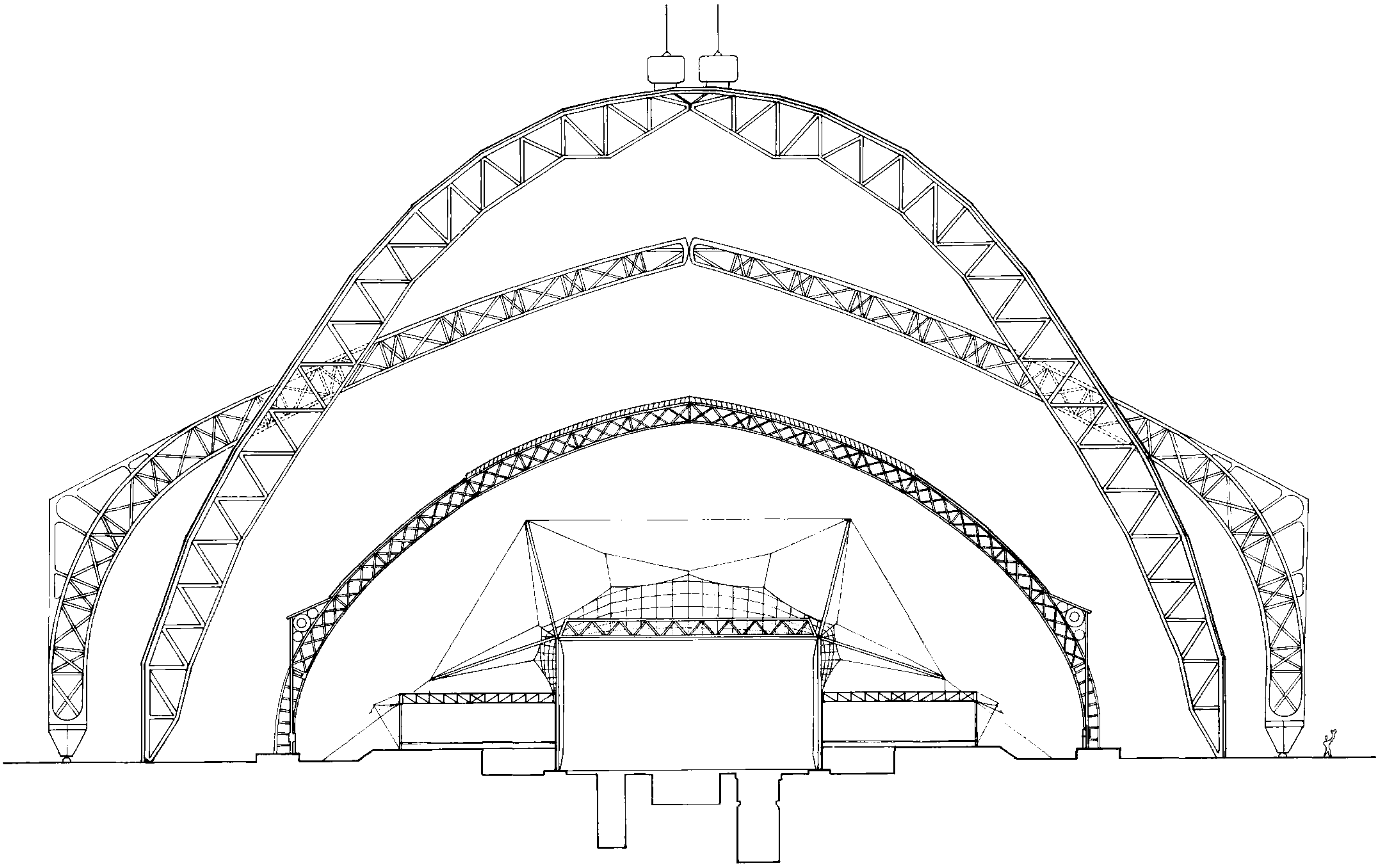
SUPERSHEDS

The architecture of long-span, large-volume buildings

Chris Wilkinson



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Firstly I would like to thank Richard Rogers, Michael Hopkins and Norman Foster, in whose offices I worked during the 1970s and earlys 80s on the design of many interesting buildings which formed the basis and reason for tackling this subject. During that time I received help and encouragement from many fellow architects including Graham Anthony, Mike Davies, John Eger, Birkin Howard, Richard Horden, Jan Kaplicky, John Pringle, Ian Sharratt and John Young.

My thanks to Peter Cook and Jenny Towndrow for helping me to start the project, also to Alan Brookes and Michael Spens for reviving it after a long break.

I have always enjoyed working with good engineers and have been able to discuss aspects of this book with Tony Hunt, who has helped all the way through, also Peter Rice, Frank Newby, Michael Coombs and Neil Thomas.

Many people in libraries and offices throughout the world have helped me obtain the wealth of illustrations for the book, and I am especially indebted to Christopher Dean for his advice and loan of material on airship hangars following our collaboration on the *Housing the Airship* exhibition at the Architectural Association.

My thanks to those from my office who have helped and suffered during the preparation of the book, particularly my partner Jim Eyre, Marc Barron, Helen Tsoi and Nicky Cousins. I would also like to thank my editor Caroline Mallinder, who has been tremendously supportive, Cluny Gillies for taking so much trouble in laying out the book, knowing it to be so important to me, and all those people too numerous to mention, who have assisted me.

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Contents

Foreword

Sheds are open large covered spaces in which society manufactures, stores, and distributes the artifacts of our time. They are used for sport, selling and exhibiting. They are in short the most universal, the most prevalent and perhaps the most typical built elements of our time. They are found everywhere, in cities, in towns, in villages and on farms. And yet they are often ignored. They are the Cinderellas of architectural and engineering discussion. Chris Wilkinson's book sets out to rectify that, and about time too.

Sheds were really an invention of ninteenth-century engineering and industrial progress. For the first time large spaces were needed to manufacture and maintain the new technologies. And with the invention first of cast iron, then in quick succession wrought iron and steel, the means existed to build larger and larger structures. The Victorian builders exploited this new found freedom and the needs which became ever more important, to the full. The great railway stations in London and at the principal provincial cities were the romantic gems of this development. There were many other examples, often elegant testaments to the technological prowess of their day. As technology moved on so did the size and variety of sheds, and the way they were used. They became ever more popular and necessary. In the 1930s and again in the 1960s they became a focus for much architectural invention as the best young architects of their time became interested in designing them and active in developing new models. The 1960s development created a trend. Today it is inconceivable to think of a shed without an architect to design it. They are important commissions for all architects young and old, large practices and small. This gradual transformation of the way sheds are designed has been an important factor in the growth of science parks, out-of-town centres and other staples of today's built environment. Elegance and sensitivity has returned to the world of shed design and many of the most innovative examples of the work of masters of modern architecture are sheds: supersheds, to use the synergy of the title.

Chris Wilkinson sets out to catalogue and explain how this change has taken place and to collect together in one volume the most important and significant examples, particularly from the recent developments. It is to be hoped that this interesting and exciting book will further stimulate discussion and development in this important area of modern construction.

Peter Rice, Engineer

Preface

There is a kind of architecture which is not formal, decorated or mannered, but which derives its aesthetic from a clear expression of its purpose and component parts, where the demands of function and economy have led to simplicity of form and construction but where the basic requirements of enclosure and structure are extended by design to create buildings of quality.

This book sets out to examine this type of building grouped under the title *Supersheds* which can be defined as buildings enclosing a large single volume of space with relatively long spans and without major subdivision.

It is a category of building which until now has largely been excluded from the mainstream of architectural classification, and left to the province of engineering. However, it is here that the skills of architecture and engineering are most closely combined in the interest of the design, and throughout the history of architecture there has been a recurring theme which celebrates this union. For example, the spatial quality and structural clarity of the Gothic cathedrals are in many ways comparable with that of the Victorian train sheds, the airship hangars of the early twentieth century and the better industrial buildings and lightweight structures of the present day, although the technology is different.

The development of these buildings has closely followed technological progress and really started in the early nineteenth century with the advent of the railways which generated the need for long-span sheds at a time when the technology of cast-iron structures was sufficiently advanced to be able to provide them. At that time of great engineering achievements, tremendous progress was made with the development of long spanning iron structures, glazing and lightweight cladding systems which, for the first time, enabled the fast and economical construction of long-span buildings. Talented engineers emerged with vision and the creative ability to design with this technology and a new vocabulary of architecture was created.

The 1850s in Britain saw the construction of the Crystal Palace by Paxton and Paddington Station by Brunel. These were two fine buildings of different use, which exemplified the spirit of this new age of architectural engineering: two vast sheds of lightweight construction which were functional, economical and which expressed a simplicity of form and clarity of structure.

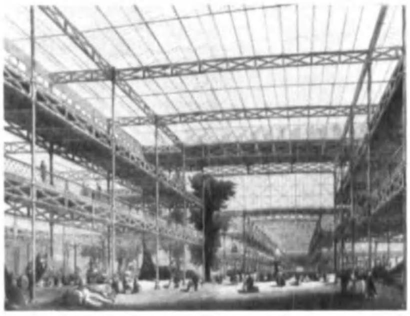
Progress in the latter half of the nineteenth century saw the development of the larger spanning vaulted train sheds such as Barlow and Ordish's St Pancras Station roof in 1865 with a span of 73 m. In France, the engineer,

A Gothic cathedral, Rheims

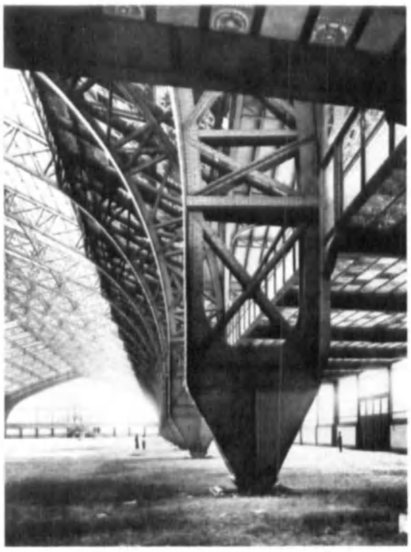
B Paddington Station

C Hangar Y, Chalais-Meudon

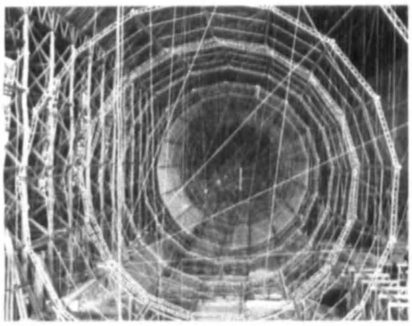
D Sainsbury Centre



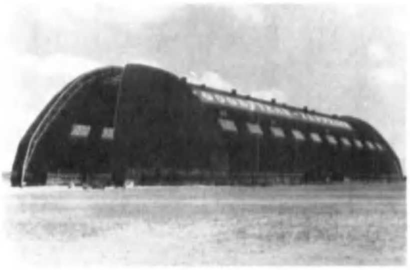
E Crystal Palace



F Galerie des Machines



G R23 under construction



H Akron Airdock

de Dion developed the structural potential of iron lattice trussed portal frames for the 1878 Paris Exhibition and eleven years later the first significant three-pinned arched structure was built by Cottancin and Dutert for the Galerie des Machines at the Paris Exhibition 1889. With a span of 114 m it was the longest ever constructed and remained so until the Centre National des Industries et Techniques was built in Paris in 1960 with a clear span of 220 m. This was a period of great innovative engineering which widened the parameters of architectural vocabulary.

In the early twentieth century many of the major technological advances changed from land to air, starting with the development of the airship and was followed by the aeroplane. The structural requirements for lighter-than-air crafts were much more sophisticated than any building requirements and encouraged the development of lightweight structures. High strength alloys were used for the first time with slender three-dimensional lattice structures and there were important spin-offs for the building industry, perhaps the major one being the need for vast sheds to house them. This generated experiments in large tented structures for mobility, floating and rotating structures to take advantage of the wind, and aerodynamic structures to avoid turbulence for docking and launching. This requirement to house the airship provided the engineering brief for economic long-span, large volume sheds which resulted in the construction of a number of elegant functional steel buildings of awe-inspiring proportions which exceeded the great Gothic cathedrals of the past. The largest of these was the Goodyear Airdock at Akron, Ohio, constructed in 1929 with an elegant parabolic three-pinned arch structure and sophisticated clam-shell doors. The streamlined shape was derived from wind-tunnel tests in order to reduce the turbulence on the launching and docking of the airship.

The aeroplane has also played a role in the development of the *shed* with the wartime requirements for economical, quick to erect, low profile hangars, and later with the need for clear-span hangars to house the larger passenger planes. More recently the emergence of the Jumbo Jet with its 60 m wingspan has generated the design of long-span space frames, cable-supported roofs and cantilevered structures. The largest building in the world, the Boeing Assembly Building at Everett, Seattle, was constructed for the manufacture of these huge planes but the technology of aircraft construction has yet to be adopted in buildings. For instance, the enormous potential for stressed-skin or monocoque construction which has reached such a high level of refinement in the aeroplane wing, has scarcely been considered in buildings, despite the preachings of those forward-looking architects such as Future Systems who constantly examine the potential for 'transfer technology'. Of course, economics plays a part, but it is nevertheless surprising that in this age of space travel, the building industry is still preoccupied with Stone Age wet construction and on-site craftsmanship.

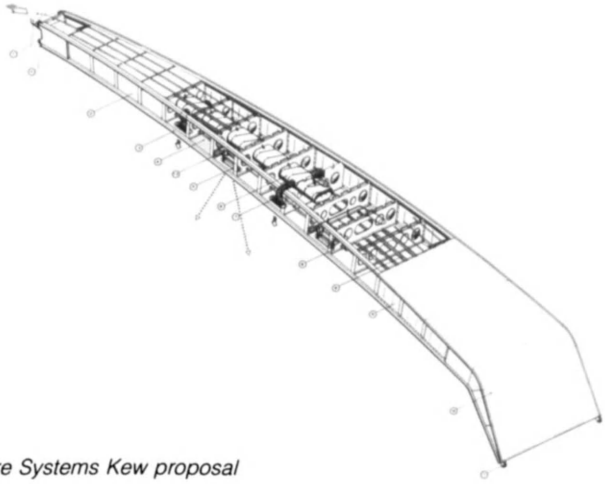
The requirements of industry are constantly changing with the development of new manufacturing techniques and the buildings which house the processes have evolved to meet these requirements. The most significant development this century has been the introduction of the production-line assembly which originated primarily in the USA for the automobile industry and created the brief for the single storey, roof-lit wide-span industrial shed which we know so well.

Considerable progress was made in the design of this form of industrial shed by Albert Kahn in the USA and his work attracted the interest of the leaders of the European Modern Movement. He designed over 2000 factories during his lifetime, most of which were strong functional forms with clear expression of purpose, structure and the materials of the building envelope, Whereas in Europe there were but a few well illustrated examples of Industrial Architecture at that time, each carefully considered, which emanated from leading figures such as Behrens, Gropius and Mendelsohn. From this we can draw the conclusion that the general standard of design for industrial buildings in Europe in the early twentieth century was dull and uninteresting, which is sadly still the case today. The buildings referred to throughout this book reflect only the prime examples of their time and are by no means representative of the general standard. Progress has been made only by the efforts of the few strong minded, talented designers who are prepared to stick to their principles and are not afraid to innovate despite the risks.

It is through their work that we are able to trace the evolution of Industrial Architecture in its response to new technology. We can see the effects of the change from steam power to electricity, the introduction of the production assembly line and the move from the heavy industrial process to the highly serviced electronics and microprocessor assembly plant.

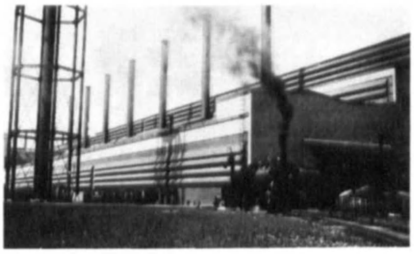
In recent times we have seen the flowering and fading of interest in the simple form of the rectangular grid or Cool Box industrial shed, which evolved since the World War II to provide flexible, multi-use space with the

I Boeing Assembly Building



J Future Systems Kew proposal

K Ford Rouge Open Hearth Building

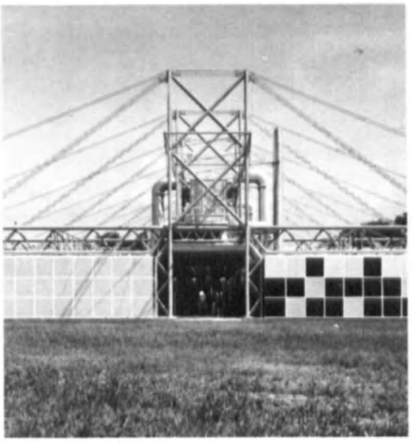


L Reliance Controls

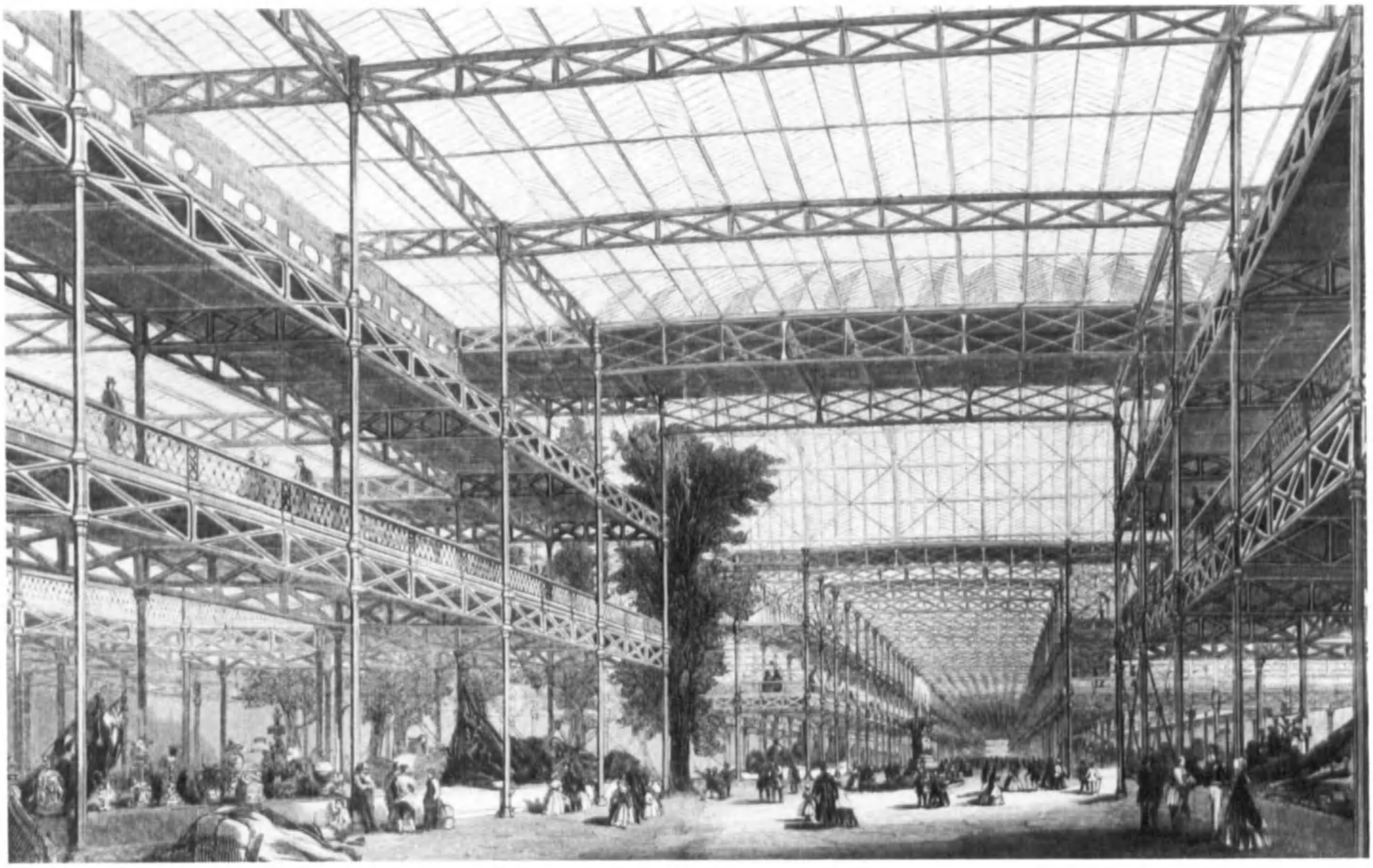
economical integration of structure and services. Hybrid forms have been developed recently to suit the image and economics of the Business Park where the shed has been largely superseded by the two to three storey B1 office building. However, the extruded shed has continued to evolve with new forms of structure and it seems likely that the requirement for economical column-free space will continue to expand particularly in the field of leisure activities. In addition, we have seen wider use and experimentation with masted tension structures, space grid structures and air-supported structures in an attempt to achieve greater performance.

There is still tremendous scope for innovation in the development of economical lightweight structures and the quest for Universal Space. It should be possible to create wider spans with less material and for less cost. With the worldwide impinging economic recession, the soaring cost of energy and the accelerating depletion of our natural resources, the essence of Buckminster Fuller's Dymaxion concept for achieving 'more with less' seems ever more relevant and the future for lightweight structures even more promising.

M Inmos factory



1.1
The Great Exhibition of 1851. Interior of the Crystal Palace in Hyde Park by Joseph Paxton. Measuring 563 × 139 m it was the world's largest building covering a ground area of 7.3 ha (18 acres)



1.1

1 Pioneers of the Nineteenth Century

Background

Man has always been a builder and throughout history he has strived to create longer spans and larger covered spaces than his forefathers. This has been made possible by the gradual development of building technology.

At first his potential was limited by the lack of tools and the use only of natural materials. Mud or grass huts and tents of animal skins provided the first forms of enclosure; then the use of stone construction provided the opportunity for the architecture of early Greek and Egyptian civilizations. However, the use only of simple forms of construction restricted their buildings to short spans with minimal void.

Kiln-fired bricks enabled the Mesopotamians in 3000 BC to construct arches with spans of up to 15 m (20 ft) and this system of laying bricks in vaults and domes continued to be used in its simple form until the Romans who were able to make great structural advances with the use of pozzolanic concrete.

In AD 118–128, the Pantheon was built in Rome with the incredible span of 43.2 m (142 ft) across the diameter of the dome, and its height at the apex was the same. The secrets of concrete technology were then lost for centuries and the amazing spanning achievements of the Romans were not bettered for 1700 years until the development of iron structures.

The domed basilica of Hagia Sophia built in AD 532–537 came close with a span of 32.5 m (107 ft) and Brunelleschi's great dome over Florence Cathedral in the early fifteenth century is almost the same span as the Pantheon, if measured across the diameter of the diagonals of the octagon. In fact, the church provided the main requirement for large span structures throughout this period where the limits of timber and stone construction were continually explored in order to create awe-inspiring spaces for the glorification of God. The most spectacular are the stone vaulted cathedrals such as Chartres where spans of 15 m over lengths exceeding 100 m with clear heights of 40 m were achieved.

In timber, roof truss and beam systems were developed from barn structures to provide larger column-free spaces for churches, halls and meeting places. One of the most spectacular is the hammer-beam roof of Westminster Hall built in the late fourteenth century with a span of 21 m (69 ft).

The first significant structure to be built with iron was the Iron Bridge at Coalbrookdale, Shropshire in 1779 with a span of 30 m (100 ft) across the River Severn, and in the same year Jacques Soufflot developed one of the first self-supporting iron roofs for a gallery of the Louvre but with the modest span of 15.8 m.

The structural use of cast iron in buildings continued to develop gradually during the eighteenth century but it was not until the early nineteenth century that rolled sections were produced and real progress was made. One of the earlier uses of cast-iron rolled sections was in the roof trusses of Euston Station in 1835 by Robert Stephenson, where T-sections were used for the principal members and a lightweight structure produced.

Another important innovation in this period was the invention of corrugated wrought iron sheeting by H. R. Palmer in 1829 which for the first time provided a lightweight roofing material that could span between structural elements without the need for secondary timber supports.

The use of iron roofs and iron-framed buildings proliferated in this period where the requirements for large spans could at last be accommodated with speed and economy and it is here that the era of the 'supersheds' started. The fast development of the railways throughout Europe provided the major generator for long-span large volume spaces but advances were simultaneously being made in industrial buildings, glazed structures for conservatories, covered malls and exhibition halls.

One of the most significant events to inspire confidence in the new technology was the competition for the Great Exhibition of 1851. It attracted innovative designs from some of the greatest engineers of the time and resulted in the construction of Joseph Paxton's Crystal Palace in Hyde Park.

The Great Exhibition Halls

The Crystal Palace for the Great Exhibition of 1851

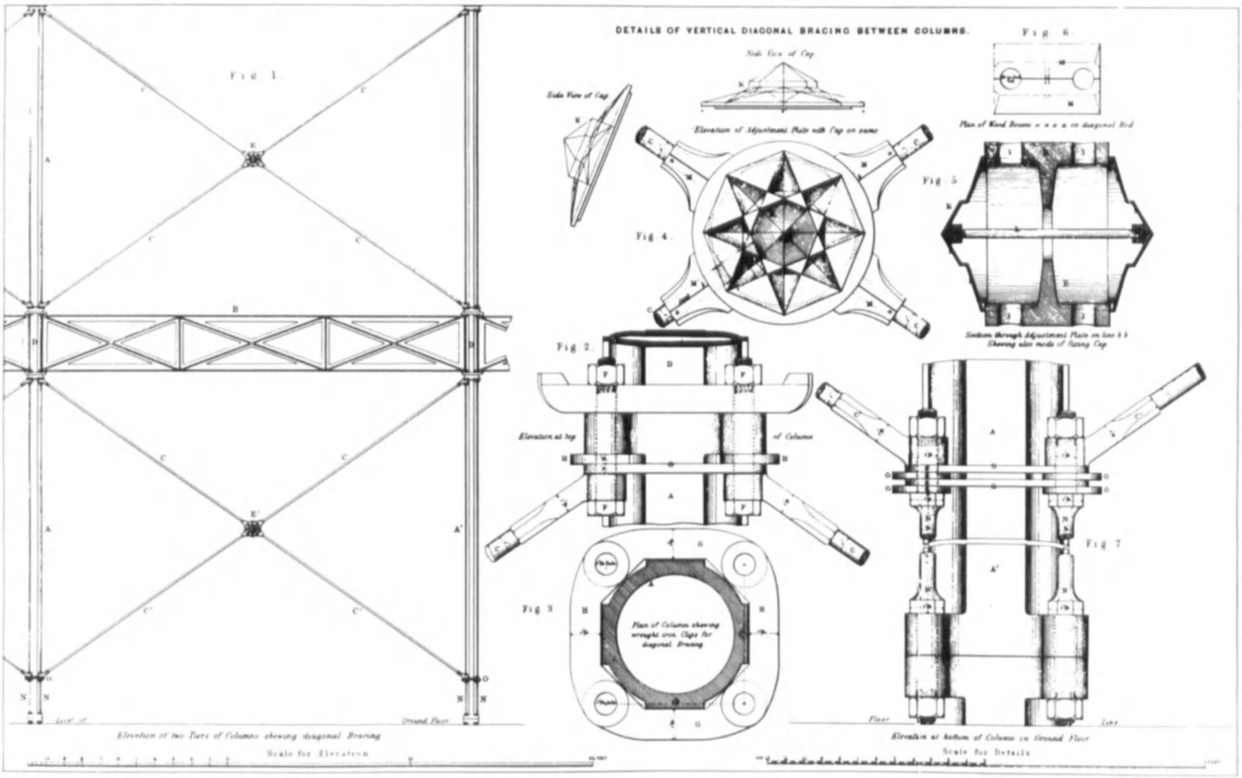
This building, constructed almost entirely of cast iron, timber and glass enclosed the largest volume of space ever up to that time, with the lightest construction and highest technology available. It was an engineering masterpiece which set a precedent for a new kind of architecture (Figure 1.1).

The overall size of the building was vast, measuring 563 × 139 m and covering a ground area of 7.3 ha (18 acres); the galleries made it more than four times the size of St Peter's in Rome, which for centuries had been the world's largest building.

In many ways the Crystal Palace embodied all the

1.2
Crystal Palace. Site erection with prefabricated components, none of which weighed more than a ton. They could be lifted into position with horse-drawn or hand-winched block and tackle

1.3, 1.4, 1.5
Crystal Palace construction details. Lightweight construction of modular, prefabricated components in timber, iron and glass based on 24 ft (7.3 m) module with three glazing furrows to a bay



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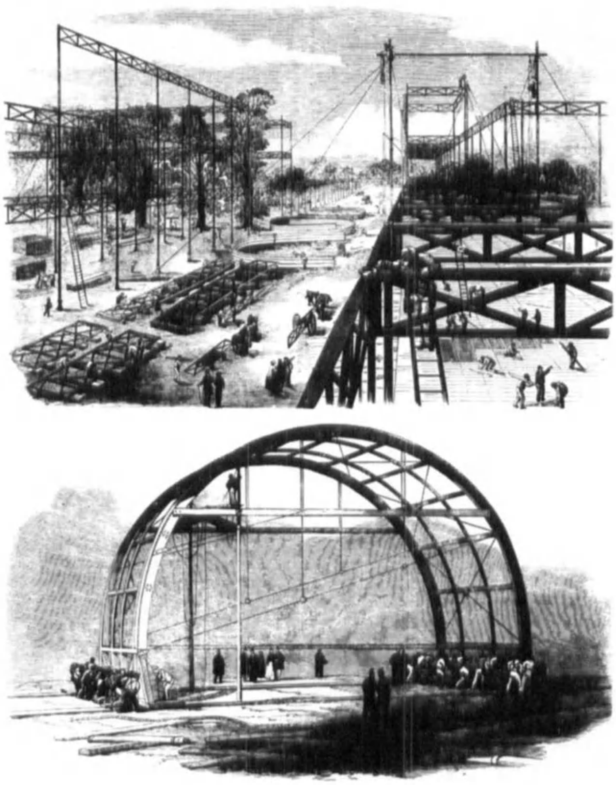

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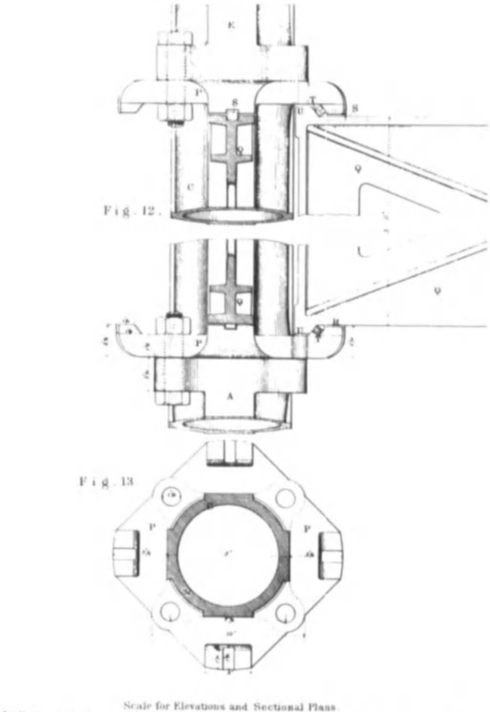

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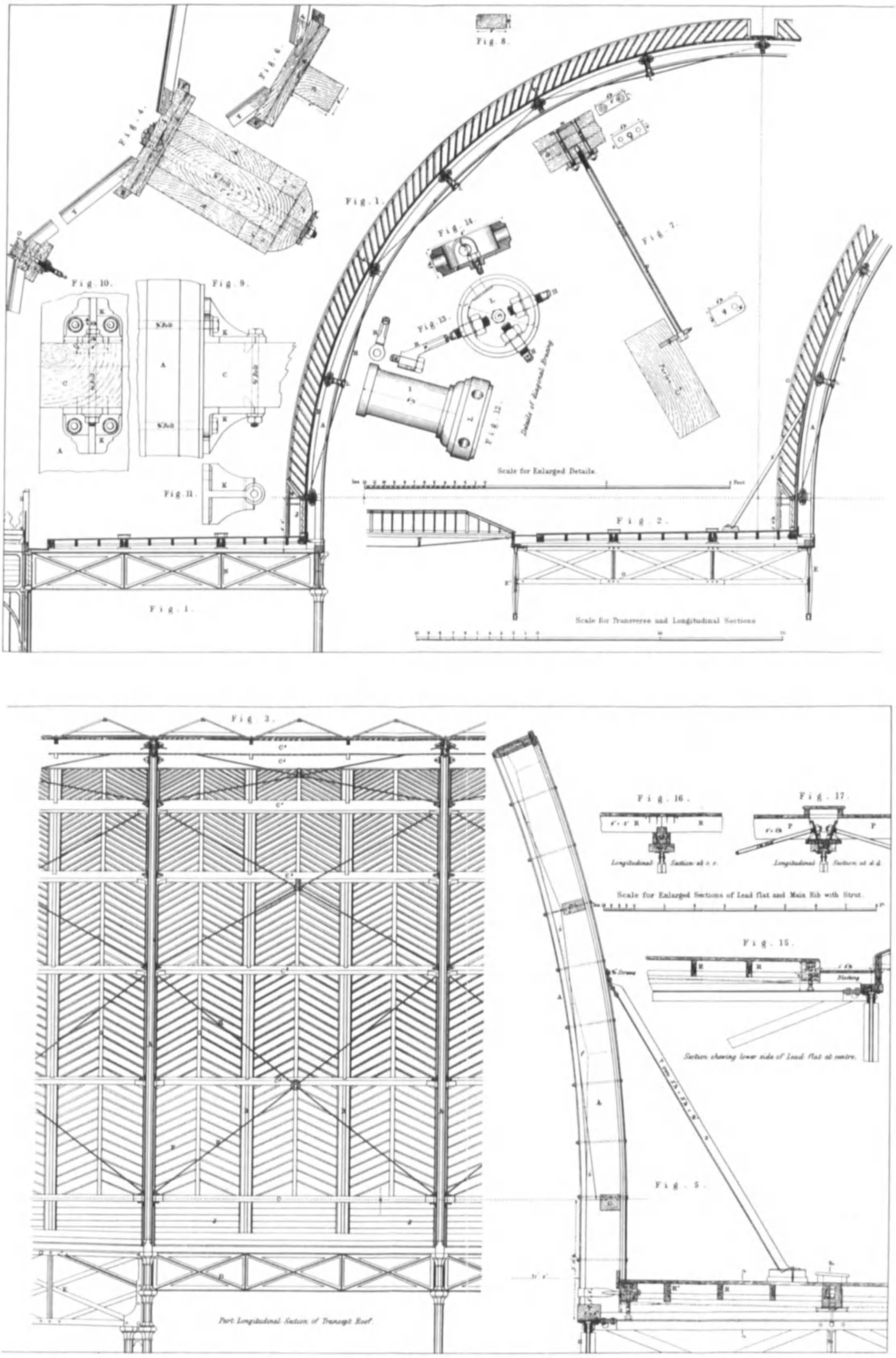


Fig. 8.
Fig. 4.
Fig. 6.
Fig. 1.
Fig. 14.
Fig. 7.
Fig. 10.
Fig. 9.
Fig. 13.
Fig. 12.
Details of diagonal Bracing
Fig. 11.
Scale for Enlarged Details.
Fig. 2.
Fig. 1.
Scale for Transverse and Longitudinal Sections
Fig. 3.
Fig. 16.
Fig. 17.
Longitudinal Section at c.c.
Longitudinal Section at d.d.
Scale for Enlarged Sections of Lead flat and Main Rib with Strut.
Fig. 15.
Section showing lower side of Lead Flat at centre.
Fig. 5.
Part Longitudinal Section of Transept Roof

1.5

essential characteristics of a modern supershed, such as modular construction, standardization, mass production, prefabrication, mechanization, lightweight construction, systems integration, rapid site assembly and demountability. All these aspects were, of course, interdependent on each other and largely dictated by the tight programme. The whole building was completed in six months which was only made possible by the standardization and mass production of the components.

Joseph Paxton, the designer, was not an architect or engineer but he had been designing glass structures for more than twenty years and had been involved in railway planning. His concept for a 'palace of glass and iron' was based on the conservatory which he had built earlier at Chatsworth. He secured the contract for the work after the failure of an international competition, attracting 250 entries, by forming an alliance with Fox and Henderson, who were well known contractors of the time. Together, they were able to offer a 'package deal' for the design and construction of the building for a fixed price with agreement to complete the tight programme. They inspired the confidence of the Exhibition Committee and justified it by completing on time, a building which came up to their expectations. In 1849 I. K. Brunel, one of the distinguished members of the Exhibition Committee, stated his hopes for the Exhibition Building: 'I believe that there is no one object to be exhibited so peculiarly fitted for competition as the design and construction of the vast building itself. Skill of construction, economy and rapidity of construction would call forth all those resources for which England is distinguished. I believe it might be much the grandest subject of competition of the whole affair'.

The brilliance of Paxton's plan lay not just in the design but in its implementation. It was a building which could not have been erected fifty years earlier, for it was a framed building of dry construction, using only iron, glass and wood.

It was built with prefabricated components based on a 24 ft (7.3 m) module. This gave three glazing furrows to a bay spanning 8 ft (2.4 m), each glass pane being 10 in (254 mm) by 49 in (1.25 m) and weighing 16 oz/ft. The heaviest components were the 610 mm (2 ft) long cast-iron girders, none of which weighed more than a ton and could comfortably be lifted into position with a system of horse-drawn or hand-winched block and tackle (Figures 1.2–1.5).

Fox and Henderson and their subcontractors used all the labour-saving devices they could during construction for economy and speed. The timber for the sash bars was run through a sash bar machine and the bars painted with a painting machine. The majority of the glazing was installed from glazing wagons that moved on wheels in the Paxton gutters.

The cast-iron columns arrived on site with their ends turned on a lathe, ensuring accurate length and a sealed joint. A canvas gasket dipped in white lead was fitted at the joints. At each floor and roof level, a 914 mm (3 ft) connection collar with its cast-iron connecting lip was bolted on top of the longer columns. This enabled the cast-iron trusses with their specially cast projections to slide into the grooves and be secured with a wrought-iron key. The success of this joint was critical for both the speed of erection and the lateral restraint of the building.

The impact of the building was immense. Small glazed palaces, glass arcades, markets and winter gardens were built all over the UK and other countries. International exhibitions sprung up throughout the world.

In Joseph Paxton's obituary in 1865, *The Times* described him as 'the founder of a new style of architecture', but it was inevitable that the main lesson to be learned, that of the architectural value of engineering and constructional simplicity, was to a large extent overlooked until the twentieth century.

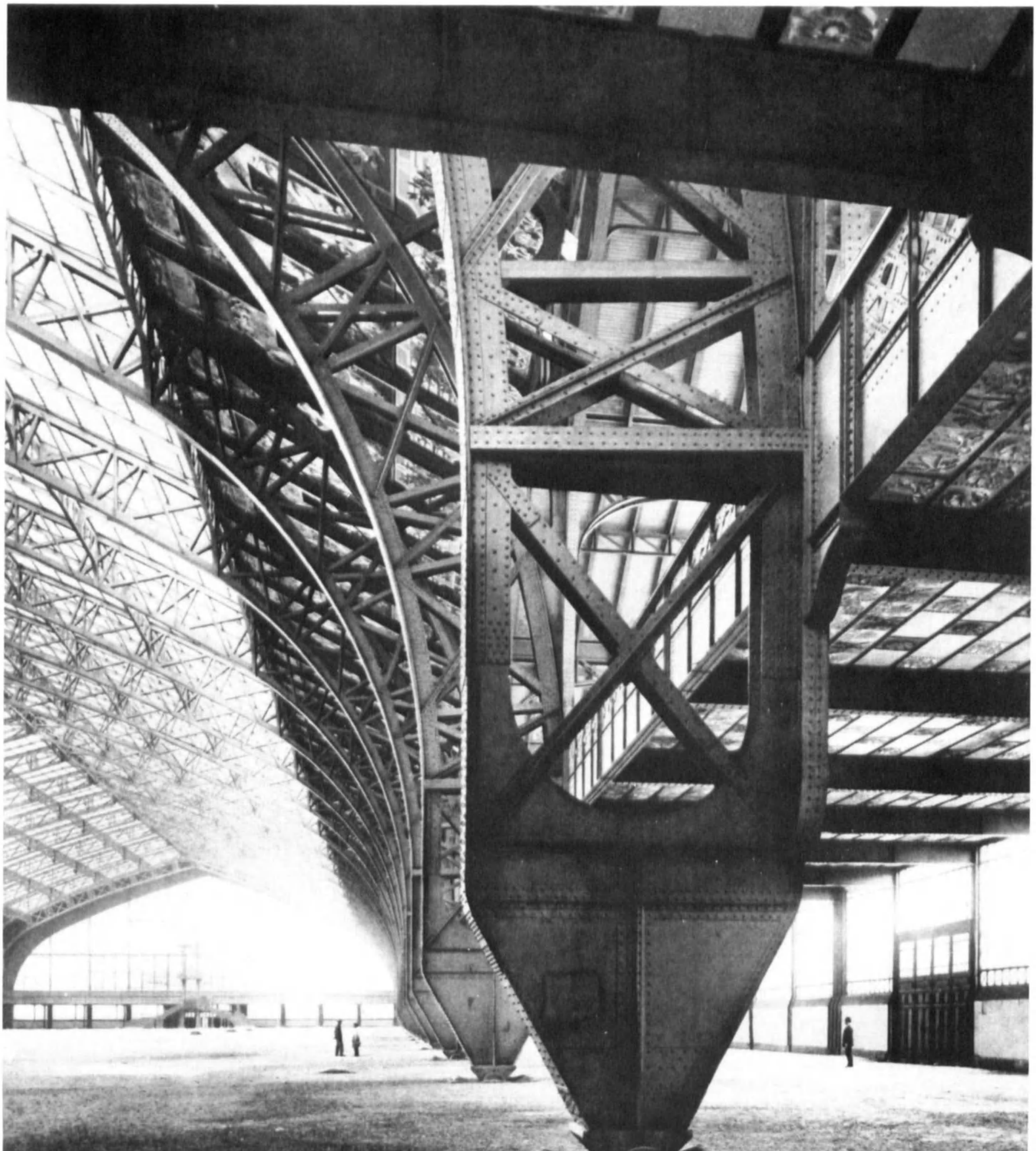
International Exhibitions

The Great Exhibition in Hyde Park was followed by the French with the *Exposition Universelle* in Paris 1855. Here the main building, the Palais de l'Industrie, distinguished itself with a span of 48 m which was the widest vaulting attempted in the period and represented a considerable advance on the Crystal Palace in this respect. Wrought iron lattice girders, partially hand forged, were used to support the glazed roof. No tie bars were included but the lateral forces were compensated with heavy lead buttresses.

It was a triumph of long-span lightweight construction, but sadly unlike the Crystal Palace, it was thought necessary to encase the exterior of the building with heavy stone walls. This trend continued in later exhibitions held in London 1862 and Chicago 1893. In other ways, however, the great exhibition halls provided excellent opportunities for engineers and designers to progress new ideas and advance building technology.

At the *Exposition Universelle* in Paris 1878, the engineer Henri de Dion progressed the science of vaulting with the first portal frame of lattice girders where the forces were transmitted directly to the foundations without tie bars. This Galerie des Machines (Figure 1.7)

1.6
Galerie des Machines, Paris Exhibition 1889 by the engineer Contamin assisted by architect Dutert: 114 m span × 420 m length × 46 m height

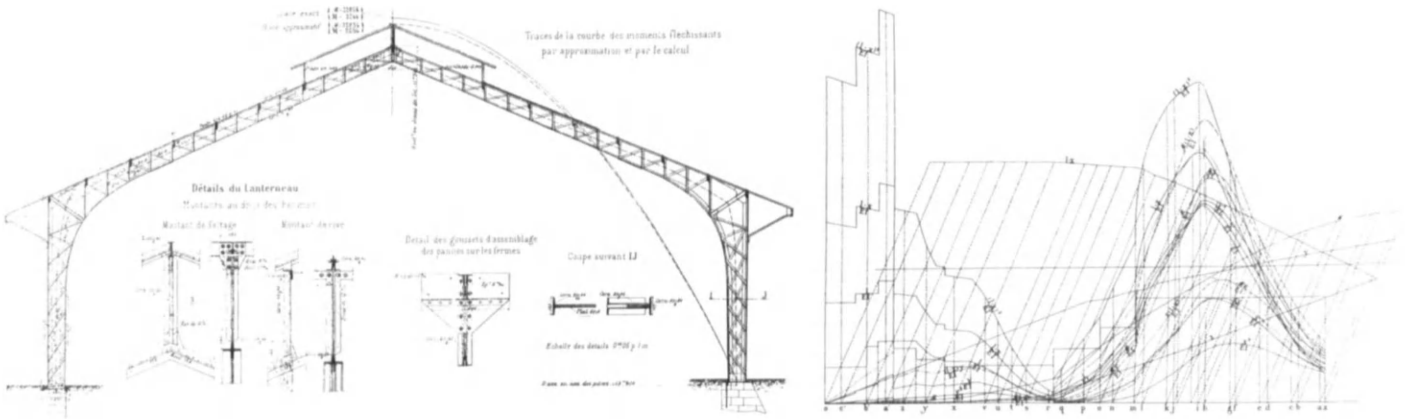


1.6

1.7
Exposition Universelle, Paris 1878. Iron portal frame by Henri de Dion spans 35 m

1.8
Interior of Galerie des Machines, Paris Exhibition 1889

1.9
Structure of Galerie des Machines innovated the three-pinned arch structure with 3 m deep steel arched trusses spanning 114 m (drawn by Dave Harris)



1.7

1.8

1.9

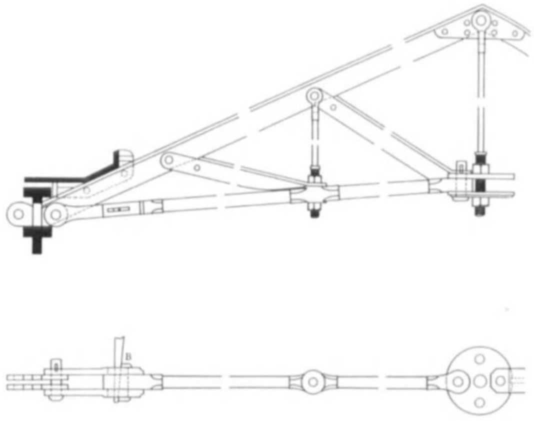
had a span of 35 m and its pitched roof shape was a forerunner of many sheds to follow. After the exhibitions, the structure was dismounted and the parts used in the construction of the first purpose built airship hangar at Chalais-Meudon.

Galerie des Machines 1889

The next major advance was at the Paris Exhibition of 1889 where the engineer Contamin and the architect Dutert constructed the legendary Galerie des Machines (Figure 1.6). This supershed represented the accumulation of constructional experience gained throughout the nineteenth century. It innovated the structural principle of the three-pinned arch, pioneered the use of structural steel and its massive proportions have never really been equalled.

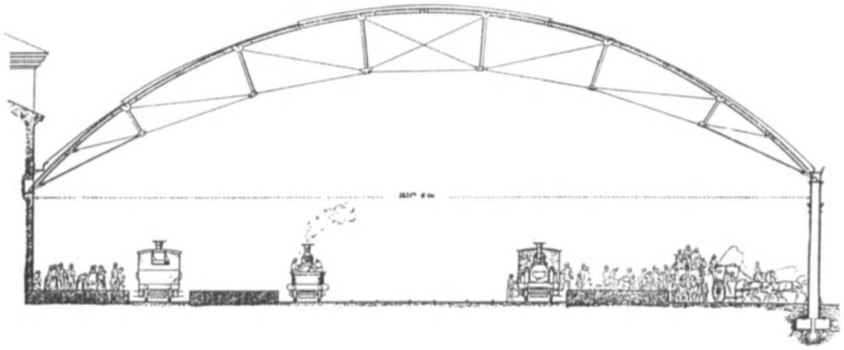
The 3 m deep lattice trusses supporting the fully glazed roof spanned an uninterrupted 114 m in a hall 420 m long × 46 m high. In describing the space created, Giedion in his book *Space, Time and Architecture* says 'the volume created represented an entirely unprecedented conquest of matter. There is no earlier example that is comparable to it in this respect'. Up to that time the widest vaulting which had been attempted was St Pancras Station. The space was so vast that two mobile trolleys were installed along the whole length above the exhibits for visitors to view from and this was so popular that as many as 100 000 people were known to have travelled on them in one day (Figure 1.8).

Each arched truss was made up of two sections joined at the top with a pin (Figure 1.9). At the base the trusses were tapered to a hinged joint, ensuring an exact distribution of the stresses and the materials used. The visual effect of this was disturbing to many people at the time, as it was contrary to normal practice and seemed to defy logic. It was, however, an important expression of structural integrity. The principle of the hinged joint was absolutely new in building construction and had only recently been first used in bridge building in the 1870s,



1.10

1.10 Euston Station train shed, opened in 1837, constructed of lightweight trusses of T-sections with rolled wrought-iron compression members spanning 12 m designed by the engineer Robert Stephenson. (a) Details of wrought-iron truss. (b) Plan details of truss



1.11

1.11 Lime Street Station, Liverpool 1849–1851; curved wrought-iron and glass roof spanning 47 m designed by Richard Turner

1.12

1.12 Paddington Station, completed 1851, designed by Isambard Kingdom Brunel in collaboration with the architect Matthew Digby Wyatt. Conceived as a glazed cathedral with 'nave' of 213 m length × 31 m span flanked by 21 m wide aisles

1.13

1.13 St Pancras Station train shed, 1868 designed by the engineer William Henry Barlow and R.M. Ordish was the longest spanning roof ever constructed at that time, with a span of 73 m

for example on Eiffel's bridge over the Douro in Portugal.

P. Morton Shand said of it 'Steel had found its form at last. Construction had once again become its own expression, its own style. Contamin's Galerie des Machines was one of the loveliest shapes in which man has ever enclosed space; but whereas hitherto it had always been imprisoned like a bird in a cage, here it floated free as the circumambient air'. This freedom was the offspring of steel and glass for like the Crystal Palace had been 38 years earlier, this building was fully glazed, which tended to emphasize the form of the structure and created an apparently limitless space where the enclosure was visually only partially defined. Sadly, this great building was destroyed in 1910.

The Great Railway Era

Next to the exhibition halls, it was the railways which contributed most to the development of long-span, lightweight structures in the nineteenth century. Huge sheds were required to provide shelter for the steam engines and waiting platforms for people and goods. Speed and economy were particularly important and great engineers like Brunel, Stephenson and Barlow emerged to test the new technology and build some of the finest iron structures ever constructed.

