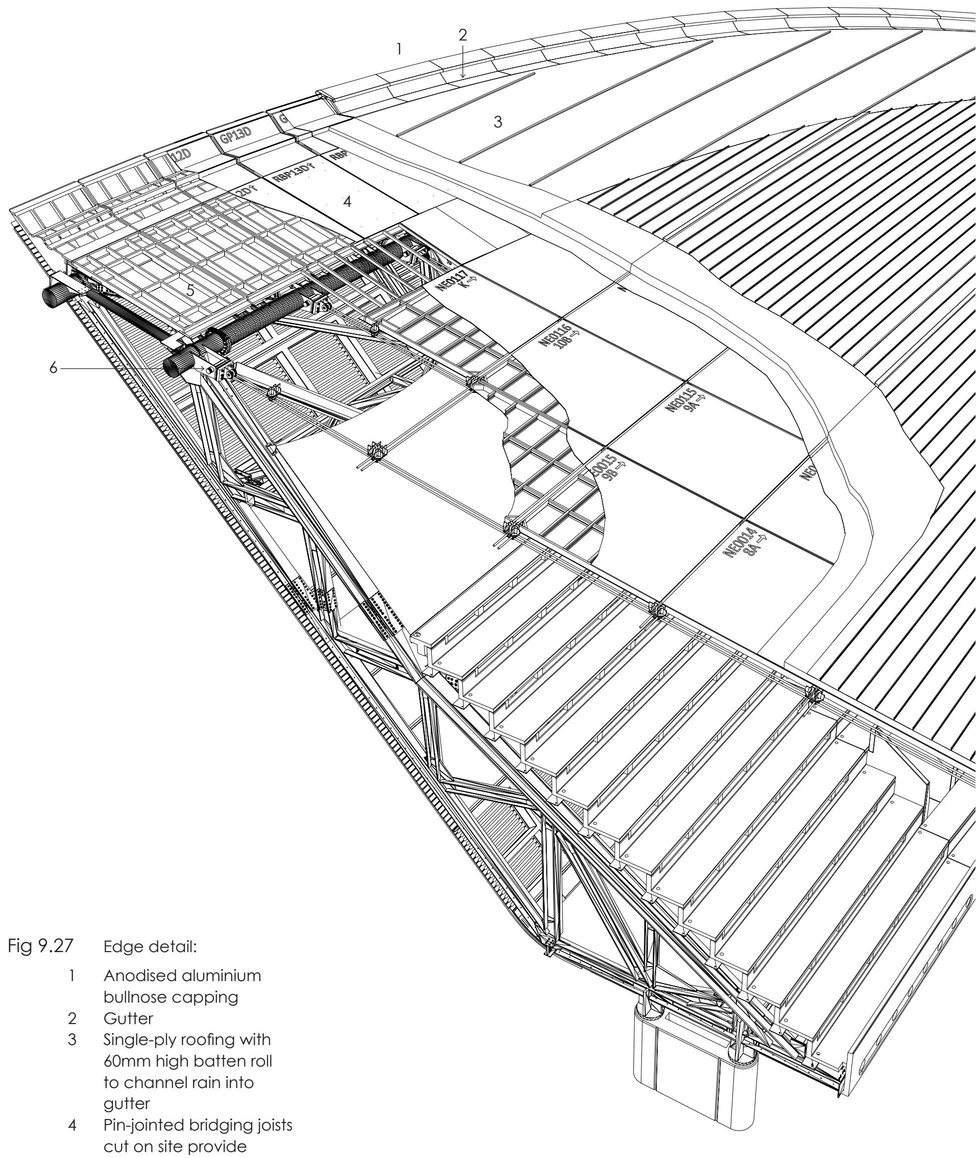


Fig 9.27 Edge detail:

1. Anodised aluminium bullnose capping
2. Gutter
3. Single-ply roofing with 60mm high batten roll to channel rain into gutter
4. Pin-jointed bridging joists cut on site provide make-up strip and allow movement between cable net system and rigid ring beam
5. Timber casette spanning between inner and outer ring beams
6. Single-pin connection between cables and brackets to ring beam

optimisation including the use of prototypes and mock-ups is very clear. The design team chose not to fill the timber cassette panels with insulation, as this would have created a potential risk of interstitial condensation.

Fig 9.28 The Velodrome is expressed in the materials aluminium, Western Red Cedar and glass

The geometry at the margins of the roof and gutter is resolved by the use of a Sarnafil PVC single ply membrane. The edge of the roof is form by an aluminium bullnose capping profile, from which the hansom Western Red Cedar wall cladding is set out. Externally only three materials articulate the Velodrome: glass, aluminium and Western Red Cedar, evoking the interior of bicycles and the track bed on which they race.[17]

Fig 9.29 Team GB: Men's Team Pursuit, heading for Gold at the 2012 Olympics

Fig 9.30 The steel cable net tensioned and ready to receive the timber cassette panels

Fig 9.31 Installing the timber cassette panels on the tensioned steel cable net

The roof steelwork is only 30kg/m^2, less than half the weight of the roof structure of the Beijing 2008 Velodrome. The use of a cable net structure saved over £2million pounds and resulted in a 3-month shorter site time. The cable net, weighing only 100 tonnes, uses 27 per cent less steel by mass when compared to steel arches. It is an excellent example of structural design optimisation, a case of achieving more with less – with the lightweight aluminium roof playing its role in a minimal material strategy. Overall, including the steel cable net, timber cassette panels, insulation and aluminium standing seam sheeting; the roof of the Velodrome weighs 70kg/M^2. The building fabric accounts for over 50 per cent of the weight of the roof.

The control of the internal comfort condition of the Velodrome were also carefully considered and integrated into the architectural intent from the outset of the design. Klaus Bode, of environmental design consultants BDSP, considered:

> One of the key challenges regarding the environmental performance of the Velodrome was to enable the fastest track-level conditions, while keeping spectators comfortable throughout the year and in different types of events, from the Games to school sessions. Passive and active systems had to allow for the high temperature (about 26°) required by the cyclists to achieve record-breaking times.[18]

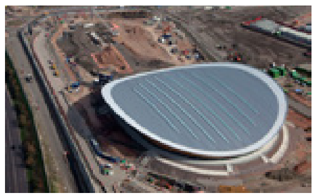


Fig 9.32 The standing seam roof completes the building envelope of the Velodrome

Having ruled out an unheated Velodrome, a three part approach was adopted: under floor heating in the infield, which provides the basic background heating; under seat heater air supply, providing fresh air and extra heat; and a high velocity heated air supply to quickly condition the arena. The components of the ventilation system are integrated below the seating. This is combined with building fabric insulation to a higher standard than required by UK Building Regulations and the exposed thermal mass of the concrete structure. The Velodrome can be fully naturally ventilated in spring, summer and autumn.

Daylight is used to provide an uplifting environment while minimising energy consumption. 'Rooflights in the main area were optimised to provide sufficient daylight for training in most of the year, resulting in [significant] reductions in energy consumption', observed Klaus Bode noting that: 'Extensive computational analysis was used to fine-tune the performance of the ventilation and lighting systems.'[19] The rooflights use self- cleaning glass with white diffusing PVB interlayers in the inner leaf of the double glazed units, thus the roof does not have cleaning accesses safety systems designed in, even in the context of UK Construction Design and Management Regulations. The acoustical internal environment of the Velodrome was equally carefully studied.

The total embodied CO_2 of the structural elements of the Velodrome is 7,400tonnes, less than 1,250kg of CO_2 per seat.[20] The Velodrome's predicted reduction in carbon emissions is 31 per

Fig 9.33 Commemorative Royal Mail First Day Cover in honour of The Men's Team Sprint Gold Medals at the 2012 Olympics

cent, more than double the ODA target of 15 per cent and better than another 2012 venue. Although this is aided by the combined heat and power unit, providing district heating to all of the Olympic venues, it is achieved by a fabric first strategy with no on site applied renewables. In essence the design achieves more with less. Demonstrating that environmentally sound architecture can be achieved by integrated design and careful material selection within tight timescales and without costing more.

Nicholas Serota reflecting on the competition to design the Velodrome: 'In appointing a young and dynamic team, versed in the language of the Hopkins practice, we knew the detail of the design would be elegant, economical and enduring.'[21]

Attention to material selection and the unity of design intent and detail will, in Nicholas Serota's opinion, 'ensure the building is easy to maintain and will look as good in 20 years as it does today.'[22] 'The Velodrome promises to enhance the experience of every user and visitor to the building for generations to come.'[23] This is the very essence of sustainability in the built environment. A well-informed brief, design excellence and high quality execution are the cornerstones sustainability. Yet the needs for such highly skilled processes are hardly mentioned in the conventional discourse of big data and technocratic 'solutions'.