The railway era started with the opening of the famous Stockton to Darlington Line in 1825, but the first major trunk railway was the London to Birmingham Line which was opened in 1837. This terminated at Euston with a grand station designed by Philip Hardwick and a series of fine train sheds designed by the engineer Robert Stephenson who later built the great tubular bridges across the Conway River and the Menai Straits. These simple utilitarian sheds were constructed with cast-iron columns, and lightweight trusses out of T-sections with rolled wrought-iron compression members. It is thought to be one of the earliest uses of this type of construction (Figure 1.10).

One of the first of the great iron arched roofs was the

Gare de L'Est in Paris (1847–1849) designed by François Duquesney. This was considered to be one of the finest stations in the world and set the pace for the 1850s. In England it was followed soon after by Lime Street Station in Liverpool and Paddington Station in London, both of which had long spanning curved iron roofs.

Lime Street Station

Richard Turner, who had been co-designer on the Palm House at Kew with Decimus Burton, was contracted to design and build the Lime Street Station between 1849–1851 (Figure 1.11). It had a curved roof of wrought-iron construction spanning 47 m over six tracks, three platforms and a roadway. The principal members were similar to standard rail sections in shape, strutted with wrought-iron members and tie rods. The covering was of corrugated iron with large areas of glazing, and it was this that ultimately failed, for the 10 mm glass in large panels bedded in putty on iron sash bars did not allow for expansion.

Paddington Station

Paddington was designed by Isambard Kingdom Brunel, the engineer of the Great Western Railway, in collaboration with the architect Matthew Digby Wyatt (Figure 1.12). It was conceived as a cast-iron and glass cathedral with a 'nave' 213 × 31 m and flanked by aisles 21 m wide. There are two pairs of 'transepts' along the sides. It is an extremely sophisticated structure with slender cast-iron arched beams supporting the elegantly glazed roof. One in three of these rest directly on an octangular column and the intermediate ones on an open web truss. Covering half of the roof is a Paxton ridge and furrow glazing system by Fox and Henderson who had just completed the Crystal Palace. This glazing provides excellent daylighting and seems to emphasize the length and slenderness of the vast structure. The decoration applied to the structure is the one element which dates the building, but in no way detracts from the spatial quality, which provides such an awe-inspiring sense of arrival.

In 1906–1916 a fourth matching shed was added on the north-east side with a span of 33 m but this sadly lacks the quality of the original structure.

Brunel was only 27 years old when in 1833 he was appointed Civil Engineer to the Great Western Railway, and it took only eight years to complete this important railway link between London and Bristol, with all its tunnels, bridges and stations. It was an incredible achievement and as if this was not enough, he designed, at the same time, the Great Western paddle steamer which was launched in 1838. This was all part of his dream for a steam route from London to New York via Bristol. At the London end, the railway terminated at Bishops Bridge for several years until the Paddington terminus was completed.

St Pancras Station

In 1868 the great arched train shed of St Pancras Station was completed for the Midland Railway. Designed by the engineer William Henry Barlow and aided by R.M. Ordish, it was the longest spanning roof ever attempted up to that time, and remained so until the Galerie des Machines was constructed in 1889 (Figures 1.13–1.15).

Still in use today, it has a span of over 73 m with a height of nearly 30 m above the rails and a length of 209 m; it covers an area of 4 acres. It was an incredible achievement for that time when the method of structural calculation was comparatively unrefined. The handsome wrought-iron lattice ribs which support the roof are about 1.8 m deep and spaced at 8.9 m centres. They each weigh 55 tons and are restrained by floor girders over which the trains run. This whole structure rests on a forest of columns under the station which used to provide a cellar for beer storage en route from Burton-on-Trent. Since so much of the trade on the line was beer, the distance between the columns was set out to suit the dimensions of beer barrels. The cellar originated because the tracks were high above the ground after crossing the Regent's Canal which is only half a mile away from the station entrance.

The station was designed for an hotel to be built in front of it, which was started in the year that the station was completed. This was designed by the architect Sir Gilbert Scott and is a masterpiece of its type, making the terminus an architectural and engineering landmark. It is hard, however, to imagine how the aesthetics of engineering and architecture could have become so remote from each other at that time.

Its awkward physical relationship with Cubitt's Kings Cross terminal may now be resolved by the interjection of a new Channel Tunnel terminal by Foster Associates (Figure 1.16). They have proposed a light, airy triangular form of vaulted shell structure to bridge the gap as part of the proposed massive regeneration of Kings Cross.

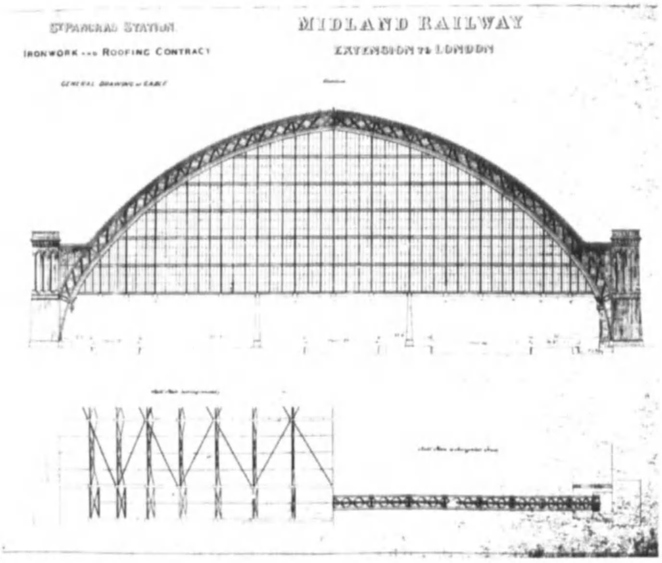
1.14
St Pancras Station. The structure of 1.8 m deep wrought-iron lattice ribs at 8.9 m centres enclosed a clear space of 73 × 209 × 30 m height

1.15
St Pancras Station. Construction detail of the ironwork and roofing contract 1868

1.16
Proposal for the new Channel Tunnel International Terminal at Kings Cross by Foster Associates 1989 attempts to resolve the awkward relationship bewteen the great Victorian railway termini at Kings Cross and St Pancras

1.17
Curving station of York, designed by William Peachey and built in 1874

1.18
The Gare d'Orléans at Quai d'Orsay, Paris, 1898–1900, designed by the architect M.V. Laloux with decorative coffering to the heavy cast-iron structure



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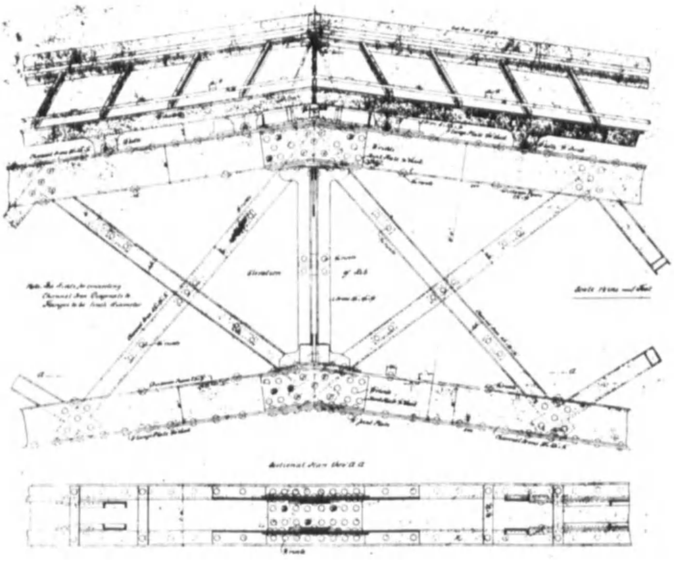


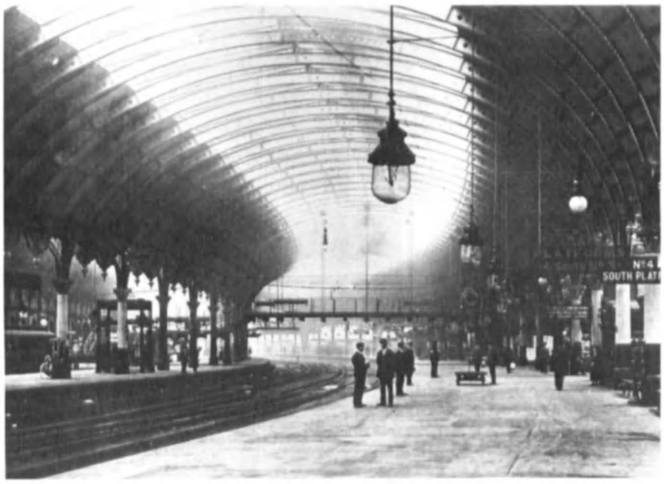
1.15

1.16

York Station

Among the most elegant examples of Victorian engineering are the curving train sheds at York Station (Figure 1.17). These were designed by William Peachey and built in 1874. The three wide-span vaulted aisles are constructed with solid web iron arched ribs at comparatively close centres. Similar to Brunel's Paddington, one in three of the ribs rests directly onto a column and the intermediate ones are supported on cross girders.

The columns are solid cast iron of the Corinthian order, which now seems somewhat eccentric for such a precise piece of engineering. The rib decoration and roof glazing



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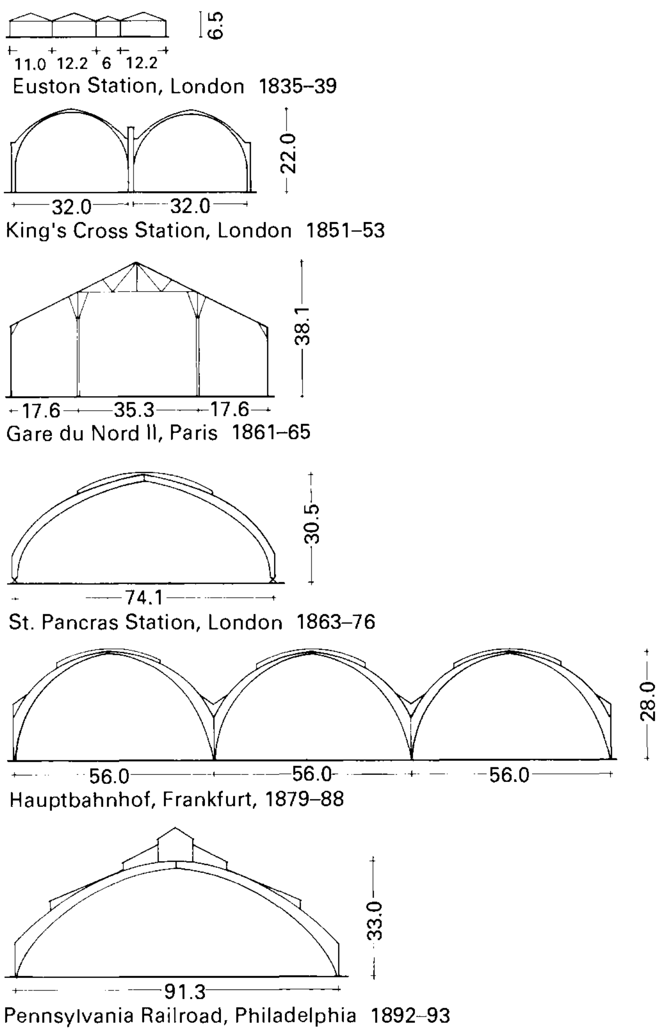
1.19
Comparison of train shed spans

1.20
Railway Station, Fantasy Projects, sketches by Erich Mendelsohn, 1914



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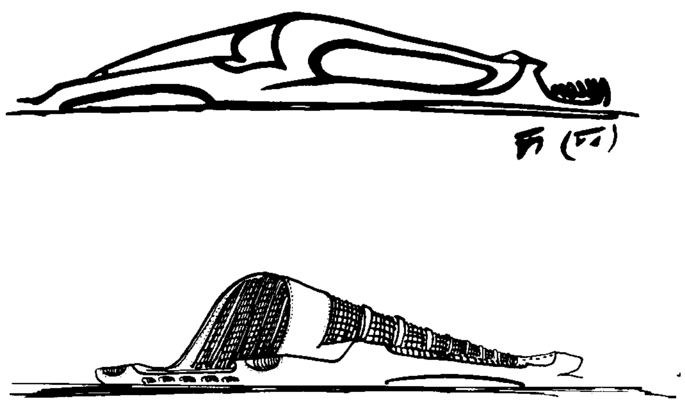


1.20

are reminiscent of Paddington. It is one of several examples of curved sheds, and as such, it is interesting to examine the spatial qualities which are produced. It would be hard to imagine the nave of a gothic cathedral curving in this manner giving a similar effect. The shape of the roof seems to be accentuated, and the structure more clearly seen. The length of the aisles is extended into the distance, producing a magical effect.

The Gare d'Orléans at Quai d'Orsay, Paris

The Gare d'Orléans, designed by the architect M. V. Laloux in 1898–1900, was an interesting variation to the iron roofed station (Figure 1.18). Its rounded vaults incorporated decorative coffering to the heavy cast-iron structure and enormous areas of glazing between ribs, which make a surprising contrast. The building, which was disliked by le Corbusier, was left abandoned for many years before being turned recently into the highly successful Musée d'Orsay.

General (Figure 1.19)

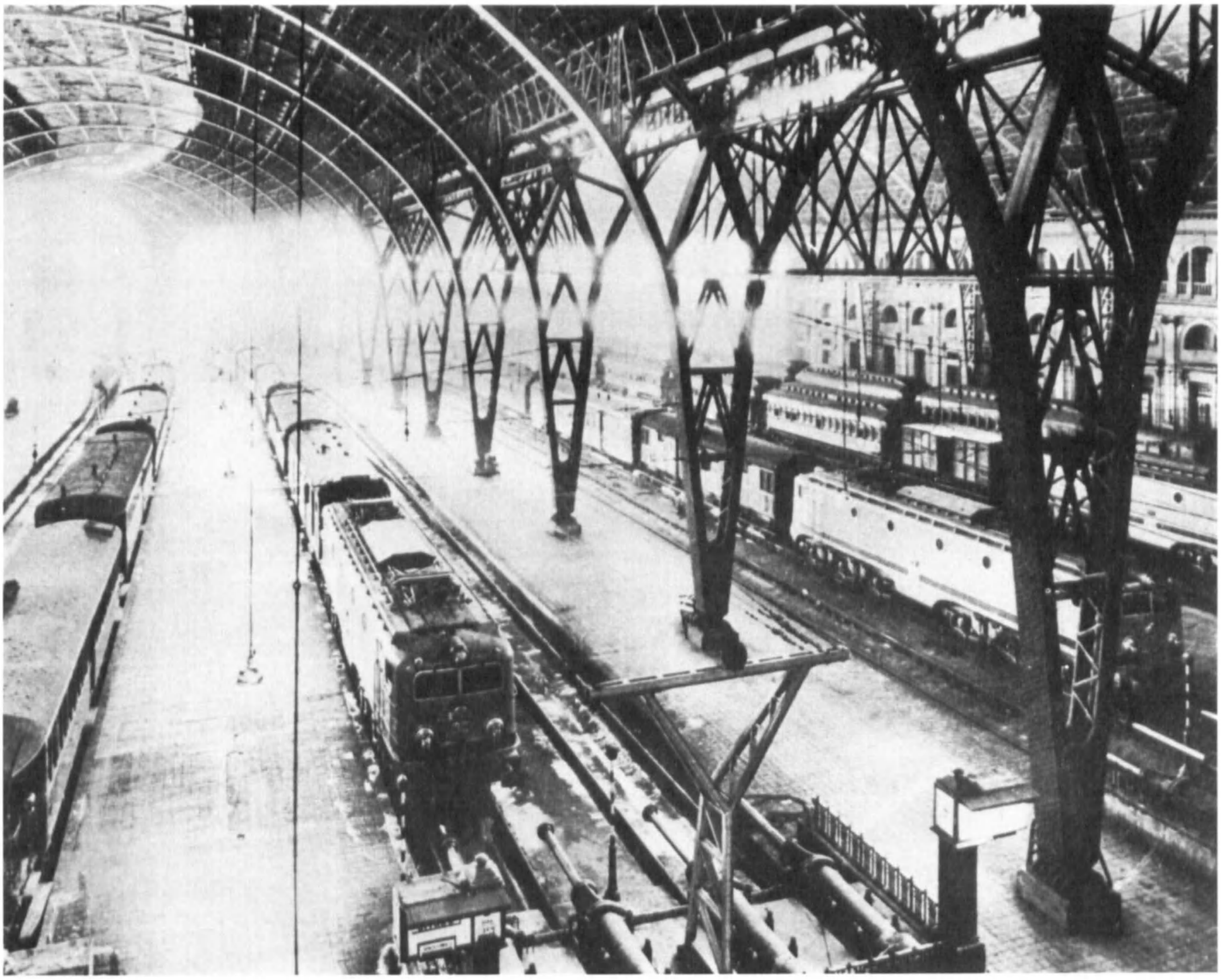
In the USA the first all iron arched train shed of significance was built at Cleveland, Ohio in 1865–1866 by B. F. Morse with a span of 55 m. In 1869–1871 Grand Central Station in New York was built with a semi-circular arched shed spanning 60 m. It had been intended that this should have rivalled St Pancras, but for some reason its dimensions fell short. Later, however, the Pennsylvania Railroad built several large train sheds which did.

The Pennsylvania Railroad Station at Jersey City, New Jersey built by W. W. Brown and W. A. Pratt in 1889 had arched trusses spanning 76 m and at Broad Street, Philadelphia, in 1892–1893 the largest single-span train shed in the world was constructed with three-pinned trussed arches spanning 91 m. This must have been an impressive building, similar in concept to the Galerie des Machines of 1889 but with a large lantern light at the apex.

In Germany the best examples of great train sheds were at Frankfurt am Main (1879–1888) by Eggert and Faust, Hamburg (1903–1906) by Reinhardt and Sossenguth, and Leipzig (1907–1915) by Lossow and Kuhne. At this time Erich Mendelsohn used the railway station as a source of inspiration for his Fantasy project sketches in which he attacked the 'codified language of architecture, and invented expressive actions'. His sketches offer strong dramatic forms for the railway (Figure 1.20).

The era of 'great train sheds' however started to fade

1.21
Barcelona-Termino Station 1924 with multi-span pin-jointed steel arched roof structure



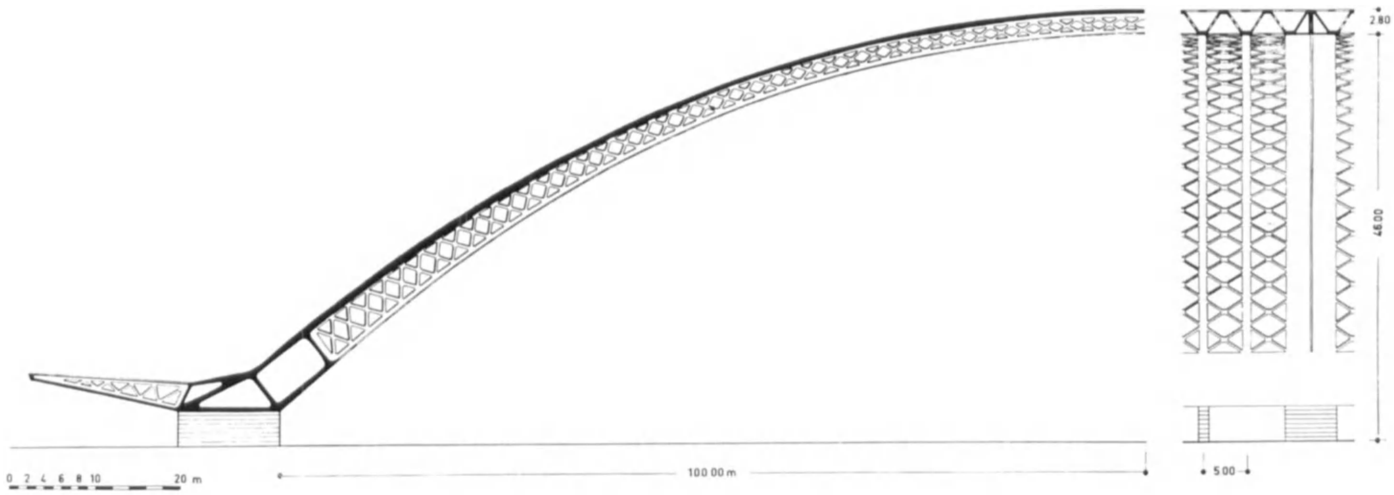
1.21

by the turn of the century and came to a halt with World War I. Stations from then on favoured reinforced concrete construction with smaller spans and lower headroom for cheaper maintenance. Notable exceptions to this were the Central Station of Milan, started in 1913 and finished in 1930, and the Terminus at Barcelona (Figure 1.21), completed in 1924, both of which had multi-span arched steel roofs incorporating pin joints. One spectacular addition would have been Pier Luigi Nervi's design for a Station Hall spanning 200 m had it been built (Figures 1.22, 1.23). This elegant structure of precast concrete arches designed in 1943 would have dwarfed all of the previous arched station roofs and provided a triumphant end to this era.

However, there has been a recent revival of interest in the railways throughout Europe, due to the development of the high-speed train. New investment has been fuelled by growing concern at the overcrowded road systems, public awareness of pollution combined with a disillusionment with air travel caused by terrorist activities and congestion at airports. The closer harmony in Europe and the agreement to the breaking down of EEC trade barriers in 1992 has led to the planning of a new network of high-speed rail links. This has inspired a new generation of railway stations and termini.

In England under the enlightened direction of Jane Priestman, British Rail Director of Architecture and Design, the Channel Tunnel high-speed train link to the

1.22, 1.23
Pier Luigi Nervi's Design in 1943 for a Station Hall with a span of 200 m in precast concrete would have given a triumphant end to the railway era had it been built



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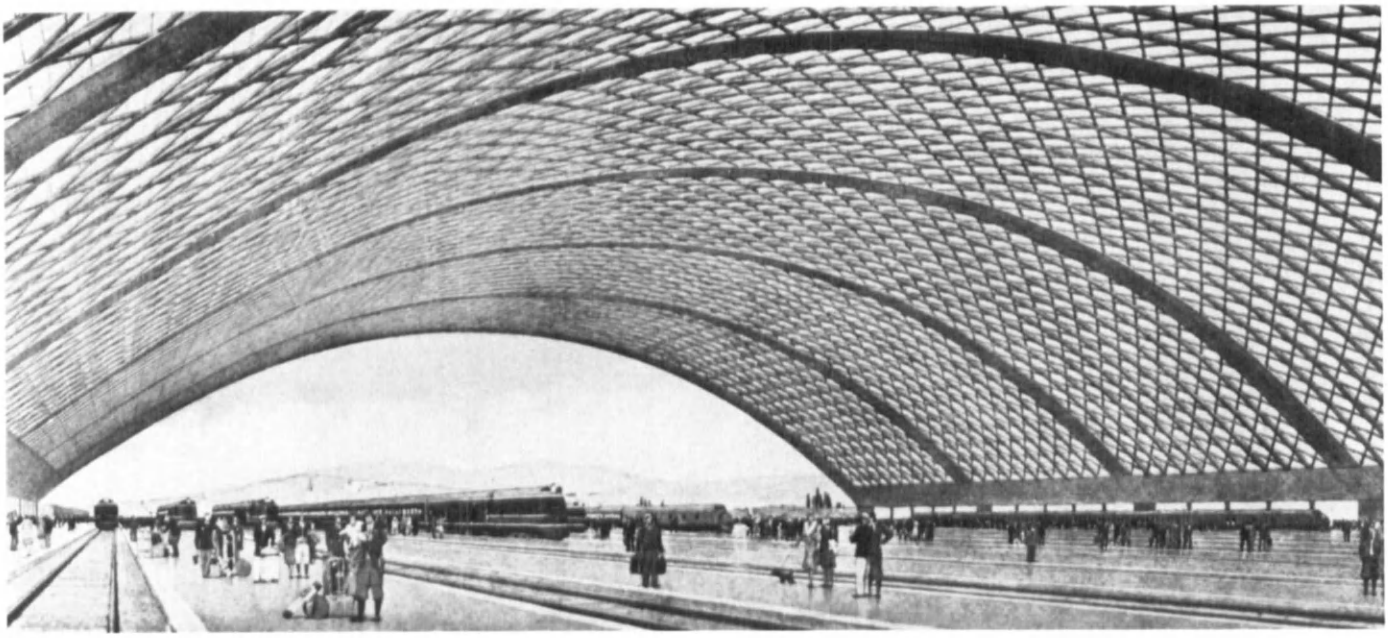


1.23

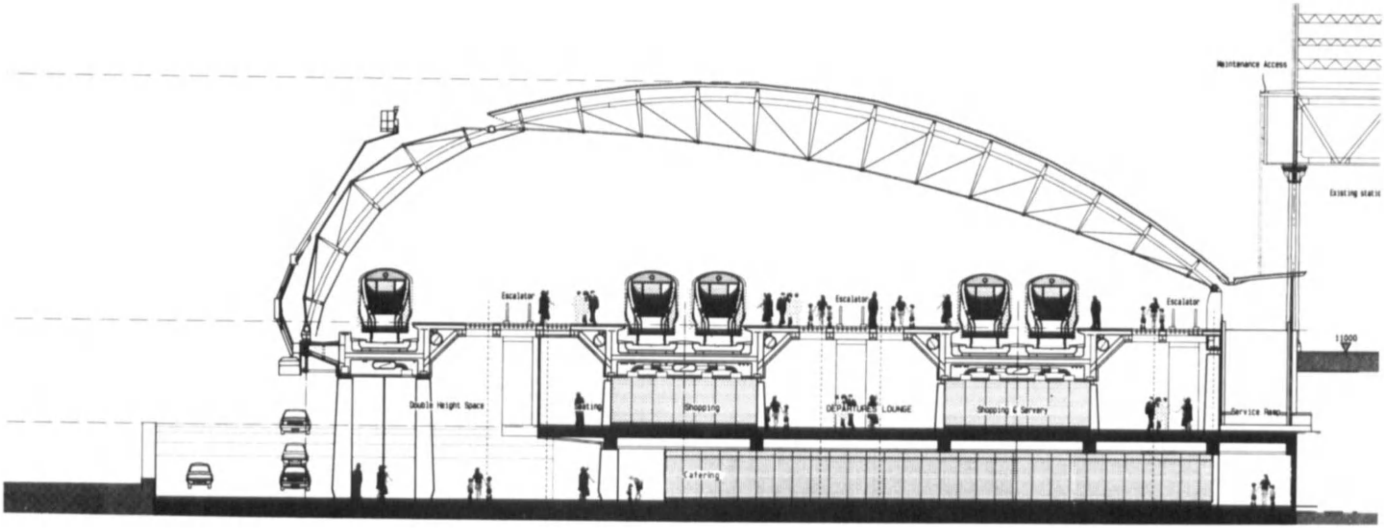
Continent has generated exciting designs for two new London termini, at Waterloo by Nicholas Grimshaw and Partners and Kings Cross by Foster Associates.

International Rail Terminal, Waterloo, London

In 1988, Nicholas Grimshaw and Partners were appointed to design the Waterloo International Terminal on the restricted site alongside the existing station, the brief being to provide a covered interchange for up to 6000 passengers per hour for the 400 m long high-speed trains (Figures 1.24, 1.25).

The architects, working in close conjunction with the engineers Anthony Hunt Associates, responded with an elegant steel arched roof structure glazed and clad in matt finished stainless steel, spanning 55 m across the tracks at its widest point and tapering down to 35 m at its narrowest end. In the true tradition of the best railway architecture, the design uses and refines the materials and technology of the day to express its form and function.

1.24, 1.25
International Rail Terminal, Waterloo, London 1988, with design proposals by Nicholas Grimshaw and Partners with engineers YRM Anthony Hunt Associates, provides an eccentric pin-jointed steel arched structure with the trusses changing from the inside to the outside of the cladding enclosure



1.24

1.25

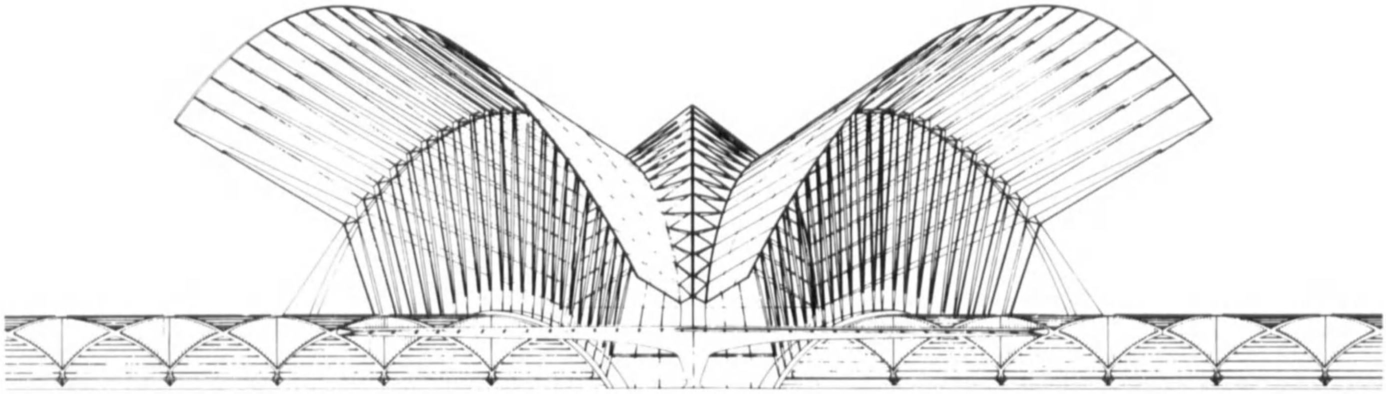
The structure is of three-pinned bow string arches, whose taper is achieved by fabricating the arch as a series of diminishing diameter tubes, which telescope down as its span reduces. The arches are much flatter than their Victorian counterparts, in order to reduce the volume of the enclosure and the top pin is eccentrically positioned to one side where the structure changes its form.

The major trusses which abut the existing station are largely covered in stainless steel and have the trapezoidal structure on the inside of the skin, whilst in a strong expression of function, the smaller trusses which are totally glazed have their skeletal structure on the outside. It is good to see such a harmonious marriage of architecture and engineering for this new age of the train.

TGV Railway Station, Lyons

Elsewhere in Europe there are many interesting proposals for new railway stations on the drawing boards, or under construction. For example the Spanish engineer, Santiago Calatrava, has prepared designs for

1.26, 1.27
Expressive lattice concrete and glass TGV Railway Station at Lyon designed by Spanish engineer Santiago Calatrava



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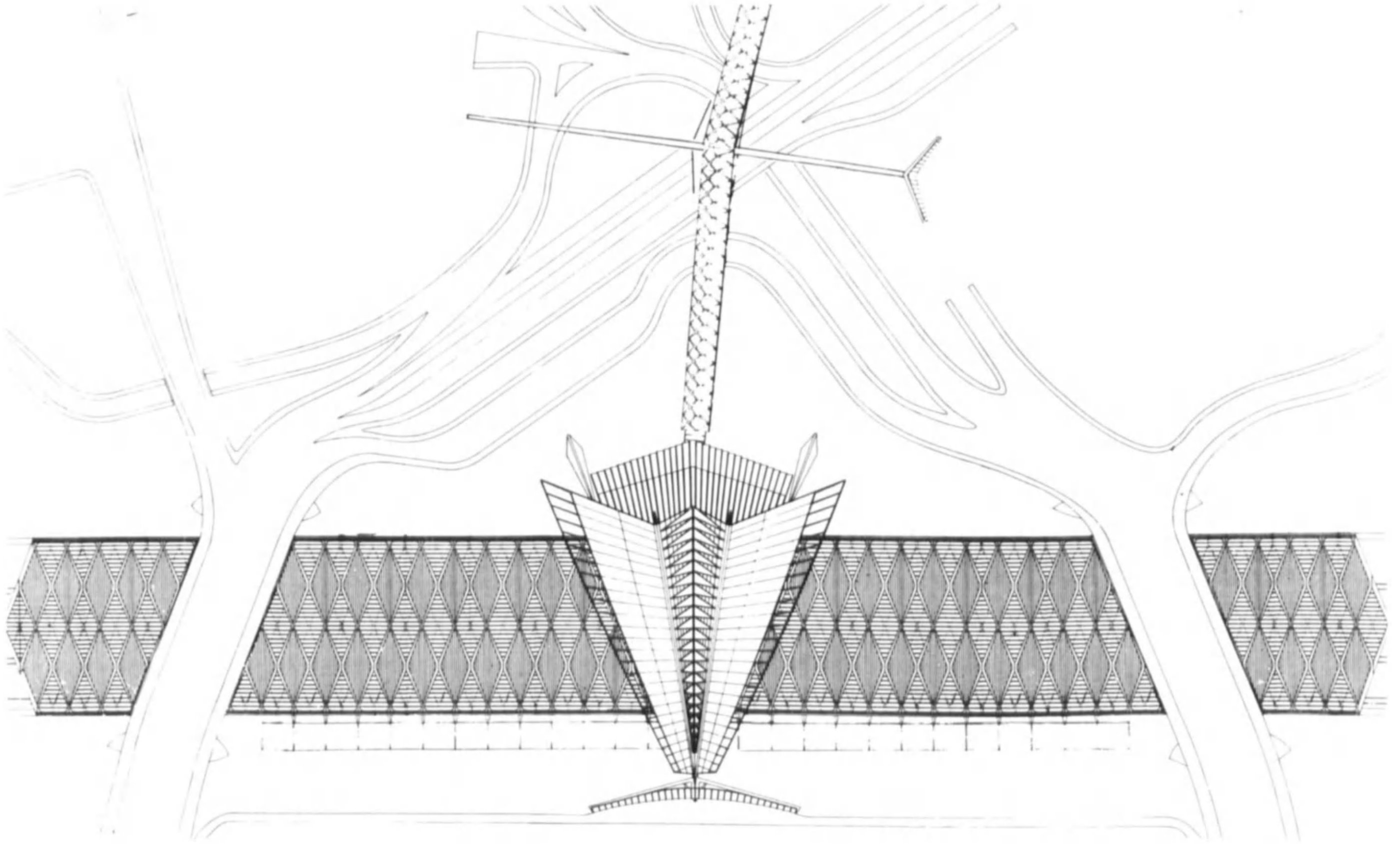


1.27

the new TGV Railway Station to be located near the airport in Lyons, where the two will be connected by an elevated pedestrian and travelator gallery (Figures 1.26, 1.27).

This train shed has a latticed concrete and glass vaulted roof spanning the sunken tracks which is crossed at the centre with a strongly expressive butterfly wing structure which forms the station. It is from here that the raised skeletal structure of the travelator snakes its way to the airport terminal. In this design, like most of his work, Calatrava has produced a thoroughly functional building in concrete which is dramatic, expressive and tremendously exciting following the tradition of Nervi and Morandi.

2 Hangars

The great feats of railway engineering in the nineteenth century were more than evenly matched in the early twentieth century by aeronautical development and later with space technology. With the progressive advancement of machines, the demands on the building enclosure were continually expanded. The early airships, due to their size, generated the construction of some massive hangars and as aircrafts grew in size and wingspan, their requirement for clear-span structures extended the boundaries of engineering practice.

Hangar design has been almost entirely the province of engineers rather than architects because the demands on the structure are so much greater than on the enclosing skin. With such large buildings, economy of materials and structure are essential, and the functional requirements prevail. One might think, therefore, that with hangars more than with any other buildings, one tried and proven solution would have become universal in application, but this is far from the case. Valid solutions to the same problem have been found in timber, concrete, steel and aluminium. Developments in jointing techniques, and structural analysis have made long-span buildings cheaper and simpler to construct. Progress in this field has always been activated by technological developments in other fields which stimulate new demands of building construction.

Airship Hangars

The history of the airship is both dramatic and shortlived, with the main activity being concentrated within the period between the turn of the century and World War II in Europe and the USA. During this time a tremendous range of different solutions to housing the airship was developed, showing amazing inventiveness and creative engineering.

The first ever purpose-built airship shed was the Hangar 'Y' constructed at Chalais-Meudon near Paris in 1879 using parts of the structure from the Paris Exposition Universelle building of 1878 which had been designed by the engineer Henri de Dion (Figure 2.1). This was an elegant building with a fine lattice-truss iron portal frame, clad in modular steel panels. Its construction was extremely advanced for that time and was the forerunner for many airship hangars and industrial buildings to follow.

It was from here that the first navigable airship, *La France*, was constructed and flown by Renard and Krebs in 1884. France had pioneered balloon flights a century before, with the Montgolfier brothers and the research of Jean-Baptiste-Marie Meusnier de la Place; interest in lighter-than-air flight was continued until the 1930s with the Société Zodiac.

It was in Germany, however, that lighter-than-air travel first started to make progress in 1900 with the successful testing of Count von Zeppelin's airship with five men on board. The first Zeppelin measured 128 m long with a diameter of 12 m and was constructed and housed in a timber-framed floating shed at Manzell on Lake Constance (Figure 2.2). This location was chosen because it provided a clear safe space to test the unpredictable craft and because the floating shed could be rotated on its anchor to face the prevailing winds. Whilst it made launching and docking easier, it created too many difficulties in manhandling the airship from boats, and later sheds were constructed on dry land although one other floating shed was constructed at Pensacola, Florida in 1916 for the US Navy (Figure 2.3). This actually looked like a boat or rather the upturned hull of a boat supported on a raft. It too was found to have little advantage over the land-based sheds, and was later dismantled and re-erected inland.

The launching and docking of these huge airships was always a tricky problem, and involved vast numbers of men pulling on guy ropes to achieve even the simplest manoeuvre. The speed and direction of the wind was critical and turbulence had to be reduced to the minimum. Much thought was given to this problem and in 1909 a design competition was organized by the Frankfurt International Luftschiffahrt Ausstellung, which produced some extremely inventive solutions.

One of the prize winners was Ernst Meier who had designed a fixed circular shed of steel lattice frame, with a series of doors around the perimeter so that the airships could be rotated within the building to face the wind direction. The most favoured and advanced solution by Albert Buss was for a central rotating shed which could dock with fixed sheds in radial positions.

Neither of these designs was built because it was thought to be too vulnerable to house several highly explosive craft under one roof. However, several simple rotating sheds were built. The first was by Steffens and Noëlle for the Siemens-Schuckert Company at Biesdorf-Berlin in 1910 (Figure 2.4). This had an external structure of rivetted lattice steelwork, which allowed a smooth internal envelope with no dangerous edges which could have punctured the airship fabric.

Later in 1914 the German Navy built a most ambitious revolving double hangar at Nordholz which was 200 m long (Figure 2.5). It took over two years to build during

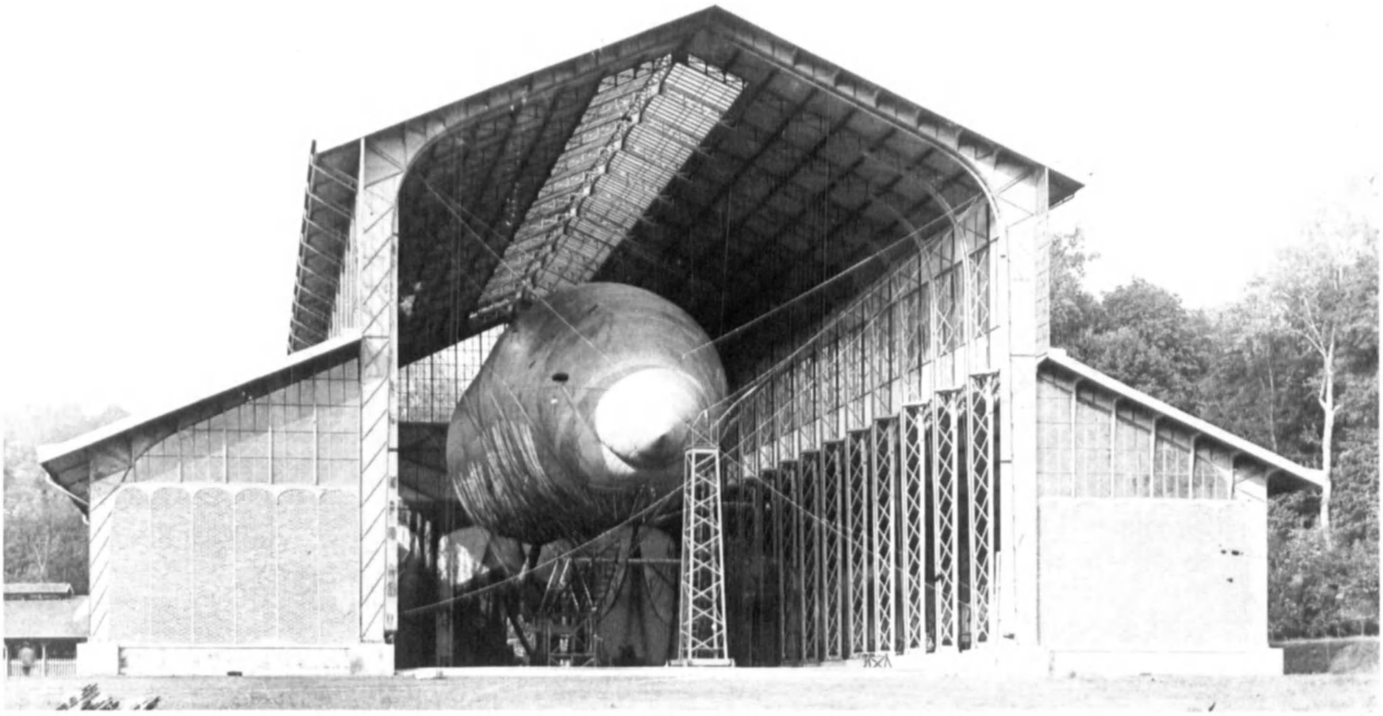
2.1
Hangar 'Y' at Chalais-Meudon near Paris 1879 is believed to be the first purpose-built airship hangar and uses parts of the structure from the Paris Exposition Universelle 1878 building by Henri de Dion

2.2
Floating Zeppelin hangar at Manzell on Lake Constance built in 1900

2.3
US Navy floating airship hangar at Pensacola, Florida built in 1916

2.4
Revolving hangar at Biesdorf-Berlin 1910 with external structure of rivetted lattice steelwork

2.5
Revolving double hangar at Nordholz built in 1914 by the German Navy was 200 m long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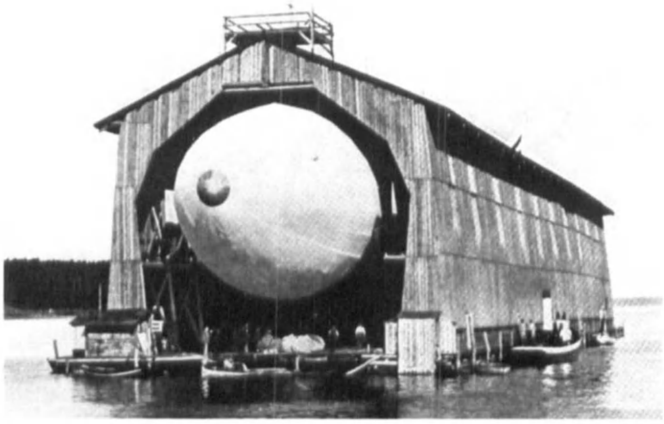
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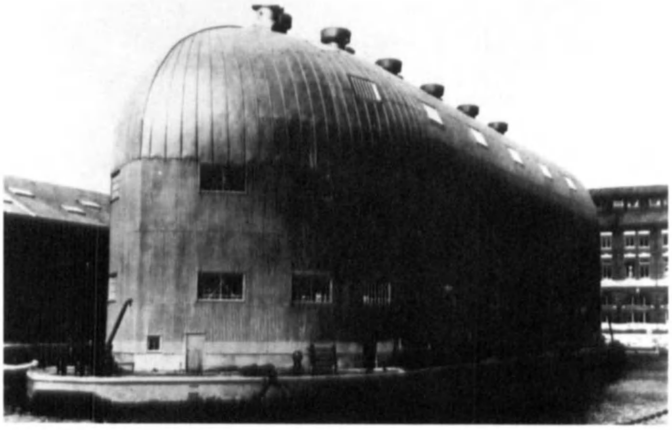
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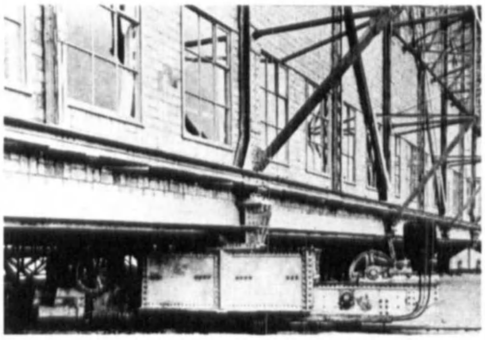

2.4


2.5

2.6
Transportable fabric-covered hangar by the Arthur Müller Co. under construction by the Italian Army 1911–1912

2.7
Masted tent shed at Frankfurt by Behrens and Kühne 1909

2.8, 2.9
Aerodynamic Zeppelin sheds were built at Dresden, Liegevitz and Poznan during World War I

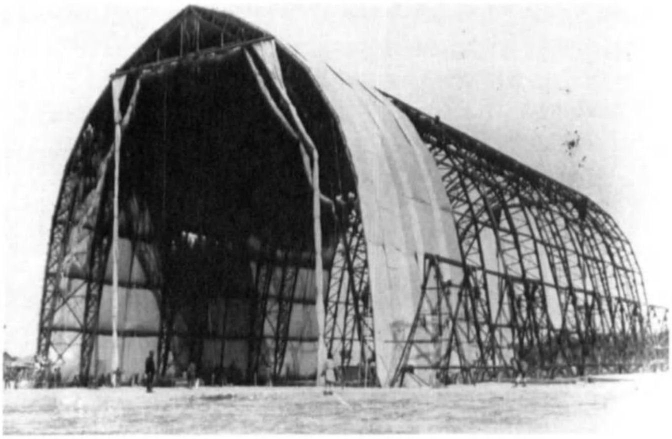
wartime, when speed was of the utmost importance so other solutions had to be found. One of the best solutions was to construct group hangars facing different directions so that at least one of them could take off no matter what the wind direction was.

Experiments were also made during this period with fabric-covered structures for transportability and speed of construction. In Germany the Arthür Muller Company patented and marketed a transportable prefabricated shed which could be assembled without scaffolding in prefabricated sections with canvas cladding. Some of these were purchased by the army for manoeuvres , and two were sold to the Italian army for use during the Italian-Turkish war of 1911–1912 Figure 2.6 shows the hangar at Tripoli.

In 1909 Behrens and Kühne produced a dramatic masted tent shed at Frankfurt measuring 121 × 49 × 22 m (Figure 2.7) and at Namur two 'A' framed demountable Zeppelin sheds were built with lattice beams resting on rails which could easily be hoisted into position. Tented sheds were also constructed in Britain and France at this time, but as the size of airships increased, they became impractical and were dropped in favour of the more practical static hangars.

During World War I the construction of airship hangars was at its peak in Germany, where more than 100 airship hangars housed more than that number of large rigid airships. At Dresden (Figures 2.8, 2.9), Liegvitz and Poznan the first aerodynamic airship sheds were constructed. Their parabolic shape of three-pinned arches and clamshell doors was calculated to reduce the detrimental effects of wind turbulence considerably during the manoeuvring of the airship in and out of the hangar as well as being a true expression of the most economical enclosing form.

The main centre of German airship activity, however, was in Friedrichshafen which was the home of the Zeppelin airship construction company from 1898 onwards and in 1908 a competition was held for the design of the first major shed. There were more than seventy designs submitted and the winning entry by the Flender Bridge Building Company was built in 1909 (Figure 2.10). It was constructed of two-pinned steel lattice flat arched trusses spanning 46 m span × 25 m



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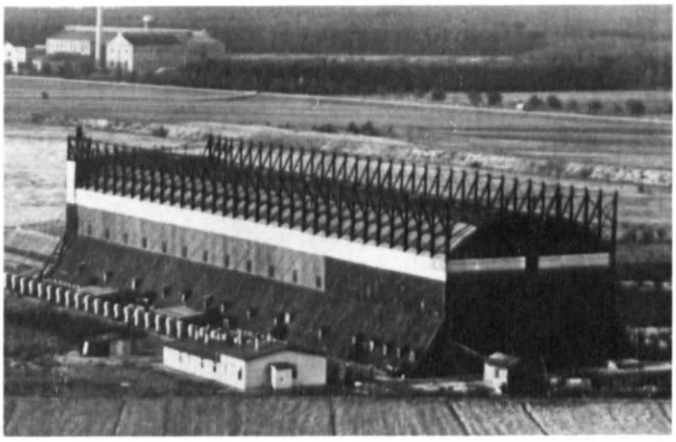

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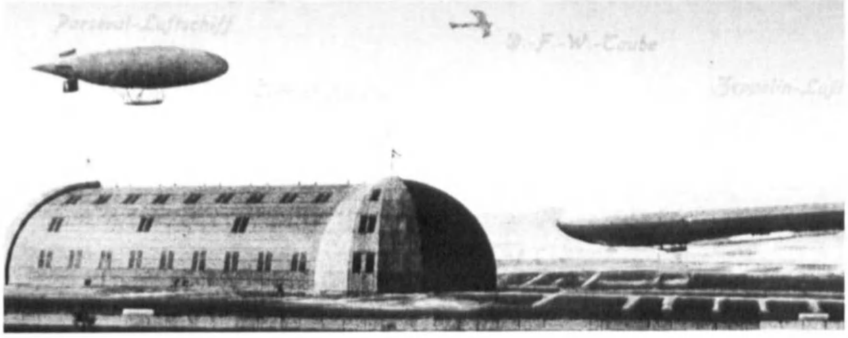

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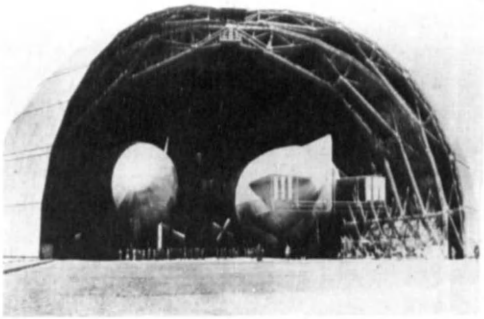
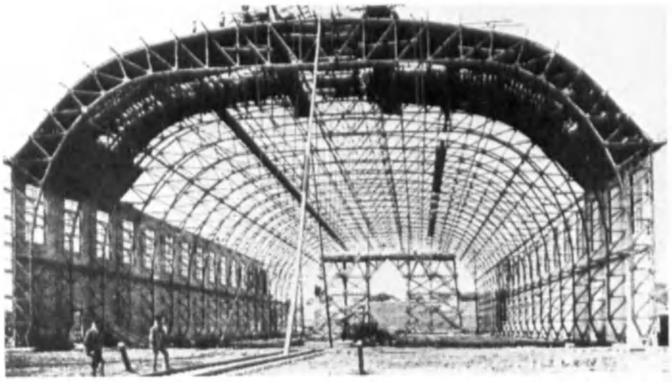


2.9

2.10
Steel structure for the double hangar at Friedrichshafen under construction in 1909 with 46 m span × 176 m long × 25 m high


2.10

high × 176 m long and could accommodate two 12 m diameter Zeppelins. Mobile working galleries were provided to allow easy access to the outer parts of the airships and a continuous ventilator with rotatable flaps was installed along the centre of the roof so that hydrogen could be quickly removed if necessary. The doors were of four sections, with the two middle ones sliding on rails and the two outer ones swing leaves, giving an operational time of 10 minutes to open an entire end wall.

In 1913 the Zeppelin Hallen Bau was formed to construct its own sheds and a series of larger single sheds was built in Friedrichshafen and nearby Löwenthal to a standard design with three-pinned steel lattice truss arches spanning 35 m at 8 m centres, 28 m high and 232 m long (Figure 2.11).

A similar form of construction was used for the last generation of German airship sheds constructed in the 1930s for the great passenger ships (*Hindenburg* and *Graf Zeppelin*) at Friedrichshafen (Figure 2.12), Löwenthal, Recife in Brazil and Rhein-Main near Frankfurt. The largest of these measured 300 × 55 × 60 m and was of conventional steel construction, the major innovation being the design of the double doors at each end, which moved on semi-circular tracks parallel with the ends of the building.

An entirely different approach to the design of large spanning tension structures was taken by the French engineer Eugène Freyssinet for the two hangars at Orly, near Paris in 1923 (Figures 2.13, 2.14). Following the successful completion of a concrete-vaulted hangar at Montebourg by the French Navy, Freyssinet progressed this approach with two vast hangars 300 × 90 × 53 m, constructed with thin folded concrete skins, vaulted in the form of a parabolic arch. In this type of construction the stresses are borne by the foundations without generating severe tension in the superstructure. This combined with the strength derived from the folded ribbed construction, meant that reinforcement was reduced to a minimum and a new economic spatial form was created. They were illustrated in le Corbusier's *Vers une Architecture* with their dimensions compared with the nave of Notre Dame. Later the great Italian engineer, Pier Luigi Nervi progressed this approach to prestressed concrete in his design for the aircraft hangars in 1935.

In Britain an airship manufacturing base was set up at Cardington by Short Brothers in 1917 for the construction of the R31 and R32 (Figure 2.15). It consisted of one large steel hangar, workshops, office buildings and a small company village known Shortstown and based on the lines of Port Sunlight and Bourneville. The hangar, designed and built by A. J. Main and Company, was enlarged in 1927 for the construction of the ill-fated R101 Airship which measured an incredible 237 m in length and had a diameter of 40 m. The building ended up being 247.5 × 55 × 55 m (Figures 2.16, 2.17, 2.18) but even so, there was still little room for manoeuvre, and it needed 300 men and a calm day before the airship could be brought in or out of the hangar.

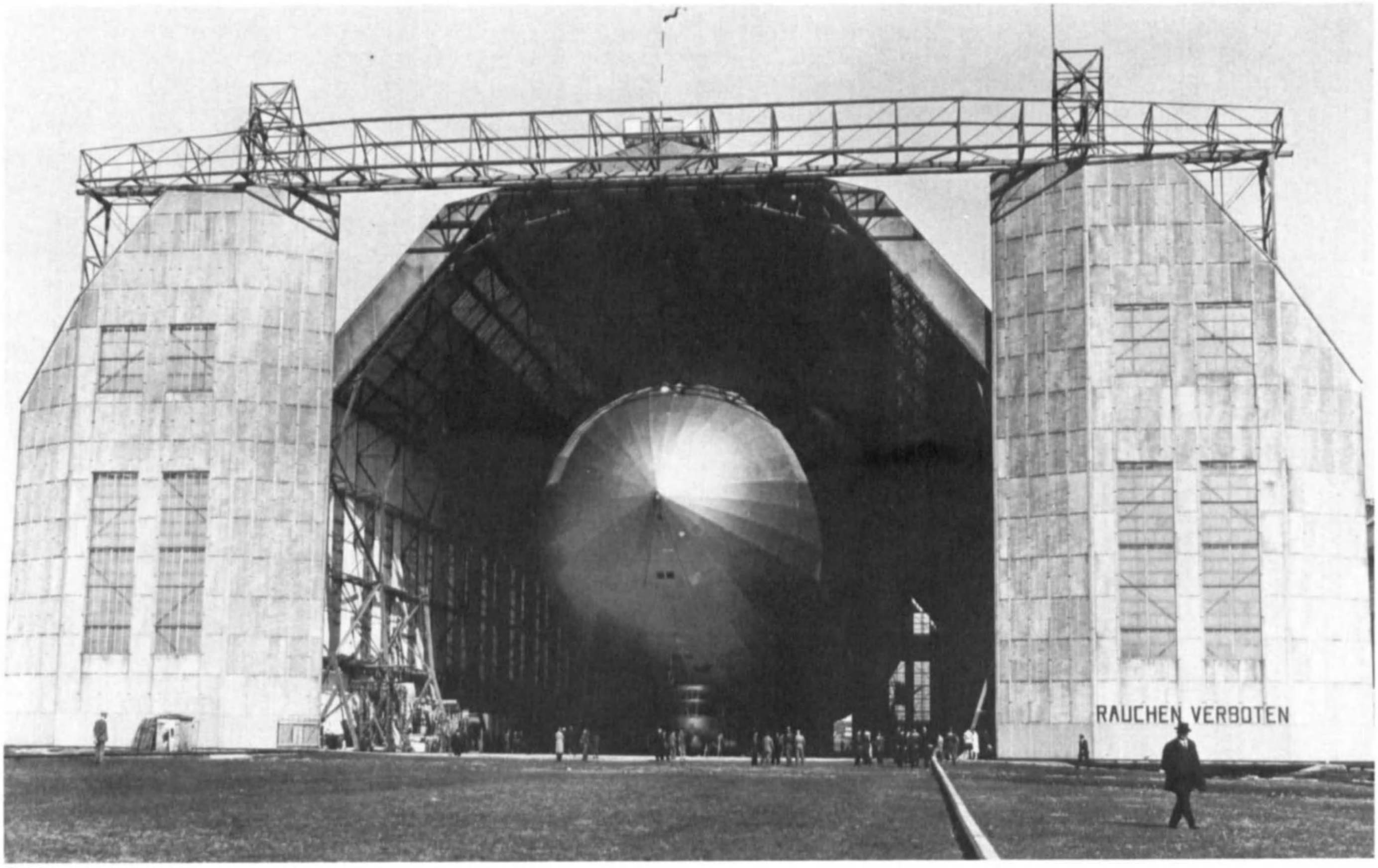
The building, which is still in use today, does have a 'cathedral-like' quality, with a vast nave and aisles constructed in lattice steel framework. The aisles are formed where the frame sets out at an angle of approximately 60 degrees to buttress the main structure. At one end, two enormous sliding doors, each weighing 940 tons, provide a clear opening of 55 × 55 m.

The twin hangar was brought down from Norfolk and enlarged to the same size as the other hangar when re-erected for the construction of the R102. Both hangars are clad in painted corrugated iron sheeting, and without a scale reference they appear modest within the landscape. They have no refined architectural details of styling yet they are, nevertheless, extremely impressive buildings and now provide a home for Airship Industries' new breed of non-rigid airships. It is sad to reflect that they were constructed for those pioneering days of airship travel which never quite fulfilled their promise. Optimism at the time of the R101 was such that a regular route to India was planned, and an even larger hangar was constructed at Karachi to receive the airships. Unfortunately, the first voyage ended with a crash landing in France, and the Karachi hangar was never used for its original purpose.

Each accident put another nail in the coffin for the development of airship travel, although there were some spectacular successes. For instance, the R100 designed

2.11
Friedrichshafen Zeppelin shed, 1913, with three-pinned steel lattice arches spanning 35 m span × 232 m long × 28 m high

2.12
Friedrichshafen Zeppelin shed, 1930, measuring 55 m span × 300 m long × 60 m high



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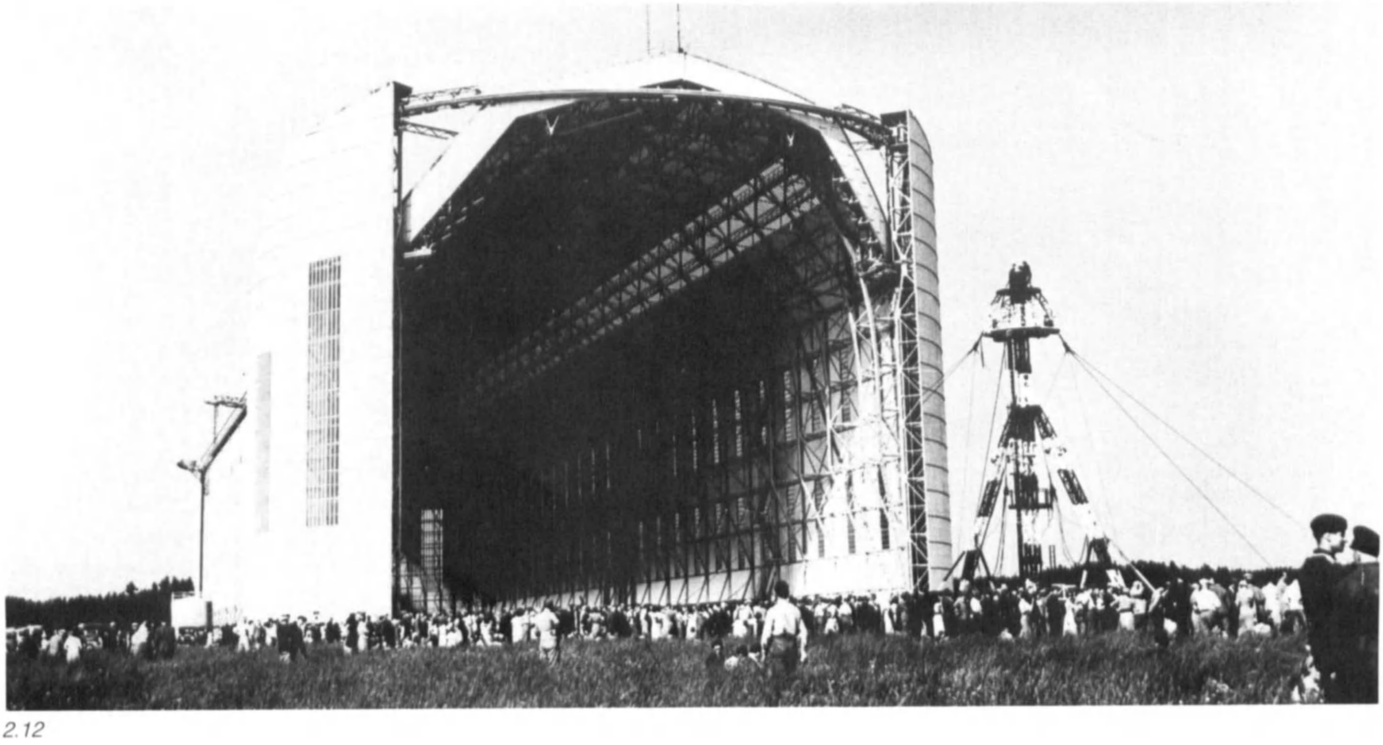
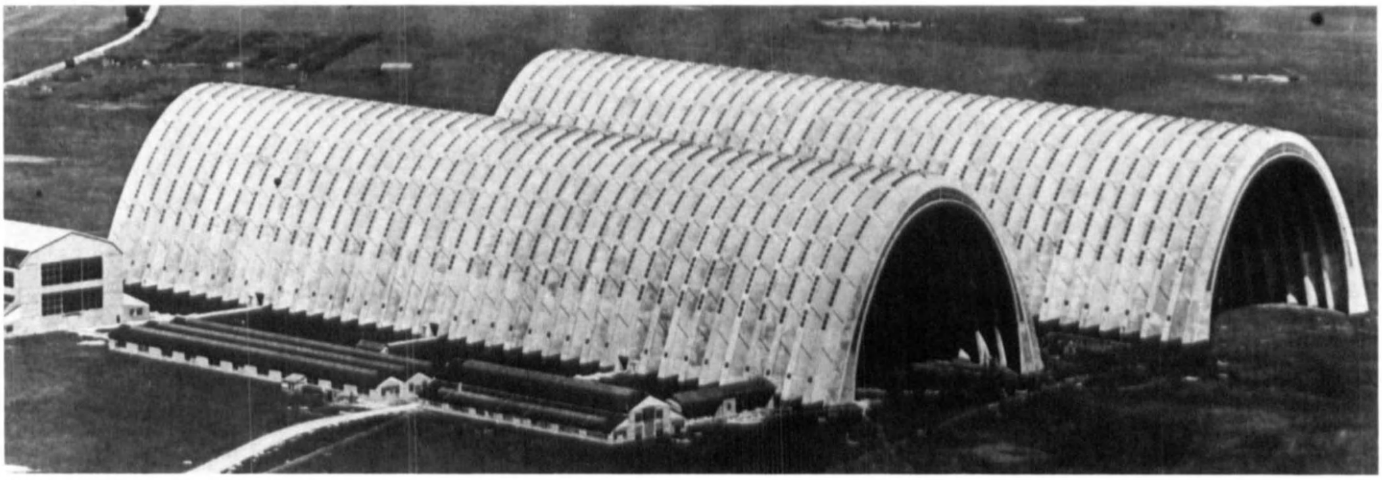


2.12

2.13
Concrete airship hangars at Orly measuring 90 m span × 300 m long × 53 m high

2.14
Concrete vaulted hangars under construction at Orly, near Paris in 1923, designed by Eugène Freyssinet

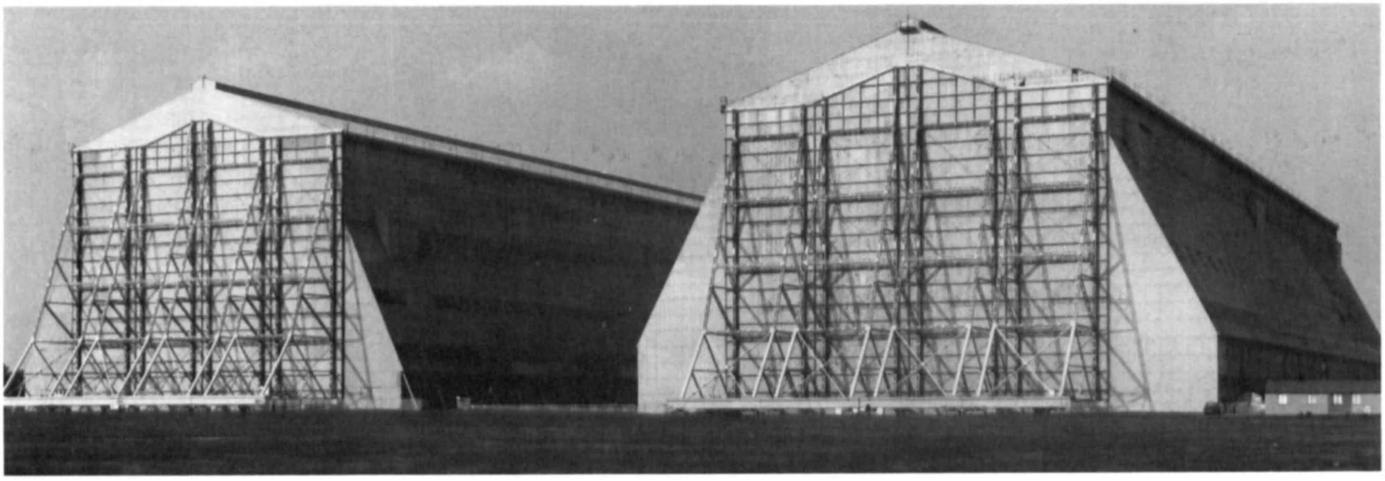


2.13

2.14

2.15
The two sheds at the Shorts Brothers' airship manufacturing base at Cardington, Bedfordshire set up in 1917 for the construction of the R31 + R32

2.16, 2.17
Cardington sheds with steel lattice three-pinned arch structure measuring 55 m span × 247.5 m long × 55 m high

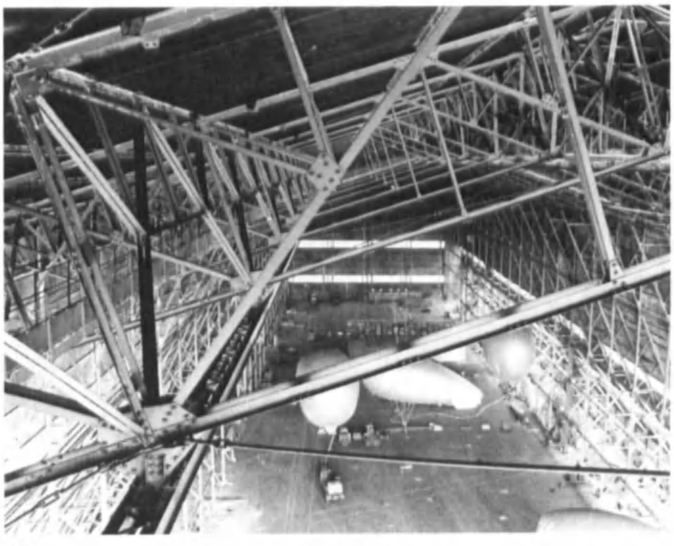

2.15

by Barnes Wallis flew to Montreal and back in 1930 and the *Graf Zeppelin* made a round-the-world flight in 12 days. Also in the 1930s the Deutsches Zeppelin Reederei operated a successful airship passenger service with regular international and intercontinental flights to North and South America.

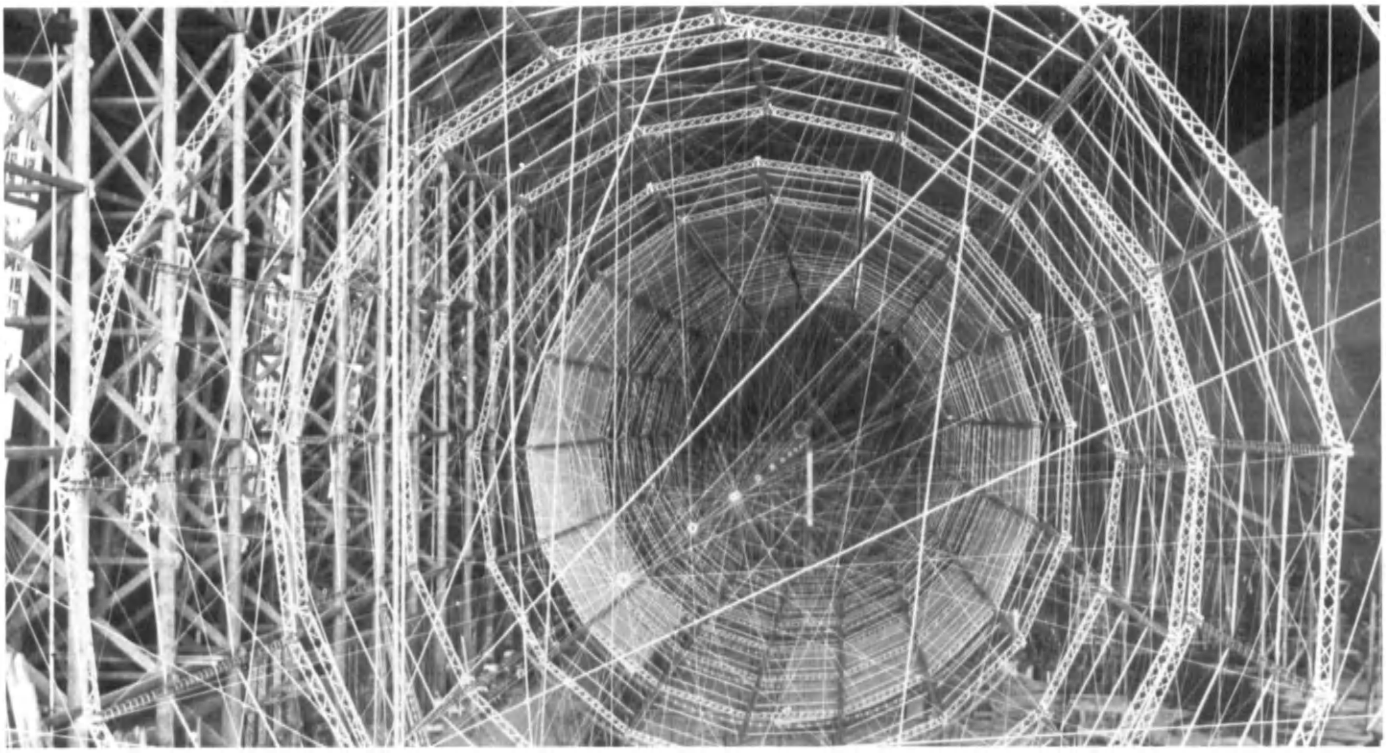
The design for the structural frames of these massive rigid crafts extended the parameters of structural theory and caused the development of lightweight alloy components. All of which has had a lasting influence on the design of buildings. It is a pity that at the time when airship travel was making progress, a suitable non-inflammable gas had not yet been produced which would have prevented the tragic end to the *Hindenburg* whilst docking at Lakehurst in 1937. For it was this terrible accident, witnessed by millions on newsreel film, that ended the airship dream.

In America, the interest in lighter-than-air flight followed Europe and reached a peak during the period between the World Wars I and II. The main generator was the US Navy who realized the military potential and set up bases around the coastline. Perhaps the best known of these is at Lakehurst, New Jersey (Figure 2.19) which became the principal flight base for transatlantic and round-the-world flights. The first hangar was constructed in 1919 to a similar design to the Cardington hangars but larger. The three-pinned arched steel lattice trusses were supported on steel A-frame bases with a span of 85 m at the pin joints, a clear height of 59 m and an overall length of 244 m (Figure 2.20). The roof and walls were clad with corrugated asbestos sheeting inset with a patchwork of casement glazing. At each end there were massive flat sliding doors, and three railway lines ran the length of the


2.16


2.17

2.18
Airship structures innovated lightweight construction with bicycle wheel structures, employing lightweight alloy components



2.18

building and beyond. Like many others of its time, it was a basic functional building with no decoration. The steel structure, however, was constructed of lightweight rolled steel sections and it is interesting to see the jointing patterns of the rivetted gusset plates, where the layout of the rivet directly reflects the pattern of forces at the joint.

One basic problem with hangars like Lakehurst and Cardington, was turbulence set up by the shape of the building causing an obstruction to the wind. This created problems with the launching and docking of airships, and it was with this in mind that the aerodynamic shed for Goodyear at Akron, Ohio was designed.

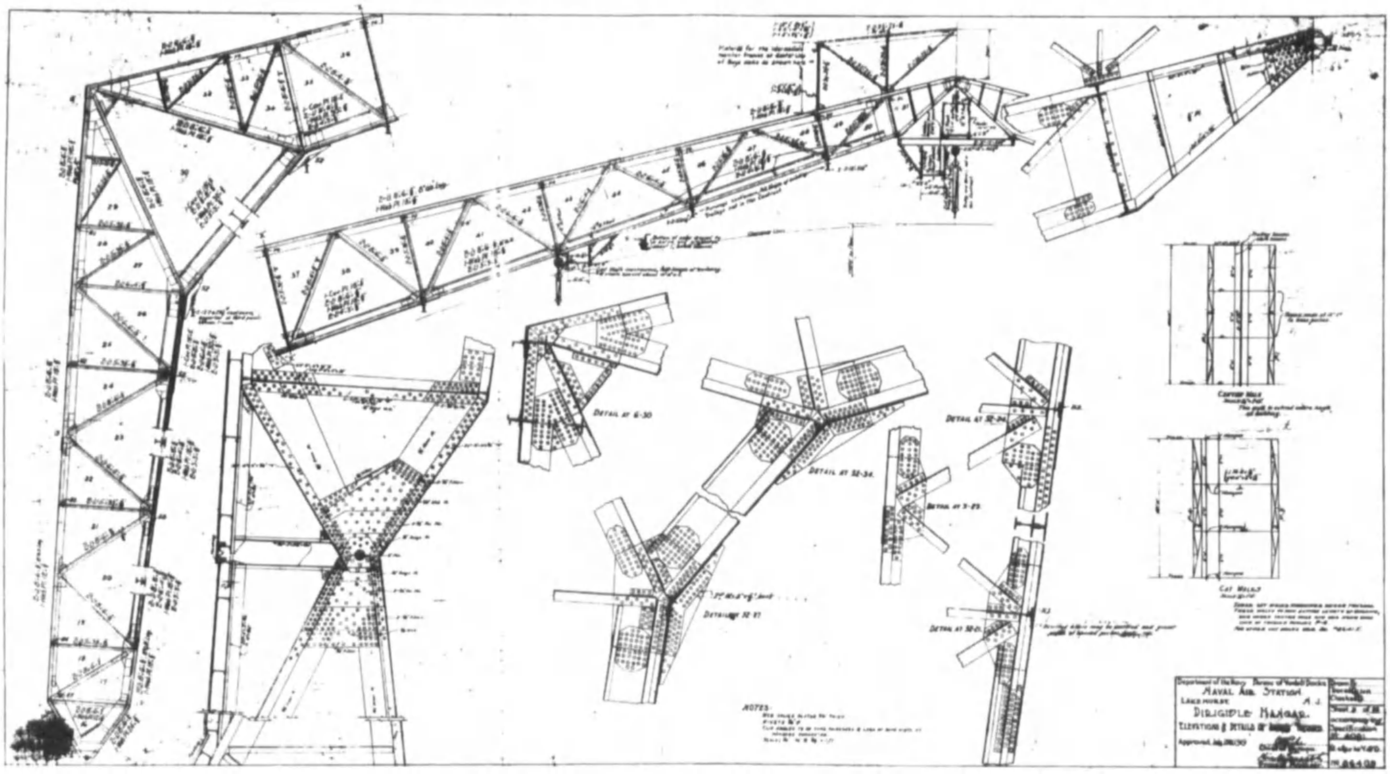
The Goodyear Airdock which is still in existence, is the world's largest clear span hangar and was built in 1929 for the construction of the US *Macon* and *Akron* Goodyear Zeppelin airships (Figure 2.21). It encloses a space 358 × 99 m with a clear height of 64 m (Figures 2.22, 2.23). The streamlined parabolic shape was derived from wind-tunnel tests, carried out by Dr Karl Arnstein, who was the director of engineering for the Goodyear Zeppelin Corporation at the time and who had been influenced by similar hangars at Dresden, Liegnitz and Poznan for the Zeppelin Company. This would have been normal procedure for the design of airships, but it was new in building design. The aim was to design a building which would offer minimum resistance to wind currents, and to reduce suction forces caused by the action of wind on the surface of the building, which can be several times greater than the wind pressure. This is extremely important for the launching and docking of airships which cannot safely be carried out in high winds, and it was this consideration which determined the design of the hemispherical or 'clamshell' doors which are so distinctive.

The structure consists of 11 parabolic arches spaced at 24 m centres connected by a system of vertical and horizontal trusses on the Deitz system of bracing. At each end of the main shell there are diagonal arches meeting the end arches at the pins, which are 244 m apart. The horizontal component of the thrust from the arches is taken up by reinforced concrete ties placed under the building floor.

The doors which are like quarter sections of half an orange are held with a pin at the top and rest on wheels which run on railway tracks. They each weigh 600 tons and the hinge pins are of hollow forged steel 432 mm in diameter and 1.8 m long, the size of a tall man. The doors are operated on a 'rack drive' system which consists of

2.19
The three-pinned steel lattice structure of the Lakehurst hangar with rivetted plate connections

2.20
Hangar No. 1 at Lakehurst, New Jersey, constructed in 1919 with a similar design to the Cardington hangars but with a span of 85 m × 244 m long × 59 m high



2.19

a 'bull gear' with great coarse teeth mounted horizontally outside the building and driven by a 125 HP motor. This engages the rack which is mounted at the base of the doors just above the wheels, and the doors are pushed around on their track.

Inside the building there are many interesting handling devices to facilitate construction of the airships. At the centre of the roof there is a continuous crane runway and at each side of this are tracks for working platforms, which can be raised and lowered to the required height. There are also inclined lifts which travel on the lines of the arches to transport men and materials to upper level platforms.

Three other large steel hangars of a similar design to the Akron hangar were constructed during this period at the US Navy bases of Sunnyvale, California; Weighmouth, Massachusetts and Weeksville, North Carolina. Of these, the steel hangar at the Moffett Field Naval Airbase, Sunnyvale, California is the most important (Figure 2.24). It was built in 1933 to house the US *Macon* (Figure 2.25) and measures 344 × 94 × 60 m. The structure is similar to the Akron Airdock although the side walls are flatter, and the steel lattice arches are pin-jointed above the ground onto a braced steel frame

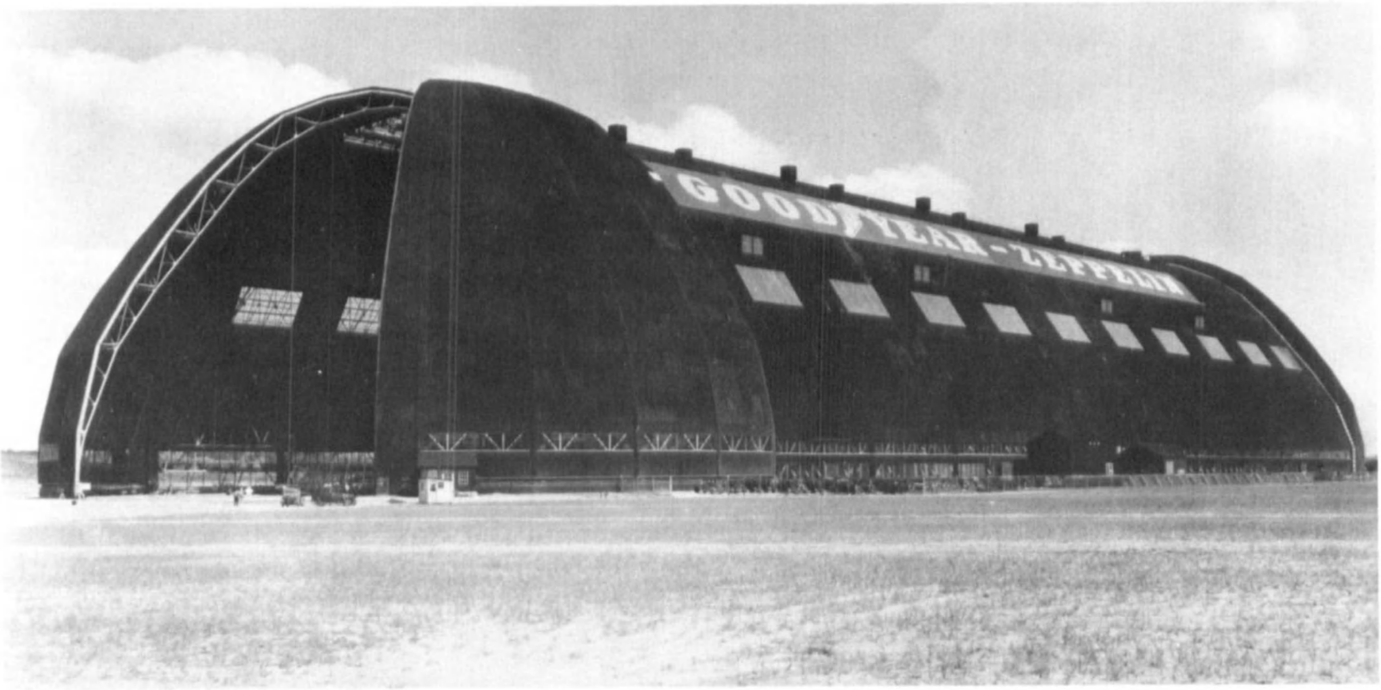
2.20

2.21, 2.22
The Goodyear Airdock at Akron, Ohio, 1929, designed by Dr Karl Arnstein, is the largest airship hangar with a span of 99 m × 358 m long × 64 m high

2.23
US Macon *docked in the Akron Airdock*

2.24
The elegant steel hangar at the US Naval Airbase at Sunnyvale, California built in 1933 with a 94 m span × 344 m long × 60 m high

2.25
US Macon *in front of Sunnyvale*

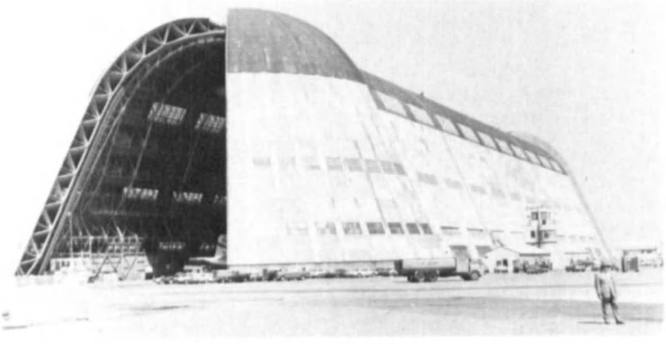


2.21

2.23

which contains the accommodation. Two huge curved doors at each end, driven on a base track are pivoted on a single pin at the top of the opening. Perhaps more than any other airship hangar, this building expresses the full qualities of a 'supershed' for it manages to combine pure function, economy and simplicity of form with an elegance and refinement.

The US *Macon* was the last of the large rigid framed airships and it was lost in an accident near Point Sur in February 1935. However, the US Navy continued to use the smaller non-rigid 'blimps', and these proved to be extremely successful for anti-submarine work during World War II. A fleet of some 200 blimps was stationed around the American coastline, and many new hangars



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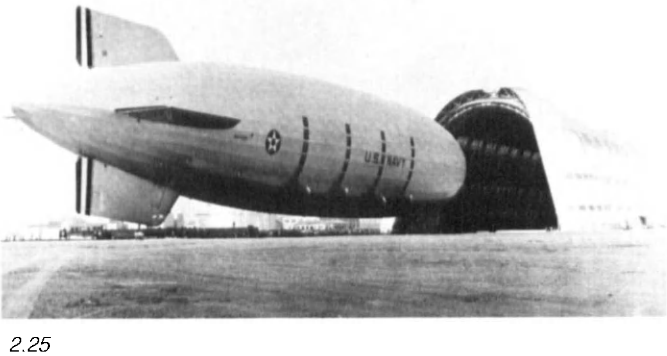
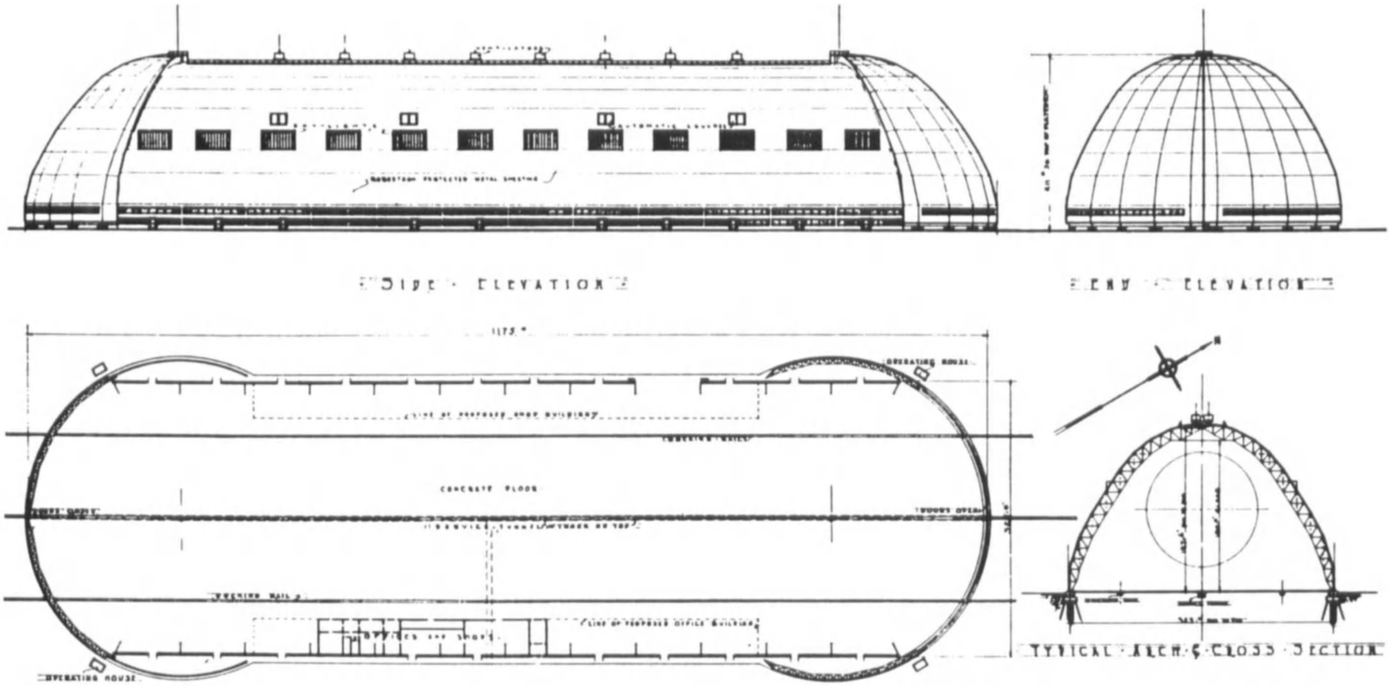


2.25

2.26, 2.27
Seventeen timber hangars were constructed between 1942 and 1943 around the American coastline for the US Navy to a design by Dr Arsham Amirkass with a span of 90.5 m × 331 m long × 90.5 m high. Hangars shown are at Sunnyvale (2.27) and Weeksville (2.28)

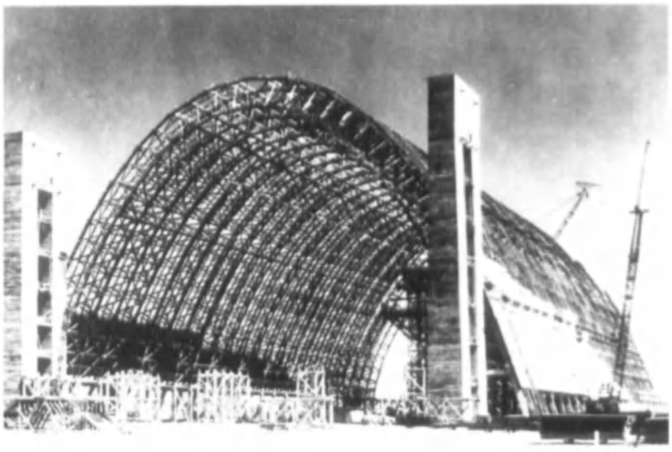
2.28
Timber hangar at Houma, Louisiana had special self-supporting semi-dome doors which rolled on rails to the side of the hangar



2.29

were built to house them. Due to the shortage of steel, which was required for armaments, timber was used in a laminated form for their construction. Examples of these can be seen at Sunnyvale, Lakehurst and Tillamook, but in all, 17 were constructed between autumn 1942 and August 1943 to the same design, under the direction of Dr Arsham Amirkass (Figures 2.26, 2.27).

At the time, they were the largest timber structures in the world, measuring 331 × 90.5 m with a clear internal height of 48 m. The parabolic arched trusses were pre-assembled on the ground into four sections and framed into a braced bay 6 m wide which was then handled into place using two travelling tower cranes. For the openings at each end of the hangars, it was necessary to separate



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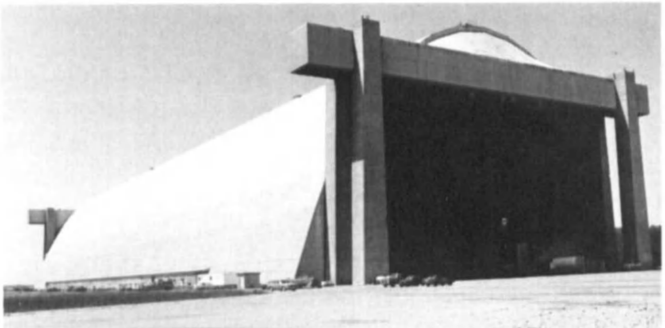

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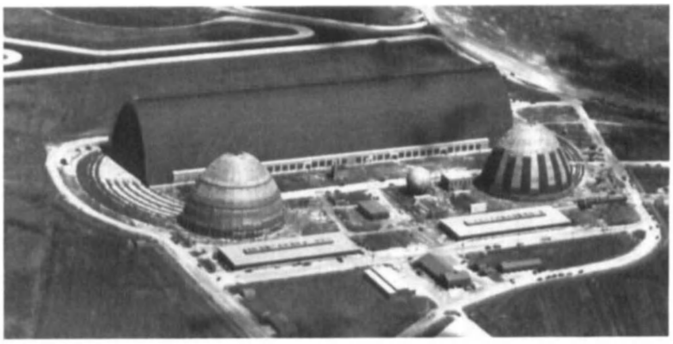
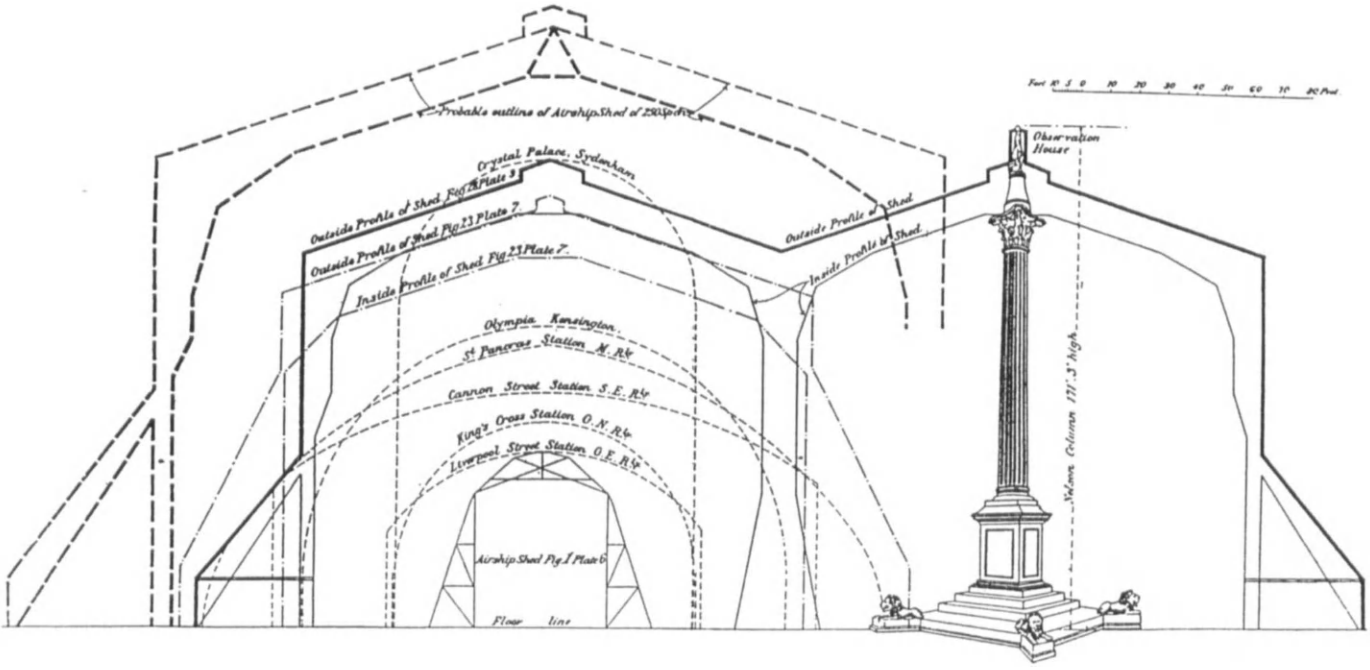


2.28

2.29
Comparison of airship shed spans with railway station roofs: the outer section is a shed spanning 90 m built later at Karachi, Fig. 28 is Howden no. 1 shed, Fig. 23 East Fortune shed of 1916



2.29

the door framing from the main structure so that loads in the longitudinal direction would not be imposed on the main structure frame. The huge flat sliding doors of timber were supported by two concrete pylons at each end. An exception to this was made at Houma, Louisiana, where the poor soil conditions could not take the load of the heavy towers, and a new door system was designed of self-supporting semi-domes which rolled on rails to the side of the hangar (Figure 2.28). When open, this door type also afforded some protection from adverse wind conditions and demonstrated the amazing inventiveness of the engineers concerned.

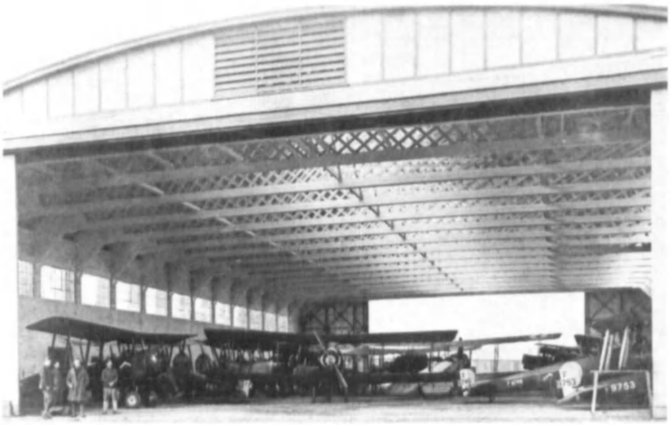
Nine of the timber hangars still exist. A comparison of airship shed spans is given in Figure 2.29. Along with the other remaining airship hangars spread about the world, they are 'like footprints of an extinct species' – to quote Martin Pawley's foreword to the catalogue of the immensely successful *Housing the Airship* exhibition organized by Christopher Dean at the Architectural Association in 1989. He went on to say that: 'the engineering achievement of the enormous airship sheds paved the way for the primacy of the structural engineer in the constellation of construction professionals that rules the built environment today. When all the great rigid airships were gone, the buildings designed to contain them remain as objects of wonder and achievement. In the end their existence alone is proof of the possibility of the return of the giant airship itself'.

There have been many attempts to revive the airships in recent years as technology has opened up new areas of potential. The continued presence of the non-rigid blimps, used for advertising, has maintained the public's interest in lighter-than-air transportation, and research into heavy-lift airships has been in progress for some time. A slight change in the economic situation could bring about a revival at any time and this nearly happened in the 1970s with the first oil crisis. In an attempt to bring cheaper fuel to Europe before the discovery of North Sea Oil, the Shell Oil Co. employed Aerospace Developments Ltd to investigate the feasibility of transporting natural gas from North Africa to Britain in giant airships of 100 000 000 ft^3 capacity.

As part of this study, the engineer Frank Newby together with the architects Gillinson Barnett were appointed to investigate the design for a hangar which would have been the largest in the world measuring 610

2.30
World War I Belfast Hangar with curved top timber trusses spanning 32m

2.31
World War II Blister Hangar



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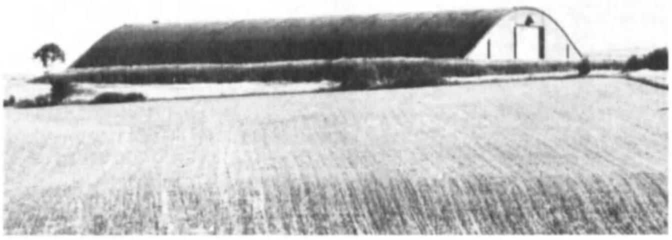


2.31

× 230 × 137m high for a single enclosure and larger still for a double enclosure. Three main types of structure were considered:

1. Conventional steel-framed construction
2. Tension structure
3. Air-supported structure.

It was concluded that a steel arched space frame vault with stiffening frames would be the most reliable and cost effective solution.

The project was abandoned when North Sea Oil was discovered so the concept of this exciting structure was never progressed. However, it is interesting that the preferred design for this enormous structure should have followed the lines of the parabolic steel hangars at Akron and Sunnyvale.

Aircraft Hangars

World War I saw the widespread use of the aeroplane for the first time, with the obvious advantages over the airships of speed and mobility. It was for this reason that canvas tent structures were often used during this period for housing the aircraft in the field.

Mobile airbases were set up by the German Airforce in 1917 known as the Jagelgeschwager Groups and nicknamed the 'travelling circus', which helped them to gain superiority over the Allies who tended to favour more permanent constructions.

In Britain, the first interesting aircraft hangar design to emerge at that time was the Belfast Hangar (Figure 2.30). This design used curved timber trusses with a trellis-like bracing to span 32m onto brick piers. It was an inefficient form of structure but the shallow curved roof form provided an inconspicuous profile viewed from the air.

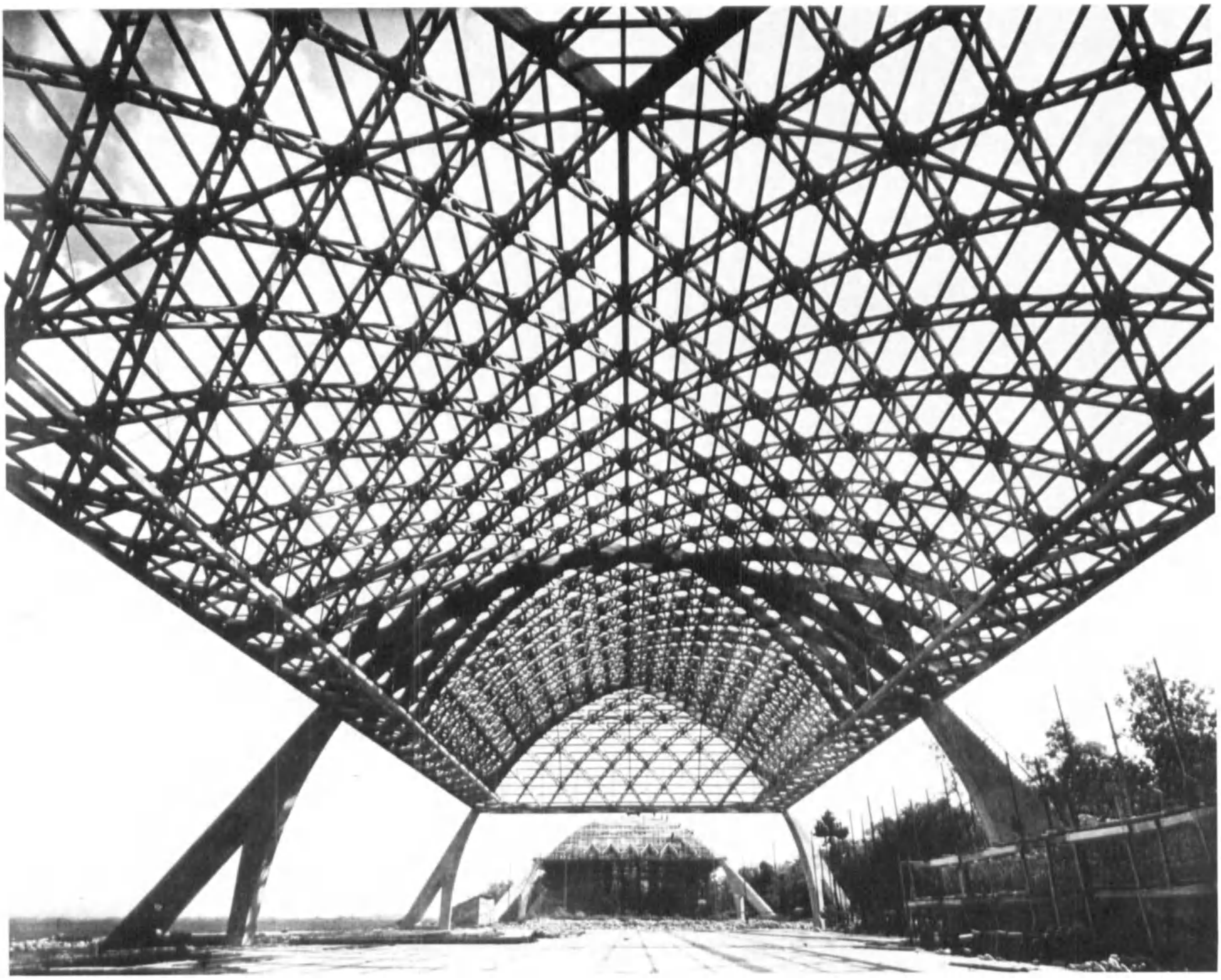
This approach was continued for aircraft hangars in World War II with the Blister Hangar design (Figure 2.31), which used a shallow curved profile for ease of camouflage and economy of materials. The corrugated iron cladding supported on lightweight steel trussed arches was developed from the successful Nissen Hut used in World War I. These were extremely efficient structures, designed for quick erection and the most economical use of materials, which was so vitally important during wartime.