Fig 9.34 The 2012 Olympic Velodrome was the first venue to be completed in January 2011

2012 Olympic Aquatics Centre, London, England: Architect Zaha Hadid Architects, 2011

The atmosphere within the 2012 Olympic Aquatics Centre was electric during the 2012 Olympic and Paralympic swimming events. The form of the Aquatics Centre, in the words of the architects is, 'a concept inspired by the fluid geometry of water in motion'[24] It has two 50m pools, a competition pool and a warm-up or training pool, with a 25m diving pool – all achieved at a capital cost of £269million and completed ready for the games in 2011.[25] To meet the audience capacity set out by the Olympic Committee, what became known as the saddlebags were added to either side of the competition pools. Thus increasing the seating capacity to 17,500 spectators – and the sightlines were surprisingly good. The saddlebags were removed after the Olympics and were replaced by curtain walling. Today the Aquatics Centre can accommodate 2500 spectators. The doubly curved wave inspired roof of 1040m^2 is clad in a dual alloy mill finish Kalzip aluminium standing seam roof, with a gauge of 1mm, an upstand of 65mm and module of 333mm for 90 per cent of the roof sheets.

Kalzip XT was specified to accommodate the rapid changes in curvature of this roof[26] Kalzip XT uses patented roll forming technology to fabricate standing seam roof panels, with concave or convex curvature as required by the geometry of a specific project. It was introduced by Kalzip in 2005 and first used on the roof of Spencer Street Station in Melbourne, Australia, architect Grimshaw (2006), see Figure 1.11.

Fig 9.35 Interface between the 2012 Olympic Aquatics Centre and its temporary 'saddle bags'

Fig 9.36 Aquatics Centre, designed by Zaha Hadid, during the 2012 Paralympics

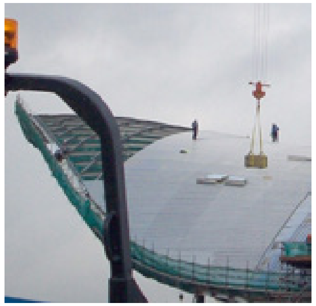


Fig 9.37 Installation of the standing seam aluminium roof of the Aquatics Centre

Lakersmere were appointed as the specialist subcontractor for the Kalzip aluminium standing seam roof of the 2012 Olympic Aquatics Centre, in part due to their experience of installing Kalzip XT. Zaha Hadid Architects' original geometry of the roof required the use of 40 per cent Kalzip XT, in collaboration with Lakersmere and Kalzip this was reduced to only 10 per cent, without compromising the geometry.[27] The aluminium roofing contact contributed only £3.5million to the capital cost of the Aquatics Centre.[28]

The thermally efficient Kalzip fixing clips are fixed to cladding rails, which are in turn fixed, via the vapour check layer, to a trapezoidal roof sheet – this zone was then filled with insulation. The soffit of the roof is clad in reddish Louro timber strips, which articulate the direction of the swimming lanes below. Just four concrete columns support the dramatic roof. The steel roof structure was fabricated in Wales by Rowecord Engineering and weighs 3200 tonnes.

Fig 9.38 The Aquatics Centre under construction

Fig 9.39 Installing the aluminium standing seam roof sheets onto the thermally efficient fixing clips

Today any citizen of London and visitors to the capital can swim in the elegance of the Aquatics Centre for just £5 for 60 minutes in the competition pool and 90 minutes in the training pool. Nearly two million people have used the pools in the two years since it re-opened to the public in March 2014.

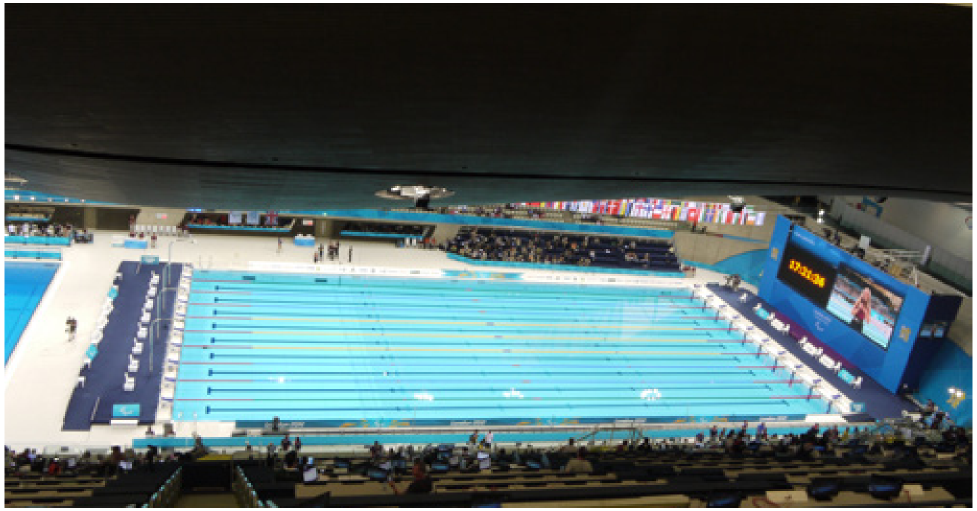


Fig 9.40 The 50 meter competition pool during the Paralympics

Fig 9.41 Night view of one of the temporary stands or saddle bags of the Aquatics Centre

Fig 9.42 In March 2014, the Aquatics Centre re-opened for all swimmers

Fig 9.43 The Aquatics Centre in 2014

Soho Galaxy, Beijing, China: Architect Zaha Hadid Architects, 2012

Soho Galaxy is a large mixed-use development in central Beijing designed by Zaha Hadid Architects as a singular flowing geometry, yet it comprises four towers that rise up 15 floors, with three floors of retail including the ground floor and 12 office floors above, providing over 360,000m^2 of accommodation. Between the towers are surprisingly spacious courtyards, which Zaha Hadid Architects describe as a reinvention 'of the classical Chinese courtyard, which generates an immersive, enveloping experience at the heart of Beijing.'[29]

Soho Galaxy was designed between 2009 and 2011, using digital form finding. The initial concept was developed via 'surface subdivision' in Maya.[30] This was then used as the geometry that formed the basis of the architect's coordination of the project via a Building Information Model (BIM) in CATIA/Digital Project. Cristiano Ceccato, Associate Director and lead architect on Soho Galaxy, observed a 'project of the size and complexity could not be accurately coordinated using 2D drawings alone.'[31] Noting that mock-ups and prototypes were vital in the design and delivery of the flowing white façades. 'As part of the design process Zaha Hadid Architects and the client elected to build a series of façade mock-ups in different materials to assess geometric complexity, contactor capability in China as well as material performance constructability and aesthetics.'[32]

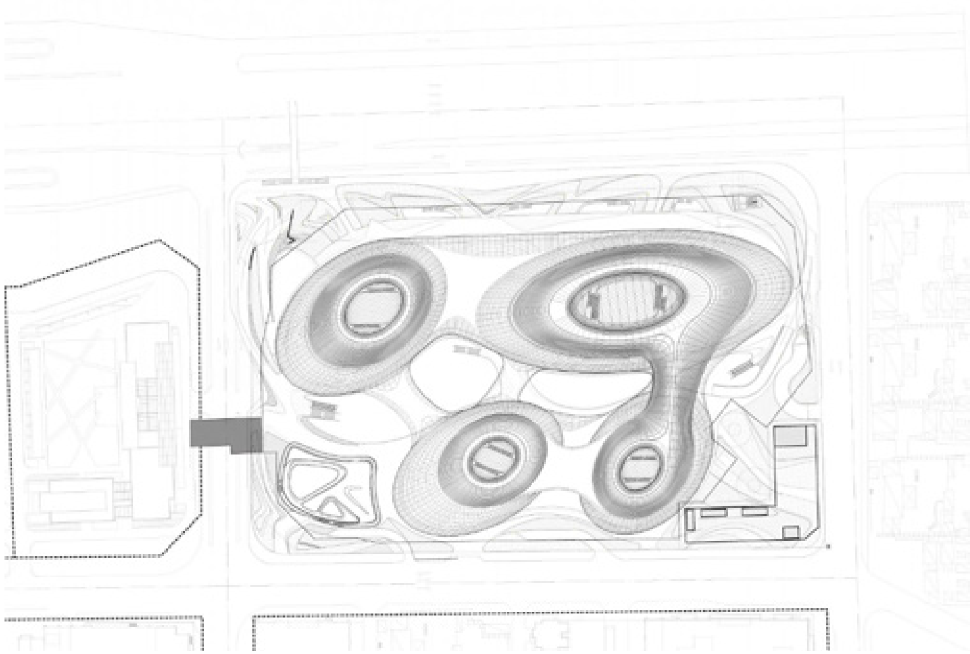
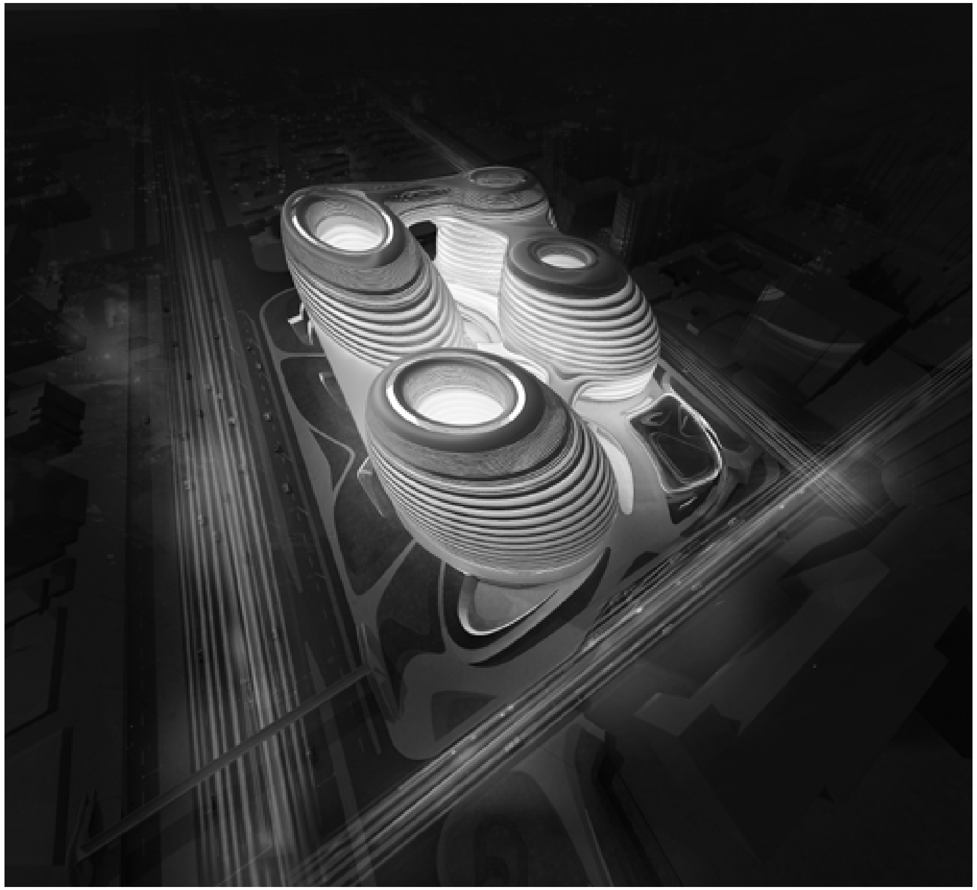