In Germany at this time, the Hünnebeck Hangar was developed with a similar shallow curved shape but with a fully demountable structure of three-pinned steel arches. This hangar was assembled flat on the ground with the two springing pins resting on rails. When the pins were drawn together, the centre of the hangar buckled upwards to form the arch.

A completely different approach, however, was taken by the Italian Airforce who commissioned Pier Luigi Nervi to design a series of hangars. He chose to use concrete for the structure like Freyssinet's airship hangars at Orly and used model analysis to determine the most economical shape and beam size. The resultant roof form was built up of curved lamella networks of reinforced concrete beams, covering an area of 100 × 41 m, with only six supports. Six of these hangars were built at Orvieto between 1939–1941 and were all destroyed by the war in 1944 (Figures 2.32, 2.33). The first hangar was cast in situ and the following ones were greatly improved with the use of prefabricated trusses to lighten the structure. The trusses were joined by welding the reinforcement bars and filling the space with high strength concrete.

The post-war period saw the escalation of air travel, and with it came a new exciting brief to the architects and engineers of the day for the design of airport

2.32, 2.33
Italian Airforce Hangars at Orvieto 1939–1941, designed by Pier Luigi Nervi with precast concrete lamella structure spanning 41 m × 100 m long



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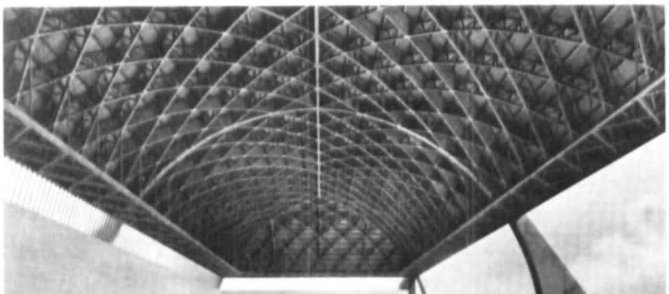


2.33

buildings, hangars and assembly plant.

In Britain one of the first interesting hangars to be built was at Filton in 1947 for the assembly and housing of the Brabazon aeroplane (Figure 2.34). This plane was the forerunner of the jumbo jet, measuring an amazing 54 m long, 15 m high and with a wingspan of 70 m, which was 10 m wider than the Boeing 747. Unfortunately, the plane was not a great success, but the building, with its two-pinned lattice structure of barrel-shaped trusses spanning 101 m has survived and has since been used for the assembly and housing of Concorde. It really is a most impressive building with its curved roof form and huge

2.34, 2.35
The Brabazon Hangars at Filton, 1947 with two-pinned steel lattice trusses spanning 101 m

2.34

2.35

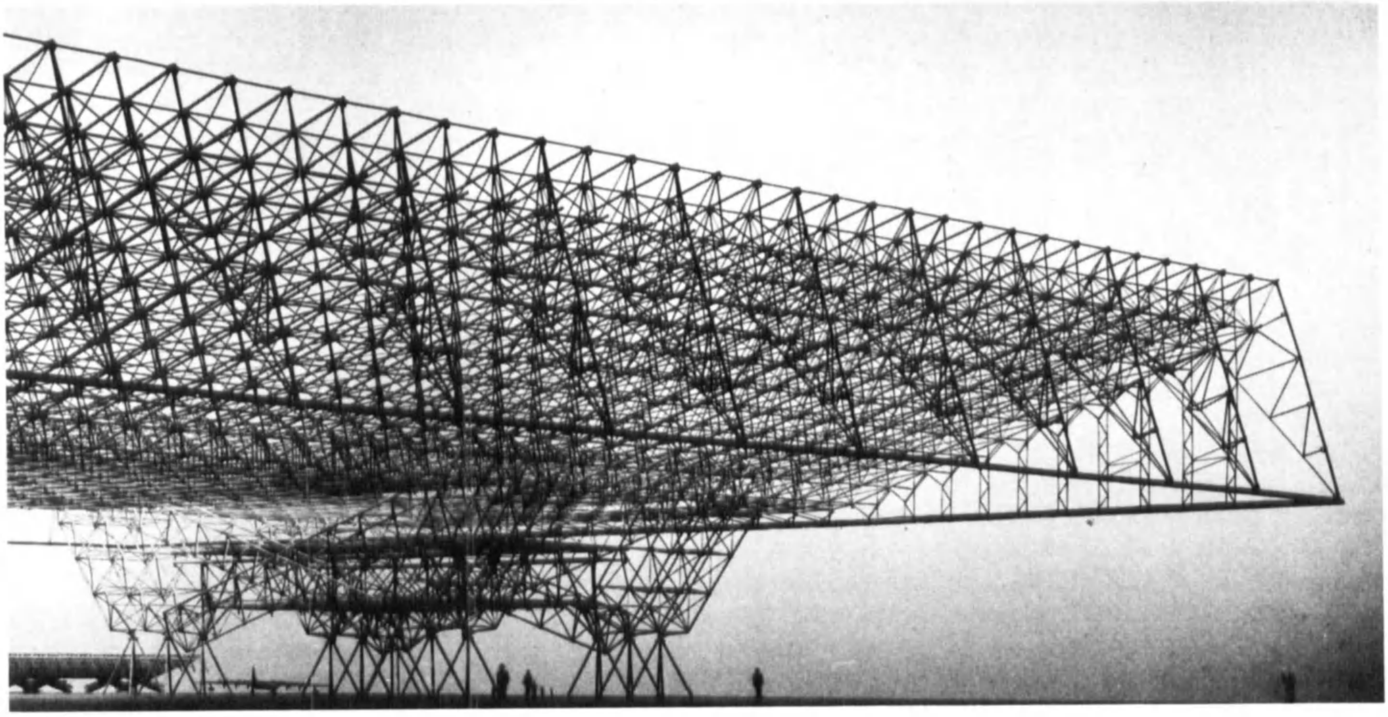
sliding, folding doors. The large gusset plate connections to the steel trusses date the structure, but there have been few buildings constructed in this country with a longer span.

Space Frame Hangars

In America in the 1950s, Konrad Wachsmann was commissioned by one of the research departments of the US Airforce to develop a structural system for the construction of large aircraft hangars (Figures 2.36, 2.36a). At that time, he was teaching at the Chicago

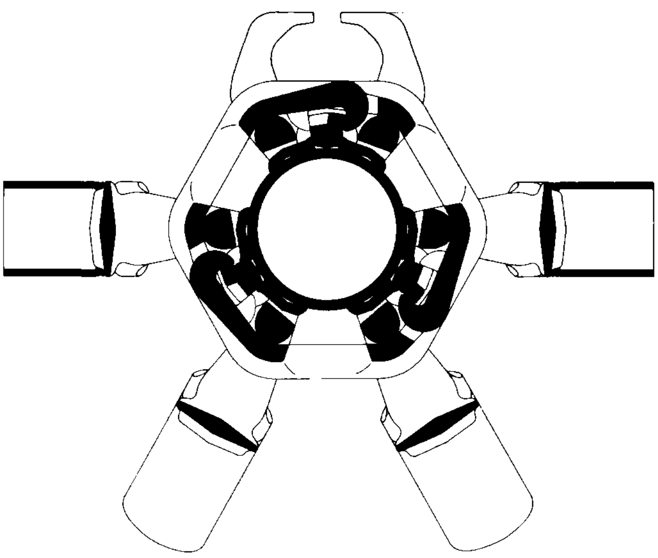
2.36, 2.36a
Project for US Airforce Hangar by Konrad Wachsmann in the 1950s with tubular steel space frame system

2.37
British Airways 747 Hangar 01 at London's Heathrow Airport designed by Z.S. Makowski with space frame roof structure spanning 135 m



2.36

2.37



2.36a

Institute of Design, and was able to use the research facilities and the help of the more advanced students to develop a tubular space frame system. It was designed as a kit of parts for mass-produced prefabrication, using steel tubes and an ingenious jointing system which could allow as many as 20 tubes to connect to the one node point. The distance between nodes was fixed at 3.05 m (10 ft) in three directions, in accordance with a constant three-dimensional module. The actual connector consisted of a combination of individual components chosen from four standard die forged elements of high-grade nickel steel. It was designed for ease of construction and demountability with the use only of a hammer and unskilled labour.

The system was applied to a project for an aircraft hangar measuring 240 × 155 m with a cantilevered roof projecting 50 m from its supports in each direction. The roof was lifted up at the perimeter to allow for the tail height of a plane with its nose in the lower section, thus maintaining the minimum volume of space. In itself, this was an interesting design solution but in addition the system had flexibility for development in numerous ways.

There are now many space frame systems on the market, and it is possible to build large-span hangars economically in this way. At London's Heathrow Airport, the British Airways Hangar 01 was built with a special space frame structure spanning 135 m to provide maintenance facilities for two jumbos at one time (Figure 2.37). Professor Z.S. Makowski designed the roof structure as a two-way continuous double layer diagonal grid, constructed out of tubular hollow sections. Assembly of the roof took place at ground level, and was raised to the required level with hydraulic jacks. The roof is stepped to accommodate the 19 m high tail fin of the jumbos, whilst maintaining the minimum volume to heat. Should a new generation of even larger planes emerge, the designers say that it would be possible to jack the roof up higher to accommodate them (see also p. 96).

The hangars at Charles de Gaulle Airport, near Paris, designed by Themis Constantinidis, also use a space grid roof which spans 78 m in each direction between four lattice towers. The roof cantilevers beyond the supports on each side of four equal faces with clear openings. The cantilever hangar has proved to be popular with airlines, because of the flexible space which it affords. This is important, as most hangars have to accommodate quite a range of different aircraft. They have the added advantage of being easy to extend without requiring any additional supports on the opening sides, so that the clear door openings can be extended with the building.

The longest spanning space frame hangar built to date is the Narita No.1 Hangar at Tokyo International Airport, Japan which has a span of 190 × 90 m.

Cable-Supported Hangar Roofs

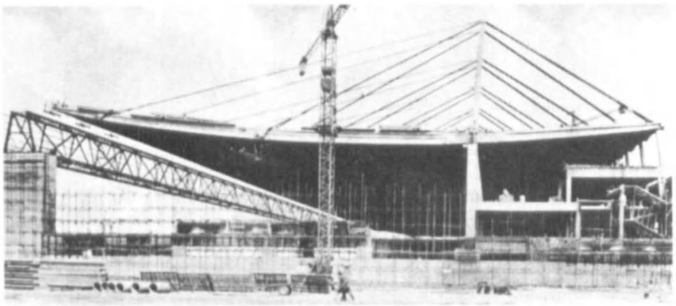
Another interesting solution to the column-free hangar has been the cable-supported roof. One of the earliest recorded examples was the Behrens and Kühne masted airship hangar of 1909, illustrated on page 17, but little is known about the details of this building. However, an interesting seaplane hangar was constructed at Cherbourg in France 13 years later where the full details were recorded in *Le Genie Civil* March 1921 (Figure 2.38). These indicate the spacing of the tapered steel masts to be at 60 m centres in one direction and 32 m in the other from which suspended cables provided intermediate support for the roof trusses. In this way a clear span of 60 m was achieved with an internal height of 7.8 m and opening doors across the full width.

It was a building way ahead of its time, as it was another 35 years before the first commercial long-span cable-supported aircraft hangars started to emerge in the USA. These were prompted by the need for longer span column-free hangars to house the larger passenger

238
Cable-supported seaplane hangar at Cherbourg in 1921 with 60 m span

2.39, 2.40
Cable-stayed hangars at the Leonardo da Vinci International Airport, Fiumicino near Rome, designed by Riccardo Morandi and completed in 1961. The precast concrete roof beams cantilever 60 m from a concrete fire wall with overhead cable support to provide a 200 m long continuous door zone


2.38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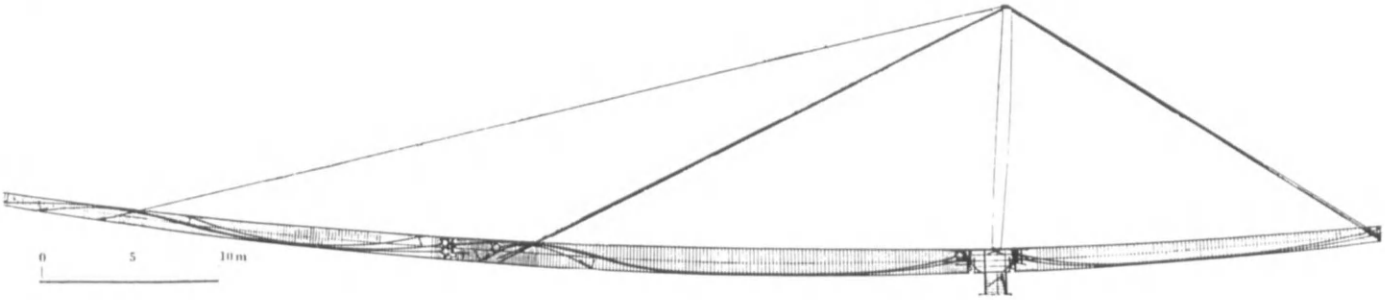


2.40

planes which were coming into service at that time. Early examples of these cable-supported roof structures were built at Kansas City Airport in 1956 and at John F. Kennedy International Airport in 1959. Two years later the Italian engineer Riccardo Morandi designed the two cable-stayed hangars for Alitalia at the Leonardo da Vinci International Airport at Fiumicino near Rome (Figures 2.39, 2.40). These hangars which measure 200 m × 85 m, have continuous opening doors down one side, and a two-storey subsidiary section down the other which is separated from the aircraft part by a fire wall. The roofs consist of a series of elegantly curved precast concrete beams which rest on the fire wall and are supported by steel cables suspended from a series of concrete masts above. They cantilever 60 m over the hangar section and are tied at the other end to the subsidiary two storey sections. All of the cables are encased in concrete for protection.

Since then, many cable-supported hangars have been constructed at airports around the world, the largest being the Lufthansa Jumbo Jet hangar at Frankfurt, West Germany with a span of 130 m.

Other Forms of Cantilevered Hangar Roofs

The United Airlines Hangar at San Francisco designed by Myron Goldsmith of Skidmore Owings & Merrill in 1960, uses an elegant and extremely economical double-cantilevered structure of mixed steel and concrete construction (Figure 2.41). The main roof structure is made up of tapered steel plate girders which cantilever 43 m on each side of a core and are tailored in depth and thickness to meet the 'real' load requirements. They vary in depth from the maximum of 4.25 m at the supports, to a minimum of 1.5 m at the outer edge. These are pin-jointed onto concrete columns which are shaped to follow the stresses of vertical load and earthquake forces. Between the plate girders, which are 15.69 m apart, spans a 1.5 m deep triangulated space frame which supports the roof, provides horizontal bracing, and prevents buckling of the compression flange of the girders. The hangar, which is designed to accommodate four DC8 jets, expresses a strong structural concept throughout and combines efficiency with simple design clarity. The structure succeeds in its attempt to 'follow the forces' and provide an economical and aesthetically pleasing design.

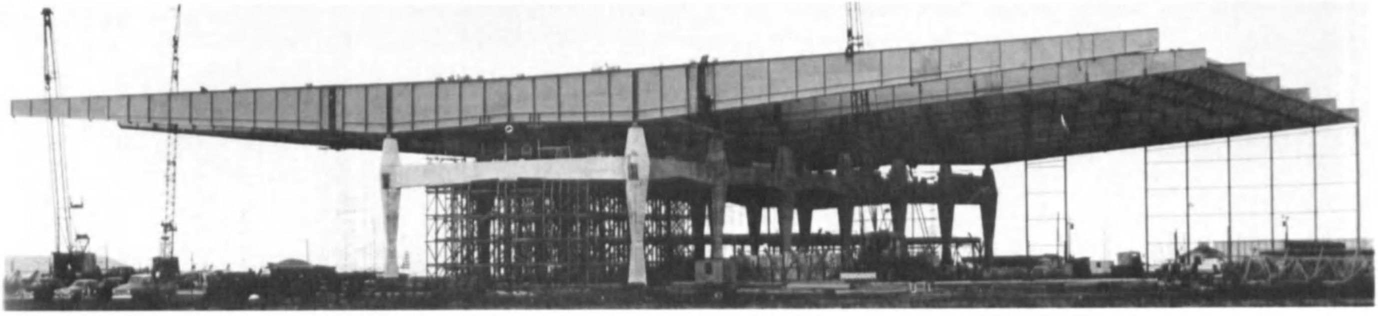
A more conventional structural approach was adopted by Albert Kahn Associates for the larger United Airlines jumbo hangar at Chicago's O'Hare Airport, which measures 98 m × 180 m (Figure 2.42). It has two main hangar areas each 78 m wide, separated by a six-storey core of offices and storage, each of which will accommodate a single jumbo jet or four medium-sized planes. The structural system consisting of five structural steel trusses in each bay, 77 m long and 7.6 m deep, intercon-

2.41
United Airlines Hangar at San Francisco designed by Myron Goldsmith of Skidmore Owings & Merrill in 1960 has double-cantilevered structure of mixed steel and concrete spanning 43 m on each side of a core zone

2.42
United Airlines Jumbo hangar at Chicago's O'Hare Airport designed by Albert Kahn Associates with steel trusses spanning 78 m

2.43
The Boeing 747 Assembly Plant at Everett, Seattle, is the world's largest building by volume with five assembly bays of 188 × 91 × 35 m high, and has a flat roof area of 24 ha (1968)

2.44, 2.45 (next page)
Steel bridge beams at Everett span 91 m onto braced steel-framed core zones providing space for the assembly of 12 jumbo jets at one time with room to manoeuvre


2.41


2.42


2.43


2.44

2.45 Everett interior, home of the jumbo jet

2.45

nected by 24 m long trusses 3 m deep was assembled on the ground into complete lengths, and hoisted into position by crane.

The emergence of the jumbo jet in 1970 greatly affected every aspect of air travel with its tremendous size of 70.5 m long × 19.4 m high × 59.6 m wingspan and created a challenge for the design of airports and the hangars to service them. In return it brought cheap airfares for all and a general increase in air travel.

Boeing 747 Assembly Plant, Everett near Seattle

It is not surprising, therefore, that the home of the jumbo jet, Boeing's plant at Everett near Seattle, is the world's largest building by volumetric capacity. With five assembly bays of 488 × 91 × 35 m high, it has a volume of more than 300 000 000 ft^3 and a flat roof area of over 24 ha (Figures 2.43–2.45).

This huge building was designed and built by the Austin Company of Cleveland, Ohio in 26 months, which included the clearing of 218 ha (540 acres) of woodland site, and the moving of 6 000 000 $yards^3$ of earth. It took the labour of 3500 men, 200 000 $yards^3$ of concrete, and 43 000 tons of steel to construct it.

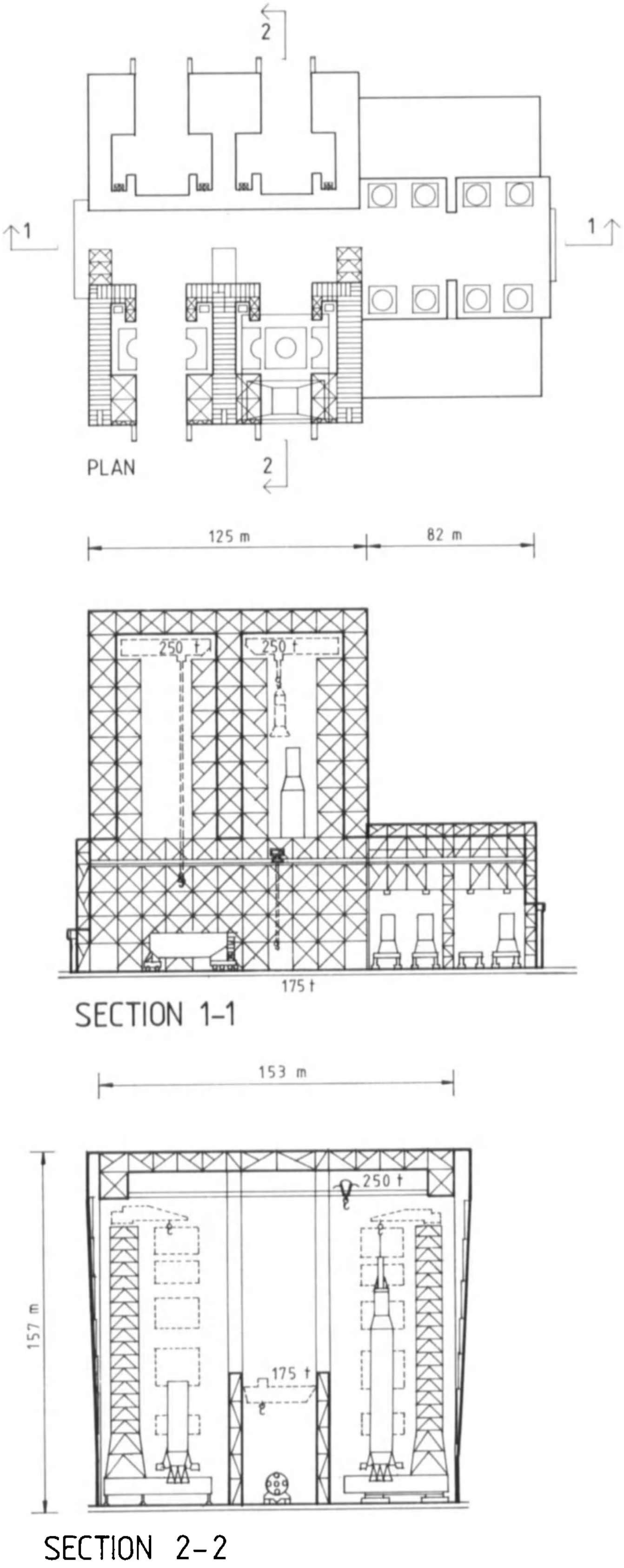
Within the building, it is possible to assemble 12 jumbo jets at one time and allow space for them to manoeuvre. The structure consists of steel lattice bridge beams which span 91 m onto braced steel-framed core zones.

2.46, 2.47
The Vertical Assembly Building at Cape Kennedy Space Centre, Florida, built in 1965 is the world's second largest building by volume measuring 218 × 158 × 160 m high

2.48
VAB's structure of braced multiple towers constructed of steel bridge-like truss system is designed to withstand hurricane force winds

2.46

2.47



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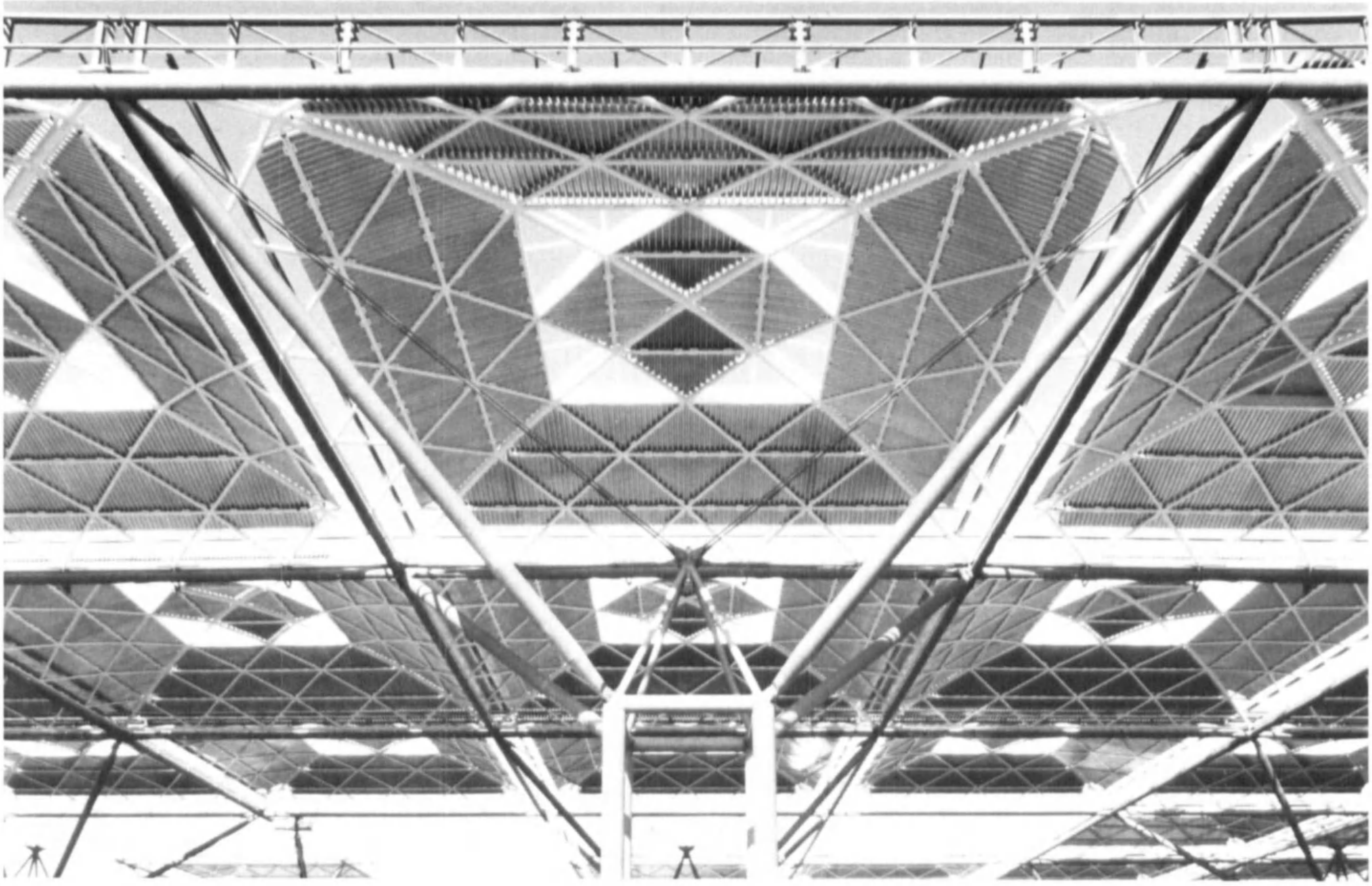

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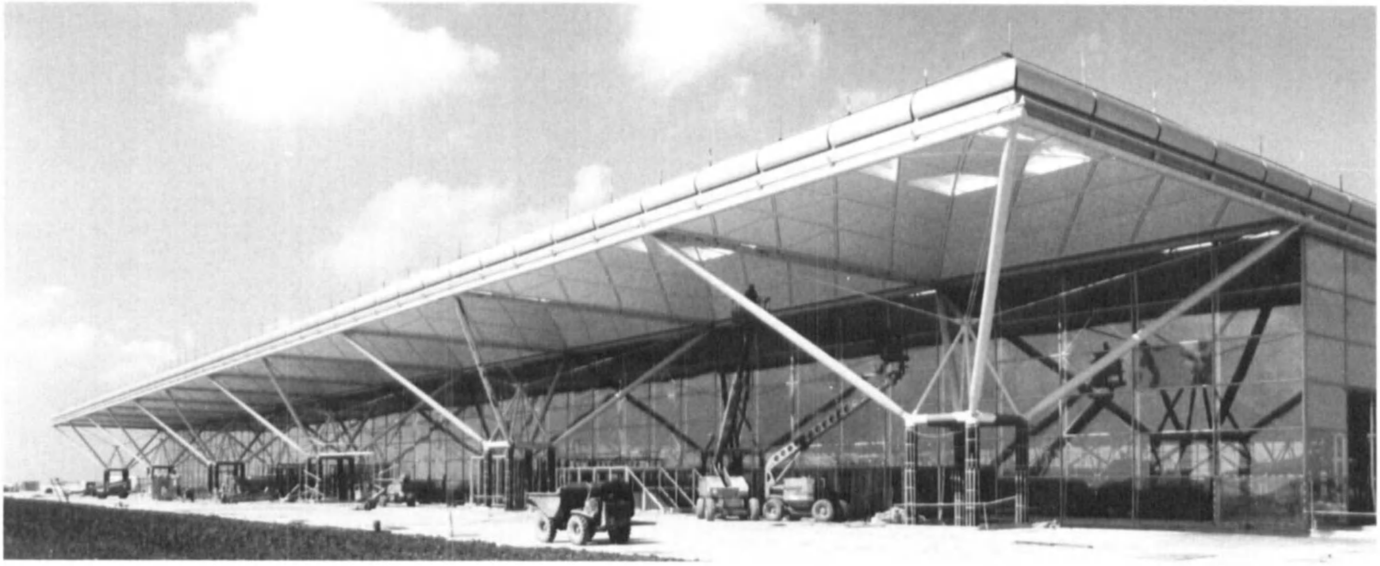

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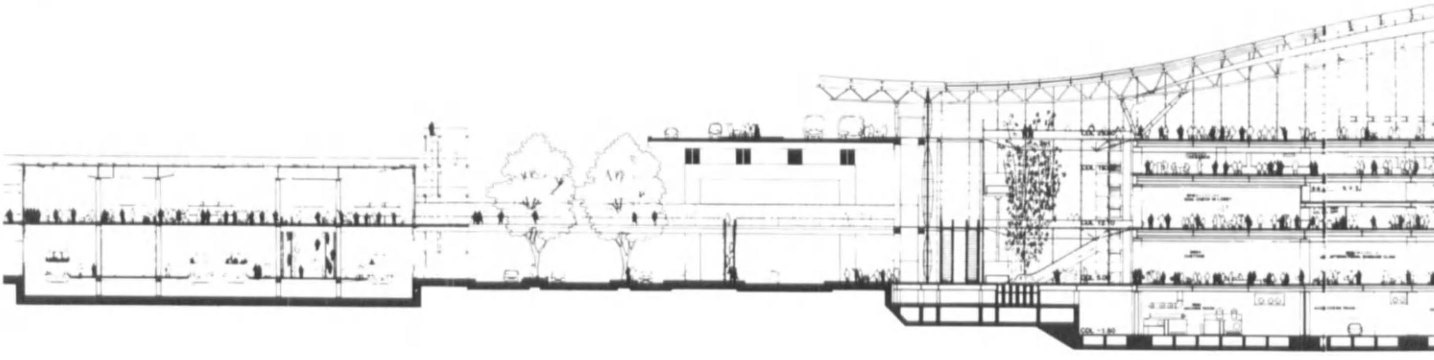
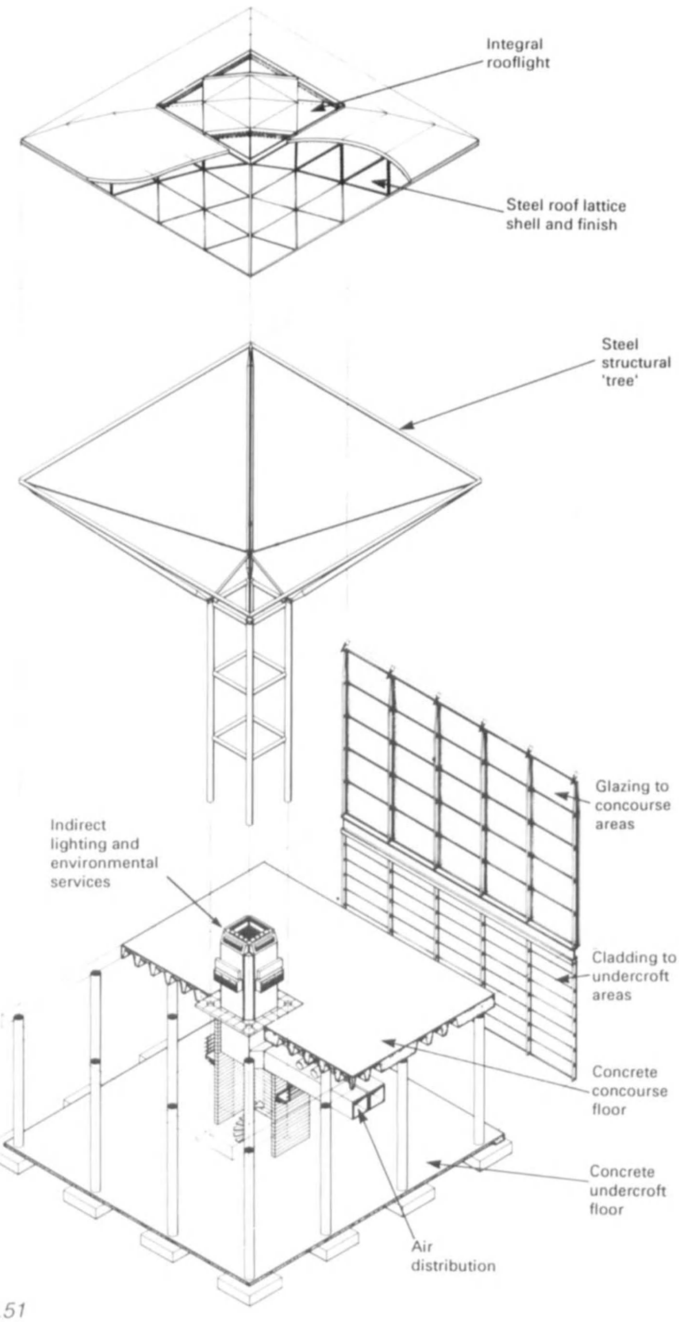


2.49, 2.50
New Terminal at Stanstead Airport, designed by Foster Associates, with umbrella roof of shallow dome supported on a grid of steel tree structures

2.51
Assembly detail of tree structure for Stanstead Airport



2.51

These contain the offices, store and lavatories on various levels, but generally the whole of the immense space is open as one great continuous volume. The roof structure houses services distribution, walkways, and a spectacular system of beam cranes which run the full width, and travel the full length of each bay. It is with these overhead systems that the assembly of the major sections of the aircraft is carried out, whilst the rest of the five million components are fitted from the ground upwards off scaffolding.

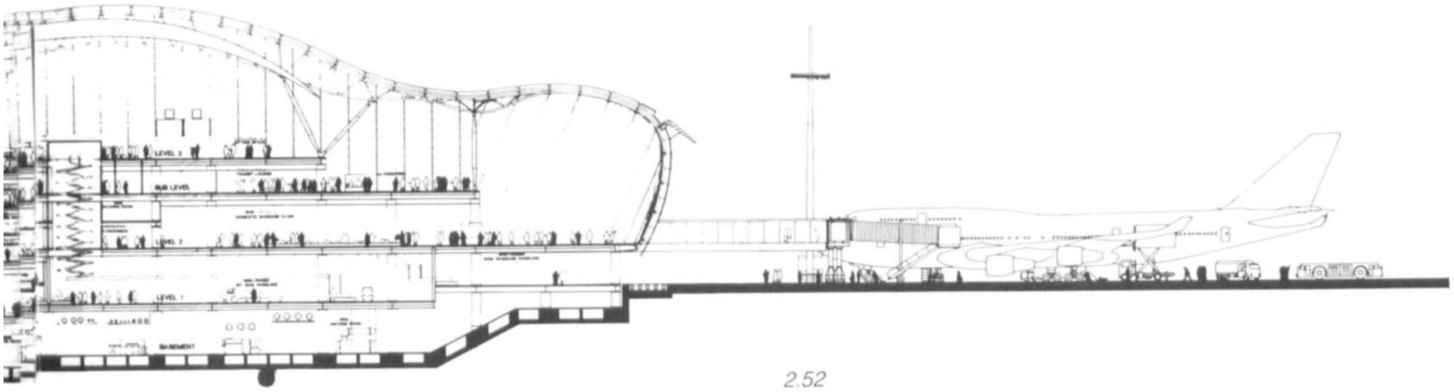
There is no daylighting, but the whole space is lit to a very high level of illumination with a continuous grid of sodium powerpacks. The ends of each assembly bay open up completely with a system of giant sliding doors, in scale with every other component in this monumental building. Entry for people, is via underground tunnels running the full length of the building under the core zones, and then by elevator up to the main production area of galleries above. The scale of the internal space, decorated with the great shiny sections of fuselage and partly assembled planes, is awe-inspiring and worth visiting.

Cape Kennedy Space Centre, Vertical Assembly Building, Florida, 1965

The nearest rival to the Boeing Plant, in size and character, is the Vertical Assembly Building at the Cape Kennedy Space Centre in Florida, which was constructed in 1965 for the assembly of Saturn Rockets as part of man's epic voyage to the moon (Figures 2.46, 2.47). It measures 218 × 158 × 160 m high, giving a total volume of 3.7 million m^3.

Its box-like shape was found to be the most economical, and most able to withstand hurricane force winds experienced in that region. For this reason, the structure

2.52
The new Kansai Airport for Osaka, Japan, designed by Renzo Piano has aerodynamic curved roof form echoing the geometry of the aircraft wing



2.52

was designed for optimum stiffness with a bridge-like truss system of braced multiple towers (Figure 2.48).

The main high bay part of the building contains four assembly bays, each capable of housing the mobile launcher and fully assembled Apollo or Saturn V rocket. The latter was the largest rocket in use, measuring 111 m high, with a diameter of 10 m at the widest point. Within each bay, there are movable working platforms which are like small self-contained buildings that can be adjusted upward, downward and in or out, encircling the rocket during checkout and preparation stages. Many of these are three storeys high, and the tolerances where they joint are only 5 mm.

Gigantic doors, in the shape of an inverted 'T' 140 m high, form the outer wall of the high bays, and each is taller than both the dome of St Peter's, Rome and the Statue of Liberty; they take 45 min to open. If it were not for the powerful ventilation system within the building, it is thought that there could be a problem with clouds forming within the space.

The low bay part of the building 84 × 134 × 64 m high, contains eight stage preparation and checkout cells for the second and third stages of the Saturn V rocket.

The outer skin consists of 9 ha (23 acres) of profiled aluminium cladding, and the structural frame 53 000 metric tonnes of steel. It is hard to imagine that this massive building, which is only part of the overall space complex, was built on sub-tropical swampland. Alligators and rare species of birds and reptile inhabit the surrounding area, apparently happy to share it with some of man's highest technology. At the time of its construction, *Architectural Forum* magazine described it as 'one of the most awesome construction jobs ever attempted by earthbound men'.

With the mission accomplished of sending man to the Moon, the vertical assembly building was subsequently converted for the assembly and testing of the space shuttle and is still in use.

New Airports

The continued growth in air travel in the 1980s has put pressure on the existing international airports throughout the world which has prompted expansion and the development of many new airports. In the south of England, Heathrow and Gatwick have continued to expand to accommodate the extra throughput but to relieve the pressure a new facility is under construction at Stanstead in Essex.

The new terminal at Stanstead, designed by Foster Associates, puts all the passenger and baggage handling activities under the one roof (Figure 2.49). All passenger movements are at the same level, which is raised above the plant and baggage handling areas, to open up views of the airfield. Above this floats an elegant umbrella roof of shallow domes supported by a grid of steel tree structures (Figures 2.50, 2.51). These are made up of four tubular columns which branch out at a high level to meet and support the module of the roof. This innovative structure provides a light, airy quality to the space which should help to reduce the stress factor of flying.

In Japan, the Kansai Airport for Osaka is being built on a man-made island with the buildings designed by Renzo Piano. The dramatic form of the buildings with their aerodynamic curved roof sections is 'generated by pure geometry based on rotated (wings) or translated (terminal) circular arcs' according to the architect's account (Figure 2.52). It is clear that inspiration has been drawn from the form and construction of the aeroplanes for the structure and appearance of the buildings. The large column-free spaces will be roofed with massive aircraft wing-type structures, designed by Peter Rice of Ove Arup & Partners. Here, as in the new Stanstead Airport, the design team has placed a great deal of importance on the relationship of the travellers to the aeroplanes. The layout allows the planes to dock close to a main circulation spine from which they will be clearly visible. Gone are the days of long walks down gloomy corridors where one loses one's orientation. The new generation of airports will have more direct planning and why shouldn't the buildings echo some of the higher technology of the aeroplane itself, like Kansai?

3.1 (facing page)
Geo. N. Pierce Plant 1906 designed by Albert Kahn Associates

3.2
Ford's Highland Plant, 1908, designed by Albert Kahn and Edward Grey for the manufacture of the Model T Ford

3 Industrial Architecture in the Early Twentieth Century

Until the turn of the century, factories were mostly of multi-storey construction and their form evolved to suit the requirements of power and servicing systems. This was invariably steam or water, and the power was distributed by vertical and horizontal shafting.

The buildings were generally long and narrow in shape, the width being dictated by daylighting requirements which relied solely on side-wall glazing. Masonry construction was used wherever possible to reduce the risk of fire, and eventually the timber elements were replaced with cast iron. Floor spans were generally of 2.75–3.75 m, three or four bays wide, and building heights ranged from four to seven storeys.

In the early years of the twentieth century, the basis of industry changed considerably with the advent of electricity and the new concept of 'production-line' assembly which emanated primarily from the automobile industry in the USA. 'Mass-production' became the answer for the expanding economics of western nations, boosted by governments for the manufacture of armaments during World Wars I and II. By necessity, industrial buildings had to provide wider column-free spaces for maximum flexibility in the layout of assembly lines. With the deeper and larger volume spaces came the need for rooflighting and efficient ventilation systems, which prompted experimentation with different roof forms.

In Britain and Europe, the early lead in industrialization was overtaken by the USA, where development was happening so fast that the governing factors in building design were speed and economy rather than appearance and quality. This led to the development of lightweight steel structures clad with mass-produced sheeting and glazing. In many ways, this can be seen as a logical progression from the pioneering days of the Victorian cast-iron and glazed structures for the railways, conservatories and exhibition halls.

US Industrial Architecture

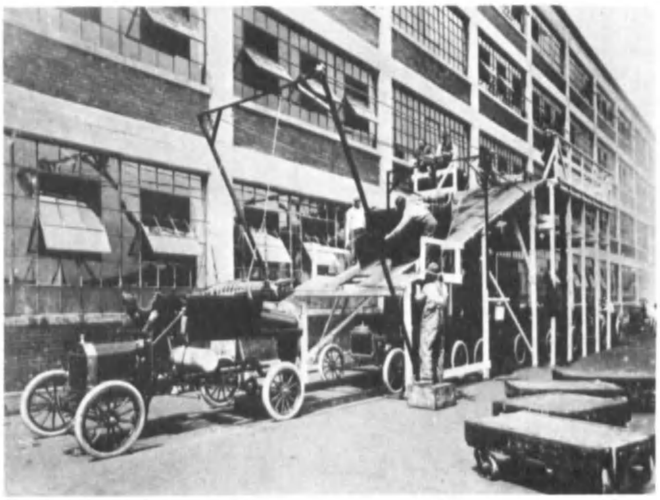
It was an exciting time for the building industry, but with few exceptions the architectural profession was slow to respond to the challenge. In the USA, Albert Kahn 1869–1942 emerged with a fresh approach to building, which was in line with the needs of industry, and during his lifetime designed over 2000 factories. It is said that he regarded 'structures and economics as the heart of the problem of factory design, and setting aside formalistic and symbolic purposes, he allowed factual performance criteria to shape the solution'. His buildings were simple, clear engineering statements which also provided pleasing visual appearance and memorable spatial qualities.

Geo. N. Pierce Plant, 1906

Kahn was fortunate to be in practice in Detroit at the start of the automobile industry and at the centre where it began to flourish. He was only 34 when he designed his first buildings for the Packard Motor Corporation in 1903 which started his long association with the automobile industry. These were conventional factory buildings, but in 1906 he designed the Geo. N. Pierce Plant in Buffalo, New York, in collaboration with the Trussed Concrete Steel Co. and Lockwood Greene & Co, a firm of Boston architects (Figure 3.1).

In many ways this was seen as 'a prototype factory

3.1

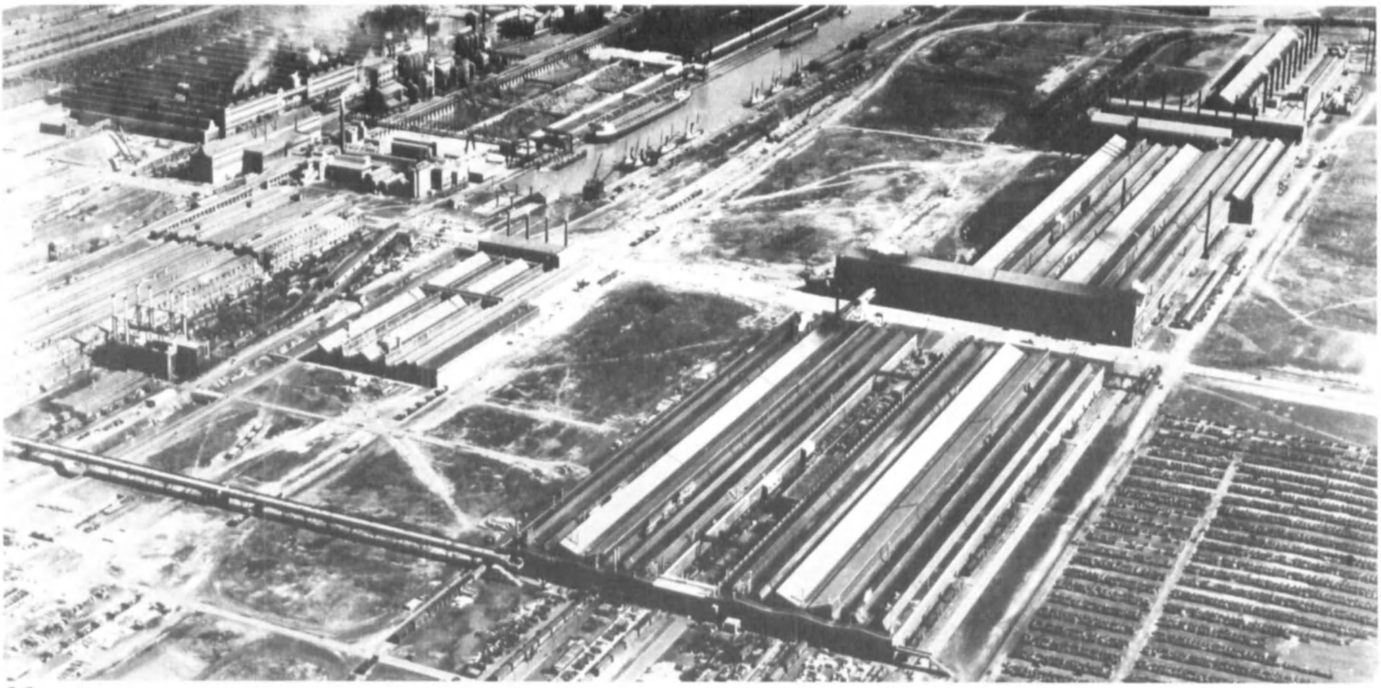


3.2

3.3
Ford Rouge Complex at Dearborn, Michigan, seen in 1938, one of the world's largest industrial complexes covering an area of 4800 ha

3.4
The Eagle Plant at Ford Rouge deisgned by Albert Kahn Associates, 15.5 × 510 m with a clear height of 9 m

3.5, 3.6
The Ford Rouge, Glass Plant, 1922, by Albert Kahn Associates measures 229 × 85 m



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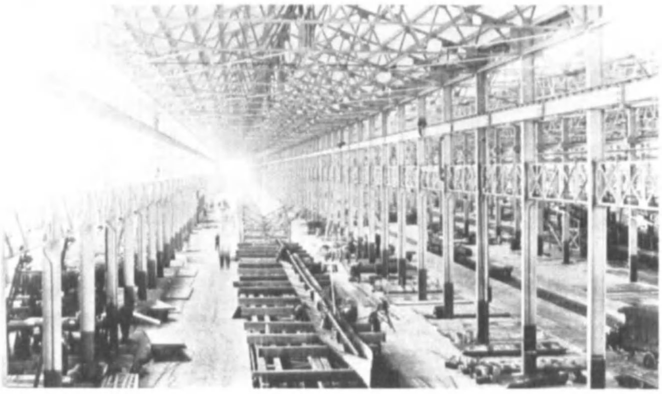

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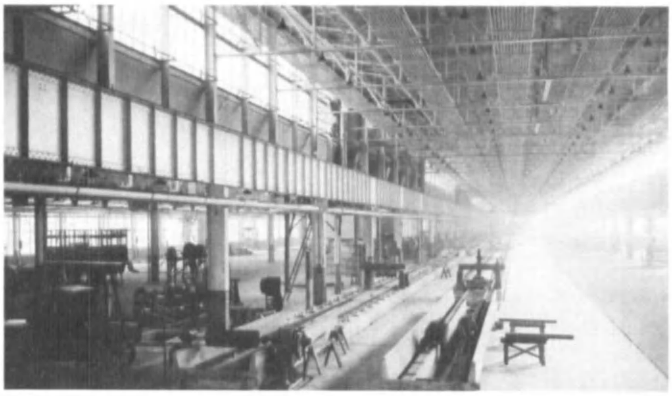

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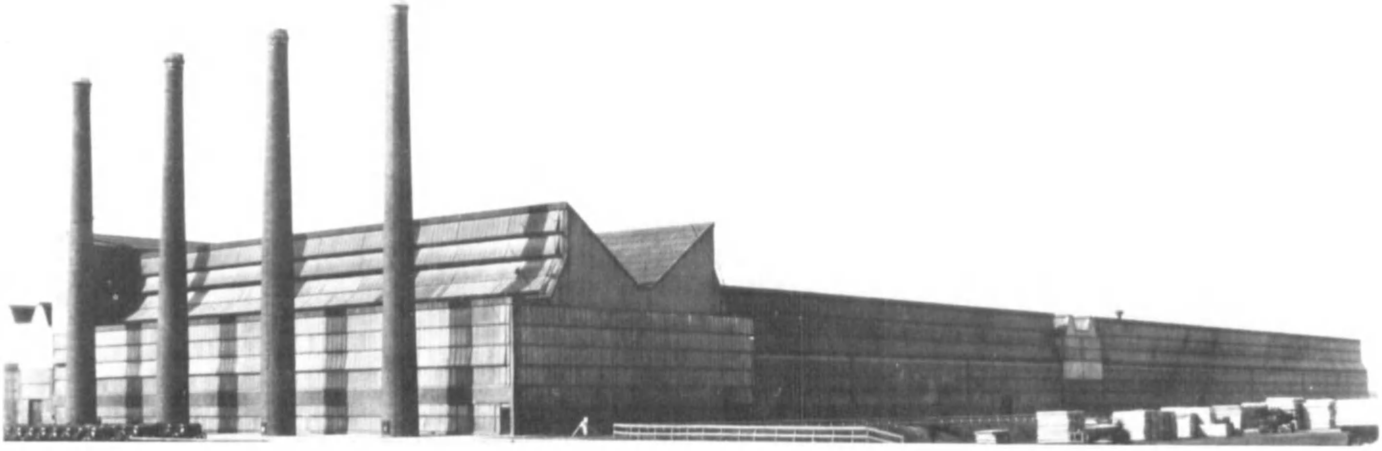

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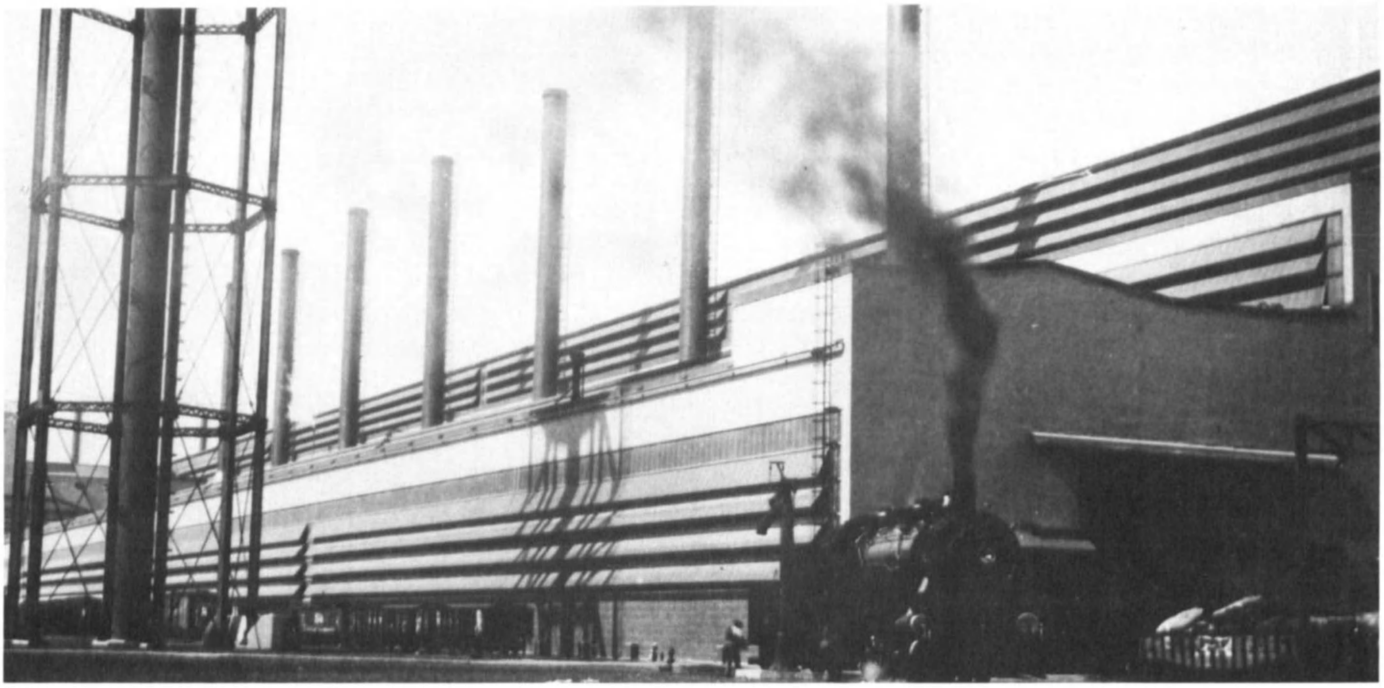
3.7, 3.8
The Ford Rouge, Open Hearth Building, 1925, by Albert Kahn Associates showing strong functional clarity and simplicity of expression



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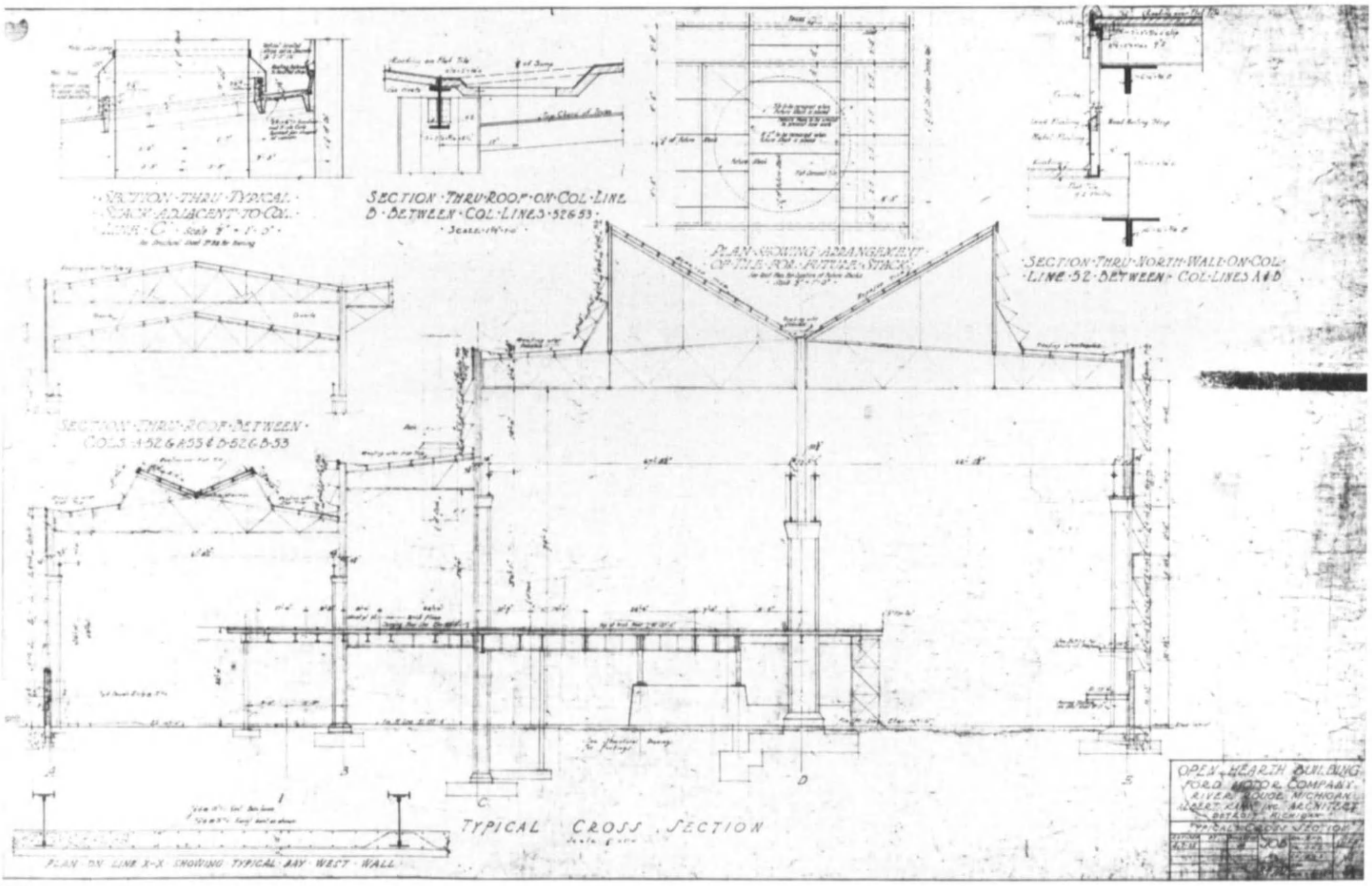


3.8

whose planning principles laid the foundation of factory design for the next several decades', for it introduced the single-storey, roof-lit, wide-span horizontal format. The various operations were located in buildings of varying structural requirements, but all were related along lines of circulation determined by the flow of work. The three main buildings were inter-related by a common structural module, which through permutations of multiples and submultiples determined the various structural grids. Because the plant was organized on a single floor, the manufacturing process itself became horizontally organized. This was made possible by the use of overall rooflighting which allowed deep working spaces. Thus, the jump was made from the multi-storey factory building to the single-storey roof-lit shed.

Through this building and the Packard factory, Kahn attracted the attention of Henry Ford and in 1908 was commissioned with Edward Grey to build the Ford Highland Park Plant (Figure 3.2). This building reverted back to the multi-storey format but was unusual in that it housed all the activities under the one roof. Its clear expression of structure and straightforward repetition of bays of floor-to-ceiling steel sash glazing set an architectural precedent which was greatly admired by the European Modernists at the time. It was featured in Gropius' *Jahrbuch des Deutschen Werkbunds* article in 1913 and according to Reyner Banham, was 'the avowed inspiration of Matte-Trucco's Fiat factory in Turin'.

Many lessons were learned, and not least of these was the need to design for expansion, for within five years the building was to expand beyond comprehension as the Model T Ford car production almost doubled in each year. To cope with the demand, Henry Ford introduced 'powered moving assembly lines' into the Highland plant in 1913. It had been used elsewhere for operations such as meat-packing, but this was the first large-scale refined system of note. The process involved moving the product-to-be by means of a powered continuous conveyance through the manufacturing stages, each of which was stationary. This proved to be more efficient in terms of men and machines and it heralded the new era of 'mass-production'.

It ultimately had tremendous effect on factory design because it polarized the need for the single-storey shed-type structures with wide column-free spaces for maximum efficiency. Lightweight steel frames provided the best structural solution, which also had the added advantage over concrete of smaller columns and fast erection.

All these points were picked up by Kahn in his next design for Ford in 1918 which was the start of the great Ford Rouge Complex on the Rouge River southwest of Detroit.

Ford Rouge Complex, 1918

The 'Rouge', as it is known in Ford, was started with government aid during World War I for the mass production of the anti-submarine Eagle Boats (Figure 3.3). The site chosen by Henry Ford was an immense area of land with good rail links and access to the Great Lakes via the Rouge River. It grew to become one of the world's largest industrial complexes covering an area of 12 000 acres. It has been described as an 'awesome leviathan which eats raw ore at one end and spews out shining automobiles at the other, at a rate of one every 53 s. In between, the ore is smelted into iron, converted into steel, transformed into engines, frames, bodies and parts'. To aid this monstrous digestive process, it operates the largest private railway in the USA.

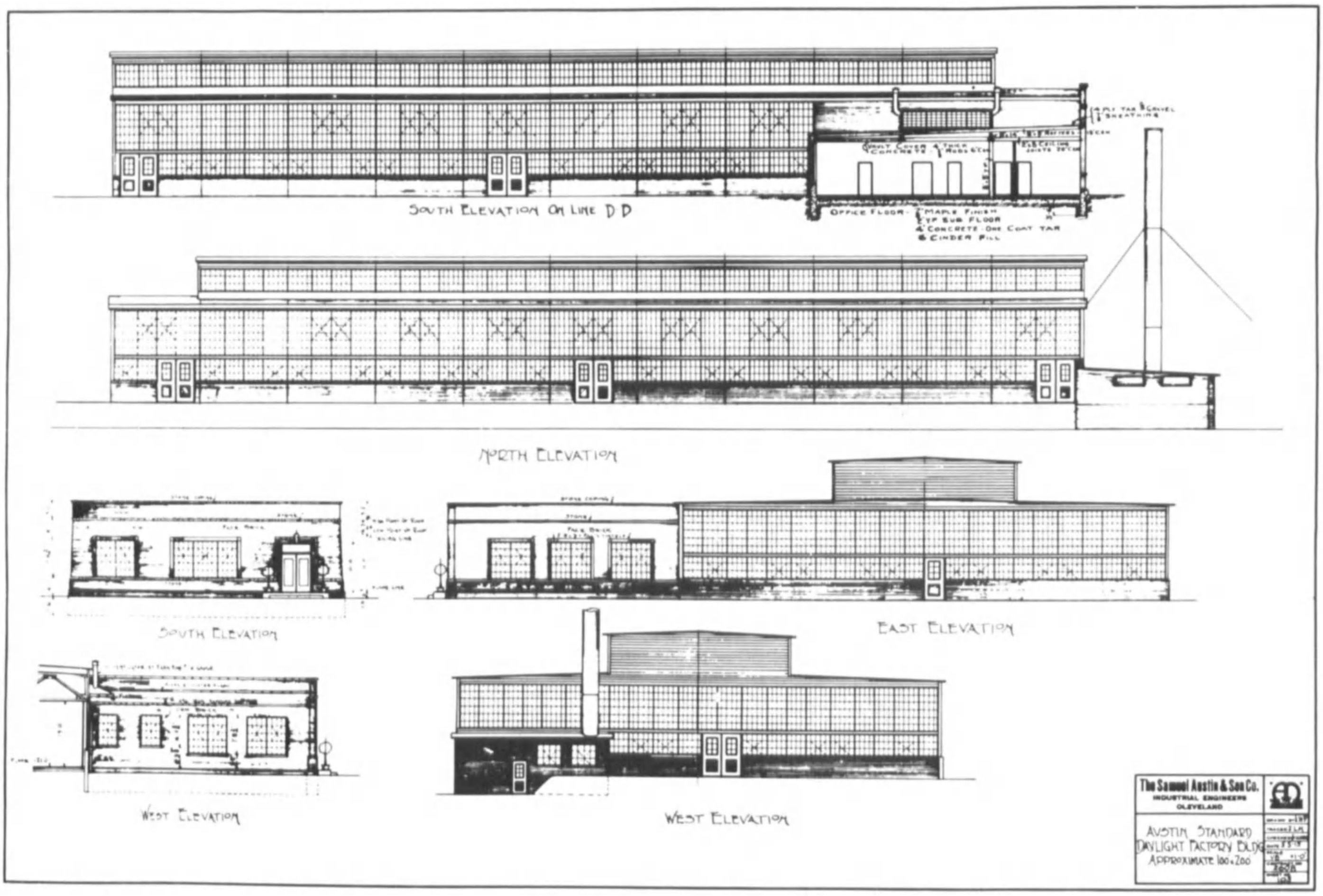
The Eagle Plant The first building known as the Eagle Plant or 'B' Building consisted of five aisles 15.5 × 510 m with a clear height of 9 m, constructed with a steel frame of lightweight 'Fink' trusses with alternate bays of monitor and clerestory lighting (Figure 3.4). The roofs were clad with cement tiles and the walls with sash glazing and asbestos panels except for the lower portion which was in brickwork.

This massive building was designed in four weeks and built in 14. In this respect it represented an advance on Paxton's innovative construction programme for the Crystal Palace 67 years earlier. The Ford magazine of the time described the operation as follows: 'As soon as the foundations are ready, the superstructure of steel and concrete and glass shoots up; floors are laid while the roof is going on and the glass going in the windows; as the floor progresses machinery is installed; so that when the last arching rafter is in place, the roofer is at hand and when the last shingle is laid, all floors, runways, assembly conveyors, machinery, lights are in place and the big plant is at once at work'.

The Eagle Plant was a straightforward shed which used the latest technology of the time to enclose a large volume of space in a fast simple and economical way.

It was followed by two other large industrial buildings on the site which also had this clarity of purpose but which had, in addition, more style in their visual appearance. These were the Glass Plant and the Open Hearth

3.9
Standard Factory by the Austin Company of Cleveland, Ohio introduced in 1914



3.9

Mills, and in many ways they set a precedent for the new 'industrial architecture' of the USA which together with the grain silos and earlier multi-storey factories was admired by many of the masters of the modern movement in Europe, including Le Corbusier (in *Vers une Architecture*), Gropius, Mendelsohn and Moholy-Nagy of the Bauhaus. This interesting relationship has been extensively investigated by Reyner Banham in his book *A Concrete Atlantis*, published in 1986.

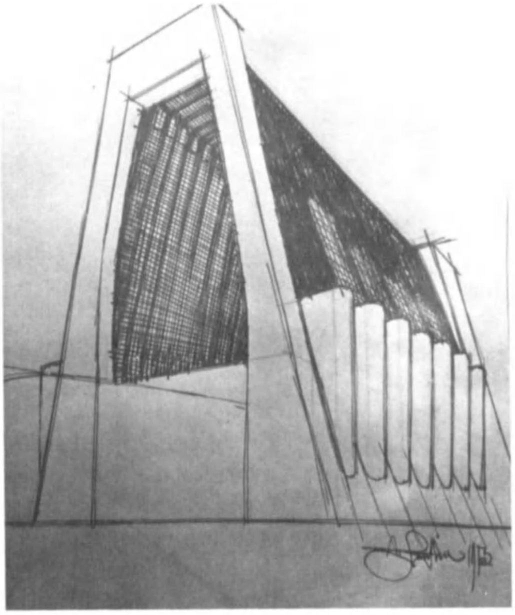
The Glass Plant, 1922 Designed to process the Ford Company's own glass, this building contained all the functions within the simple rectangular plan 229 × 85 m (Figures 3.5, 3.6). The process lines ran the length of the building stemming from four great furnaces which ranged across the south end. A railway ran down the length of the west wall which brought in raw materials, and a balcony crossed the building at the mid-point which housed lavatories, lockers and supervisors' office. All these functions were expressed in the external form of the building. The main production area had a roof of alternating large and small monitors. The large monitors coincided with the main process lines which gave off intense heat, and this system was only interrupted by the balcony whose higher roof carried two runs of smaller monitors which cut across the main runs. At the end, the roof over the furnaces had the highest monitors of all because the temperatures were greatest, and these also ran at right-angles to the main roof lines. Four tall chimney flues at the south end provided an impressive termination to the horizontal lines of the building.

The Open Hearth Building, 1925 This quality of functional clarity and simplicity of expression is repeated in the Open Hearth Building in 1925 (Figures 3.7, 3.8). It was designed to produce the company's own steel in a

3.10
Marché aux Bestiaux, Lyon. Slaughterhouse designed by Tony Garnier with a clear span of 80m

3.11
Airship Hangar Project by Antonio Sant'Elia, 1908–1914

3.10



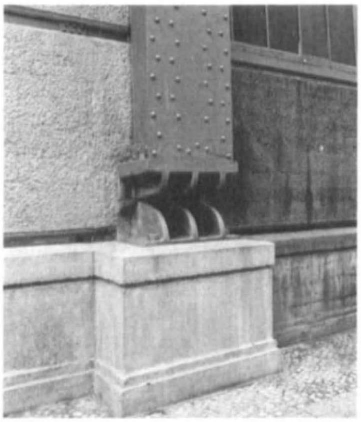
3.11

3.12

3.12, 3.13
AEG Turbine Factory designed by Peter Behrens in 1909

3.14
Detail of pin joint at base of column to the AEG Turbine Factory

3.13



continuous process which involved keeping a reservoir of molten metal constantly in the furnaces to be drawn off as needed for pigging and immediate transfer to the forging press. This transpired to be one of Ford's less successful ideas, and in the end the process was converted to more traditional methods.

All functions were contained in one shed measuring 325 x 73 m with four aisles of varying spans and heights. The structure consisted of steel columns supporting lightweight steel trusses and the cladding was made up with horizontal bands of glazing and Gunite (a spray-on material coating 50 mm thick). Once again the chimneys added dramatic expression to this bold functional building.

Standardization

At the same time as Albert Kahn's pioneering work with the automobile industry, another major development occurred in the USA which concerned the construction of industrial buildings. This was the concept of a 'standard steel-framed factory' which was first introduced by The Austin Company of Cleveland, Ohio in about 1914. Having completed 53 buildings for the National Lamp Company in a very short space of time, W.J. Austin reasoned that 'a large portion of the Country's factory building needs could be fully met with a comparatively few standard building units' with the idea that standardization would facilitate mass production and reduce costs.

In many ways it made perfect sense that the building industry should follow the line that the majority of industry was taking. The Austin company were a go-ahead construction firm which had already pioneered the 'package-deal' method of 'design and build' which they advertised as 'The Austin Method of Undivided Responsibility'. They used to offer to produce the plans while the excavation was being made, but with mass production of standard components, they were able to promise the structural steel for delivery the day after signing the contract. This must have been an extremely tempting offer for any expanding manufacturing company at that time, and it is not at all surprising that The Austin Company should have achieved such success. They described the benefits of standardization as follows: 'manufacture on a quantity basis, equalization of production over slack periods, reduction of maintenance costs, elimination of poor design, reduction of labour and machine costs, closer co-operation and a uniform degree of safety and efficiency during and after construction'.

The Austin standard industrial building was the Model T Ford of the construction industry: both were produced fast and cheaply. There were 10 standard Austin buildings which had interchangeable standard units. They were mostly single-storey shed structures with varying heights and spans designed to accommodate the assembly lines for the full range of industry, from lamps to locomotives. Different roof configurations provided daylighting and natural ventilation to suit the need. A variety of standard industrial buildings is available throughout the world today, and it is perhaps surprising that they have not become more universally accepted.

European Industrial Architecture 1900–1945

In Europe after the turn of the century, there was a growing admiration for 'the machine' and an interest in the potential for a new industrial architecture by academics. In 1904 the French architect Tony Garnier drew his vision of an imaginary 'Cité Industrielle' planned around the needs of factories and communication systems, with conveniently placed housing for the workers. He predicted that 'industrial requirements would be responsible for the foundation of most towns in the future'. He was never given the opportunity of building the industrial city, but was able to demonstrate some of his ideas in the design of a vast slaughterhouse and cattle market in Lyon 1909–1913 (Figure 3.10). Most of the buildings were of concrete, but the market hall had an impressive vaulted roof of steel and glass spanning approximately 80 m.

Also in France at this time Auguste Perret was experimenting with the expression of structure with glazed infill panels in his garage in the Rue Ponthieu, Paris, in 1906, which was to influence the early beginnings of the 'modern movement'.

In Italy between 1908–1914 a group of young visionaries intoxicated by technology, produced their 'Futurist Manifesto'. Their ideas were expressed in poetry, painting, sculpture and in the powerful drawings of Antonio Sant'Elia (Figure 3.11). These dramatically conveyed an image of a new architecture aspiring from the technology of machines and transportation systems. Tragically, he was killed in action during World War I and never had the opportunity of putting these ideas into practice.

AEG Turbine Factory, 1909

It was in Germany at this time, where the major progress was made in industrial architecture. In 1906 the directors of one of the largest industrial firms in Germany, the Allgemeine Elektrizitats-Gesellschaft (AEG) appointed Peter Behrens as design consultant, and in 1909 he designed the now famous Turbine Factory for them (Figures 3.12–14). The structure consists of a series of three-pinned steel arches with six facets to the roof, supported on tapered steel columns which sit on expressively designed hinged base-plates. The columns are exposed on the inside and outside faces of the external walls with huge expanses of glass infill panels. The corners of the structure, however have massive concrete forms inscribed with horizontal lines at intervals suggesting a rusticated vernacular. At the ends of the building, the faceted arch profile is expressed in the manner of a classical temple, which seem incongruous with the simplicity and clarity of the rest of the structure.

However, it is clear that the architect at that time still thought it necessary to add architectural expression to the structural form of the building. Peter Behrens was one of the leading members of the Deutsche Werkbund which was established in 1907. Its chief aim was 'the refurbishment of workmanship and the enhancement of the quality of production'. Artist, workman and industrialist were to collaborate in producing honest goods of artistic value.

The Werkbund Exhibition at Cologne, 1914

It reached its peak of activity with the Werkbund Exhibition at Cologne in 1914 in which Peter Behrens, Walter Gropius, Adolf Meyer, Bruno Taut and others collaborated. The most talked about work was Gropius' glazed office building, but the Machine Hall also had great significance (Figure 3.15). It continued the tradition which started with the Great Exhibition in Hyde Park in 1851 for a great hall constructed for the glorification of the latest machine technology.

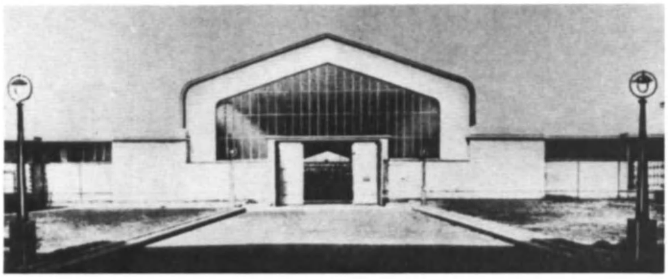
With the other international exhibitions which followed, the more adventurous architects and engineers were able to extend the known boundaries of building construction. Whilst the Paris Exhibition of 1889 succeeded in breaking the world records for the tallest structure and longest span building, the Werkbund Exhibition at Cologne was more concerned with style and architectural expression. The Machine Hall was conceived as a 'Model Factory'. It had a single clear-span vaulted structure with plain, carefully detailed glazing at the gable ends. The roof cladding extended down the side walls with an elegant curve over the non-existent eaves giving the 'wrap-over' skin quality much sought after in present-day sheds. Generally it can be said that this building provided a respectable architectural aesthetic for the simple factory shed which was picked up in the Modern Art Glass building by Foster Associates 58 years later and which has become universally accepted.

Erich Mendelsohn also made an important contribution at this time, firstly with his 'Fantasy Projects' in which he attacked the codified language with his richly expressive drawings and later with his buildings. His architecture revelled in dynamic plastic forms, unrestrained by the self-imposed disciplines of the Modern Movement. In his design for the Hat Factory at Luckenwalde, for instance, he produced a series of irregular volumes characterized

3.15
The Machine Hall at the Werkbund Exhibition, Cologne, 1914, was conceived as a 'Model Factory'. For comparison see Foster Associates Modern Art Glass Factory, Thamesmead

3.16
Hat Factory at Luckenwalde designed by Erich Mendelsohn (1923)

3.17
Chrysler Half-Ton Truck Plant, Detroit, 1937, by Albert Kahn Associates



3.15

3.16

by triangular shapes and angles (Figure 3.16). Whilst the main sheds bore a resemblance to traditional industrial forms, the Dye Works was given a most extraordinary and powerful form, which was placed on a central axis balanced by the electrical power plant at the other end of the site. It was a bold, expressive piece of design, uninhibited by any traditional forms of architecture.

British Industrial Architecture 1900–1945

In Britain at this time the architectural profession seems to have generally missed the exciting potential for a new industrial architecture, which may have partly been attributable to the familiar characteristic attitude of industrialists dragging their heels over investment and progress. Certainly the early lead in industrialization was now lost to its European and American competitors.

With the exception of a few isolated examples such as Sir Owen Williams' factory for Boots at Beeston, Nottinghamshire in 1930, British industry seemed prepared to make-do with the 'dark satanic mills' left over from the Victorians, and simple-span proprietary sheds. A typical shed would have been constructed with a light steel frame with fink, warren or 'N' roof trusses spanning about 10m, which would have been clad with asbestos or corrugated iron sheeting and with patent-glazed rooflights in narrow continuous bands. Brick facades often provided a more important street frontage justifying the title 'decorated shed'. Such buildings without insulation or adequate ventilation could hardly have provided a very satisfactory working environment.

Beautiful Factories

In the United States, Albert Kahn became more involved with the quality of the working environment and in the design of 'beautiful factories'. Perhaps the best known example was the Chrysler Half-Ton Truck Plant at Mound, near Detroit, built in 1937 (Figure 3.17). This was a large building measuring 1385 × 122 m with fully glazed external walls and a clean, crisply detailed appearance. The complex roof structure provided a large loft space for ventilation and monitor rooflighting with a structure of cranked solid-web steel beams. The columns are on a grid of 12 × 18 m but the cranked beams cantilevered a further 3.6 m on each side. This building was way ahead of its time, as was the Glenn Martin Assembly Building which was constructed in the same year.

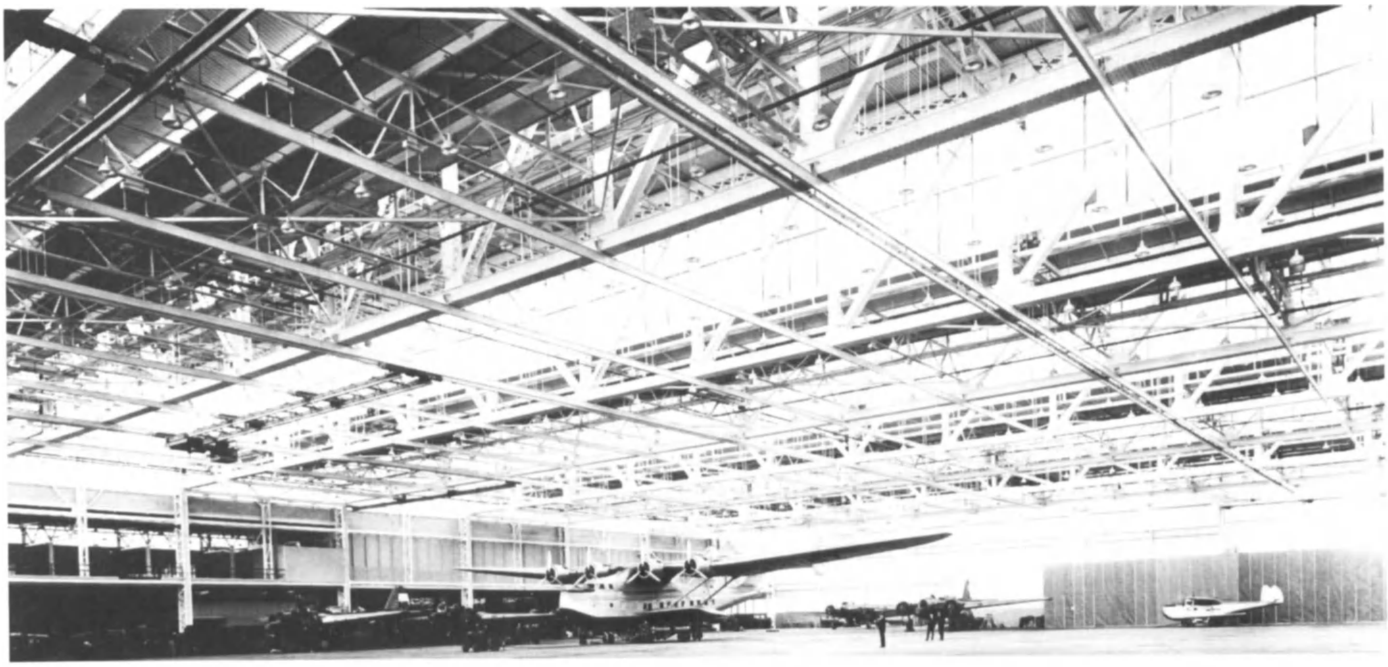
It was conceived as a single column-free space 91 × 137 m in plan and 13 m high for the assembly of aeroplanes (Figures 3.18–21). Up to that time no

3.17

3.18
Glenn Martin Assembly Building, Baltimore, 1937, by Albert Kahn Associates, Interior

3.19
Mies van der Rohe montage of Glenn Martin interior

3.20
Glenn Martin Assembly Building



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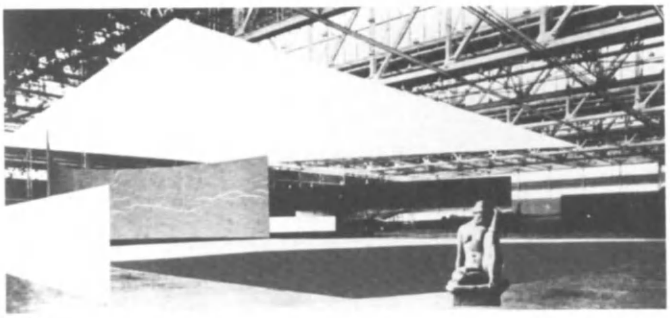
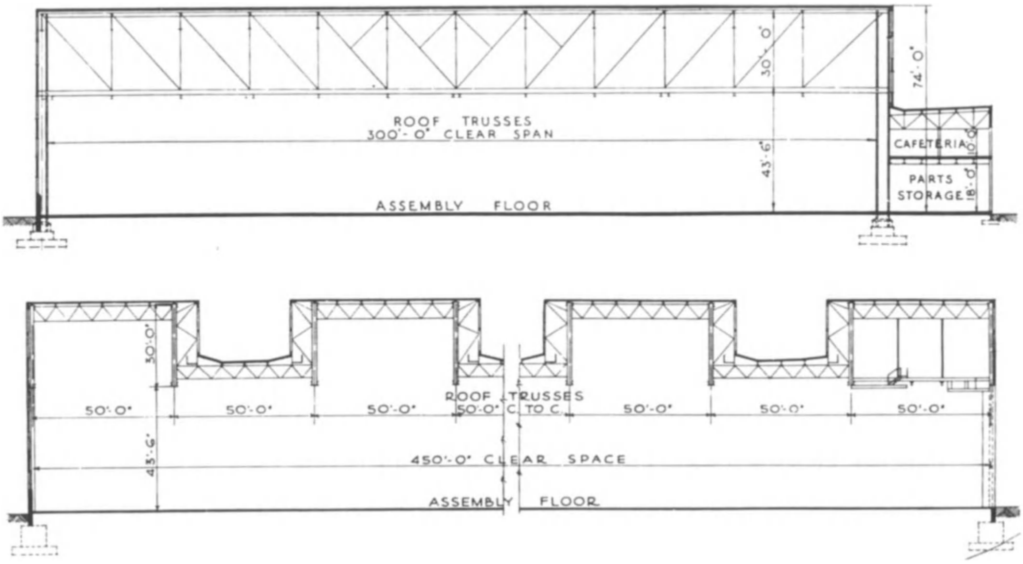


3.19

3.20

3.21
Glenn Martin Assembly Building: Albert Kahn Associates' drawing showing roof structure with a 91 m span



3.21

3.22, 3.23
The Chrysler Corporation Tank Arsenal in Detroit, 1942, by Albert Kahn Associates

building had been constructed with a flat span anywhere near as great as 91 m (300 ft). The Galerie des Machines in Paris 1889 exceeded it with a span of 114 m but this was achieved with three-pinned arches. Many bridges had spans far in excess of this and it is likely that they provided the inspiration for the structure for the Glenn Martin Assembly Building. It is said that an inter-office competition of sorts was held amongst several design teams each preparing different proposals which were judged according to the weight of steel required. The lightest scheme, in terms of pounds per square foot of roof supported, was chosen which had single span, parallel chord Pratt trusses, 91 m long and 9 m deep placed at 15 m centres. The upper and lower chords of the trusses consisted of pairs of built-up 500 mm deep channels spread 457 mm apart, back to back. A 762 mm closing plate was riveted across the top of the upper chord and the bottom of the lower chord. Verticals and diagonals were also constructed with pairs of similar members. The roof followed alternate bays on the upper and lower lines of the trusses forming monitors which were glazed at the sides. Lateral forces were countered by the usual 'X' bracing in the walls and between trusses. The whole of one end of the building was designed to open onto the airfield, with three huge doors 14 m high in two horizontal sections, which lifted vertically.

It was indeed a magnificent constructional achievement, and the space enclosed was massive, well lit and extremely exciting. Mies van der Rohe used the interior photograph illustrated for a montage, to present his idea for a grand, column-free concert hall (Figure 3.19). He placed a number of free planes horizontally and vertically to represent walls and ceilings which could be moved as required. To Mies this building admirably represented the concept of 'universal space' which was one of the major aspects of his philosophy.

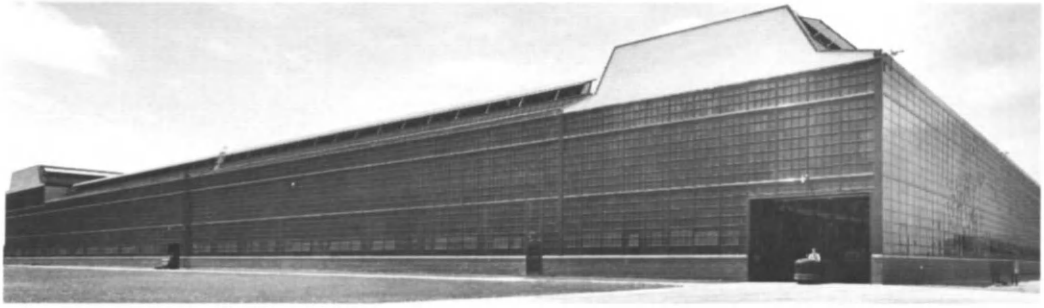
Wartime Manufacturing Buildings in the USA

The outbreak of war in 1939 generally gave great impetus to those industries which could be converted into the manufacture of armaments. The automobile and aircraft manufacturing industries were prime examples and in the United States this stimulated the construction of some interesting buildings. Speed and economy were of the utmost importance and it is not surprising that the government of the day turned to those firms which had established reputations for meeting deadlines.

Chrysler Corporation Tank Arsenal, 1940

Albert Kahn Associates were commissioned by the government between December 1939 and December 1942 to design 200 million dollars' worth of construction to be carried out at break-neck speed. The Chrysler Corporation Tank Arsenal in Detroit was one of these frenzied examples yet the quality of the architecture is worthy of note (Figures 3.22, 3.23).


3.22


3.23

The building had the familiar rectangular plan measuring 420 × 158 m with a clear height of 8.8 m with a railway spur running through the entire length of the building delivering materials to the 23 sub-assembly bays which opened onto it. The structure was designed for maximum economy with a lightweight steel frame of Pratt trusses; the external walls were almost completely glazed with a bland square grid of steel sashes.

It seems to be a thoroughly well worked out solution, yet the pressures on the design team must have been tremendous for, in June 1940, Chrysler had been directed to produce tanks though they had no previous experience. A site was bought and construction started at the end of September and the first tanks were

3.24
Conslidated Vultee Plant at Fort Worth, 1942. Fully air-conditioned black-out factory for the assembly of wartime bomber aircraft with two bays measuring 1219m × 61m, designed and built by the Austin Company

3.24

produced only six months later, five months ahead of schedule.

Consolidated Vultee Plant at Forth Worth, 1942

The Austin Company were also actively involved in the war effort. In the late thirties they had developed the concept of a 'windowless factory' with controlled environmental conditions. The aim was to simulate those conditions 'prevailing out-of-doors on a perfect June afternoon' for 24 hours a day, all the year round. In 1938 they had completed the first such plant for the Simonds Saw and Steel Company, and this became the forerunner for the country's wartime 'blackout factories'. The most spectacular of these were the twin bomber assembly plants at Fort Worth for Consolidated Vultee and at Tulsa for Douglas (Figure 3.24).

The assembly bay of the Fort Worth was built as a clear undivided space four-fifths of a mile long, 1219 × 61 m weighing 171 tons each. There were no windows and this huge space was lit entirely from rectified fluorescent fittings. All surfaces were of light colour for maximum reflectance. The whole building was air conditioned, and when it was later enlarged into a completely integrated aircraft plant, it became the world's second largest air-conditioned building. It was second only to the Pentagon, but this may now have been exceeded.

The photographs of the assembly bay taken during the production of wartime bomber aircraft show the breathtaking scale of the space. An unparalleled level of productivity was achieved during those troubled times which was facilitated by buildings such as this designed with care for maximum functional performance, and many of the principles were later transferred to the new generation of post-war industrial buildings.

4 Evolution of the Well Serviced Multi-Use Shed

The second half of the twentieth century has seen a series of evolutionary changes in the requirements of buildings which, as always, have been directly related to the technological developments. One of the most fundamental changes has been the move from an age dominated by the 'Machine' to a life dependent on electronic wizardry. The move into the electronic age was prompted by World War II with the acceleration of research into radar and electronic systems. Later this knowledge was put to use in the development of television, computers and electric gadgetry, which with mass-production methods and credit systems, could be marketed to the general public on an international basis.

With the invention of the transistor at the Bell Telephone Laboratory in 1948, the computer industry developed at an amazing speed and generated the potential for tasks which hitherto had been impossible. At the same time the building boom, which followed expansion of industry and the post-war population growth, encouraged the use of new structural concepts, materials and construction techniques, whilst the need for speed and economy prompted the development of prefabricated systems for structural frames and the building enclosure.

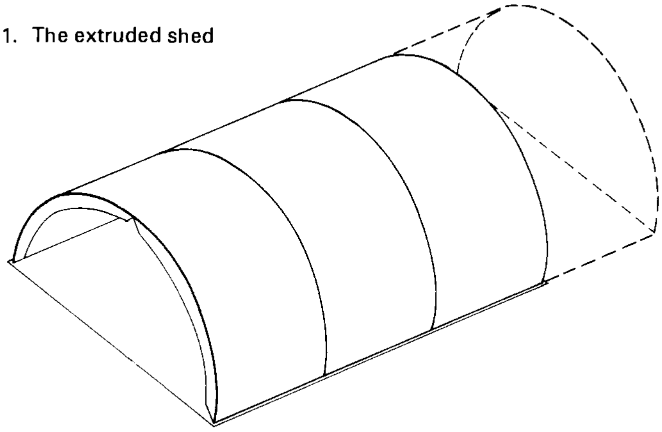
Higher levels of mechanical and electrical services were required to provide greater environment controls for the new generation of industrial buildings designed for the assembly of electronic components. The ambiguity of the building user requirements for management and assembly workers encouraged the design of flexible buildings able to accept change in use and levels of servicing plus the capability to expand. The need for column-free spaces in schools, sports halls and commercial buildings, coupled with the need for economy, extended the use of the industrial shed into other fields.

In essence, here was the brief for the 'well-serviced multi-use shed' which has become one of the most significant building forms in the post-World War II era. The key design factors are; function, flexibility, economy, integration of structure and services, speed of erection, extendibility and use of technology. Traditional details which relied on craftsmanship have had to give way to component assemblies designed to the correct tolerances and performance specification. The multi-disciplinary design team evolved to ensure that all the functional requirements of the building were accommodated and a new form of architectural language evolved which expressed the functions of structure, services and technology.

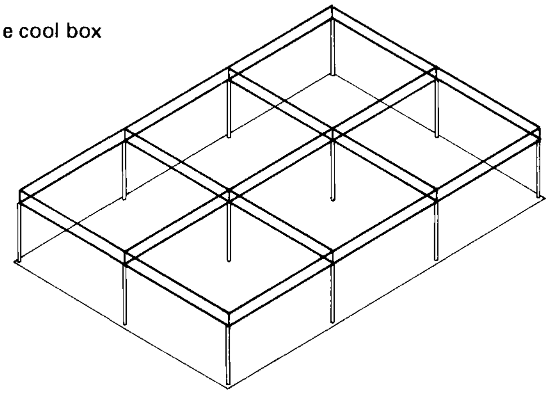
Since World War II developments in the basic form of sheds, many different lines have followed which can be broadly grouped into three categories for comparison (Figure 4.1):

1. Extruded shed
2. Cool box
3. Special structures

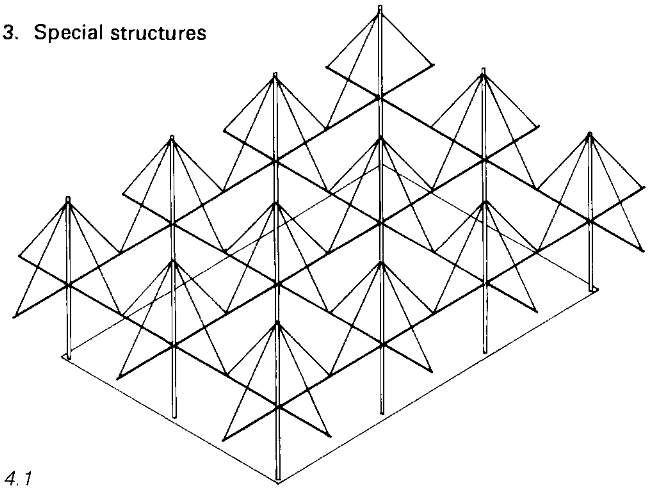
1. The extruded shed



2. The cool box



3. Special structures



4.1

4.1
Diagram showing the three categories of post-war shed

In general terms, the extruded shed category which includes Foster's Visual Arts Centre at the University of East Anglia, can be seen as a progression from the Victorian Machine Hall and early twentieth-century airship hangar, whilst the 'Cool Cool Box', as it was described by John Winter in his book *Industrial Architecture* published in 1970, is a new form of multi-span shed which evolved in the 1950s to suit the highly serviced requirements of the electronics industry. This is the true 'well serviced multi-use shed' which aroused the interest of the architectural critics of the 1970s.

The third category covers the masted structures such as Fleetguard and Inmos Micro Processing plant from the Richard Rogers Partnership and the Renault Centre by Foster Associates and the Schlumberger Research and Development Plant by Michael Hopkins Architects. This building type is a phenomenon of the 1980s which could best be described as architectural engineering, where the three London architectural practices were all closely related, but worked separately with two innovative structural engineering firms, Ove Arup and Partners and Anthony Hunt Associates. Friendly rivalry between the engineers, and between the architects led to the generation of a series of exciting sheds which move beyond the cool box and explore the image and potential of lightweight structures, high performance cladding and glazing systems, servicing arrangements and plan forms.

In the second part of this chapter we will take examples from each category for examination and comparison, but first we will look at the major influences on the architectural language and design thinking.

Major Influences

Apart from the normal and specialist design requirements, there have been a number of important influences which have shaped the architecture of the second half of the twentieth century.

The first and perhaps the most important is *The Machine*, which was so greatly admired by the masters of the Modern Movement and the Futurists. Le Corbusier in *Vers une Architecture*, under the title 'Eyes Which Do Not See' published images of liners, airplanes and automobiles of the 1920s to represent *l'esprit nouveau*, and scarcely an article has been published on the work of Norman Foster or Richard Rogers which does not mention the machine.

The influence is there, and the practice of *transfer technology* which involves extracting materials and systems from the more advanced technology of aeroplane, car and boat construction. Today, we have the added super technology of the NASA space programme which has already provided many terrestrial 'spin-offs', such as 'Teflon' which is popularly used on non-stick saucepans and has more usefully given fabric structures the necessary ingredient to create self-cleaning tensile membranes where cable-nets are no longer required.

The *computer* is another important influence, of a similar vein, which has allowed faster and more accurate structural analysis, giving a wider range of options to explore. We are still in the early days of computer-aided drafting so it is still too early to examine the effects which this has had on architectural design.

The other major influences have come from the work and teachings of five designers who saw the evolution of the Modern Movement through the post-war period and into the 1960s. They are: Charles Eames, Buckminster Fuller, Jean Prouvé, Konrad Wachsmann and Mies van der Rohe.

The philosophy of *Charles and Ray Eames* was epitomized in the design for their own house in Santa Monica (Figure 4.2). It was constructed in 1949 with 'off-the-peg' industrial components, such as steel decking, standard open web joists and steel sash windows, all of which were left exposed to express their own function. This was new to domestic architecture, and a fresh new aesthetic was created from 'the industrial image' and 'kit of parts' approach.

Buckminster Fuller explored the boundaries of technology, generating new forms and applications for the building industry (Figure 4.3). His geodesic structures introduced a range of exciting possibilities for large-scale enclosing forms. He preached a new all-embracing design concept related to the performance of buildings, in which more could be achieved with less in the use of advanced technology, and stated that you only need to weigh a building to know the state of technology it is built with.

Konrad Wachsmann's contributions were concerned with the use of modular systems and with bringing the science of industrialization into architecture (Figure 4.4). He advocated that architects should study and understand industrial methods of production, the behaviour of materials and the assembly of components.