Fig 9.44 Zaha Hadid Architects' roof plan of Soho Galaxy

Fig 9.45 One of the courtyards of Soho Galaxy

Fig 9.46 [below] Zaha Hadid Architects' digital model of Soho Galaxy, early 2011



An identical area of façade was prototyped in sheet metal, steel plate, glass-reinforced polymers (GRP) and glass-reinforced concrete (GRC). This process led to the selection of 3mm thick polyester powder coated aluminium sheet, with 4mm thick sheet when the panels need to be walked on for maintenance.[33] The first façade prototype, using 3mm thick polyester powder coated aluminium sheet, was produced by Permasteelisa in October 2009.

At this early stage, Zaha Hadid Architects continued to optimise the geometry of the façade in order to minimise the areas of double curvature, which in turn reduced process costs associated with the delivery of the façade, whilst retaining the flowing design intent of Soho Galaxy. Cristiano Ceccato observed 95 per cent of the façade could be 'implemented as single-curve sheet metal.'[34] Taking this optimisation process a step further Zaha Hadid Architects replaced as many of the developed surfaces with cones as was possible. Cristiano Ceccato notes that 'within each conical strip, each constituent facia panel is identical' with a parametric definition of cant angle, radius height and panel-arc length.[35] An indicative size of a panel is 1200 × 2000mm with a

Fig 9.47 The first prototype fabricated by Permasteelisa in October 2009 from 3mm polyester powder coated aluminium

Fig 9.48 The 3mm polyester powder coated aluminium of the prototype fabricated by Permasteelisa

Fig 9.49 Tender stage prototype produced by Yuanda in China

controlled dimensional variation.[36] The third stage of optimisation was to group the cones into families of components, Cristiano Ceccato recorded the outcome as a 'total of over 52,000 different façade components, of which 18,000 were glazing units and 34,000 façade panel units', in 800 families of components.[37]

The facades were tendered using a combination of 3D BIM and 2D formal documentation. A 497 page AO façade 2D package was produced by the architect in September 2010. Each potential façade contactor was required to produce a 1to1 façade prototype. Figure 9.49 shows the 1to1 façade prototype produced by Yuanda as part of the tender process, again using 3mm polyester powder coasted aluminium sheet. In areas needing maintenance access the aluminium sheet thickness was increased to 5mm.[38] During this period the steel frame was rapidly being erected on site with cladding starting during the first quarter of 2011. Soho Galaxy opened in November 2011.[39] This project, with its unitary geometry yet diversity of uses; retail, entertainment and offices, opened to critical acclaim – offering a potential new urbanism for China.

Fig 9.50 Soho Galaxy, Beijing, by Zaha Hadid Architects

Danish National Aquarium – Blue Planet, Copenhagen, Denmark: Architect 3XN, 2013

Major aquaria are local and regional tourist attractions that typically don't have local rivals. The Blue Planet Aquarium designed by 3XN opened in March 2013, and is one of the largest in Northern Europe. It replaced a white modernist building in Charlottenlund designed by C.O. Gjerløv-Knudson (1939), which was too small after over 60 years of collecting aquatic specimens. In 2007 an architectural competition was held and won by 3XN. The new site is a promontory in Amager, on the coast just north of Copenhagen, yet accessible from Kastrup Metro station. The architects took inspiration from a vortex in a shoal of fish; to some, the new Danish National Aquarium is reminiscent in form of a starfish. It is the fish and other aquatic life, in 53 tanks with over 20,000 specimens, who are the stars of this tourist destination.

The aquarium is organised around a central circular void, which continuously shows the BBC documentary by David Attenborough, Blue Planet, from here all wings of the vortex are perceivable; from the Ocean to the Faroe Islands and even the restaurant and auditorium, all the potential routes are clearly understandable by the visitors. Administration is housed in the wing next to the entrance.

Fig 9.51 Danish National Aquarium - Blue Planet, architect 3XN, who drew inspiration from the vortex generated by a shoal of fish

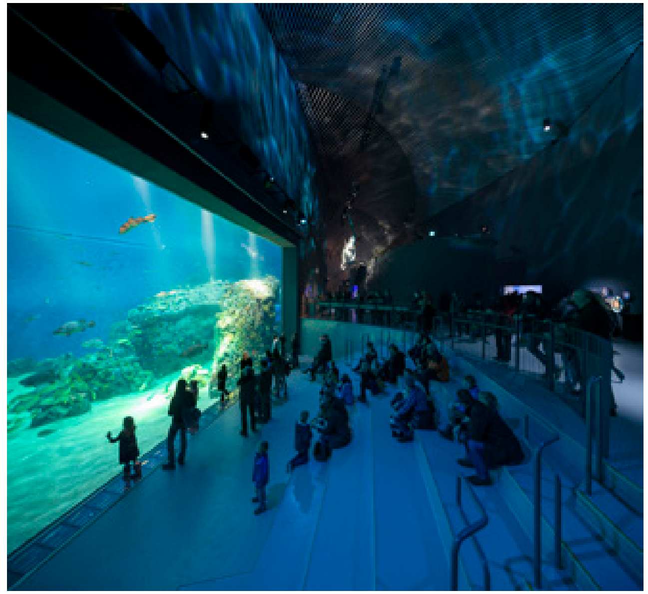


Fig 9.52 The perspex wall of the Ocean Aquarium

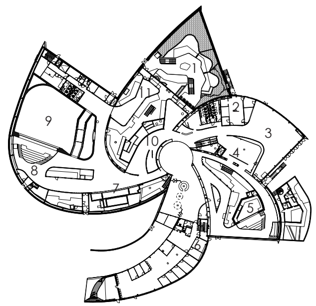


Fig 9.53 Plan of the Blue Planet, architect 3XN

1 The Amazonas
2 School Service
3 Restaurant
4 Auditorium
5 The Faroe Islands
6 Sea Lions
7 Coral Reefs
8 Octopusses
9 The Ocean
10 The Lakes of Africa
11 The Cave

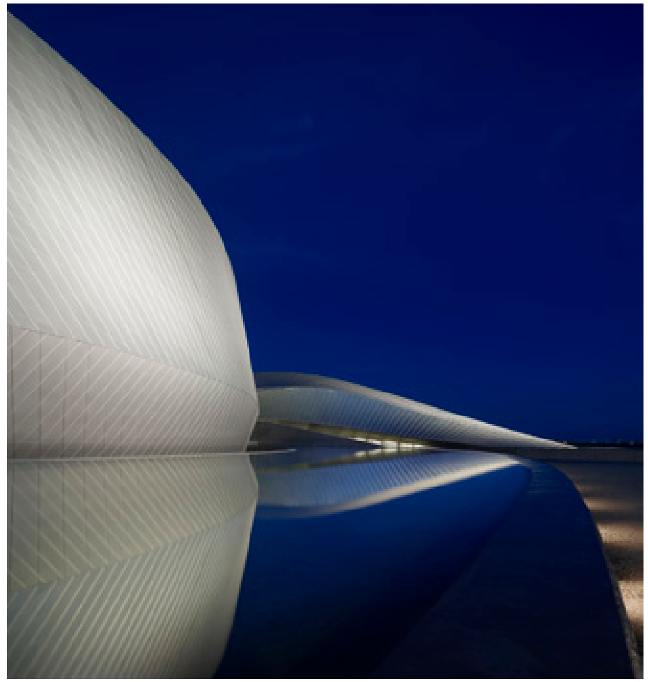


Fig 9.54 The Blue Planet Copenhagen, 2013

Blue Planet is clad in a continuous surface of aluminium shingles. This is 1.2mm thick rolled and coil-coated aluminium Falzonal ® manufactured by Novelis in Göttingen. Novelis' Falzonal® is finished with clear PVDF 25µm on the external surface and 3µm on the inner surface. Rainwater can be collected from this roof and used in the aquarium without treatment. The architects' confidence in the aluminium cladding is demonstrated by it plungeing directly into the reflecting pools that collect the rainwater. Noting that aluminium has longer durability if it is washed by rainwater as discussed in TSC Report 1, *Aluminium and Durability*.[40]

Fig 9.55 The shingled aluminium cladding dips into one of the reflective pools

The rhombic shingles are about 0.5m² in area and 40,000 identical shingles clad the aquarium. Identical except where they have been folded or cut in response to the form of the building and are joined and sealed with a lapped and welted detail. 200,000 stainless steel clips were used for the non-visible fixing of the shingles, installed by specialist subcontractor Kai Andersen A/S.