Jean Prouvé was also dedicated to industrialized architecture and through his many projects, demonstrated the potential of lightweight structures and the applications for pressed metal components, extrusions

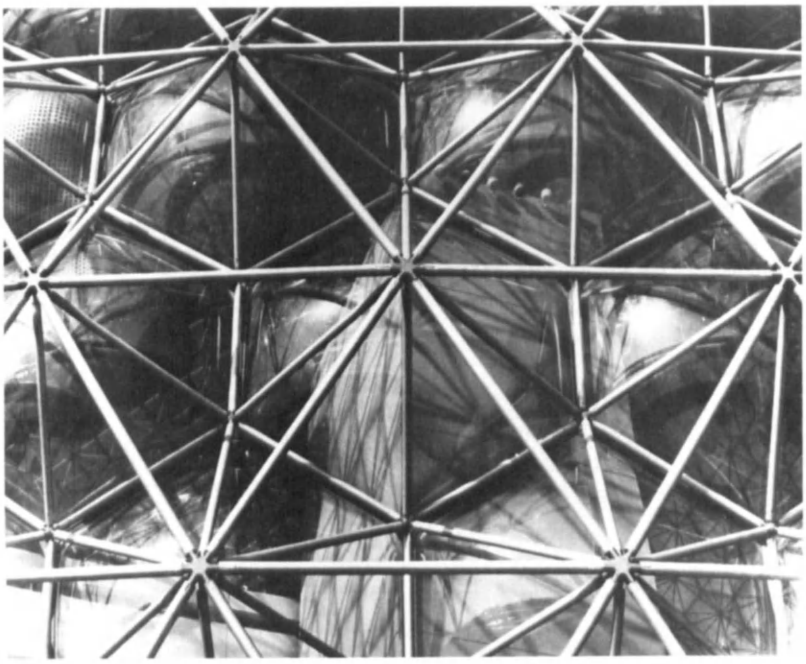
4.2
Interior of Charles and Ray Eame's House at Santa Monica constructed with off-the-peg components in 1949

4.3
Detail of the environmentally responsive dome at the Montreal Expo '67 designed by Buckminster Fuller with Geometrics Inc. and Cambridge Seven Associates (photo James Mellor)

4.4
Node detail of Konrad Wachsmann's steel space frame system in 1950s

4.5
Cladding mullion detail by Jean Prouvé in 1938–1939


4.2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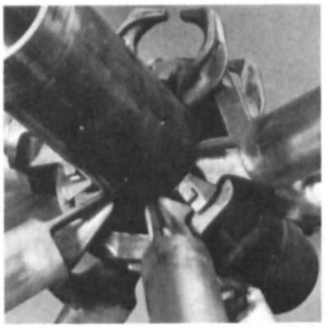
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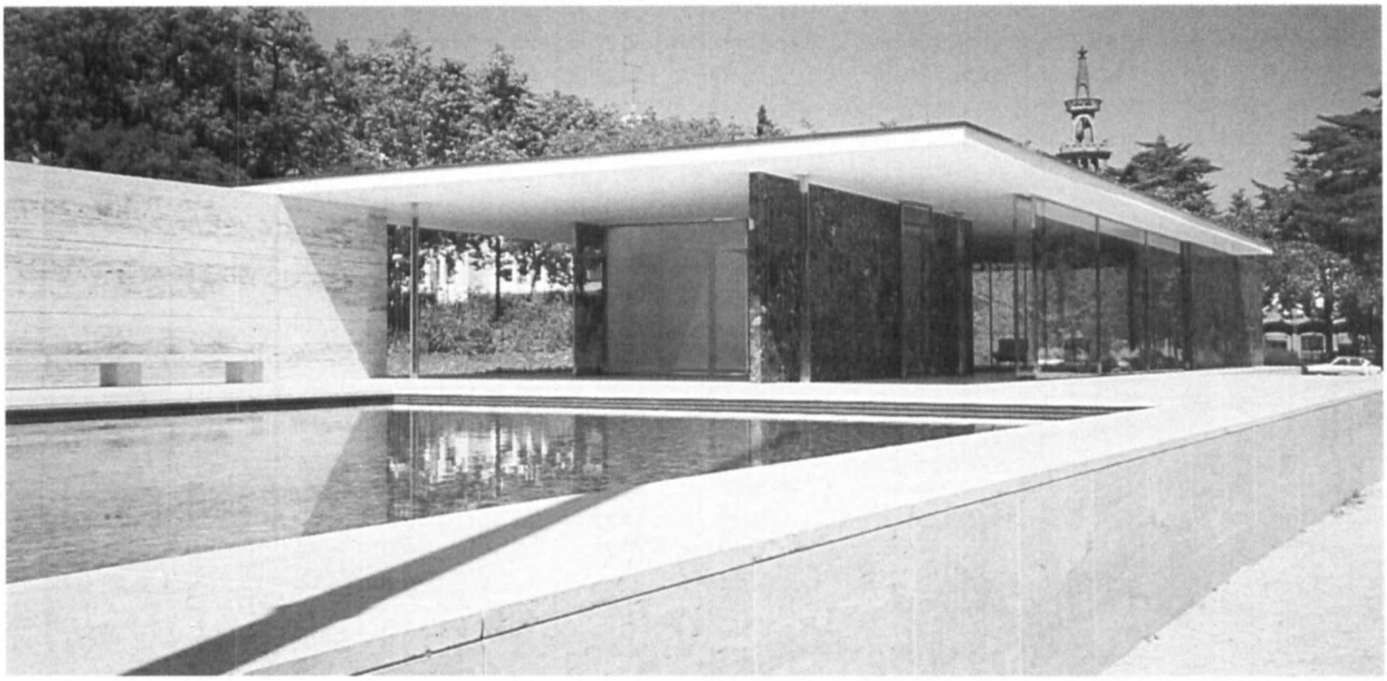
4.5

4.6
The Barcelona Pavilion designed by Mies van der Rohe in 1933, as re-erected 50 years later

4.7
Appleby Frodingham Steel Rolling Mills designed by Sir Frederick Gibberd in late 1940s with monitor lights and steel portal frame

4.8
Proprietary pitched portal frame as advertised by Conder



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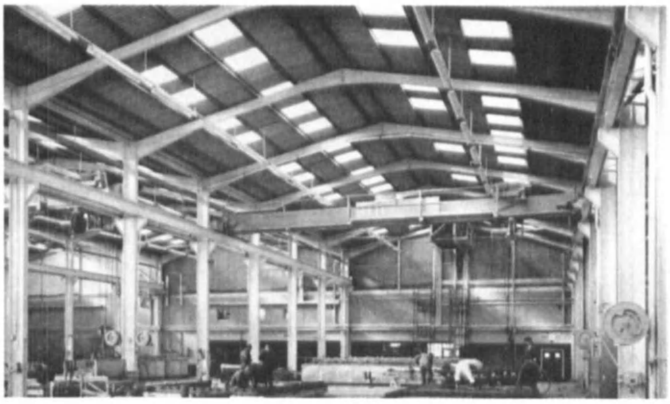


4.8

and fabricated panel systems (Figure 4.5).

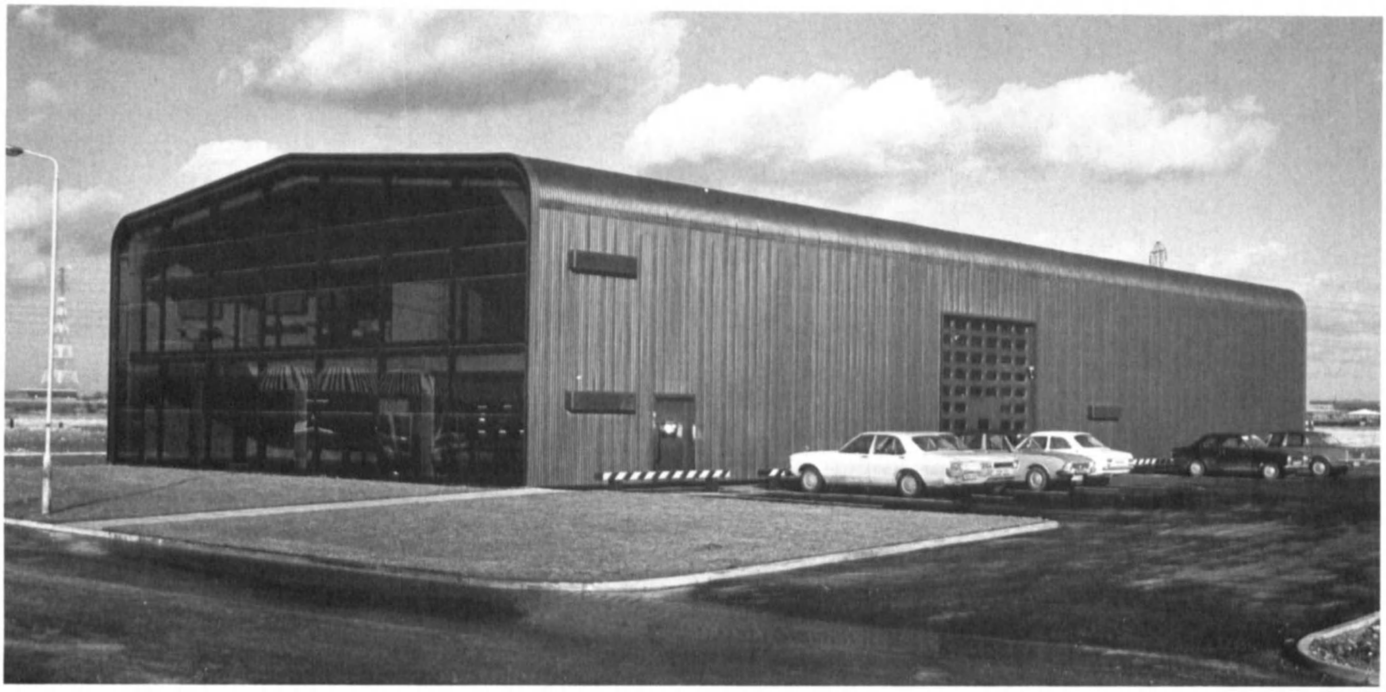
The work of these designers effectively brought the vocabulary of industrial production into architecture, whilst the work of *Mies van der Rohe* provided a major source for the aesthetic. His Seagram building in New York defined a vocabulary for the urban skyscraper whilst his Illinois Institute of Technology Campus influenced the design of both public buildings and industrial sheds. The skilful use of steel in the Farnsworth House, and the strong spacial forms of the Barcelona Pavilion (Figure 4.6) were also a great source of inspiration for architects. John Winter in his book *Industrial Architecture* identifies two buildings widely publicized in 1952: '...The Handkerchief Mill in Blumberg, Germany, designed by Egon Eiermann and the Dynometer building at the General Motors Research Centre, Detroit by Eero Saarinen. Both are framed in black painted steel and both have a precise industrial aesthetic derived from the work of Mies van der Rohe. Soon the influence spread, and many elegant square industrial buildings were built'.

The Extruded Shed

The extruded form of shed, which had been characterized in the pre-war factory by pitched lattice truss roofs, continued to develop after World War II with the introduction of the rigid portal frame. This was made possible by the development of structural welding

4.9
The Modern Art Glass office and warehouse designed by Foster Associates in 1972 with steel portal frame and wrap-around cladding

4.10
The Palmerston Infants School, Liverpool, designed by Foster Associates with simple multiple-span portal frame



4.9

4.10

techniques for steel frames, and precasting techniques for reinforced concrete. The rigid frame had several advantages over the fink or warren roof trusses for it no longer required a steep pitched roof, and the loading capacity could be increased economically. This provided greater flexibility for the design and the shape of the roof which led to experiments in north lights and monitor rooflights to achieve more even daylighting distribution.

An early example of this can be seen in the illustration of the Appleby Frodingham Steel Rolling Mills designed by Sir Frederick Gibberd in the late 1940s (Figure 4.7). Here the roof is shaped with a complex arrangement of monitor rooflights which provide good daylighting to the heavy engineering process.

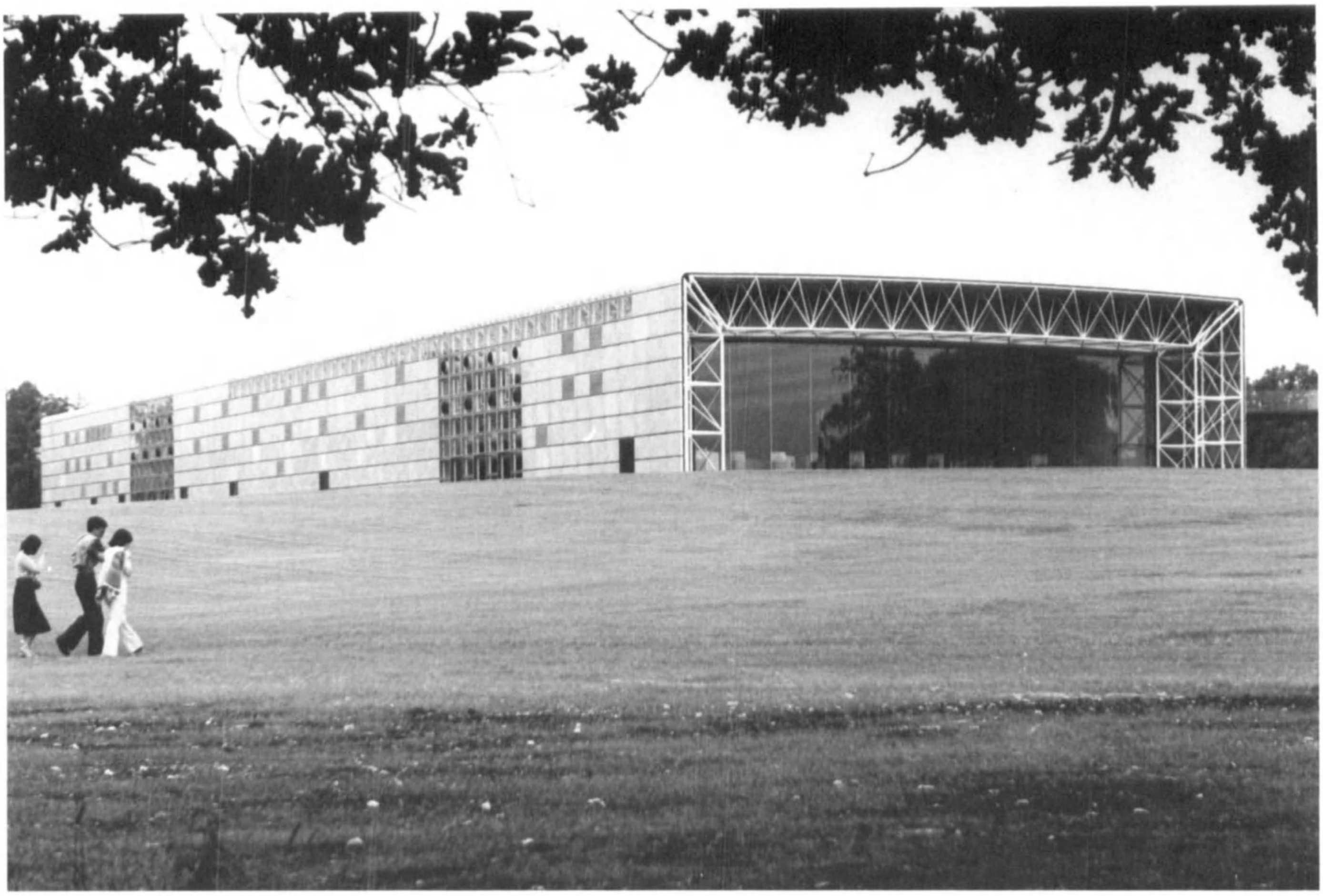
However, the more conventional form of shallow-pitched portal frame gradually became established as the standard form of factory shed in Britain. It was popularized by steel and precast concrete fabricators who offered package deals for design and build of their standard off-the-shelf sheds (Figure 4.8). The systems typically relied on a series of standard junction pieces onto which the required length of beam or column could be bolted in order to achieve the desired height and span. There is no limit to the length, which can be increased by simply adding more bays. This type of shed is fast to erect, economical and appropriate for housing storage facilities or simple production processes where the services are not complex.

In 1972 the architects Foster Associates used a low-cost pitched portal frame for their Modern Art Glass office and warehouse at Thamesmead and created an award winning piece of industrial architecture (Figure 4.9). The shallow pitched frame, painted bright yellow, was clad with bright blue corrugated aluminium sheeting which wrapped around the eaves and ridge with gentle rolled bends. The showroom was placed at one end with the office above, set behind an elegantly designed glazed wall which offered a view of the building in section. The clarity in expression of its form, precision of detailing and use of colour made an elegant building out of this simple form of shed, which was slightly reminis-

4.11, 4.12
The Sainsbury Visual Arts Centre at the University of East Anglia by Foster Associates with structure by Anthony Hunt Associates. A simple 'memorable' space measures 135 × 35 m with 7.3 m clear height (1978)

4.13
Norman Foster sketch of spatial arrangement in plan

4.14
Norman Foster sketch of spatial arrangement in section



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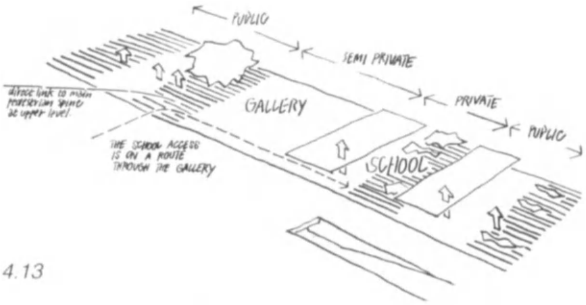

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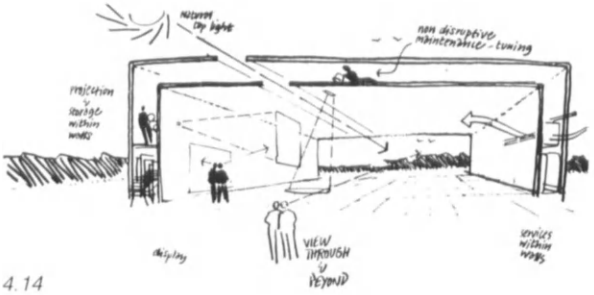


4.14

cent of the Model Factory at the Werkbund Exhibition in Cologne in 1914 (see Chapter 3).

The same architects used a lighter weight portal frame for the Palmerston infants school in Liverpool (Figure 4.10) and were later to progress the extruded form of shed close to its limits with the design for the Sainsbury Visual Arts Centre at the University of East Anglia.

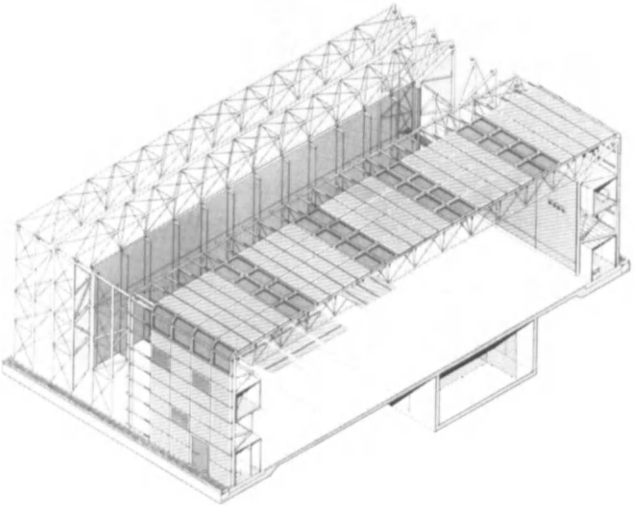
The Sainsbury Visual Arts Centre at the University of East Anglia

This building was designed to house the art collection of Sir Robert and Lady Sainsbury, together with the university School of Fine Arts, senior common room and restaurant (Figure 4.11). All of these activities are housed in the single 'memorable' space measuring 135 × 35 m with a clear height of 7.3 m in which there are two open mezzanines (Figure 4.12). The structure is a prismatic

4.15
Axonometric drawing of UEA showing the components assembly

4.12

lattice framework of 2.5 m triangular trusses of tubular steel spanning onto triangular towers of the same depth. It is clad on the outside walls and roof with a modular moulded aluminium panel system and on the inside by a system of fixed and movable perforated louvres, creating a service zone between the skins. With the ends fully glazed, the enclosing envelope is perceived as a breathtakingly simple extrusion, its proportions being large enough in scale to create the awe-inspiring spatial quality of the best airship hangar but with the refined detailing and finishes of a quality building. Every aspect has been carefully considered, refined and executed with the utmost precision. The plan is simple and so correct that it is hard to imagine it any other way yet it has the flexibility for a complete change of use should this ever be required (Figures 4.13, 4.14). Its relationship to the landscape is sensitive and carefully contrived to open up the best views in each direction from the end glazing.

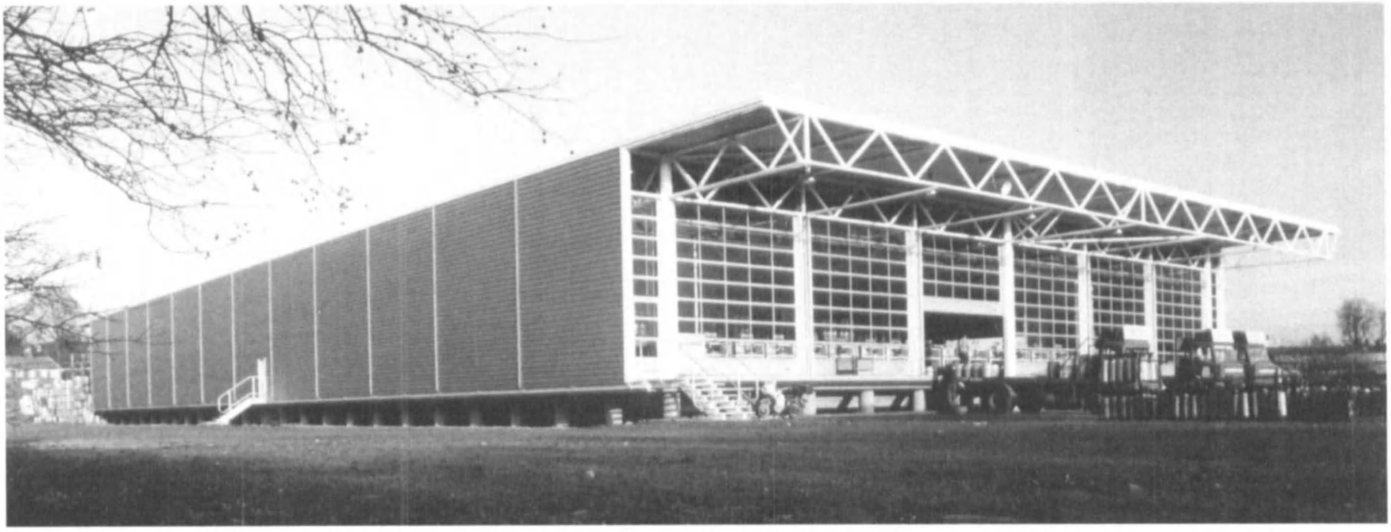


4.15

4.16
New Draught Beer Department for Greene King Brewery at Bury St Edmunds by Michael Hopkins Architects (1979)

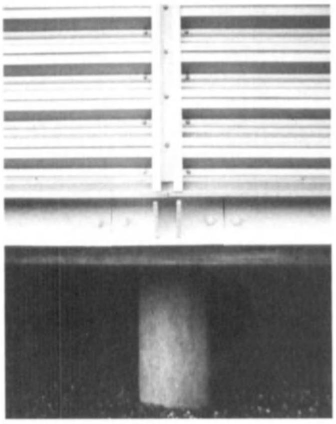
4.17
Cladding detail to Greene King designed by the author for Michael Hopkins Architects with extruded aluminium top-hat section on joint lines between panels of horizontal profile steel sheeting

4.18
Plan of Greene King Brewery is a diagram of the process housed within the building



4.16

The structure by Anthony Hunt is visually pleasing, economical and exceptionally efficient in that it also provides a wrap-around service zone for plant, services and back-up facilities such as toilets, stores and darkrooms (Figure 4.15). Peter Cook described this in the *Architectural Review*, December 1978 as: 'the conceptual key . . . a 2.5 m extrusion that forms the wall and roof. It is constant and all providing. The more ubiquitous it becomes, the more potential it has to eliminate the need for small rooms and special occurrences. It renders this building as the second generation of the well-serviced shed, where cubicles, capsules, things dangling down from the roof and crawling across the floor are apparently



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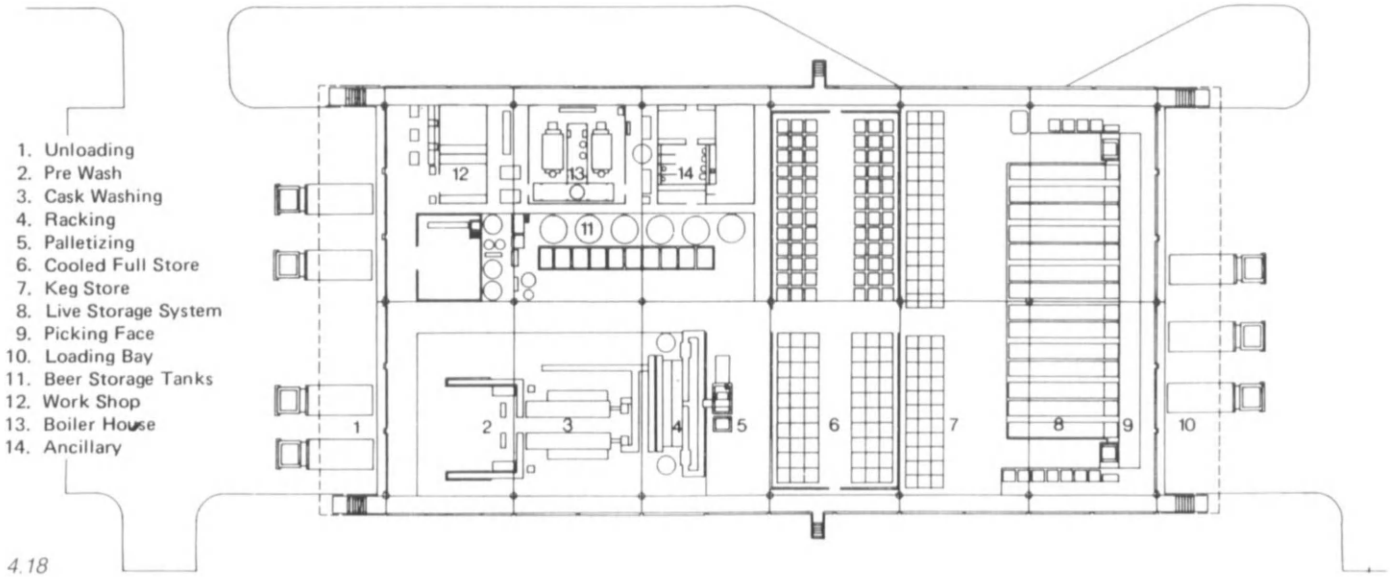


4.18

eliminated, or rather reduced to the status of apparatus within the membrane'.

The interior space is pure and appropriately neutral with excellent daylighting from the extensive rooflights which shimmers through the automatically controlled louvres. Suzanne Stephens wrote of it in *Progressive Architecture* February 1979 that: 'the ceiling becomes Foster's tour de force. One's eye is constantly pulled up and out by its horizontal stretch of layered planes. The transparency, and translucency created by the filigree of ceiling louvres, structure, ducts and catwalks, with strips of glass and aluminium panels above, skilfully mesh to a work of art'.

It is an exciting, glamorous and thoroughly modern building, which manipulates technology to create pure space, form and light. Stephen Gardner wrote of it in the *Listener*: 'This shimmering structure of superplastic aluminium whistles past the grim cement grey of the University buildings like the Paris to Marseilles Mistral Express, immaculate in its pure green landscape' and Alistair Best in the *Architects Journal* 1982 described it as 'the last word in sleek sheds and the end of the line for that particular form'.

However, whilst it is unlikely that a building of similar quality will ever be built in this form, it is not the end of the line for the extruded shed. Other successful solutions have been achieved for different uses, different budgets and in different locations.

Greene King Brewery, Bury St Edmunds

The Michael Hopkins Architects design for the Greene King Brewery in Bury St Edmunds which was completed soon after the Sainsbury Centre is a good example (Figure 4.16). This is a tough, industrial building for the washing, racking (filling), storage and distribution of beer casks, sited in the flood plain of a river behind the main brewhouse. Here, the building layout is a simple diagram of the process which it houses, with the delivery of returned empty casks to one end, which travel by conveyor to be washed, racked and palletized (Figure 4.17). Full pallets are transported by fork lift truck to a cooled store before being transferred to the live storage (conveyor) system at the other end of the building, for loading onto the dray vehicles and distribution to the pubs.

This building received several architectural awards in recognition of the care and attention to detail that went into each element of the design. For instance, the low-budget profiled cladding (Figure 4.18), which is thoroughly appropriate to this type of building, has been modulated into 4 m wide bays with the use of a specially extruded top-hat section and immaculately detailed down to the placing of the screw fixings. This same cladding is consistently used throughout for all the interior and external surfaces of the main enclosure except for the ends of the building which consist of a battery of purpose-designed glazed up-and-over doors. These elegant doors, which are electrically operated, give clear access to the loading bays and provide good daylight whilst the beer is protected from the sun by the overhanging canopy.

The building services and process pipework are all distributed within the 1.4 m deep steel lattice roof trusses and drop to their required locations on specially designed aluminium ladders. Another special feature is the raised base slab, which was designed to avoid the risk of flooding from the nearby river but which also relates to the tailgate height of the dray vehicles.

Patera Building System

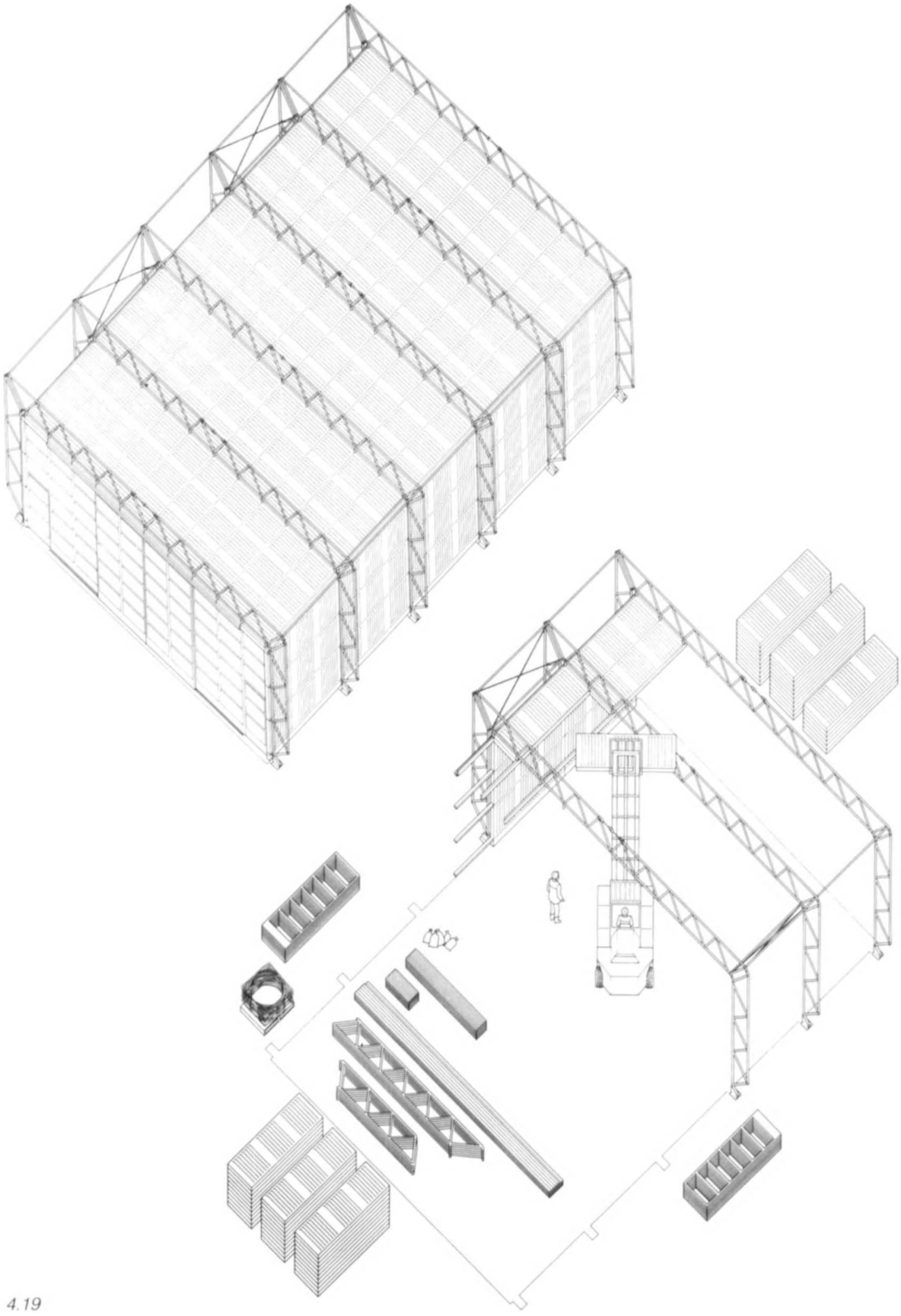
The same architects went on to design the interesting Patera building system for use as nursery industrial units (Figure 4.19). This system of tubular steel trusses and composite steel panels with glazed end walls could be erected in 10 days by a team of three to four men and fork lift truck. It placed the structure on the outside of the cladding to provide a clean internal shell with maximum flexibility of use, and had the added advantage of preventing the Building Regulations' requirement for fire protection for buildings located close to site boundaries.

B + B Italia Office Building

The concept of the 'contained space', clear of structure was used earlier by Mies van der Rohe on the Crown Hall at IIT in Chicago, where the black painted girders were placed on the outside of the skin and in England at the Wills Tobacco Factory where the external Corten steel lattice trusses spanned 90 m. Whilst it can be seen that there are many advantages to this approach, it does, however, create a weathering problem for the roof penetrations which has deterred all but the ardent technologists from following this course.

This problem was overcome in the B + B Italia office building at Como, Italy, by Piano Rogers with a double roof construction (Figures 4.20, 4.21). Here the structure and services are protected from the weather and kept independent from the 'contained space' which is left free

4.19
Patera System, components assembly drawing by Michael Hopkins Architects structure designed by Mark Whitby working with John Pringle



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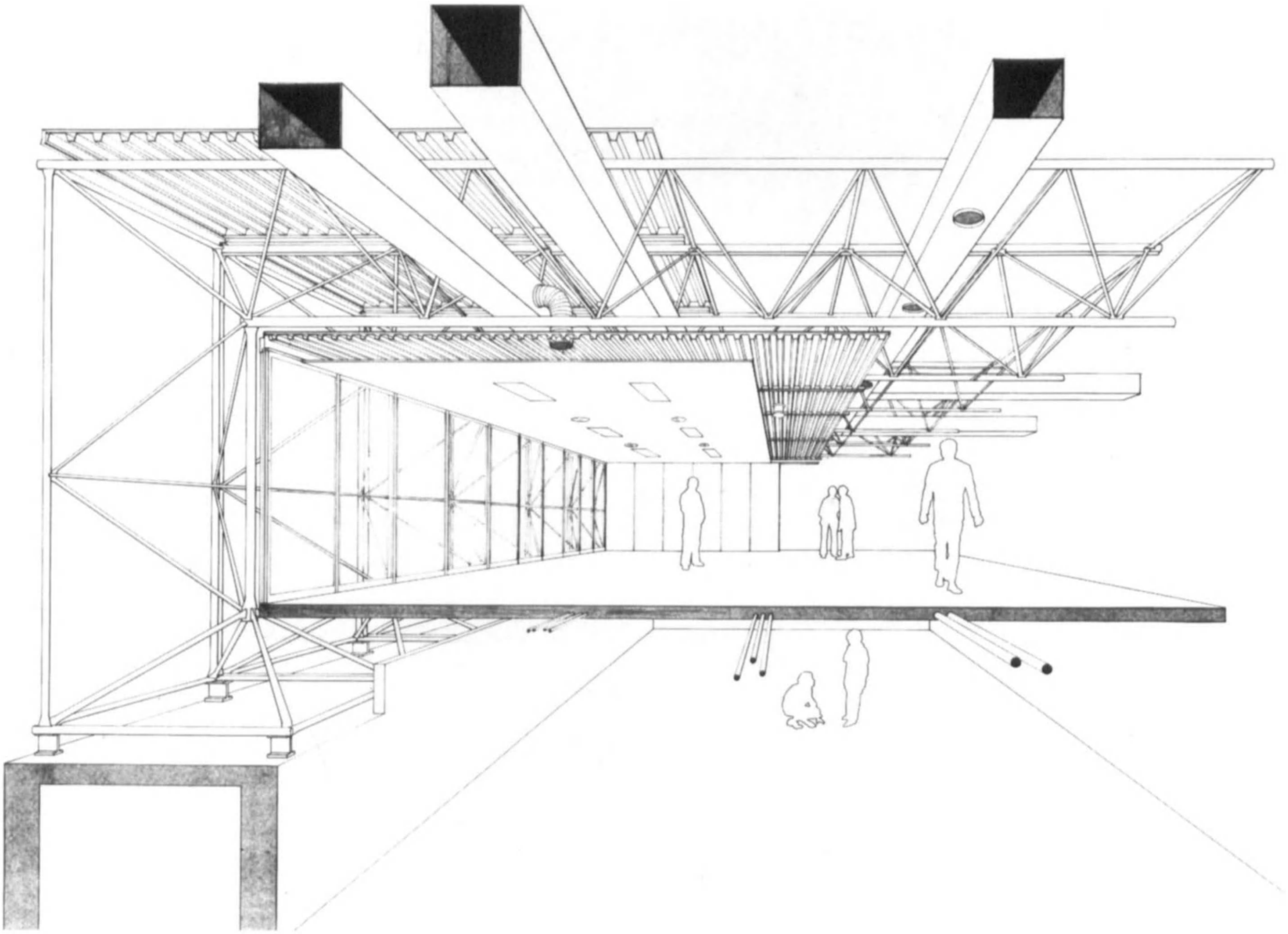
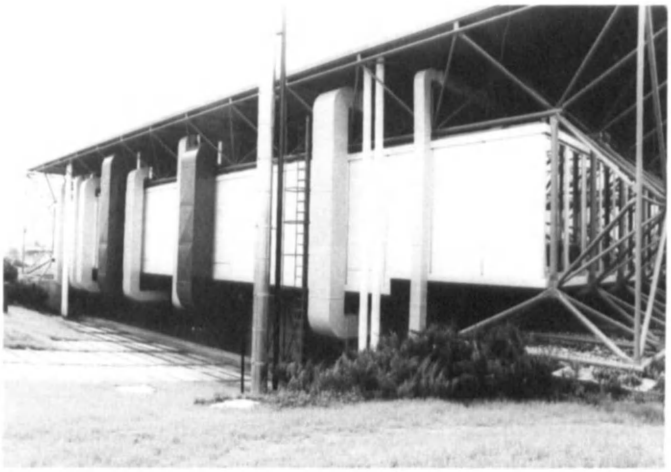
4.20, 4.21
B + B Italia Office building at Como, Italy, by Piano Rogers, has uninterrupted 'contained space' with wrap-around space frame structure (1973)



4.20

and adaptable to changing organizational requirements. The structure consists of tubular steel three-dimensional portal frames spanning 30 m, off which the office container is suspended and provides a zone for the main services above and below the container. This building from the same team that designed the Centre Pompidou in Paris, makes a clear, uncompromising statement of separating the two main elements of structure and services from the spatial enclosure.

Another structural form which has been used successfully for the extruded shed is the arched barrel vault, like many of the early railway station roofs, such as Paddington and St Pancras, which were constructed with great arched iron trusses tied at the base. Towards the end of the nineteenth century the first pinned arched structures, such as the Galerie des Machines for the 1889 Paris

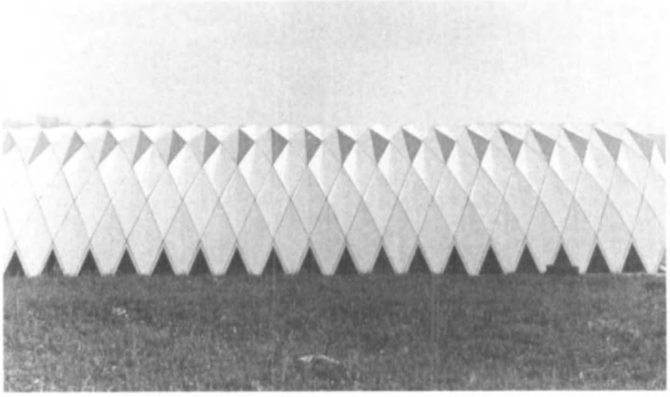


4.21

4.22
Woodworking Shop in Genoa, designed by Renzo Piano with folded steel plate structure construction in 1960s

4.23
Mobile structure for sulphur extraction in Pomezia, near Rome, designed by Renzo Piano with reinforced polyester panel system

4.24
Immaculately designed IBM aluminium connector detail for the laminated timber members



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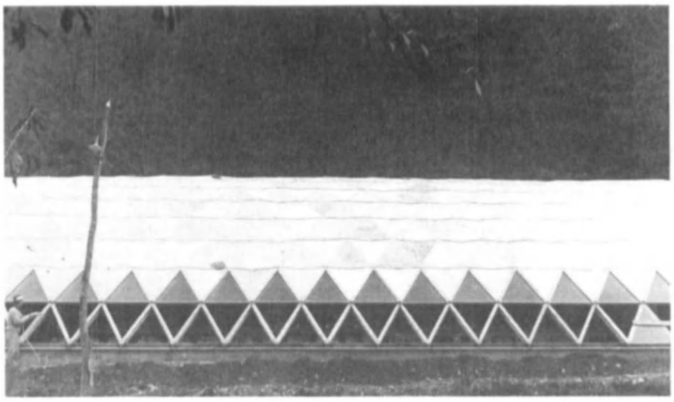


4.23

Exhibition, were introduced with the advantages of easier construction, and being statically determinate so that the stresses in it and the reactions at the supports could easily be calculated. Elegant parabolic three-pinned arched structures were later used for the aerodynamic airship hangars in Germany and the USA. Freyssinet and Nervi both used concrete vaulting for hangars and this principle of arched vaulting has continued to be used to provide an economical form of extruded enclosure.

Woodworking Shop, Genoa

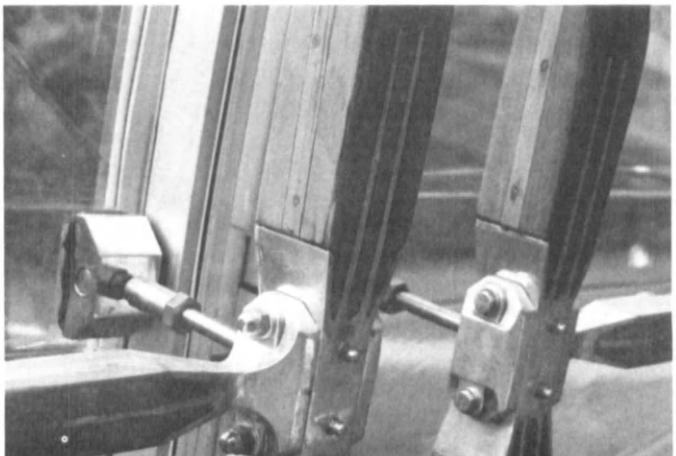
The Italian architect Renzo Piano, whose name constantly appears in this book as a great innovator, researched the use of vaulted structures to provide minimum cost industrial shelters in the 1960s. He first produced a folded steel plate structure for a woodworking shop in Genoa, using automotive industry production techniques (Figure 4.22). Rolls of sheet steel were automatically cut to length and brake pressed to form each of the five folds. Each element, weighing 25 kg could easily be assembled so that a 100 m^2 enclosure could be constructed by two men in one week.

Sulphur Extraction Structure, Pomezia

A similar principle was used for a mobile structure for sulphur extraction in Pomezia near Rome, only this time a lightweight reinforced polyester panel system was used which had the advantage of being naturally lit through the translucent panels (Figure 4.23). Here, the panels had steel bolted connections at the edges and a steel reinforcement strip to aid dimensional stability, the structure being made up of three arches, two diagonals along the panel joint lines and one along the fold in each panel.

IBM Travelling Technology Exhibition

In 1982 Renzo Piano returned to this vaulted form for the structure of the IBM Travelling Technology Exhibition. Working with Peter Rice of Ove Arup and Partners as the structural engineer, he designed an elegant, lightweight, demountable structure, using shaped laminated timber beams with polished cast aluminium connectors to support the polycarbonate sheet pyramids which formed the enclosing skin (Figures 4.25, 4.26). This 50 × 10 m structure had to be light in weight for transportability as well as being easy and quick to erect and dismantle for it was to travel around to all the major cities in Europe in 18 purpose-built trucks with only three weeks allowed for its erection in each place. The concept was so fresh and exciting that it appealed to a much wider range of people than most modern buildings. The use of materials and detailing of connections was innovative and pleasing.



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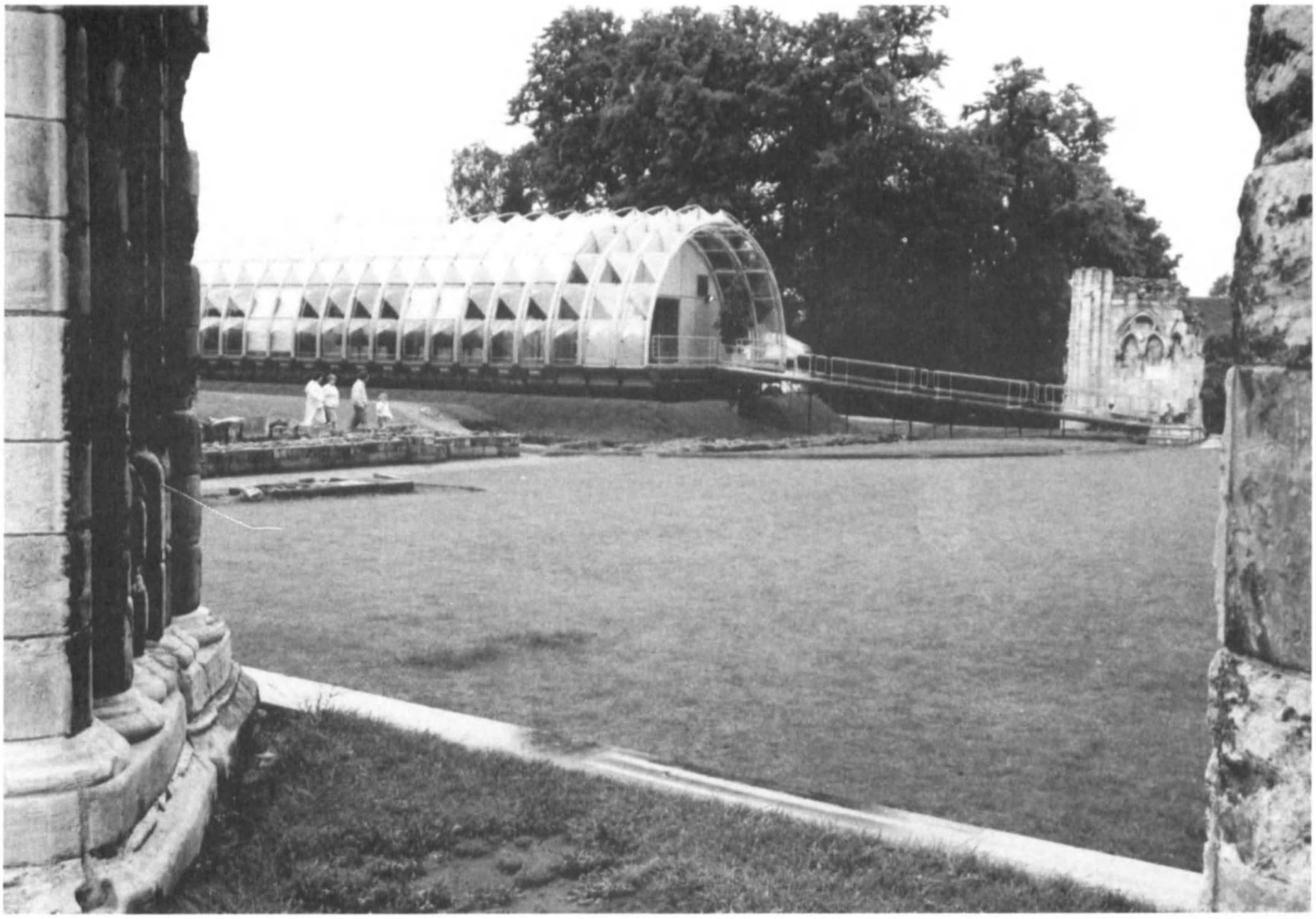
4.25
IBM Travelling Technology Exhibition designed by Renzo Piano, as erected in York with landscaping and site supervision by Chris Wilkinson Architects

4.26
Exterior of IBM TTE as erected in London showing the polycarbonate pyramid and laminated timber arches with polythene sheet gutters, supported on a raised steel floor structure with adjustable jacks

4.27
Interior of IBM TTE with planting and extra shading devices. The interior span is 10 m



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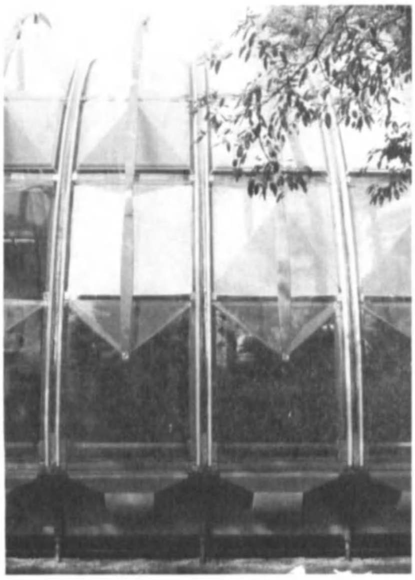

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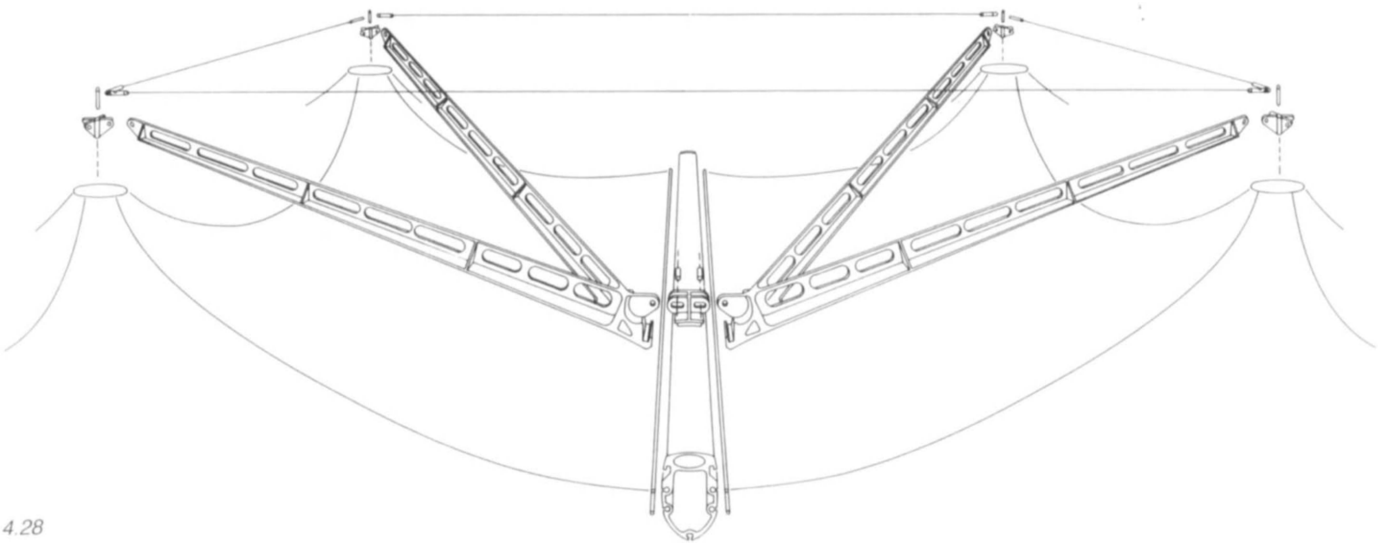
4.28, 4.29
Glasgow Eurodome Competition entry by Aidan Potter and Stephen Pimbley with engineering by Neil Thomas of Atelier One



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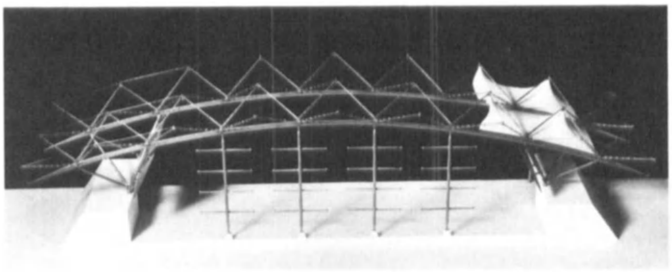

4.29

Reyner Banham wrote: 'This object is a work of architectural art in its own right, the complexity of its functions and connections is an architectural composition richer than many complete buildings'.

Cardiff Bay Visitors' Centre

The extruded form of shed has consistently been adopted for a wide range of uses and has been modelled by successive designers to suit their own specific requirements. A particularly innovative interpretation has recently been completed by Alsop, Lyall and Störmer for the Cardiff Bay Visitors' Centre (Figure 4.30).

Here the architects, working with the structural engineers Atelier One, have used a complete wrap-around oval section for the long vaulted structure, constructed of plywood panels bolted on to mild steel ribs. A fabric membrane provides the watertight skin around the plywood, out of which shapes are cut in an unusual pattern to admit light. The whole structure is raised off the ground on a steel undercarriage and the simple clear form of the building makes a dramatic appearance in the Cardiff Bay dockland setting.

Architects often say that their best designs never get built, and certainly there are many exciting schemes that remain on the drawing board which often incorporate the more innovative ideas. Two such projects are the Glasgow Eurodome competition entry by Aidan Potter, Stephen Pimbley and Neil Thomas and the Future Systems Project 115 for an industrialized unit.

Glasgow Eurodome

The young team of architects Aidan Potter and Stephen Pimbley working with the engineer Neil Thomas proposed an interesting structure for the Glasgow Eurodome Competition of extruded aluminium yacht mast sections for the main beams supporting cast aluminium purlin wings which are pretensioned with stainless steel rigging (Figures 4.28, 4.29). This lightweight filigree structure was designed to span the 36 × 100 m space with a shallow curve on triangulated supports. An enclosing membrane of two skins of pvc-coated polyester is attached to the main beams and hung from the purlin wings.

Future Systems Industrial Unit Project 115

The above project uses yachting technology to create a high performance lightweight structure. The Future Systems Industrial Unit Mark 3 (Project 115) is one of a series

4.30
Cardiff Bay Visitors' Centre by Alsop, Lyall and Störmer, with engineering by Atelier One

4.31
Mark 3 Industrial Unit (Project 115), designed by Future Systems, investigates the use of alternative technology to create a high performance lightweight building structure

of projects where they have investigated 'transfer technology' which is the use of other forms of appropriate technology in buildings (Figure 4.31). Here they have proposed a standard interlocking aluminium deck, normally used for emergency aircraft runways, in place of oversite concrete for the base. The arched enclosure is built from standard 'Trusscore' sandwich panels with integral stiffening and insulation. The panels are formed into a three-pinned arch with rigidity introduced by outrigger tension cables support. Accommodation including plant and offices is provided in groups of standard American Army Portacabin-type containers located alongside the main enclosure and the windmill generator is intended as a supplementary power source. The technology for this project is all available and it could easily be realized for an enlightened client with the right backing.

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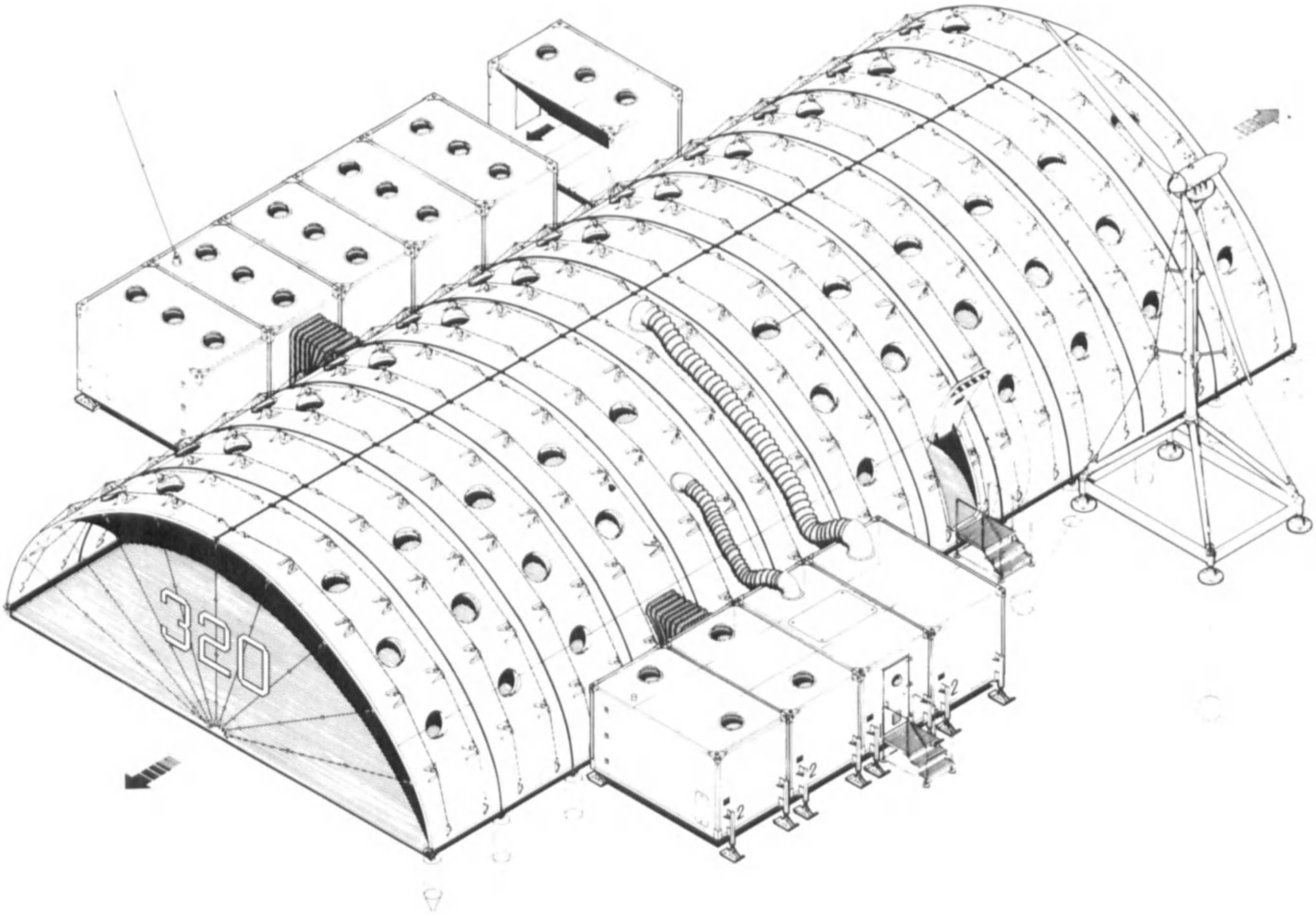

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4.32
An early Skidmore, Owings and Merrill steel and glass box house. The Republic Newspaper Plant at Columbus, Indiana, with functions on display

4.33
Manufacturing plant for Portable Power Tools at Wheeling, Illinois, designed by C.F. Murphy Associates in 1964 with Miesian use of black steel frame with brick and glazed infill

4.32

4.33

The Cool Box

The name describes the form of flat-roofed shed designed on a rectangular grid of multiple spans which is characterized by the refined and understated details of Mies van der Rohe. It originated in the USA with the wartime black-out factories where deep plan, windowless spaces were built for aircraft and armaments manufacturing. High levels of productivity were achieved in a totally closed environment with the aid of good artificial lighting and air conditioning (see Chapter 3). This led to experiments, after the war, with the 'Windowless Factory' which negated the traditional pitched roof and sawtooth configuration for north light glazing.

Of course, these flat-roofed sheds did not have to be windowless and social concern for the possible psychological problems of the occupants led to the reintroduction of external glazing. However, with the growing dependence on mechanical and electrical services, the flat roof provided a reduced volume to ventilate, with a lower headroom and flat soffit height for even lighting and easier services distribution.

Analysis of economic structural forms in the early 1960s led to the design of various forms of square and rectangular column grids, ranging from 10 to 18 m using either universal rolled steel sections or open web lattice trusses spanning onto steel columns.

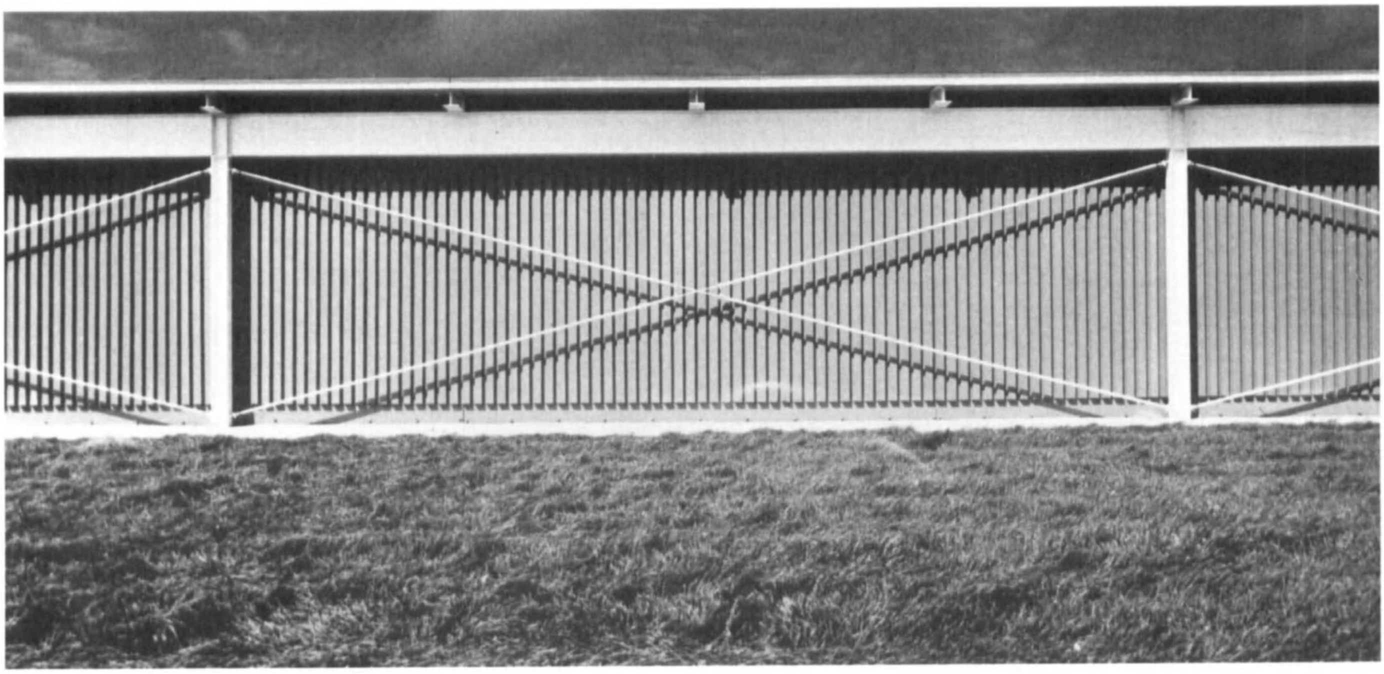
In America in the 1960s, Myron Goldsmith, partner in charge of design at Skidmore, Owings and Merrill, progressed the design of the flexible shed with a series of buildings taking the steel frame to the outside of the factory skin in order to express the structure more clearly, as can be seen in the design for *The Republic Newspaper Plant* at Columbus, Indiana (Figure 4.32). This crisply detailed steel and glass box, houses the printing presses, administrative offices and cafeteria under the same roof, and all these functions are on display, through the glazed skin. The printing machine is allowed to become a major visual element in the design like a piece of sculpture, whilst the exposed steel frame extends the industrial image throughout the building, even into the carpeted areas.

Also from Chicago, the architect C.F. Murphy designed an elegant manufacturing plant for *Portable Power Tools*, Wheeling, Illinois in 1964, along Miesian lines with an exposed black painted steel frame with brick and glazed infill (Figure 4.33). This large rectangular building measuring 146 × 43 m on a square grid of 14.63 m (48 ft) also houses all of the company's functions under the one roof and allows greater flexibility for

4.34
Reliance Controls Ltd plant at Swindon in 1965 by Team 4 pioneered the clear expression of structure in this country

4.35
The Cummins Engine Company plant at Darlington in 1966 by the American architects Roche and Dinkeloo, uses Corten steel in an expressive manner

4.36
Craig Ellwoods's design for SDC Electronics Co. at El Segundo, near Los Angeles in 1961 was an important influence on other architects at the time



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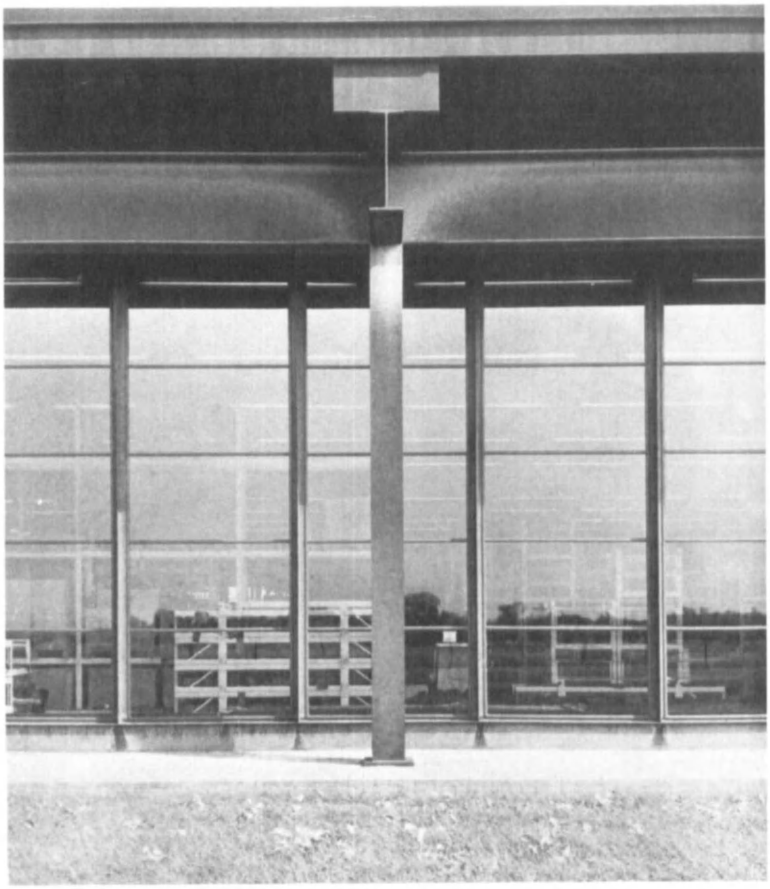

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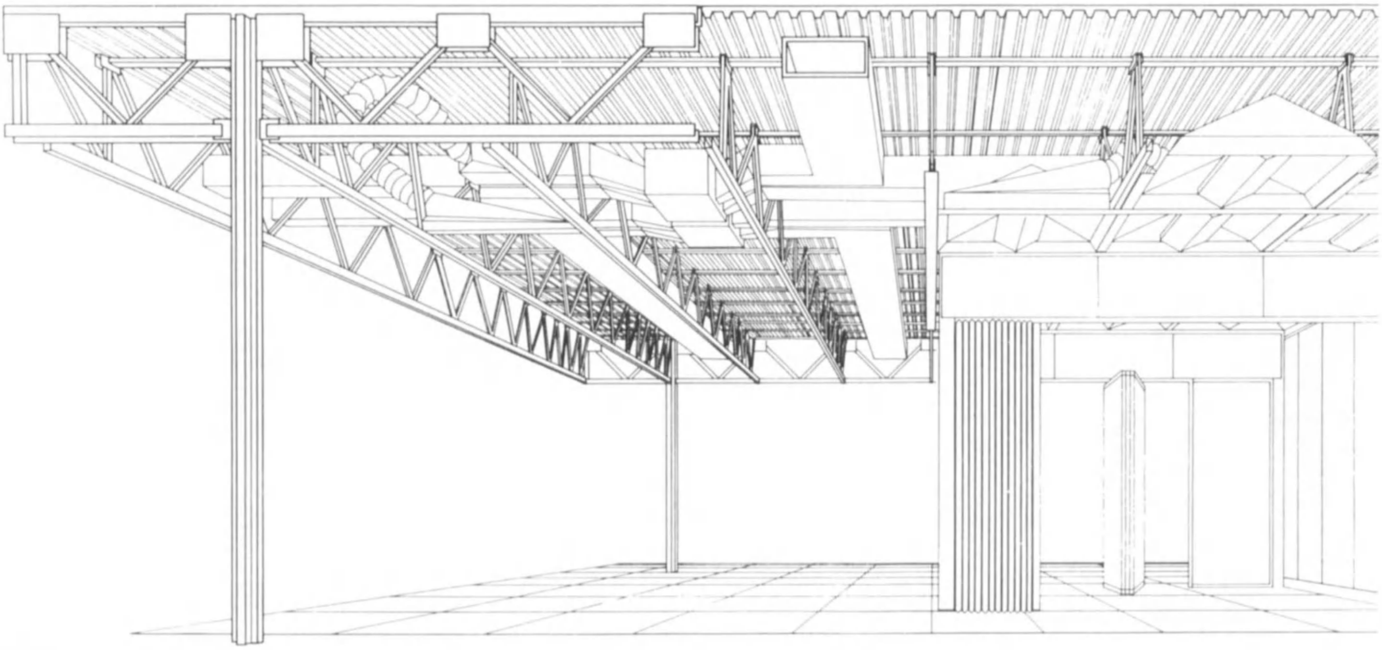
4.37
The SCSD System for the California School building defines the four major elements of structures; roof, deck, services and partitions

4.40
Advanced Factory Unit design at Milton Keynes



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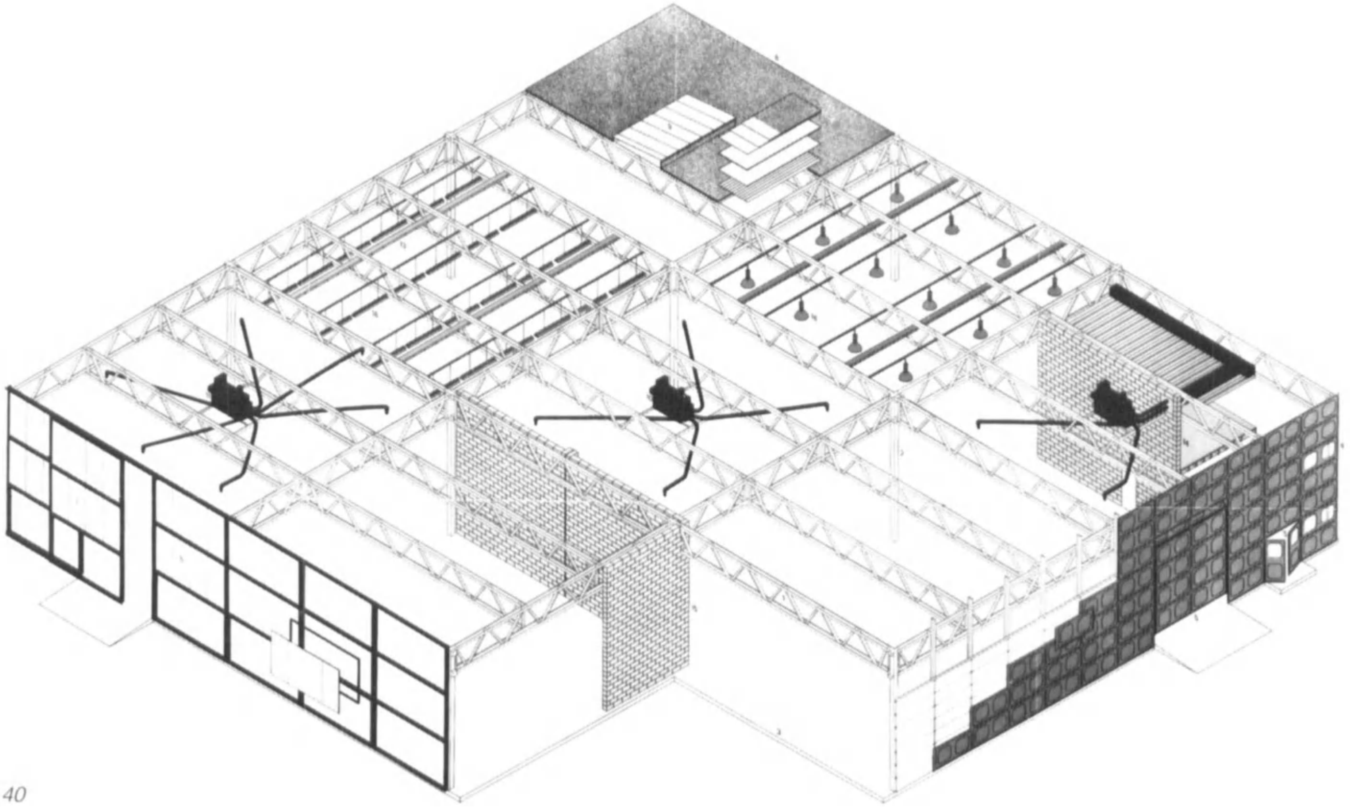


4.40

changes of layout.

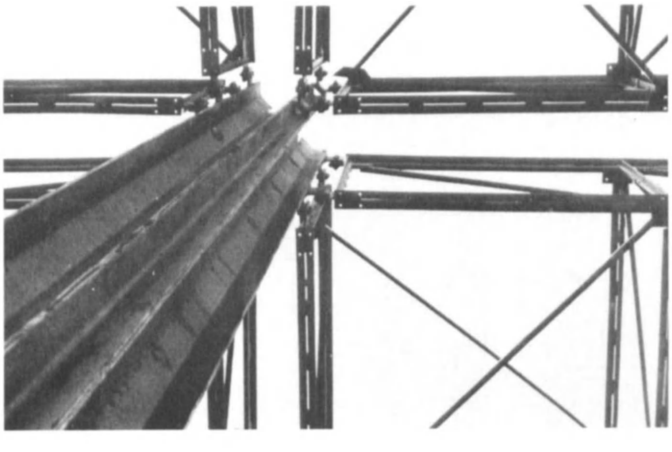
In Britain in the mid-1960s, two fresh new industrial buildings progressed this approach with a new vigour and expression, hitherto unknown in this country. These were, the building for Reliance Controls Ltd at Swindon, designed by Team 4, and the factory for Cummins Engine Co. at Darlington by Kevin Roche and John Dinkeloo Associates.

In 1965 *Reliance Controls Ltd*, manufacturers of electronic equipment, needed to start production as quickly as possible and their brief to the architects was to design a low cost, flexible building which could be completed in under 11 months. This was achieved with an elegant and practical solution by the architects Norman and Wendy Foster, Richard and Su Rogers working with the structural engineer Tony Hunt (Figure 4.34). The steel frame of welded I-beams supported on a 12 × 12 m column grid, is expressed throughout for visual clarity and provides a flexible space. Purlins at 3 m centres support the flat, lightweight steel trough roof-deck; the exterior skin is constructed with vertical profiled steel sheeting and patent glazing, set back from the structure, and wind bracing on the external columns has been used for visual effect. In this building, all the major elements are clearly legible and carefully detailed, resulting in a straight forward and apparently effortless appearance.

The English base for the American firm, *Cummins Engine Company* was constructed on a slightly higher budget, but also provides an elegant yet economical solution. This large building houses 14 678 m^2 of production space as well as administrative, drawing office space, and the usual amenities under the one roof (Figure 4.35). The same structure was used for all these activities, in order to provide the maximum flexibility, so that one space could change with another as and when required. All areas are air conditioned, with roof-mounted units, each of which handles six structural bays. The structure is of welded I-beams supported on a 9 × 18 m column grid, and each purlin is spaced off the primaries to allow space for services distribution. The steel used is an oxidizing type, which is left unpainted to form an even coating of rust. This was a natural choice for Roche and Dinkeloo as they had formerly been associated with Eero Saarinen, who had pioneered the use of Corten steel in buildings. Steel and glass are the major elements of this fine building and the steel is exposed throughout for visual expression. The exterior skin is completely glazed and set back from the structure, serving to enhance it. Neoprene gaskets support the horizontal bands of glazing between the steel mullions which are special at 1.8 m centres.

Craig Ellwood's design for *SDC Electronics Company factory* at El Segundo near Los Angeles in 1961 used a different structural and architectural vocabulary for a similar function. This huge building, measuring 170 × 142 m, has a lightweight steel lattice-truss roof structure on a 14.63 m square column grid (Figure 4.36). The perimeter columns are placed on the outside of the external walls with the trusses passing through glazed slots between concrete cladding panels. In this way the structure adds visual interest to the otherwise plain elevations and it has the advantage of making future expansion easier without disruption to the building. The detailing of these few elements is immaculate, with steel cruciform columns, made up of welded I-sections and neat truss connections. The 150 mm precast concrete panels were cast in steel channels which were left in place to ensure a high degree of dimensional accuracy.

4.38, 4.39
The USM-Stahlbausystem Haller designed by Bruno and Fritz Haller in the 1960s is based on a 14.4 × 14.4 m grid of steel trusses supported on four columns



4.38

4.39

4.41
The Ford Parts Redistribution Centre at Brownstown, Michigan designed by Albert Kahn Associates in 1970 measures 550 × 500 m without any daylighting and is believed to be the world's largest building in terms of ground area covered

Systems Approach

In the same year, Ezra Ehrenkrantz designed a system for Californian school buildings using a similar steel structure of flat lattice trusses on a square column grid (Figure 4.37). The *SCSD system* of four elements (structure and roof deck, air conditioning, lighting and partitions) provided a means of integrating structure and services, leaving the architecture free to control the appearance and finishes. In many ways it progressed some of the ideas from the *CLASP* system for Hertfordshire schools which had been developed in 1948 to provide a fast and economical means of providing new schools to cope with the post-war birth rate bulge.

The Ehrenkrantz system was extremely successful in California and the influence of the 'Systems Approach' spread to Europe. In Switzerland, in the 1960s, the architects Bruno and Fritz Haller, developed an integrated structural steel system specifically for industrial buildings. They had been commissioned to design a flexible office furniture factory for U. Scharer's Sohne AG at Munsingers, of economic construction which could be assembled quickly to reduce the high labour costs. Based on a 1200 mm module for horizontal and vertical dimensions, they developed a system of structural frame with integrated components for roofing, cladding and services. The system, known as *USM-Stahlbausystem Haller* is manufactured by Scharers and has been used on a number of other projects (Figures 4.38, 4.39). The basic unit is a 14.4 × 14.4 m grid of steel trusses 1.2 m deep and supported on four corner columns. These support the roof of 4.8 × 4.8 m lightweight concrete slabs, and are designed to take 2-ton craneways in either direction, as well as containing all services distribution within the depth of the trusses. The columns are constructed of four structural angles, which are open in the centre and accessible from all four sides for mounting the roof trusses and fittings. The cladding is of solid or glazed panels 1.2 m high by 2.4 m mounted onto structural steel 'T' sections which also serve as wind bracing.

In general, it was a well worked out system of high technical competence and flexibility. Although economical in design, it was not cheap and one might suspect that this is the main reason for its somewhat limited application in other countries.

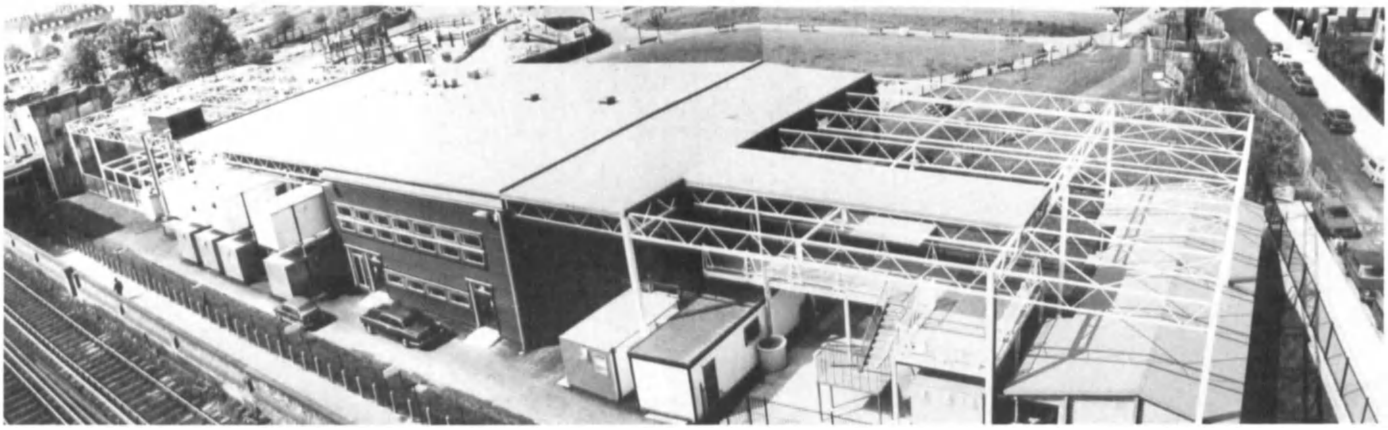
No system has really succeeded in achieving universal application, although the fundamental principles of modular construction and systems co-ordination have become integrated into general design practice. Perhaps this is because architects tend to prefer designing new systems rather than designing with systems.


4.41

At the outset of the new town of Milton Keynes, in Bedfordshire, much careful thinking was put into the design for a standard *Advanced Factory Unit* versatile enough to house almost any small industrial process. Inspired by the 'systems approach', the Milton Keynes Development Corporation architects designed a system for a basic shell with optional 'packages' to tune it up to the customer's requirements (Figure 4.40). A 12 × 12 m structural grid was chosen for maximum flexibility, with secondary trusses at 4 m centres to support the flat roof deck and services. The 1200 mm deep lattice trusses were designed to carry services and air-handling equipment within the roof zone. A clear height of 5.5 m below the bottom boom of the trusses provided generous working height for fork lift trucks, most machinery in common use, and the facility for mezzanine level offices. Various cladding options were offered in pressed steel, GRP or glazing, to suit the function and budget.

This was a brave attempt to provide the optimum factory shed, and to demonstrate its flexibility, the corporation architects used the prototype for their own offices. With this type of building, it is the structure, which more than any other element, decides the degree of flexibility for the building. The choice of column grid, span and beam depth relate to a compromise between function and economy. Generally spans of 12 m would be considered near the minimum to give flexibility of layout for any production line or storage process. Spans of 18–20 m would normally be preferred and can prove to be as economical. It is also an important consideration that 18 m trusses are the largest which can be fabricated in one length and easily transported by road. Larger spans are essential for some functions and can be

4.42
Cedric Price's Inter-Action Centre, Kentish Town, provides a steel structure under which activities and events can happen



4.42

economical, especially with space grids and tension structures but they restrict expansion to large increments.

The *Ford Parts Redistribution Centre* at Brownstown, Michigan, designed by Albert Kahn Associates in 1970, uses a column grid of 18 × 15 m with 2 m deep steel lattice trusses to cover a floor area of 71.16 acres (Figure 4.41). It is believed to be the world's largest building in terms of ground area covered, and the dimensions of the main part of the building exceed 550 × 500 m with no daylighting. Unitary heating and ventilation packs are mounted on the roof, and all services are distributed within the structure. Conveyor systems have been kept independent from the main structure in order to save costs for with such a vast structure, the engineers calculated that 'one unnecessary pound of steel per linear foot could result in an excess of over 5 tons for the job'.

In contrast to this building, which provides a large flexible space of little architectural interest, Cedric Price's *Inter-Action Centre* in Kentish Town makes an important architectural statement concerning flexibility (Figure 4.42). He uses the steel structure as a framework under which activities and events can happen. The building is intended as a community arts centre which can respond to the needs of local action groups covering a wide range of activities.

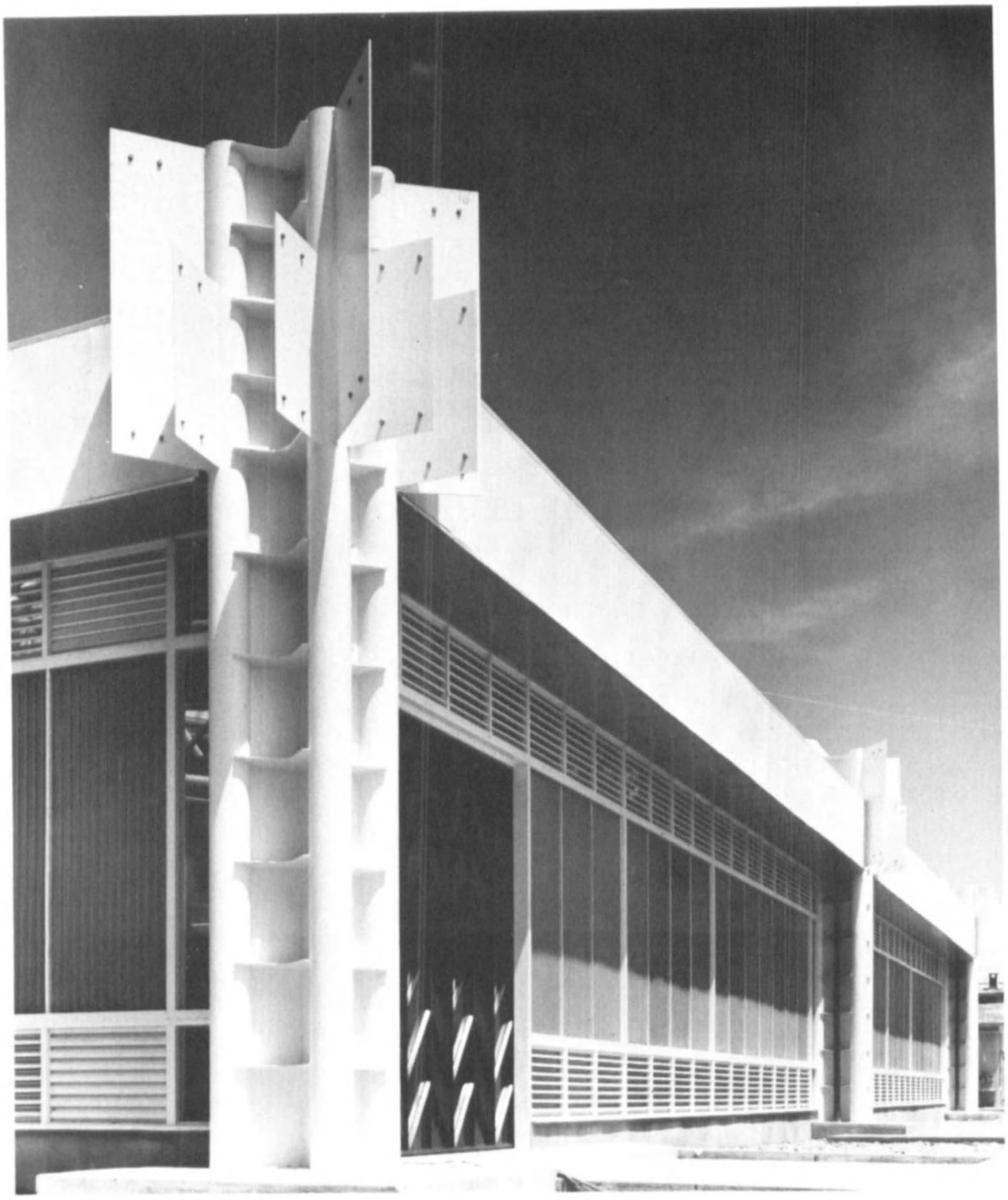
The structural frame covers an area of 2022 m^2 but initially only part of it was enclosed for use as a meeting hall, studios and gymnasium. Portakabins have been plugged-in here and there to provide temporary additional accommodation. The planning module of 3.6 × 3.6 m relates to cladding spans and the column grid is 14.4 × 10.8 m. It is intended that windows and doors can be added or removed as required and services tuned up if necessary. The only fixed elements are the base slab and structural frame.

The Japanese architect, Kisho Kurokawa in his *Canning Plant* at Sagae, Yamagata in Japan, made a clear architectural expression of the building's requirement for flexibility and expansion. Designed as a fruit canning plant, it had to be flexible, for the fruit packing season only lasts from June to October and at other times the building is used for making corned beef (Figures 4.43, 4.44).

The structure consists of a uniform system of clusters of tubular steel columns and trusses which span the 17 × 17 m bays diagonally, with secondary trusses orthogonally placed between trusses. Each of these bays forms a self-contained element and the building can be extended in any direction by adding the desired number of bays. The prefabricated trusses are connected to the column clusters by means of the large gusset plates which are welded to the column heads. These appear on all of the columns, including those on the perimeter to allow for future expansion and are expressed clearly as part of the aesthetic.

During the 1970s in London, the architects, Foster Associates progressed design for the 'optimum cool box' almost to the limit through a series of industrial and commercial projects. For example the *aluminium extrusion plant for SAPA* at Tibshelf, was provided with a pure white box of unrelenting profiled vertical sheeting, where only the plant and services provided relief with the use of bright colour (Figure 4.45). This building was seen as the ultimately simple undecorated shed and marked the end of the line for this form of architectural exploration. By highlighting the need for more complexity, it helped to stimulate the development of the richer masted structures of the 1980s such as Renault and Fleetguard. However, at the time of the design of SAPA, Foster Associates were demonstrating a new language of architecture based on clear expression of structure,

4.43, 4.44
Kurokawa's Canning Plant at Sagae, Japan, makes a clear expression of the building's requirement for flexibility and expansion. Key: 1. administration; 2. social centre; 3. research laboratory; 4. meat canning plant; 6. transformer station; 7. stores for empty cans; 8. connecting annex with conveyor belt; 9. fruit canning plant; 10. stores for finished products; 11. old storage sheds; 12. oil tank for heating plant



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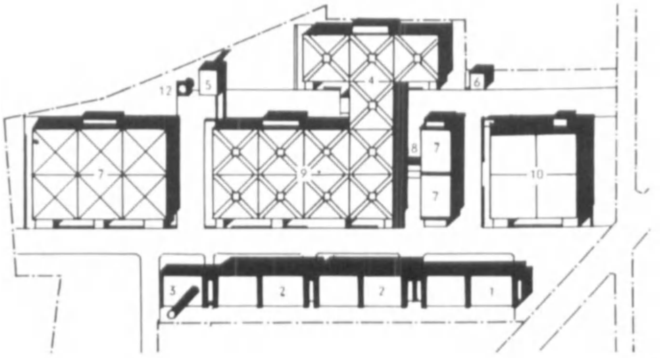


4.44

services and cladding with use of the latest materials and construction techniques, although it can equally be interpreted as the natural progression of the 'Modern Movement' translated into the technology of the day.

This approach can be clearly seen in their design for the temporary headquarters building for *IBM UK Ltd* at Northern Road, Cosham, built in 1973, where the architects translated the brief for a series of temporary huts into an immaculately detailed fully glazed building. The economy of the single enclosure measuring 146 × 73 × 3.6 m with its low wall-to-floor area ratio and

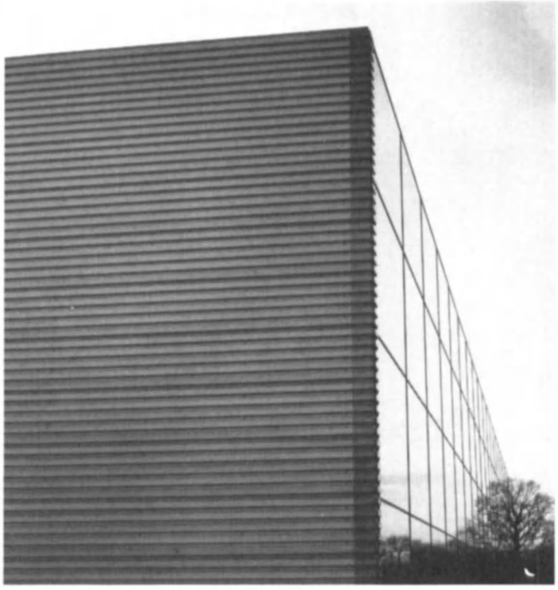
4.45
At the time, the SAPA aluminium extrusion plant at Tibshelf by Foster Associates was thought to be the optimum cool box, with its skin of unrelenting white profiled sheeting (1972)

4.46
The immaculate glass box for IBM UK Ltd at Northern Road, Cosham, designed by Foster Associates showed what could be done with the repetition of well designed simple elements

4.47
IBM Greenford by Foster Associates provides a simple form of shed to house a variety of uses on several floors (1978)

4.45

4.46



4.47

repetitive elements enabled the use of higher quality materials. It demonstrated the advantages of high performance, factory-made components for fast and economical construction and has proved to be such a highly successful and flexible workspace, that it is still in use 20 years later, still being constantly rearranged inside and still looking immaculate.

In a subsequent building for *IBM at Greenford*, the same architects designed a flexible multi-use shed to house parts storage and distribution, workshops and offices all under the one roof. This building measuring 113.4 × 116.4 × 12 m was designed on a 8.1 × 27 m grid to suit the high bay racking module, with a steel lattice truss frame of rectangular hollow sections (Figure 4.47). It is really a big, well designed box, clad in horizontal profiled steel sheeting with one fully glazed wall which uses the maximum standard toughened glass sheet size for economy and scale. A special corner panel of grp was fabricated to provide the tight radius bends and the same kit of parts was used in the design of the highly serviced computer installation in a linked but separate building.

4.48
The Herman Miller factory in Bath designed by Nicholas Grimshaw & Partners provides a flexible building with interchangeable cladding panels

4.49
Michael and Patti Hopkins' house in Hampstead uses industrial components in a friendly and domestic way (1977)

4.50
A cladding panel can be interchanged by two unskilled men in one hour

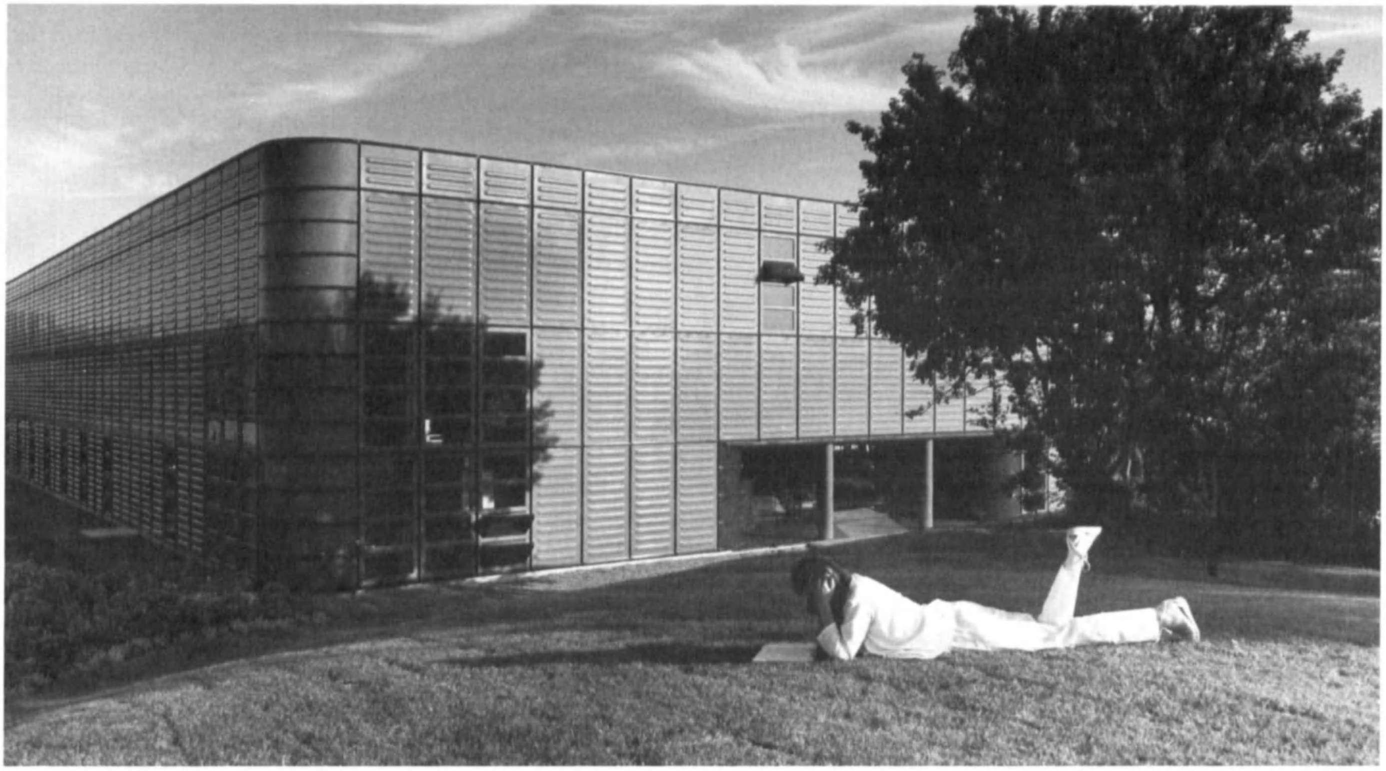
4.48

4.49

4.50

It was at this time that one of the partners, Michael Hopkins, left to form a separate practice which started with the design of his own *house in Hampstead* (Figure 4.49). This was constructed of similar industrial components, with a steel structure of lattice beams with square hollow section columns, and clad in profiled sheeting with frameless sliding glass panels. As the Eames House had 30 years previously, it demonstrated the potential for using industrial components in a domestic building and was widely published as an example of new 'high tech'

4.51, 4.52
Herman Miller Distribution Centre in Chippenham, Wiltshire with purpose-designed cladding by Nicholas Grimshaw & Partners



4.51

style. In fact it represented a clear thinking approach to the design of efficient, flexible buildings using the technology and materials of the day, and was not concerned with 'style'.

A similar approach to design was represented in the work of Nicholas Grimshaw & Partners at that time. Their two buildings for the American furniture manufacturer, Herman Miller Ltd at Bath in 1976 and Chippenham in 1982, took the standard form of steel structure and experimented with two entirely different cladding systems.

The *furniture manufacturing building at Bath* was conceived as a totally flexible building throughout. The cladding is designed on a 1.25 × 3 m grid of interchangeable panels (Figure 4.48). Here the solid panels are constructed of an insulated double skin of glass reinforced fibre (grp), and it is possible for two unskilled members of the client's staff to interchange a panel within one hour (Figure 4.50). Several changes have been carried out since the building was completed so to some extent this facility has been justified.

4.52

The emphasis on flexibility has been extended to all the elements of the building, with equal dexterity. The structural frame is constructed of steel universal sections on a 20 × 10 m column grid, and the internal space is left undivided. Primary services are distributed along the length of the building supported from the secondary beams, and there are catwalks suspended below for easy non-disruptive maintenance and change. Even the toilet facilities are moveable. They are located in a standard, but carefully designed Portakabin which can be moved by one of the client's fork lift trucks to any one of the 15 locations within the building. This unit was delivered and installed in one day, and it could easily be moved in a weekend, without causing any disruption to the normal working day. Should the working population of the building increase or if it were to be subdivided into different tenancies, additional facilities can easily be plugged-in to the system.

The second project at Chippenham, Wiltshire was for a *Distribution Centre* of 6970 m^2 with a minimum internal height of 6.5 m. It had to be capable of being expanded to up to three times its initial size and able to accommodate a wide range of potential uses such as offices, manufacturing, paint spraying and canteen facilities (Figures 4.51, 4.52). To meet these requirements for flexibility a grid of 36 × 14.4 m for the central bays and 28.8 × 14.4 m at the ends, was chosen for the steel frame with a specially designed cladding system of interchangeable panels. Solid pressed aluminium panels, fixed windows, fire doors and personnel doors may all be unbolted and moved to any location on a 2.4 × 1.2 m grid. In addition, a secondary level of flexibility is achieved with a series of add-on secondary components such as external lights, ventilation louvres and components allowing service transitions.

These are simple sheds to provide flexible space for a variety of functions, and this flexibility is expressed in the external skins of interchangeable panels. The client, Herman Miller, has always been a progressive furniture manufacturing company who has promoted good design both in their products and their buildings. This policy has paid-off, for in the 1950s they had commissioned Charles Eames to design the beautiful aluminium group and shell range of chairs which have been a 'best-seller' ever since. For their new *production factory at Holland, in the USA*, they commissioned a building which was to be 'formally integrated into the Herman Miller image' (Figure 4.53). Once again the brief called for a flexible building to house the production, warehousing and administration, capable of being expanded to three times its initial size.

The design by architects Coudill Rowlett Scott and Houston uses a simple steel frame of open web lattice trusses on a square column grid, clad with a smooth metal composite panel system. The buildings are set into a landscaped berm, to reduce their bulk and a raked glazed strip at the base provides ventilation and a view out. A radiused acrylic parapet provides daylight and finishes off the smooth stream-lined appearance and provides one of the smoothest skins imaginable.

A similar approach was taken by the American architects Davis Brody and Associates for the *Estée Lauder Laboratories* in New York State. This cosmetics factory is situated beside the Long Island Expressway and the long sleek white building was intended to attract the attention of passing motorists in order to promote the image of the product (Figure 4.54). Here the seductive external skin is formed with insulated sandwich panels sheathed in white porcelain enamelled steel, and there is no doubt that it has succeeded in being an eye-catching advertisement for the company.

There is an appealing glamour to the smooth skin shed, when detailed competently, which conjures up images of the future, although it actually uses the technology of today, drawing inspiration from the automobile and boat building industries. The same structural frame can be clad in a variety of different materials, modules, colours and textures to suit the brief or image required. Two good examples are the UOP Fragrances factory at Tadworth by Richard Rogers & Partners and the Advanced Industrial Unit at Warrington by the Farrell Grimshaw Partnership.

The *UOP building* completed in 1973 pioneered the use of grc (glass reinforced concrete) for its full height cladding panels, which were coloured in bright yellow (Figure 4.55). Each panel, which measures 5.2 × 2.4 m is either plain or punctured to contain the window, door or ventilation openings. Joints between panels are sealed with neoprene compression gaskets. It is a slick but economical flexible shed, with a strong imagery and presence derived from its smooth brightly coloured cladding with its rounded openings.