The scale like skin of the Danish National Aquarium should remain reflective due to the clear PVDF coating. It renders the form of the building ambiguous in scale and continuously adapts with the weather in its seaside location.

Fig 9.56 Clear PVDF coated aluminium shingles of the Blue Planet reflects the changing environmental conditions of its setting

Fig 9.57 Rainwater is collected from the reflective pools and used in the aquarium

Fig 9.58 Winter time at the Blue Planet, Copenhagen

Manor Works, Sheffield, England: Architect Architecture:00, 2014

Manor Works has been carefully designed in the context and topography of its site by architect Architecture:00, making the most of a back lands site in southeast Sheffield. This industrial incubator building is robustly detailed with an internal palette of exposed concrete, timber and plywood. It offers managed workspace for local start-up businesses from industrial or workshop units to offices, combined with shared resources for the local community. The workspace is arranged to encourage the workers of the start up companies to meet and share experiences and opportunities. In essence the opposite of the earlier lock-ups on the site. The interior would not look out of place on a university campus. It is robust yet has an almost domestic quality. This very economic building is part of the knowledge economy, yet it costs less than £1700/m^2 providing 1,600m^2 of occupyable space for a capital cost of £2.7million. The section makes the most of the site offering a range of spaces, with the communal areas located along the south façade, relating to a pedestrian footpath and local playing fields beyond. At its lowest level, Manor Works opens out on to this footpath onto a modest play area, commissioned as part of the project.

Fig 9.59 Perforated aluminium cladding of the east and south façades of Manor Works

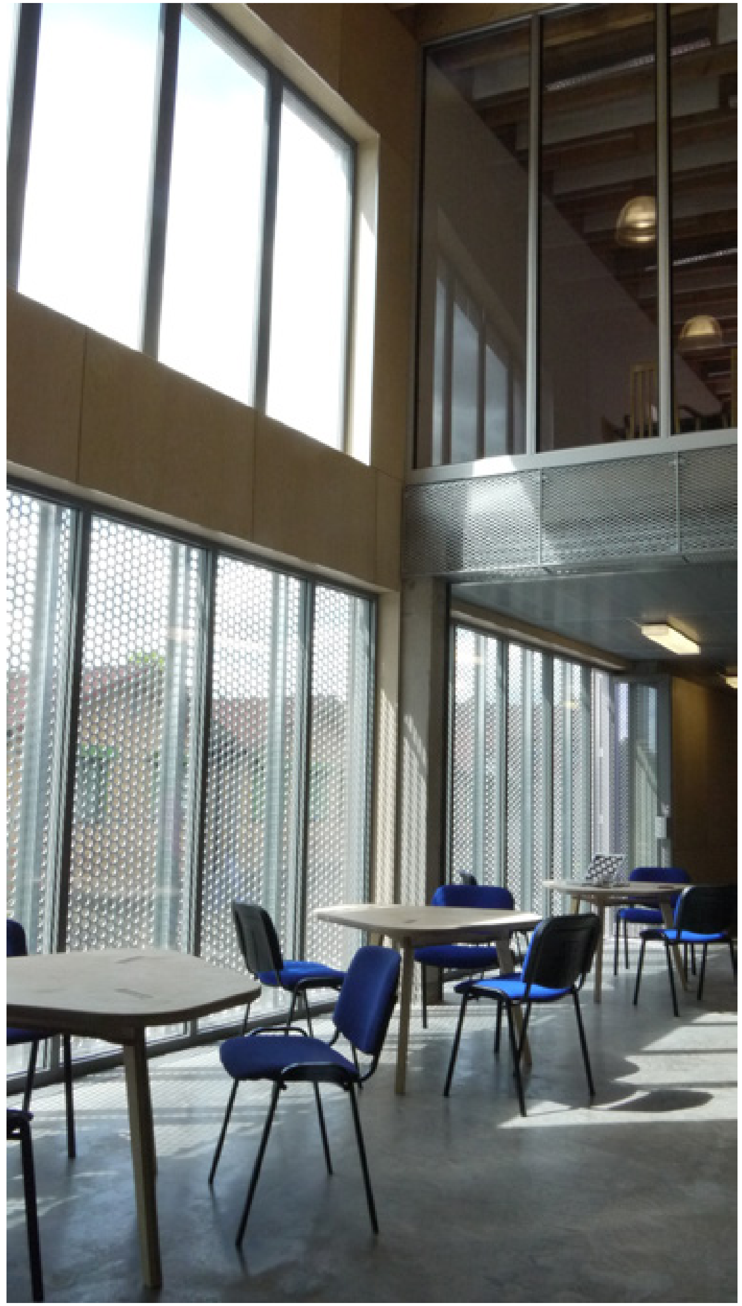


Fig 9.60 The perforated aluminium skin provides continuity and solar shading

The north and west façades comprise standard composite metal panels. The east and south are unified by perforated aluminium rainscreen panels, which become the skin of the project and act as solar shading and securing screens. These generously perforated aluminium panels also act as supports for climbing plants. Manor Works opened in February 2014 and won a national RIBA Award in the same year. The RIBA judges observed ‘Manor Works balances the need to be secure with a real and tangle desire to be welcoming and accessible, inviting the local community to explore and make it their own.’[41]

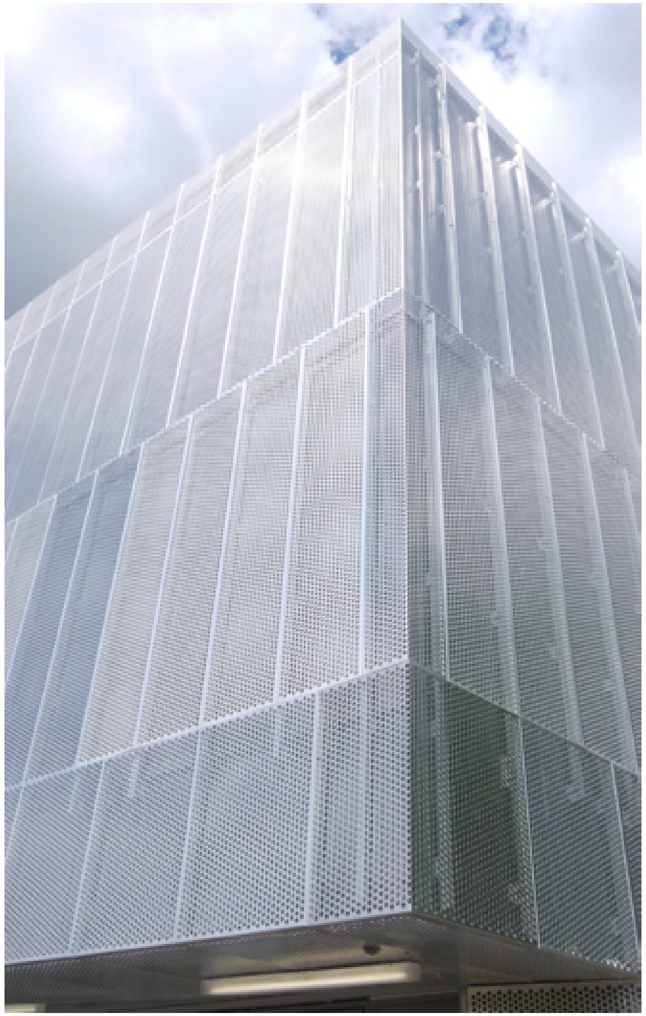


Fig 9.61 The perforated aluminium sheet is simply folded to form the corner of the east and south façades

Fig 9.62 The perforated aluminium cladding also provides support for climbing plants

Fig 9.63 Manor Works by Architecture: 00, photographed 2014

Notes

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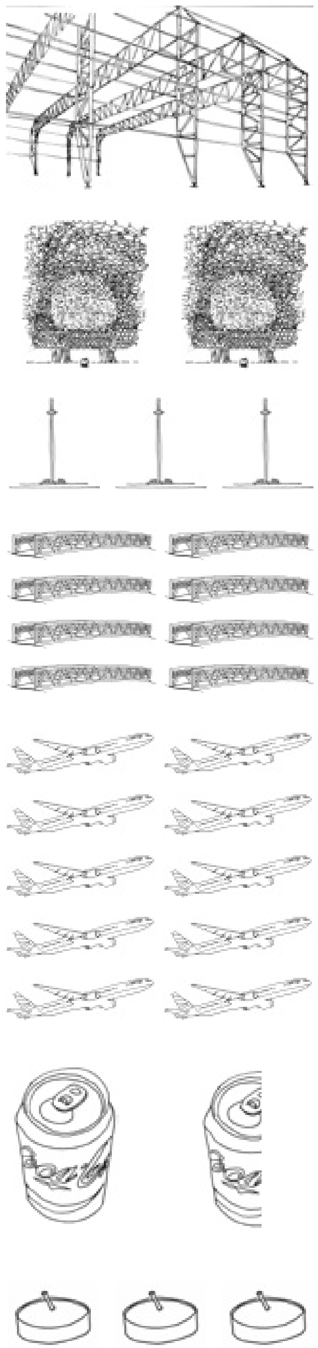
Interim Conclusion

Aluminium, as evidenced in this report, can be reasonably described as a good servant of sustainability and an ally in the pursuit of excellence in architecture and infrastructure. It may form the highly visible and durable surfaces of overcladding, such as Guy's Hospital, or as an unseen 'hand' supporting photovoltaic panels. The former has a carbon payback period of only 12.5 years and the later is increasingly contributing the carbon balance of projects, such a 240 Blackfriars Road, with a clear progression from low carbon projects to architecture that is carbon neutral and even net contributors to the local energy grid.

The contribution of aluminium to design excellence is clear throughout this report, be the date of a product 1948, as in the Jaguar XK 120, or the 606 Universal Shelving System design by Dieter Rams in 1962. This shelving system is still on sale today and fully compatible, whatever the date of your first or latest purchase. This adaptable, extendable and fully reusable system is an excellent example of a sustainable product that has its routes in an era known for the 'white heat of technology' – to quote the future British Prime Minster Harold Wilson in the autumn of 1963.[1] Architectural examples of aluminium and excellence include the Comet Flight Testing Hanger in 1953, the Climatron in 1960 or the Hive in 2015.

To construct the Comet Flight Testing Hanger in 1953, just over 180tonnes of aluminium was used to form the aluminium structure, decking and cladding, see page 303 for the detailed breakdown. Figure 10.1 takes the mass of the Comet Flight Testing Hanger as the base case and calculates how far this quality of aluminium will go to produce other case study projects or products featured in this report, all examples have been rounded to the nearest whole or half, as necessary. In all examples only the mass of the aluminium components is used to form the comparison.

What will you do with 1 tonne or 1 kg of aluminium in your next proposal, project or product?



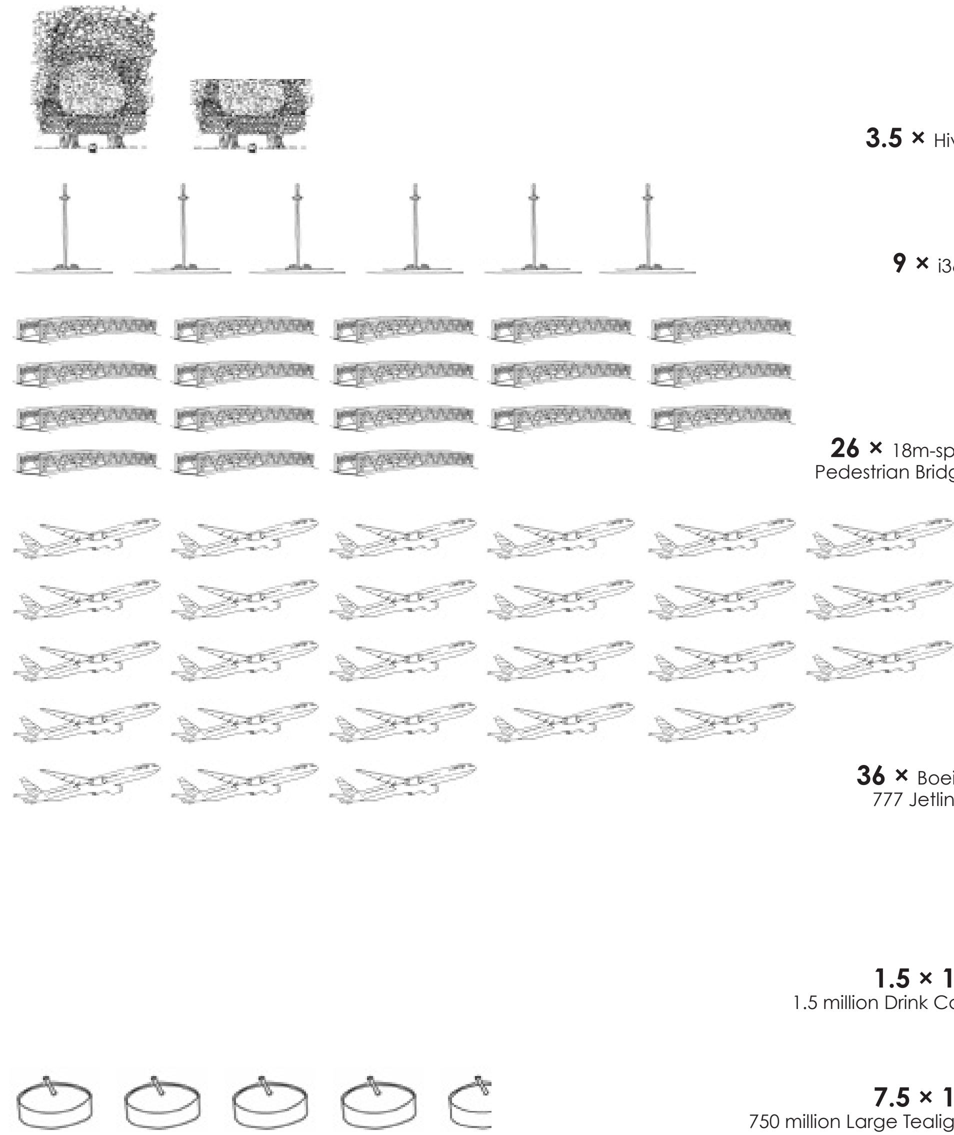


Fig 10.1 Comparative applications of aluminium by mass, from the Comet Flight Testing Hanger to humble tealights

The Stirling Prize, awarded by the Royal Institute of British Architects, is one of the best accolades a project, its client and design team can receive and it is held in high regard the world over. The award was founded in 1996, in honour of the architect Sir James Stirling (1962–1992). This report includes a number of Stirling Prize winning projects that utilise the qualities of aluminium alloys, from the Gateshead Millennium Bridge, 2001 by WilkinsonEyre to the Everyman Theatre by Haworth Tompkins Architects in 2014.

In the past two years the Stirling Prize shortlist of six projects per year, has included eleven aluminium-rich projects.

Fig 10.2 Gateshead Millennium Bridge, 2001, designed by WilkinsonEyre

Fig 10.3 Library of Birmingham designed by Meccano Architecten for Birmingham City Council, shortlisted for the Stirling Prize in 2014, its building fabric includes silver and backmetallic polyester powder coated solar shading

Fig 10.4 London Bridge Tower (the Shard), designed by Renzo Piano Building Workshop for Sellar Property Group, shortlisted for the Stirling Prize in 2014, its aluminium curtain walling

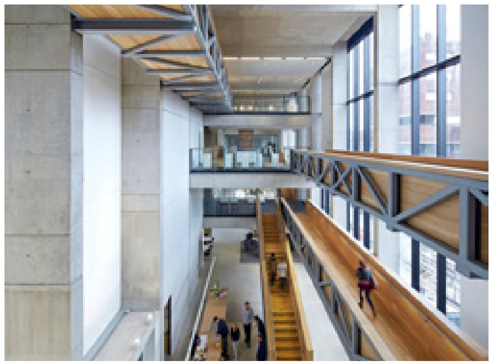


Fig 10.5 Manchester School of Art, designed by Feilden Clegg Bradley Studios for Manchester Metropolitan University, shortlisted for the Stirling Prize in 2014, its building fabric includes black anodised curtain walling

Fig 10.6 London 2012 Aquatic Centre designed by Zaha Hadid Architects for the Olympic Delivery Authority, shortlisted for the Stirling Prize in 2014, its building fabric includes a mill-finish aluminium standing seam roof

Fig 10.7 Everyman Theatre, designed by Haworth Tompkins for Liverpool and Merseyside Theatres Trust, winner of the Stirling Prize in 2014, its building fabric includes black anodised waterjet cut solar shading

Fig 10.8 Maggie's Lanarkshire designed by Reiach and Hall Architects for Maggie's Cancer Caring Centre, shortlisted of the Stirling Prize in 2015; its building fabric includes 8mm anodised aluminium 'light catchers'

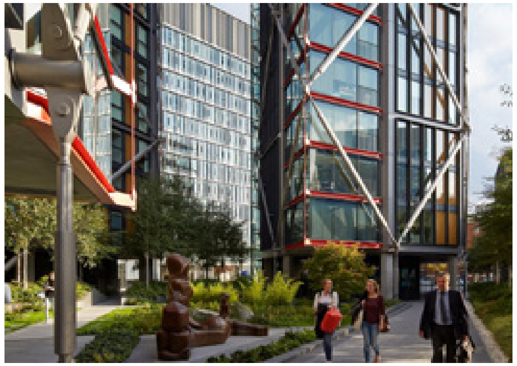


Fig 10.9 Neo Bankside designed by Rogers Stirk Habour + Partners for GC Bankside, shortlisted of the Stirling Prize in 2015; its building fabric includes polyester powder coated cladding and curtain walling

Fig 10.10 University of Greenwich Stockwell Street Building designed by Heneghan Peng Architects for University of Greenwich, shortlisted of the Stirling Prize in 2015; its building fabric includes perforated anodised aluminium internal acoustic wall cladding

The beneficial qualities of aluminium appear to be well understood by architects and it has become the background material of contemporary architecture. However, if the wide-ranging benefits of this durable and lightweight material were better understood – it has a much greater potential, especially in the realm of lightweight structures.

Fig 10.11 The Whitworth Gallery designed by MUMA for The University of Manchester Estates and The Whitworth shortlisted for the Stirling Prize in 2015; its building fabric includes extruded aluminium solar shading to gallery rooflights.

Fig 10.12 Burntwood School designed Allford Hall Monaghan Morris for Wandsworth Borough Council, winner of the Stirling Prize in 2015; its building fabric includes polyester powder coated aluminium windows

On the 4 July 2012, CERN (European Organization for Nuclear Research) announced the discovery of the Higgs Boson, a particle with a mass region around 126 GeV, arising from the ATLAS and CMS independent experiments, both conducted on the Large Hadron Collider (LHC).[2] Located near Geneva, the LHC is the world's most powerful particle accelerator, with a 27-kilometre circumference that is 175m below Switzerland and France. The LHC became operational in September 2008. CERN describes the LHC:

> Inside the accelerator, two high-energy particle beams travel at close to the speed of light before they are made to collide. The beams travel in opposite directions in separate beam pipes – two tubes kept at ultra high vacuum. They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. The electromagnets are built from coils of special electric cable that operates in a superconducting state, efficiently conducting electricity without resistance or loss of energy. This requires chilling the magnets to -271.3°C – a temperature colder than outer space.[3]

Aluminium gets stronger at very low temperatures. Bayards manufactured the bottom tray of the LHC from aluminium extrusions, which were friction stir welded with a precision 360° orbital welding machine.[4] High technology from the aluminium industry enables the fabrication of sophisticated research equipment. Aluminium not only contributes to people's lives and culture, it contributes the cutting edge of particle physics and our understanding of the composition of the universe.

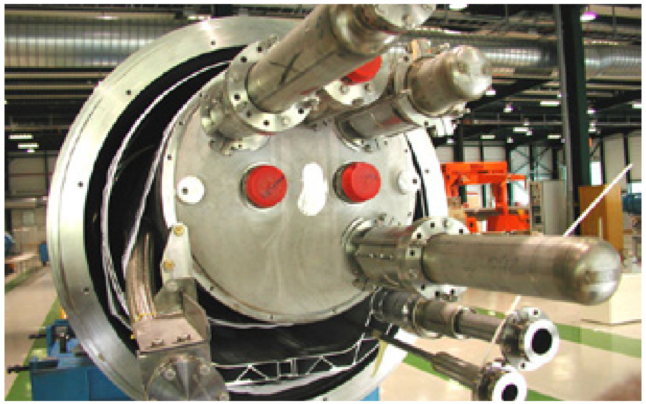


Fig 10.13 The Large Hadron Collider at CERN

Fig 10.14 Friction stir welding, the bottom tray of the Large Hadron Collider at Bayards

Fig 10.15 Friction stir welding machine at Bayards

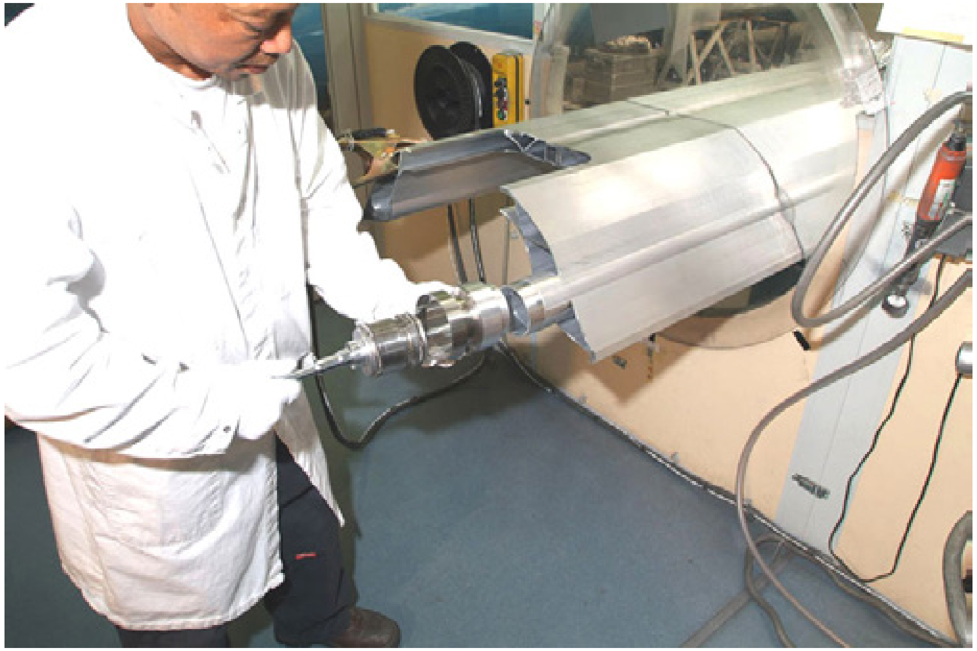


Fig 10.13 Bayards fabricated the bottom tray of the Large Hadron Collider at CERN from friction stir welded aluminium extrusions

Notes

1 H. Wilson, *Labour's Plan for Science*, Leader of the Labour Party at the Annual Conference, Scarborough, 1 October 1963, http://nottspolitics.org/wp-content/uploads/2013/06/Labours-Plan-for-science.pdf (accessed April 2016).
2 http://home.cern/topics/higgs-boson (accessed April 2016).
3 http://home.cern/topics/large-hadron-collider (accessed April 2016).
4 http://www.bayards.nl/en/high-tech (accessed January 2016).

Glossary

Age Hardening: precipitation from solid solution resulting in a change in properties of a metal alloy, usually occurring slowly at room temperature (natural ageing) and more rapidly at elevated temperatures (artificial ageing), typically resulting in components with higher yield stress.

Air infiltration rate: is the tested measure of the rate of airflow through a building fabric and it is typically measured in $m^3/m^2/hr$.

Alloy: combination of a metal with other chemical elements (or chemical element) to form enhanced properties, with the parent metal such as aluminium as the primary material.

Angularity: conformity to, or deviation from, specified angular dimensions in the cross section of a shape or bar.

Annealing: heating and gradual cooling to modify the properties of a metal, alloy or glass, to attain acceptably low internal stresses or desired structure or both.

Anodising: an electrochemical method of producing an integral oxide film on aluminium surfaces.

Anodising quality: describes material with characteristics that make it suitable for visible anodising, after appropriate preliminary treatment.

Anthropocene: proposed term for the current geological epoch where humankind has altered the environment and ecology of Earth to the extent that it is being recorded in the Earth's crust.

Bayer process: the most commonly utilised industrial process for extracting alumina from bauxite ores.

Billet: a cast aluminium product suitable to use in an extrusion press, usually of circular cross-section but may also be rectangular, or elliptical.

Bow: the deviation in the form of an arc of the longitudinal axis of a product.

Buffing: a mechanical finishing operation in which fine abrasives are applied to a metal surface by rotating fabric wheels for the purpose of developing a lustrous finish.

Building Information Modelling [BIM]: a holistic approach to the design of architecture and infrastructure, based on the shared use of three- dimensional digital models. Building Information Models include data on materials, scheduling and performance, among other categories, for the purpose of design, visualisation, simulations, and structural and environmental analysis.[1]

Burr: a thin ridge of roughness left by a cutting operation such as routing, punching, drilling or sawing.

Circumscribing circle diameter (CCD): the smallest circle that will contain the cross section of an extrusion, designated by its diameter.

Cold work: plastic deformation of metal at such temperature and rate that strain hardening occurs.

Composite construction: the combination of materials with very different mechanical properties to form a single component.

Concavity: a concave departure from flat.

Concentricity: conformity to a common centre, for example, the inner and outer walls of round tube.

Container: a hollow cylinder in an extrusion press from which the billet is extruded, the container can be rectangular or elliptical.

Conversion coating: treatment of material with chemical solutions by dipping or spraying to increase the surface adhesion of paint.

Corrosion: the deterioration of metal by a chemical or electrochemical reaction with its environment.

Design for Disassembly (or **Design for Deconstruction**) **[DfD]**: a principle applied during the design process that results in the detailing of reversible joints, connections and attachment mechanisms between building materials and components, thus enabling future reconfiguration, relocation, reuse and recycling.[2]

Die-casting: metal casting formed in a mould, typically steel, appropriate for high volume production.

Direct extrusion: a process in which a billet, in a heavy walled container, is forced under pressure through an aperture in a stationary die.

Draft angle: taper on vertical surface of a pattern or mould to permit easy withdrawal of pattern or product from mould or die.

Drawing: the process of pulling material through a die to reduce the size and change the cross section.

Drift test: a routine sampling test carried out on hollow sections produced by bridge or porthole methods, in which a tapered mandrel is driven into the end of the section until it tears or splits.

Electrolytic colouring: a two-stage colour anodising process.

Etching: the production of a uniform matt finish by controlled chemical (acid or alkali) treatment.

Etching test: the treatment of a sample using a chemical reagent to reveal the macro-structure of the material.

Elastomer: this is the general term used to describe a material, synthetic or naturally occurring, which has rubbery or elastic properties.

Embodied energy (also known as cumulative energy use): the sum of all energy consumed in the production of materials, goods or services including extraction, manufacturing and fabrication, often described through embodied energy assessments. Recurring embodied energy: energy needed over time to maintain, repair or replace materials, components or systems during the life of a building.

Extrusion die: metal plate or block, typically steel, used for forming materials in the extrusion process, where the cross section of the extruded material takes the negative form of the die.

Extrusion ratio: the ratio of the cross-sectional area of the extrusion container to that of the extruded section (or sections in the case of multi-cavity dies).

Fillet: a concave junction between two surfaces.

Free machining alloy: an alloy designed to give small broken chips, superior finish and/or longer tool life.

Full heat treatment: solution heat treatment followed by artificial ageing.

G-value indicates the degree to which glazing transmits heat from sunlight, expressed in a number between 0 and 1. The lower the g-value, the less heat is transmitted.

Grain growth: the coarsening of the grain structure of a metal occurring under certain conditions of heating.

Grain size: the main size of the grain structure of a metal, usually expressed in terms of the number of grains per unit area or as the mean grain diameter.

Hall–Héroult process: an electrolytic process for the reduction of alumina into liquid aluminium. It is the most commonly utilised industrial method of primary aluminium production.

Hardness:the resistance of a metal to plastic deformation usually measured by controlled indentation.

Heat treatable: an alloy capable of being strengthened by appropriate heat treatment.

Holocene: a geological epoch that began about 11,700 years before 2000AD, and simply means *entirely recent,* in ancient Greek.

Homogenisation: a high temperature soaking treatment to eliminate or reduce segregation by diffusion.

Indirect method: a process whereby a moving die, located at the end of a hollow ram, is forced against a stationery billet.

Life Cycle Assessment (LCA): an approach to quantifying the environmental impacts of a product or service across its life cycle.

Cradle-to-grave Life Cycle Assessment (LCA): considers all the aspects of a product's life cycle (i.e. raw material extraction and processing, manufacture, transportation, use, repair and maintenance, and reuse, disposal or recycling).

Cradle-to-gate Life Cycle Assessment (LCA): an alternative LCA scope that focuses on the environmental impacts associated with material extraction, manufacturing, transportation, construction or assembly. For building products this scope is often used to represent materials at point of sale, when they are more easily compared and delineated, as well as when use and end-of-life processes are uncertain. However, cradle-to-gate assessments do not capture the full environmental impacts of goods or service and are not permitted for life cycle comparisons between materials or products (see ISO 14044).[3]

End-of-life recycling method: a methodology for the treatment of recycling in LCA that is based on a product life cycle and material stewardship perspective. It considers the fate of products after their use stage and the resultant material output flows.[4]

Recycled content method: a methodology for the treatment of recycling in LCA that looks back to where a material was sourced, and provides a measure of waste diversion. This approach is based on a waste management perspective, where the general aim is to promote a market for recycled materials that is otherwise limited, uneconomic or underdeveloped.[5]

Light transmission: a Lt-value indicates the amount of visible light that progresses through a glazed façade.

Lightweighting: the process of removing mass from a design, such as a car, whilst maintaining (or improving) all other functional performance criteria.

Logs: a cast aluminium product suitable for extrusion shipped in lengths of 7-8 metres.

Lost foam casting: a metal casting formed in a ceramic 'jacket' or investment mould from which the foam pattern is vaporised by the action of the hot metal as it is cast.

Lost wax casting: a metal casting formed in a ceramic 'jacket' or investment mould from which the wax pattern has been removed by heating, prior to casting.

Mandrel: core or former used in filament winding or the extrusion of hollow sections.

Mean diameter: the sum of any two diameters at right angles divided by two.

Mean wall thickness: the sum of the wall thickness of tube, measured at the ends of any two diameters at right angles, divided by four.

Mechanical properties: those properties of a material that are associated with elastic and inelastic reactions when force is applied, or that involve the relationship between stress and strain. These properties are often incorrectly referred to as 'physical properties'.

Method: the system of gates, feeders and risers used to feed a mould cavity to ensure an even distribution of metal with a constant rate of solidification, avoiding the formation of unwanted cavities in a casting is called the method.

MIG welding: in Metal Inert Gas welding a direct current of reverse polarity is struck between the work piece and a continuously feed welding rod, which acts as filler and electrode. Penetration cannot be as closely controlled as in TIG welding.

Monocoque: a structure in which the stiffness is generated by the form of the skins or shell only. Monocoque is literally French for 'single shell'.

Operational energy: the energy required to provide a comfortable and productive internal building environment. This includes the energy required to heat, cool and provide electrical services such as artificial lighting to a building during its use. **Energy efficiency measures [EEM]** (or **energy conservation measures [ECM]**): measures implemented to reduce energy consumption in a building. These may include changes to technologies or human behaviour.

Overcladding: the process of placing insulation and a new durable skin over an existing building without removing the existing building fabric, to improve the thermal performance of the building whilst also addressing other issues such as water ingress or interstitial condensation, air infiltration and appearance.

Pattern: a pattern is a positive of the finished cast component and incorporates the feeders and risers. It is used to form the mould cavity.

Pit corrosion: localised corrosion resulting in small pits in a metal surface.

Platen press: used for laminating, a platen press comprises a rigid frame that supports two rigid and flat plates or platens, which can be brought together to under pressure. The flat plates can be heated to reduce cure time.

Porthole die: an extrusion die, also known as a hollow die, which incorporates a mandrel as an integral part. A bridge die and a spider die are special forms of a porthole die – all used to produce extruded hollow sections from solid billets.

Polymer: organic chemical compound of molecule(s) formed from repeated units or chains of smaller molecules or atoms.

Power mix: the specific mix of electricity generation energy resources such as: hydro, nuclear or thermal (coal, oil and gas).

Primary energy: an energy form found in nature that has not been subjected to any conversion or transformation process. It is energy contained in raw fuels, and other forms of energy received as input to a system. Primary energy can be nonrenewable or renewable.

Press brake: method of forming sheet metals into profiled linear component(s) using the action of a top and bottom tool, forming the component under pressure.

Pultrusion: lineal component, typically incorporating fibre reinforcement, which is also drawn through a die.

Quenching: controlled rapid cooling from an elevated temperature by contact with a liquid, gas or solid.

Rainscreen cladding: an external cladding that forms an airspace that is drained, ventilated and can be pressure equalised. It protects the inner layers from heavy wetting and solar radiation. Typically the joints are open. The thermal performance and control of permeability are within the inner layer of the wall and do not form part of the rainscreen.

Recyclability: the quality of a product or material in which all or part of its value can be recovered at the end of its useful life, with minimal loss or change of quality and properties.

Recycling: the process of recovering valuable materials or resources from products at the end of their useful life, from waste streams or from production processes.

Reuse: the process of using something again or more than once. Often the reuse of a building will involve the introduction of a new programme of use – for example, changing the use from office to residential. The reuse of components will typically involve the same function but in a new assembly. Reuse can also refer to the use of reclaimed materials for their original purpose.

Roll forming: a method of producing a profiled linear sheet metal component by the progressive development of the shape by roll form tools.

Sand casting: a metal casting formed in a sand mould.

Spinning: a flat sheet of the metal is rotated at speed and formed over a hardwood or steel tool. Forming components with a rotated geometry only.

Strain: defines how far the atoms or molecules of a solid material is being pulled apart by an external force.

$$\text{Strain} = \boldsymbol{e} = \frac{\text{increase in length}}{\text{original length}} = \frac{\Delta \boldsymbol{L}}{\boldsymbol{L}}$$

Strain is a ratio and therefore has no units.

Stress: Is a measure of how hard the atoms and molecules of a solid material are being pulled apart or pushed together as a result of an external force.

$$\text{Stress} = \boldsymbol{s} = \frac{\text{Force}}{\text{Area}} = \frac{\boldsymbol{F}}{\boldsymbol{A}}$$

Stress is measured in Nm^{-2}.

Solution heat treatment: a thermal treatment in which an alloy is heated to a suitable temperature and held for sufficient time to allow soluble constituents to enter into solid solution, where they are retained in a supersaturated state after quenching.

Superplastic alloy: an alloy with high ductility, which is the product of a fine and stabilised grain structure. A superplastic alloy is capable of elongation of up to 1000 per cent.

Temper: stable level of mechanical properties produced in a metal or alloy by mechanical or thermal treatment(s).

TIG welding: in Tungsten Inert Gas welding, fusion between the metal components is induced by the arc, which burns between the electrode and the work piece, with filler rod being fed independently. This is shielded from the atmosphere by an inert gas such as argon.

Thermal conductivity or k-value is a measure of how easily heat passes through $1m^2$ of material 1m thick under the influence of 1°C temperature difference and is measured in W/mK.

Thermal resistance or R-value: the measure of resistance to heat flow through a material, measured in m^2K/W. U-Value is the inverse sum of the thermal resistances of all of the layers of a construction including the inner and outer surfaces.

Thermal transmittance or U-value: the property of a building fabric element, which describes the steady state heat flow, denoted by the symbol U, hence U-value, measured in W/m^2K. It is defined as the quantity of heat, which flows in unit time through one unit area of an element, when the difference between the temperature of the air on the two sides of the element is 1°C.

Specific U-value terminology:
Ucw: thermal transmittance of the total curtain walling (cw = curtain walling).
Ug: thermal transmittance of the glass or glazing (g = glass).
Uf: thermal transmittance of the frame (f = frame).
and
Uw: thermal transmittance of the total window (w = window).

Twist: a winding departure from a flat plane.

Ultimate tensile strength: the maximum stress that a material can sustain in tension under a gradual and uniformly applied load.

Young's modulus: expresses how stiff or floppy a material is, designated by E.

$$\text{Young's Modulus} \quad E = \frac{\text{Stress}}{\text{Strain}}$$

Notes

1 BIM definition based on US National BIM Standard – US Version 2 (an initiative of our National Institute of Building Sciences).

2 B. Guy and N. Ciarimboli, *DfD: Design for Disassembly in the Built Environment: A Guide to Closed-Loop Design and Building*, City of Seattle, King County, WA, pp.3–4, available online at www. lifecyclebuilding.org/docs/DfDseattle. pdf (accessed April 2015). This digital publication acknowledges C. Morgan and F. Stevenson (2005), *Design and Detailing for Deconstruction*, SEDA Design Guides for Scotland, Issue 1, Glasgow, p. 4, available online at www.seda. uk.net/ assets/ les/guides/dfd.pdf (accessed November 2014) for extensive use of adapted excerpts.

3 International Organization for Standardization (2006), *ISO 14040:2006 Environmental Management: Life Cycle Assessment – Principles and Framework*, second edition, ISO, Geneva.

4 J. Atherton (2007), *Declaration of the metals industry on recycling principles*, The International Journal of Life Cycle Assessment, 12(1), pp. 59–60.

5 Ibid.

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The Towards Sustainable Cities Research Team

Michael Stacey Architects

The practice has a thoughtful approach to the design of architecture. Michael Stacey Architects' aim is to contribute to people's lives and the culture of contemporary society through the informed knowledge of humanity, study of architectural precedents and urban habitats, combined with a detailed understanding of materials and fabrication processes. This knowledge base is underscored by a long-term commitment to research. The benefit of using a component-based architecture and off-site manufacturing is that it is possible to create high-quality and cost-effective architecture delivered with the shortest possible site time. This has been demonstrated on projects at a number of scales including the Regional Rail Stations, Cardiff Bridges and Ballingdon Bridge. The approach of Michael Stacey Architects is based on systems of components, yet each architectural project is client and site specific.

www.s4aa.co.uk

KieranTimberlake

The practice brings together the experience and talents of nearly 100 professionals of diverse backgrounds and abilities in a practice that is recognised worldwide. KieranTimberlake's projects include the programming, planning and design of new structures as well as the conservation, renovation and transformation of existing buildings, with special expertise in education, government, arts and culture, civic and residential projects. KieranTimberlake seeks ways to improve the art, quality and craft of architecture through research into new materials, processes, assemblies and products.

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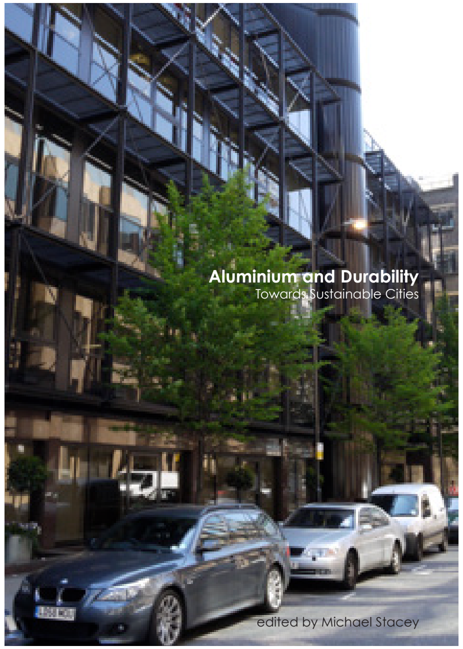

Aluminium and Durability

The durability of aluminium is probably one of the most important qualities of this metal when used to form architecture and infrastructure.

Charting almost one hundred years of the use of aluminium in architecture and the built environment, based on 50 built works from 1895 to 1986, with four historic exemplars being inspected and presented in depth. Twelve twentieth century award winning and historically significant aluminium based buildings were inspected leading to the successful non-destructive testing of aluminium finishes on three of these projects.

Written and edited by Michael Stacey.

Aluminium Recyclability and Recycling

Aluminium is almost infinitely recyclable and this is well understood. This research identifies that aluminium-based projects dating back to 1950 that have been disassembled have all been recycled. 1950 is the first year of entries in IAI's global mass flow model. The research reviews the reasons why buildings are demolished and rates of material recovery at the end of use. Key examples of short-life and relocatable architecture are set out, alongside the future role of Design for Disassembly [DfD]. This research also identifies that there is a much wider uptake of cast aluminium components in architecture than may have been expected.

Written by Michael Stacey.

Aluminium and Life Cycle Thinking

Life cycle thinking challenges architects, engineers and contractors to be mindful of the life history of any manufactured product and more specifically to understand the inputs (energy and water) and outputs (emissions to the environment) that result from the transformation of matter into product and from product to disposal. This report uses Life Cycle Assessment, a modelling method, to quantify and compare the environmental impacts and benefits associated with aluminium building components to those associated with alternative materials.

Written by Stephanie Carlisle, Efrie Friedlander, and Billie Faircloth.

The **Towards Sustainable Cities Research Programme** is funded by the International Aluminium Institute [IAI] and undertaken by Michael Stacey Architects with KieranTimberlake and the Architecture and Tectonics Research Group [ATRG] of The University of Nottingham. The research is structured around the primary benefits of aluminium, as articulated by the *Future Builds with Aluminium* website (*http://greenbuilding.world-aluminium.org*), which is a sector-specific component of *The Aluminium Story* (*http://thealuminiumstory.com*). Towards Sustainable Cities is a three-year programme quantifying the in-use benefits of aluminium in architecture and the built environment.

The Hive at The Milan Expo 2015, designed by artist Wolfgang Buttress

Aluminium: Flexible and Light

Towards Sustainable Cities

Aluminium: Flexible and Light, written by Michael Stacey, with contributions from Philip Beesley and Brian Ford, additional research by Michael Ramwell and Philip Noone, and further input from Stephanie Carlisle, Efrie Friedlander and Billie Faircloth of KieranTimberlake.

This forms part of the Towards Sustainable Cities – Quantifying the In-Use Benefits of Aluminium in Architecture and the Built Environment Research Programme, funded by the International Aluminium Institute [IAI] and undertaken by Michael Stacey Architects with KieranTimberlake and the Architecture and Tectonics Research Group [ATRG] at the University of Nottingham.

The **Towards Sustainable Cities Research Programme** is structured around the primary benefits of aluminium, as articulated by the *Future Builds with Aluminium* website (*http://greenbuilding.world-aluminium.org*), which is a sector specific component of the *Aluminium Story* (*http://thealuminiumstory.com*). *Towards Sustainable Cities* is a three-year programme quantifying the in-use benefits of aluminium in architecture and the built environment.

A primary aim of this research is to quantify the in-use carbon benefits arising from the specification of aluminium in architecture and the built environment, to complement the relatively well-understood emission savings from the use of aluminium transportation applications and through the recycling of aluminium scrap. A vital goal of this research is to quantify the potential contribution of aluminium towards the creation of sustainable cities – a key task now that over half of humanity lives in urban areas.

Key case studies demonstrating and quantifying the carbon savings arising from the specification of aluminium based architecture include: **Kielder Probes** by sixteen*(makers), **Guy's Hospital Tower** by Penoyre & Prasad, **dlr Lexicon** by Carr Cotter & Naessens, **i360** by Marks Barfield Architects and **the Large Hadron Collider** at CERN.

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