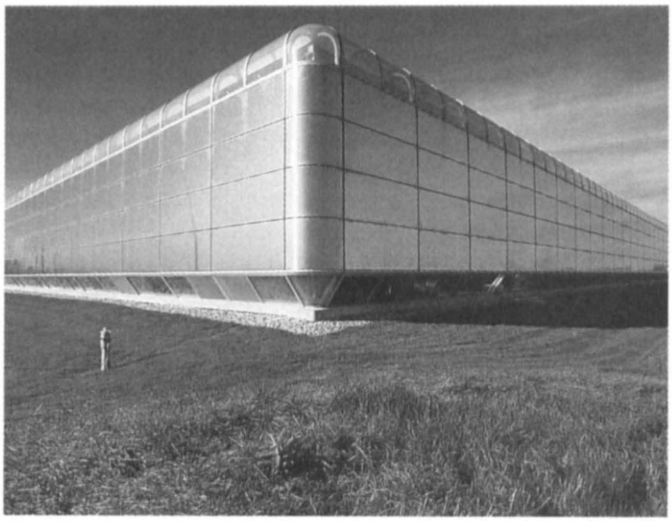
The Farrell Grimshaw Partnership's *Industrial Unit design at Warrington* uses a shiny silver cladding of aluminium finished Alucobond panels zipped into a neoprene pressure gasket ladder grid (Figure 4.56). The module is 2.4 × 1.25 m and all the panels interchange. At the time, this building clearly demonstrated the potential alternative to the stereotype profiled sheeting with its slick but economical modular cladding system.

4.53
The Herman Miller production factory at Holland, USA, has a smooth polished skin designed by Coudill Rowlet Scott and Houston

4.54
Seductive smooth skin of the Estée Lauder Laboratories in New York State by Davis Brody & Associates

4.55
The UOP fragrances building by Richard Rogers & Partners in 1973 pioneered the use of glass reinforced concrete for its full height cladding panels

4.56
The Warrington Industrial Unit design by the Farrell Grimshaw Partnership provided a strikingly slick skin of Alucobond aluminium panels on a neoprene pressure gasket ladder grid (1979)



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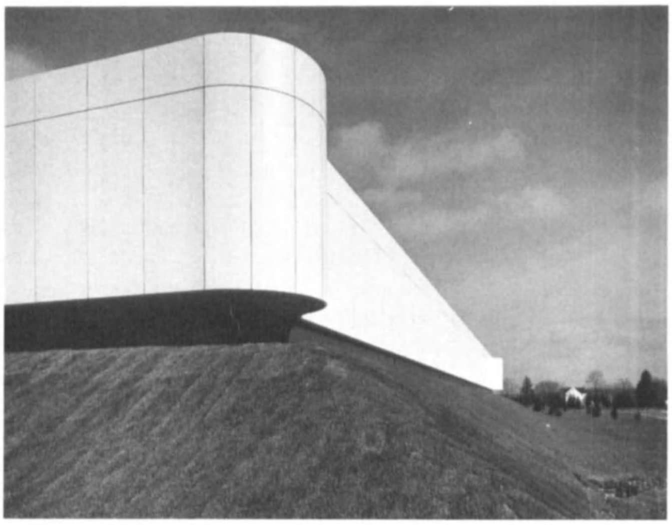

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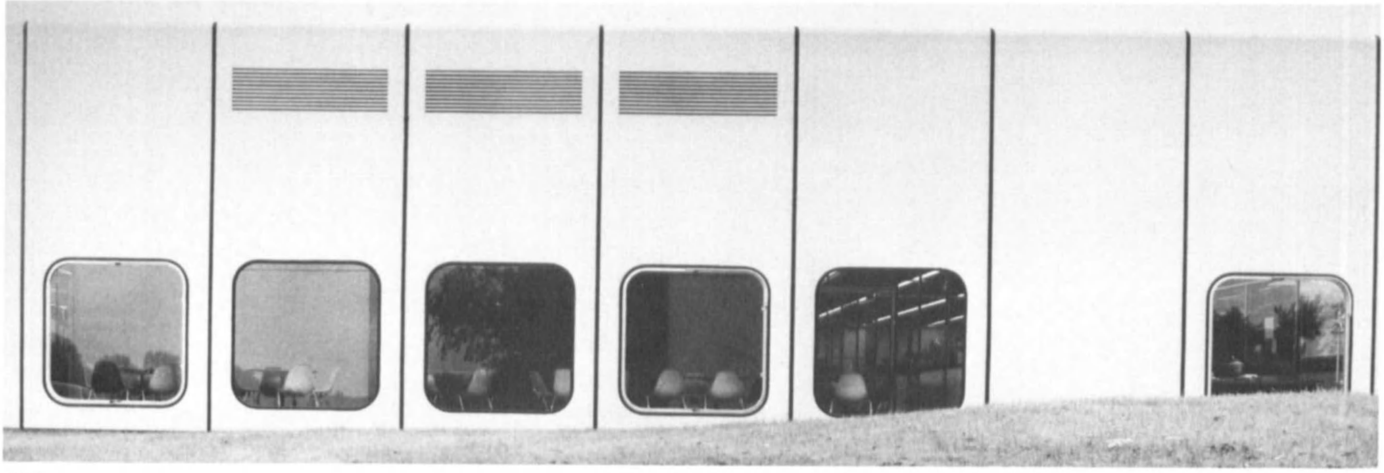


4.55

4.56

4.57, 4.58
The Menil Museum in Houston, Texas, by Renzo Piano is a refined architectural statement in a city of 'one-liners'

4.57

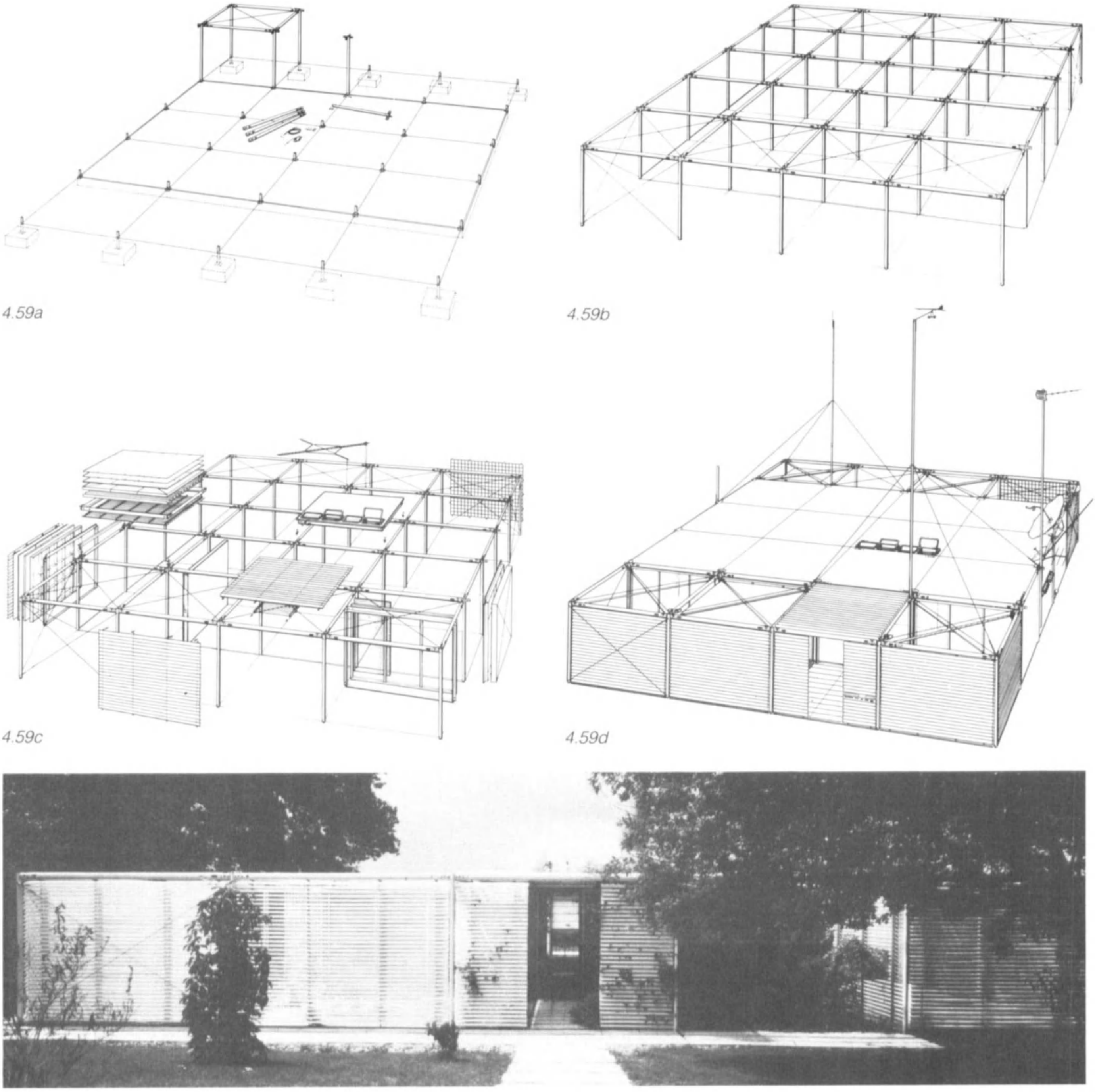
4.58

The restless pursuit, in design terms, for the slick shed and optimum cool box was not progressed with the same vigour through to the 1980s. Instead there was a move towards more complex structures such as the masted cable supported roofs of Richard Rogers' Fleetguard and Norman Foster's Renault Distribution Centre, which are illustrated in the following section on Special Structures. However, there were exceptions, one of the most notable being the Menil Collection Museum at Houston, Texas designed by Renzo Piano and completed in 1986.

The *Menil Museum* (Figures 4.57, 4.58) is more than just a shed although it has a single storey steel frame on a rectangular column grid with a continuous flat roof. It is a carefully considered piece of modern architecture designed to suit the special requirements of Mrs Dominique de Menil for the housing and display of her unique collection of art. The architects noted that she wanted:

'a building which fitted into its environment, which would house the collection of over 10 000 items where they could be seen but not all displayed at the same time, which had a spacious interior and a compact exterior, which was solemn but not monumental. Then what should be given priority above all else, was the possibility of displaying the works of art in natural lighting, so that when viewed, the strength of each work could be felt through the changing pattern of light caused by the clouds.'

4.59
a–e. Yacht House 1, 1983, in the New Forest, designed by Richard Horden Associates: erection sequence



4.59a

4.59b

4.59c

4.59d

4.59e

The resultant building meets all these requirements. It has a refined, understated external appearance with an air of mystery. The interior has a clear, spacious appearance with an extraordinary quality of natural light from above which filters through the carefully considered external louvre structure. The materials of its construction are plain and simple but carefully chosen and immaculately detailed. It is altogether a most refined and economical building, of its day yet timeless.

In an entirely different way, Richard Horden progressed the 'systems approach' to the multiple span grid structure through the 1980s with an innovative windframe structure using yacht mast technology (Figure 4.59). Drawing inspiration from the Tornado catamaran he sails, Richard Horden designed a protype house in the New Forest using aluminium spar sections from Proctor Masts with stainless steel rod rigging on a 3.6 m square grid. From this prototype, a flexible system has been developed for a variety of potential uses including office, computer room and leisure facilities which can incorporate as many modules as is required.

The windframe is incredibly lightweight and can be erected by hand in a matter of hours rather than days, which makes it an extremely low cost option, and a wide choice of infill panels is available for the cladding to suit the requirements.

4.60, 4.60a
Renzo Piano's Italian Industry Pavilion at the Osaka Expo in 1970 experimented with reinforced polyester panels on an external steel structure

4.61
Renzo Piano and Richard Rogers' Centre Pompidou in Paris (1977)

Special Structures

At the start of the 1980s in Britain there was a move away from the simple industrial shed and towards more expressive, complex structural solutions. It is hard to define exactly what prompted this interesting occurrence, and it is almost certainly not due to any one event but to a number of interrelated factors. However, it resulted in a series of exciting masted structures initially from the offices of Richard Rogers, Norman Foster and Michael Hopkins.

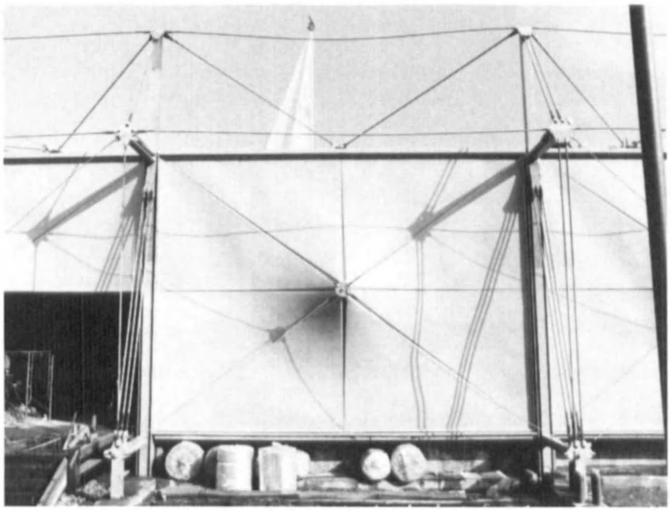
The concept for masted structures was not new. It had been used in bridge building since the early nineteenth century and in buildings since at least the early twentieth century. The Behrens and Kühne masted airship hangar of 1919 is illustrated on p. 17 with (on p. 32) the 1921 seaplane hangars at Cherbourg. Masted structures with cable-supported roofs had been a popular way of providing large column-free space for aircraft hangars for some time and had been used for leisure activities but not for industrial buildings. In fact, there were few examples of the use of lightweight structures at all in industrial buildings, despite the research carried out by Frei Otto and other interested engineers.

However, the Italian architect Renzo Piano had experimented with forms of lightweight structures and in 1966 had built a factory in Genoa with a reinforced polyester membrane on a prestressed steel frame. Much of the experience gained in this building was used in the design for his *Italian Industry Pavilion* at the Osaka Expo in 1969–1970, which was an external tension structure with translucent reinforced polyester membrane cladding panels (Figure 4.60, 4.61). This was an innovative building which generated a new language combining technology with delicacy and detail to make architecture. There were several other interesting examples of lightweight structures at this Expo including an air-supported structure for the American Pavilion by Davis Brody and a masted structure for the British Pavilion by Powell and Moya.

It was soon after this that Renzo Piano and Richard Rogers won the international competition for the *Centre Pompidou* in Paris, which with its exciting external structure and exposed services, pioneered the technological approach to architecture and it was here that Peter Rice, the structural engineer from Ove Arup and Partners, joined the team. He not only provided a workable structure for the 48 m wide spans, but one which was both innovative and legible, with the steel lattice trusses balanced on cast-steel rocker beams (gerberettes) which are supported on spun steel hollow columns and connected to an outer tension column and bracing system. It is a powerful building of monumental importance, for it stands as a testament to Modern Architecture. People either love or hate it, but they do not ignore it, and it works as a cultural centre attracting thousands of people every day.

Fleetguard Distribution Centre

In 1979, following the completion of the Centre Pompidou, Richard Rogers and Peter Rice collaborated on the design for a Manufacturing and Distribution Centre in Quimper, Brittany for Fleetguard, a subsidiary of the Cummins Engineering Company (Figure 4.62). A masted steel tension structure was used on a 18 × 18 m grid which with a total steel weight of 47 kg/m^2 was about 17% less than a conventional structure of comparable bay size (Figure 4.63). The 355 mm diameter tubular steel columns which project 8 m above the roof take the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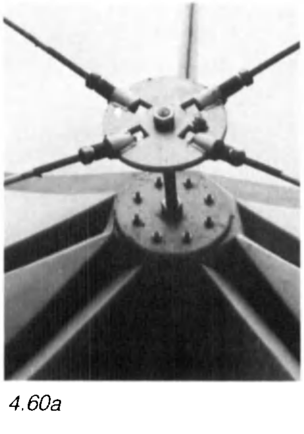

4.60a

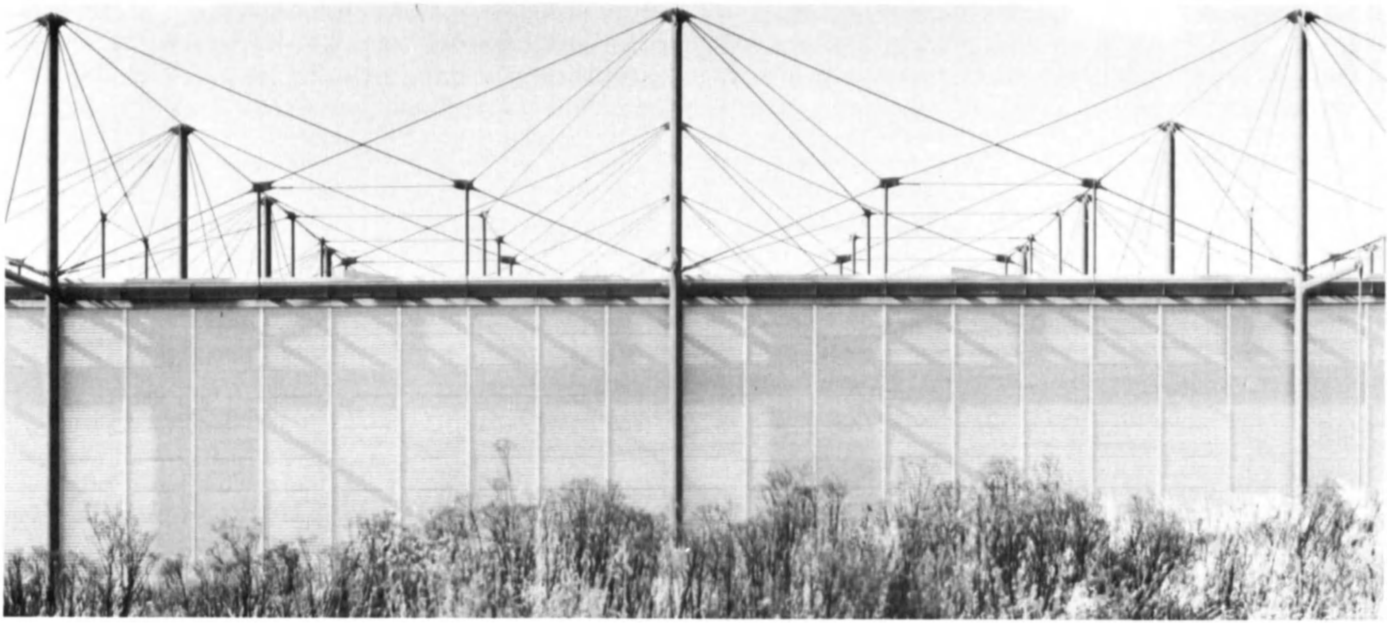

4.61

4.62
The Fleetguard Distribution Centre at Quimper, France, designed by Richard Rogers & Partners in 1979 with Peter Rice of Ove Arup & Partners was the first of a series of masted structures

4.63
The 18 × 18 m column grid with cable supports to the roof at 6 m centres provides an economical structure with a total steel weight of 47 kg/m^2

4.64
The 355 m diameter columns project 8 m above the roof

4.65
The striking masthead plated detail is coloured bright red with the rest of the steelwork



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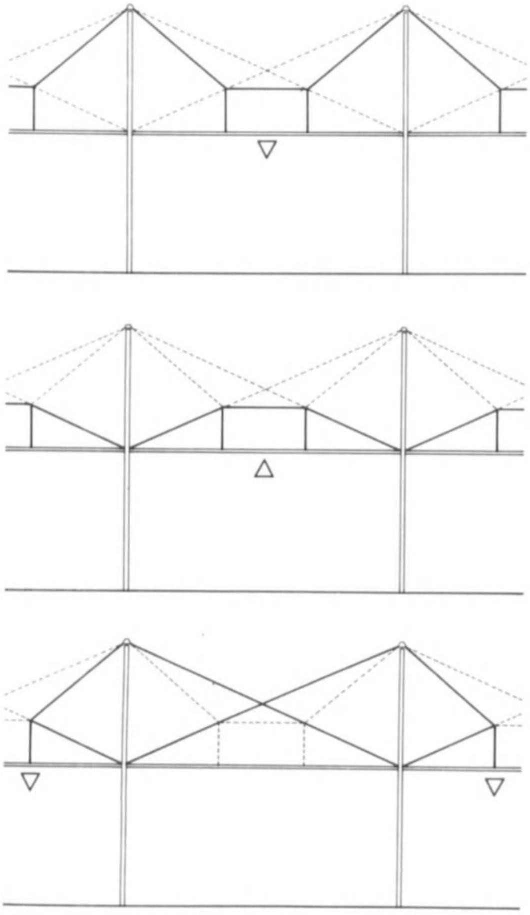

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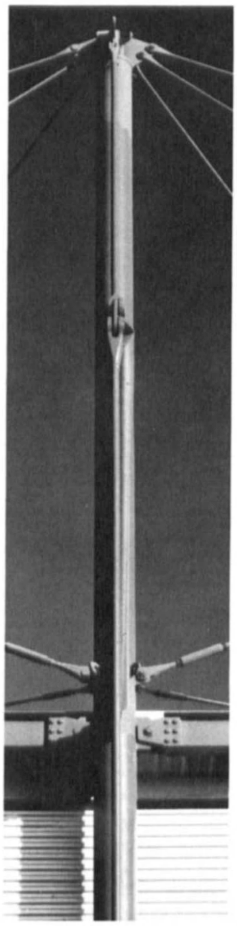

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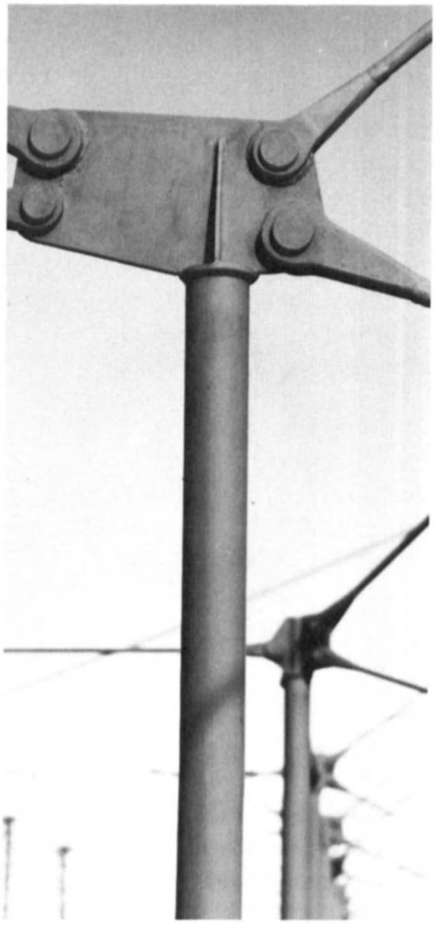


4.65

tension rods which support the roof on a 6 m grid, thereby reducing the span to a third of the bay size (Figure 4.64). In addition, a secondary set of rods is provided to counteract the effects of extreme wind loads and uplift. Finally a third set of rods is provided on the lines of columns to provide complete interchangeability of all the bays and to enable full asymmetrical service loads to be applied. The internal beams which support the roof deck are standard rolled steel sections which carry the compressive forces, as well as acting as bending members between the internal points of support.

The diagrams produced for the *Architectural Review* in February 1982 show how the suspension structure counteracts forces and how a reduction in the height of building was achieved, which was an important consideration in the brief. In addition to the clarity of the structural form, it should be noted that every aspect of its visual appearance has been carefully considered and designed to be functional, to express its purpose and to look visually pleasing. This approach can be seen in the beautifully designed connection plates at the top of the masts, whose elegant shape and strong bright red colour appear so dramatic on the skyline (Figure 4.65).

This building clearly demonstrated a new approach to the common industrial shed, with its exciting external structure, which could be justified by its reduced weight of structural steel and less bulky appearance. It was followed soon after by another masted shed for Renault in Swindon by Foster Associates, with Michael Manning of Ove Arup and Partners as the engineer.

Renault Distribution Centre

After the cool boxes for SAPA and IBM, the slick shed for MAG and the finely tuned hangar for the Sainsbury Centre at UEA, Foster Associates approached the brief from Renault with a fresh and more expressive outlook (Figures 4.66, 4.67). As always, the same clear analytical approach to solving the functional requirements of the building remains, together with the use of innovative technology and immaculate attention to detail. Early studies of the requirements for flexibility and expansion led the design team to progress a concept of 24 m square umbrella modules (Figure 4.68) which could be grouped in any configuration required to suit the site or internal layout. The eventual solution maintains this concept but with a continuous portalized structure of undulating beams supported from tubular steel masts with tension rods. These 16 m high masts adorned with huge steel castings for the tension rod joints, and the perforated tapered steel beams, create a strongly expressive structure evocative of some of the bes Victorian engineering (Figure 4.69).

This huge building measuring 300 × 108 m sits well on the 6.5 ha site and is designed with 100% expansion capacity. The main bulk of the building is warehousing which occupies the rectangular element and the ancillary accommodation comprising offices, training workshops showroom and staff restaurant occupies the tapering portion of the site leaving a single complete bay at the end of the building as an open entrance canopy or porte cochère.

In comparison with Rogers' Fleetguard building (Figures 4.70, 4.71), it appears to be a more complex heavier structure and its weight is greater at 59 kg/m^2 but this is partly due to its wider span of 24 m agains 18 m. Its legibility is helped on the outside by the position of the cladding being set back from the column lines and on the inside where the columns and beams are expressed.

Both buildings succeed in providing wide-span, flexible spaces in an economic and exciting way with minimum bulkiness. They both achieve this with elegan masted tension structures but conceived and engineered in quite a different way.

Richard Rogers later progressed the Fleetguard concept with the design of a shopping centre in France, with an increased span of 28.8 m. The *Centre Commercial S Herblain* (Figures 4.72, 4.73) at Nantes in Brittany completed in 1987, uses a similar structure to Fleetguard but with the doubling of columns in one direction to reduce the span. This creates a more complex arrangement of tension cables on the roof, but provides an extremely economical structure. Its strong visual appearance creates an identity for the shopping centre, which is easily visible and helps to attract people to it.

Each of these highly structured buildings has a comparatively low level of services due to its usage, and would have been approached differently if this had no been the case, which can be seen in Richard Rogers other project at this time for the Inmos Microprocesso Factory at Newport, South Wales.

4.66, 4.67
The Renault Distribution Centre at Swindon by Foster Associates in 1980 provided an exciting alternative masted structure soon after Fleetguard

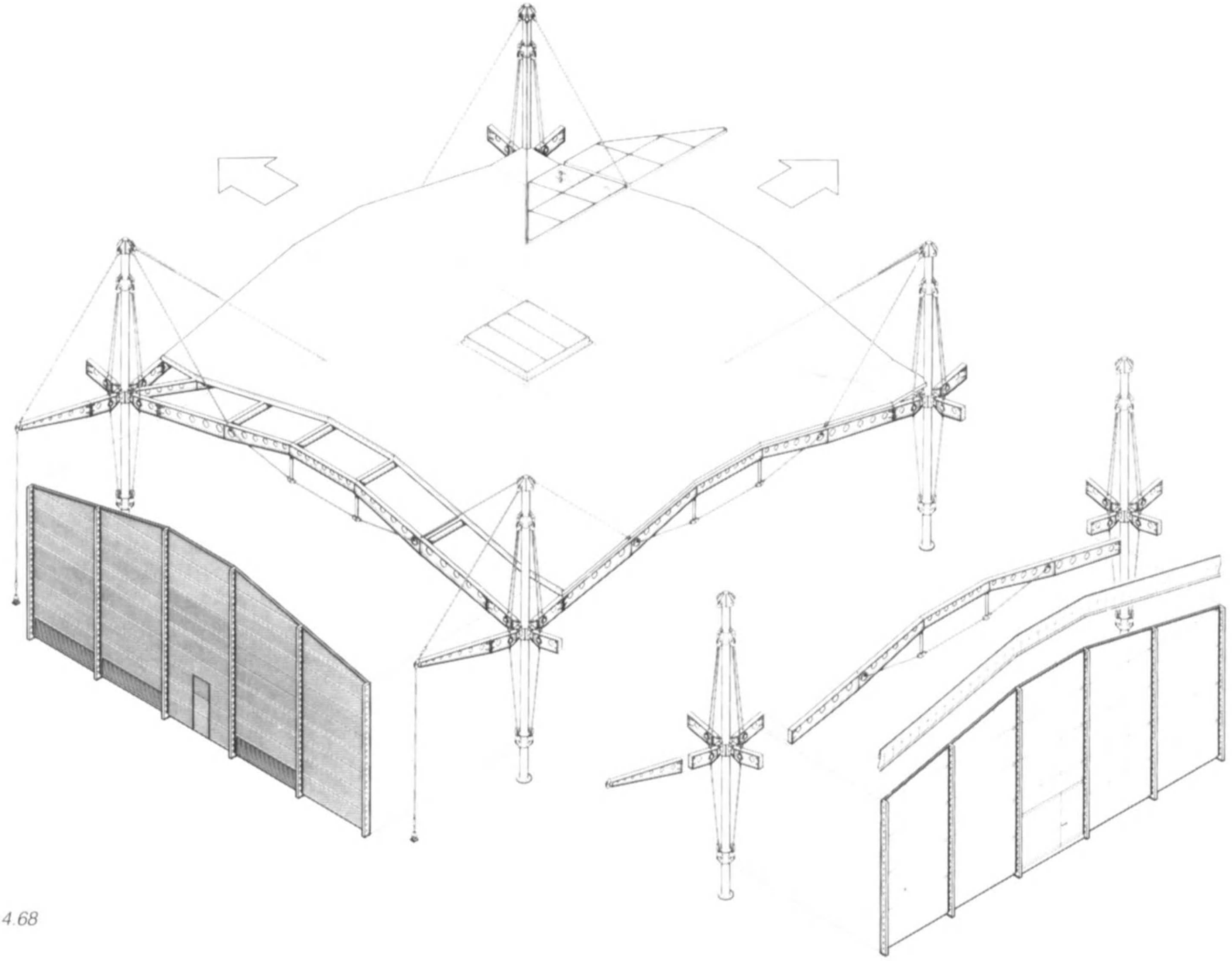
4.66

4.67

4.68
The Renault structure is based on 24 m square umbrella modules

4.69
The masts form an interesting roofscape to the Renault Distribution Centre

4.70, 4.71
Compare the masted structures of Renault and Fleetguard



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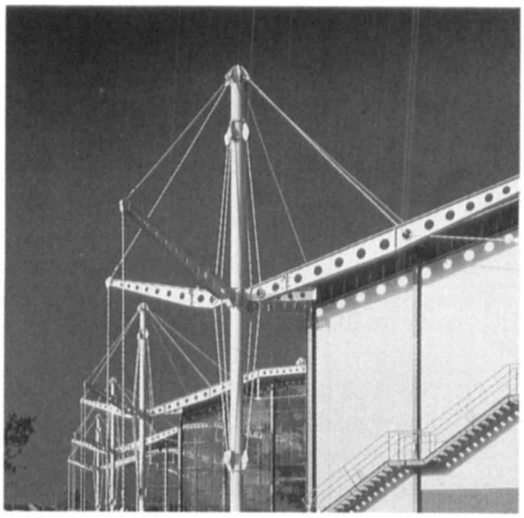

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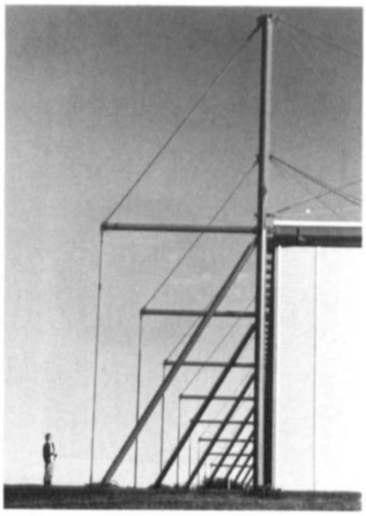

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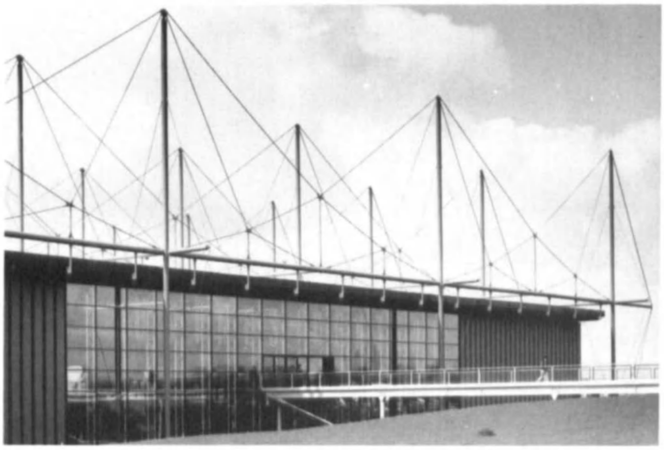
4.72
The St Herblain structure is based on a 28.8 m grid

4.73
General arrangement of the Centre Commercial St Herblain by Richard Rogers & Partners



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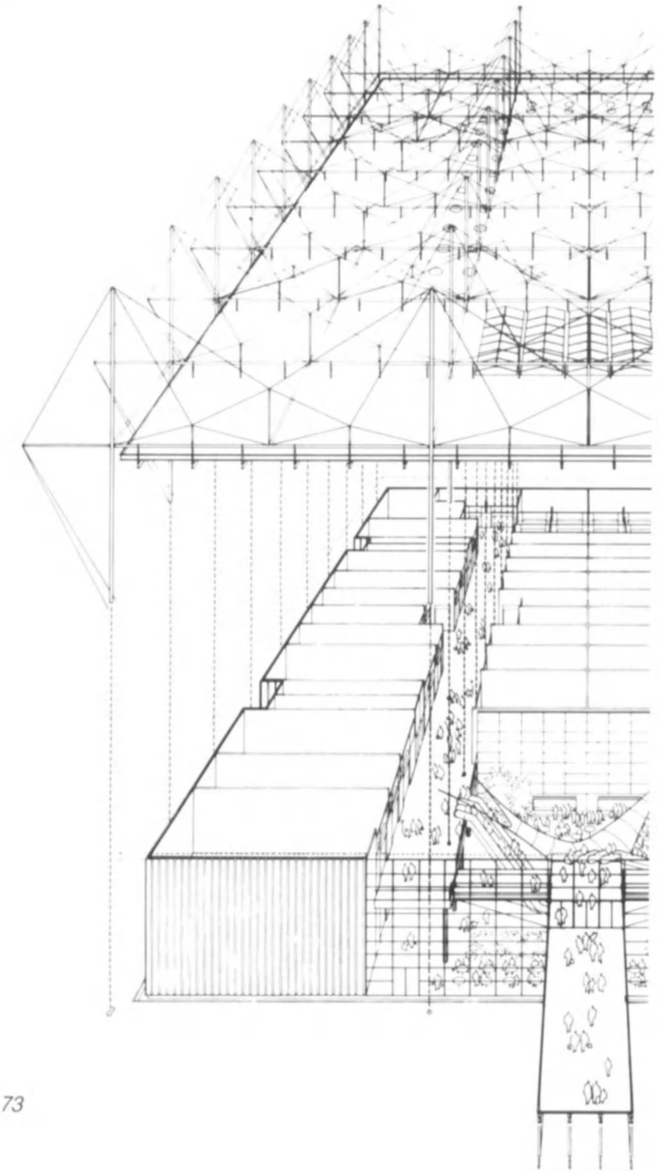


4.73

Inmos Microprocessor Factory

The brief for this building required an exceptionally high environmental control for the production of microchips (Figures 4.74–4.78). Air in the production area had to be absolutely clean to cut down on the failure rate of water production, a process minutely sensitive to dust. In addition to these production facilities, office and other ancillary space was required, which led the architects to develop a concept of a linear circulation spine with wings on either side for the different activities. The offices and restaurants are on the south side of this spine and the clean room production areas are to the north. The structure of the spine is extended vertically with masts and a gantry which houses the massive volume of air-handling equipment. From the masts, a system of tension rods provides intermediate supports to the 36 m spanning tubular steel trusses from which the roof is hung. Clear, column-free spaces are thus provided for the main accommodation, and the extremely high level of servicing is distributed externally above the roof.

It is a clear, strong concept which provides column-free flexible space and an efficient means of plant and services distribution for a highly serviced building. The structure, which was engineered by Anthony Hunt working closely with Mike Davies of Richard Rogers and Partners, is both economical and clearly legible. In discussion with Anthony Hunt, he confirmed that the complexity of its movement and stress paths would have been difficult to analyze without the use of a computer and, in fact, this was the first design to benefit from their new computer installation. The services, which are so important to the production are clearly expressed and suitably form an important part of the architecture.

It is one of the most interesting industrial buildings of its generation because of its innovative response to a challenging new brief. For once the client and planning authority were prepared to back the design team and allow a clear concept to be worked through without compromise.

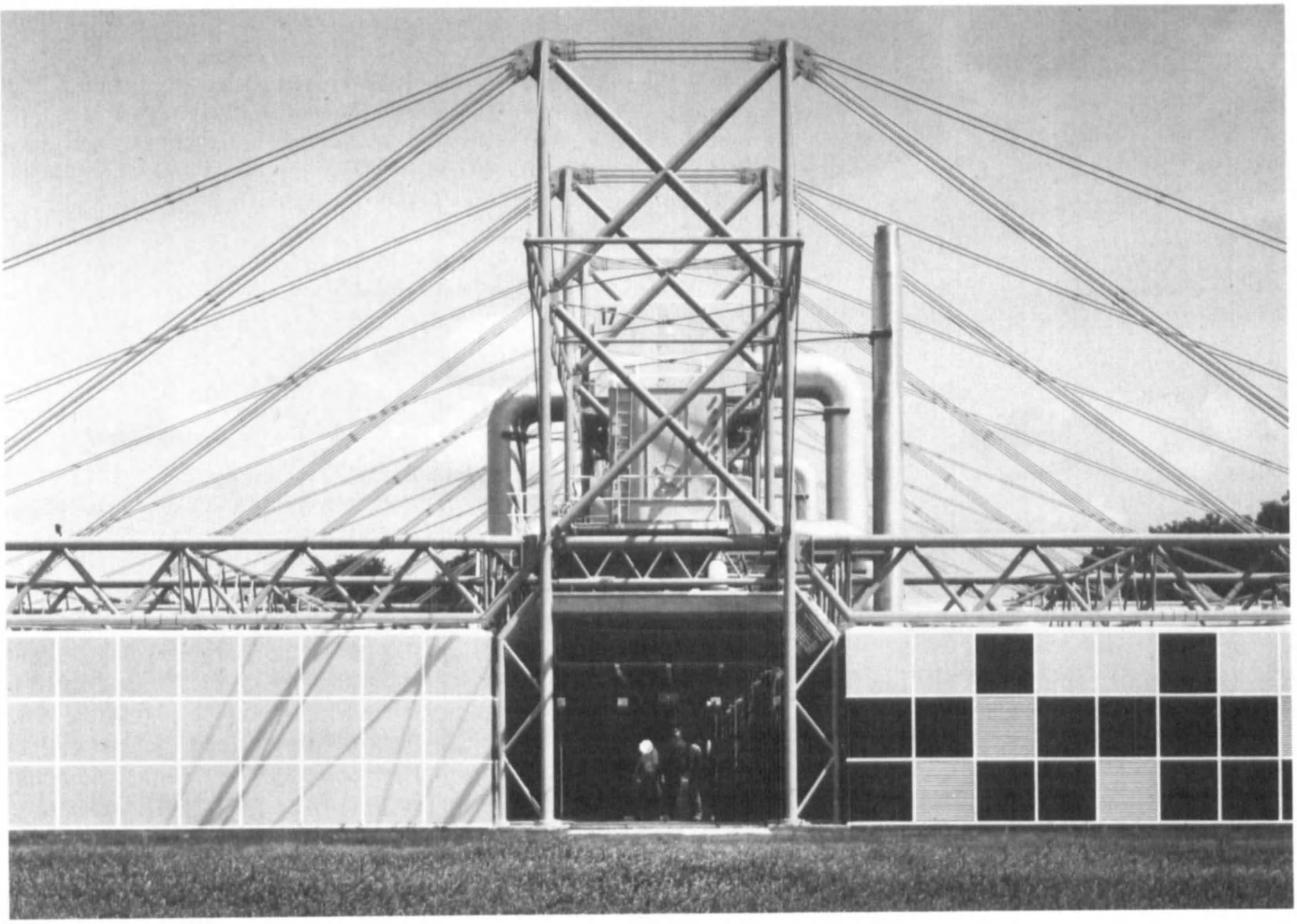
Patscenter, Princeton

A similar formula was used again by Richard Rogers and Partners for the Patscenter Laboratories at Princeton, USA, on a smaller scale and with a different structure by Peter Rice of Ove Arup. Here the span is 22.8 m for the main accommodation on either side of an 8 × 80 m long arcade. Again the plan works well, with the spine acting as a street and meeting place for the staff who inhabit

4.74
Inmos Microprocessor Factory in South Wales by Richard Rogers & Partners with Anthony Hunt Associates has 36 m clear space trusses on either side of a masted spine with intermittent tension rod supports to reduce weight of structure

4.75
The linear circulation spine has the production areas on one side, the administration and staff facilities on the other, and the services plant above

4.76
The plant gantry above the circulation spine houses the massive air-handling plant required for the microprocessor production areas



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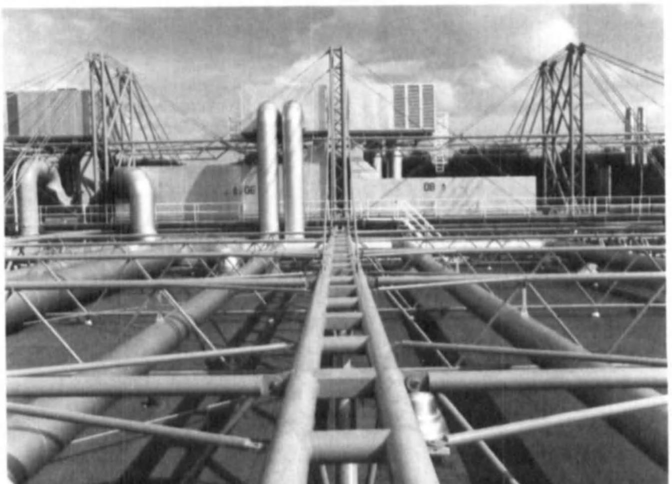

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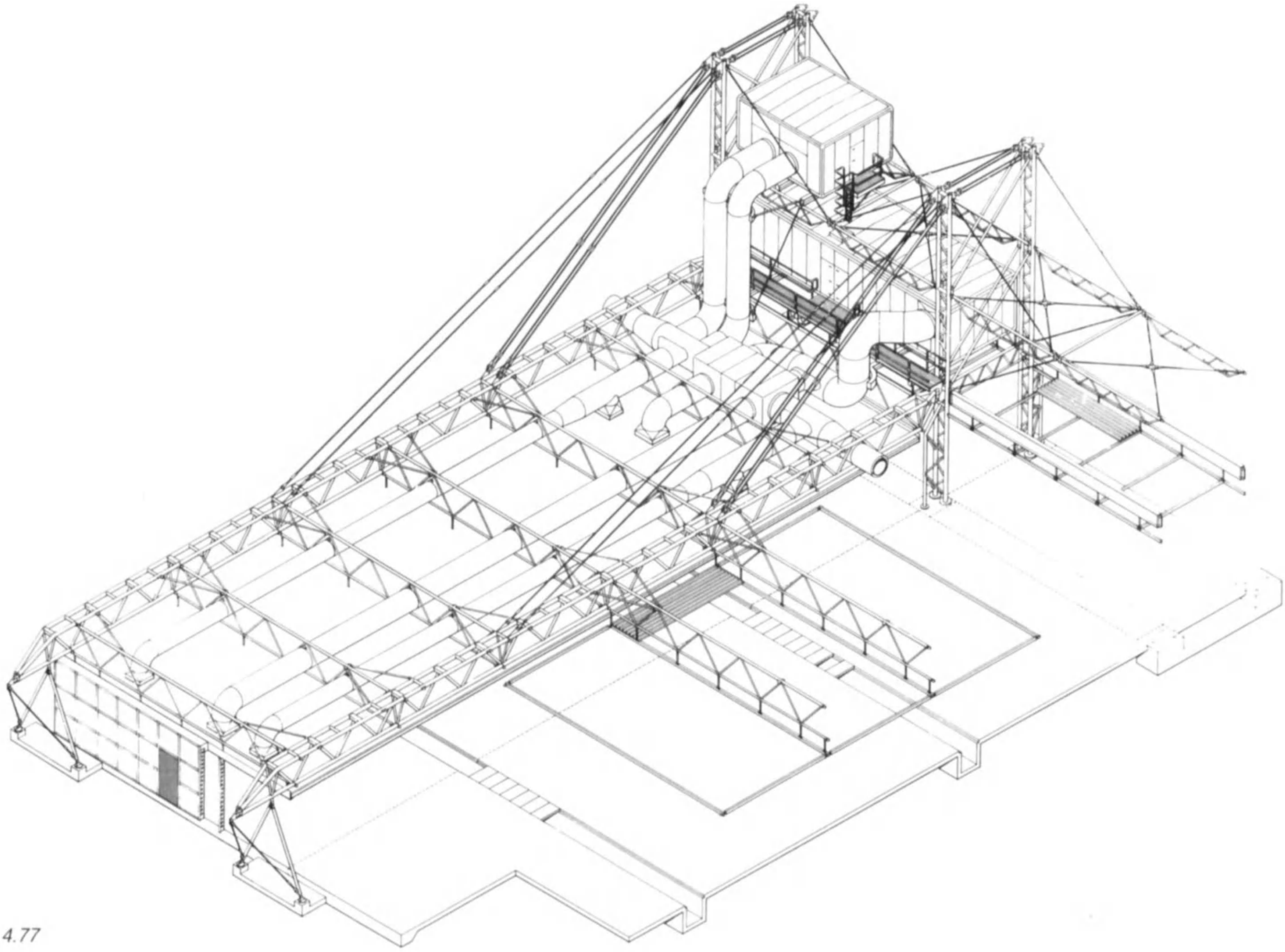
4.77
Components assembly drawing shows integration of services with structure

4.78
Inmos entrance



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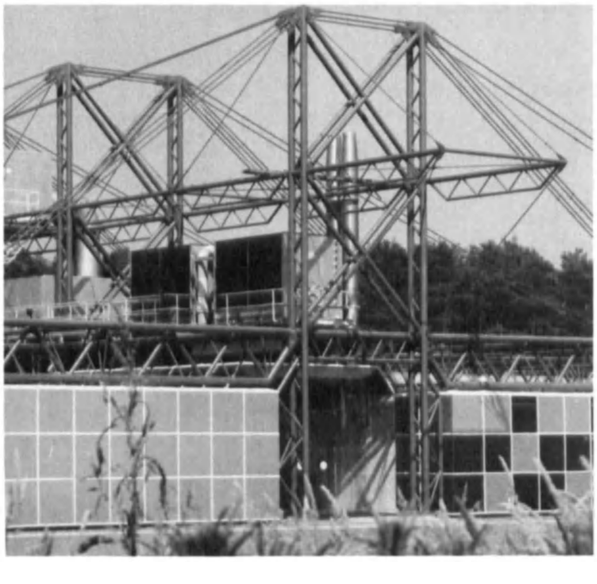


4.78

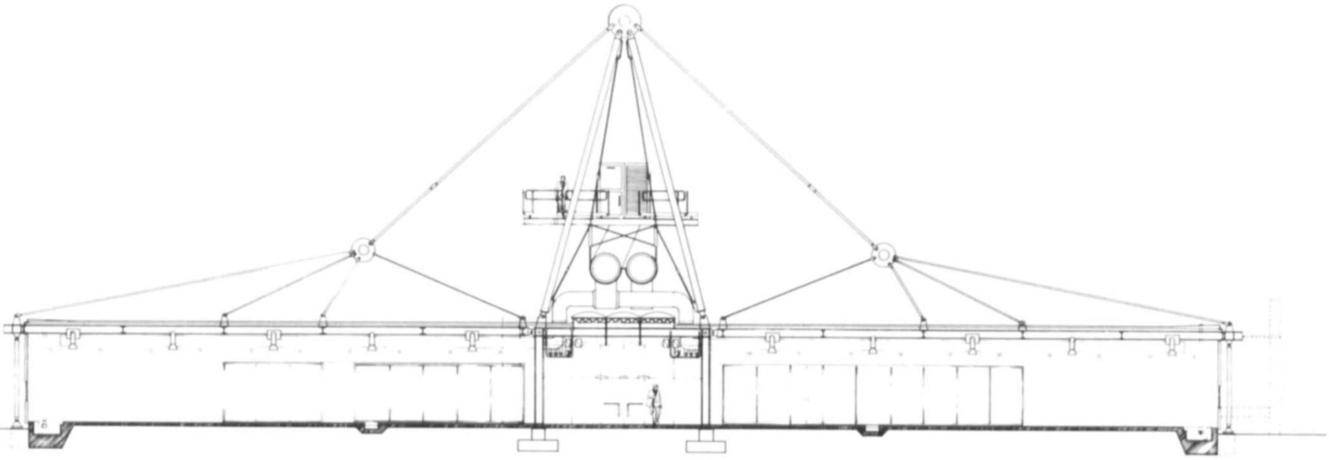
the column-free flexible office or laboratory spaces on either side (Figures 4.79, 4.80).

The structure appears to be a simplification of the Inmos structure by Anthony Hunt and to some extent reflects the different approaches of these two talented engineers as well as the different realities of the American and British construction industry, which was a point noted at the time by Peter Buchanan in the *Architectural Review* July 1983. Certainly the Patscenter structure is simpler and more legible, but then it is a smaller less heavily serviced building. It also makes greater use of the suspension structure to reduce the size of the main beams, and to support the plant. In this respect it is closer in concept to the Fleetguard building than to Inmos. The choice of the Polo ring at the top of the masts is interesting for, although it is a functional means of joining the tension rods, it also appears as a slightly stylized piece of expressionism, but why not?

4.79
Patscenter, Princeton designed by Richard Rogers & Partners, has a similar arrangement to their Inmos building with the main accommodation located in column-free spaces on either side of a circulation spine

4.80
The structure for Patscenter, Princeton by Peter Rice of Ove Arup & Partners is simpler and more legible than Inmos but it is a smaller less heavily serviced building

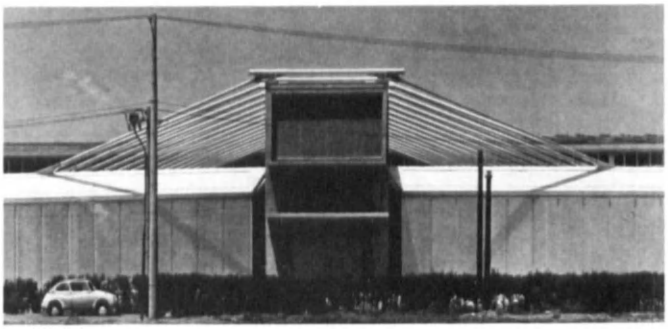
4.79



4.80

4.81, 4.82
Cummins Engine Plant at Shotts designed by Ahrends Burton & Koralek. The form of the glazing is slightly reminiscent of Luckenwalde, p.47

4.83
Printing plant at Haramachi, Japan, designed by Kenzo Tange in 1967, has central spine with services, plant, lavatories etc. in a concrete box girder above leaving the production areas completely clear



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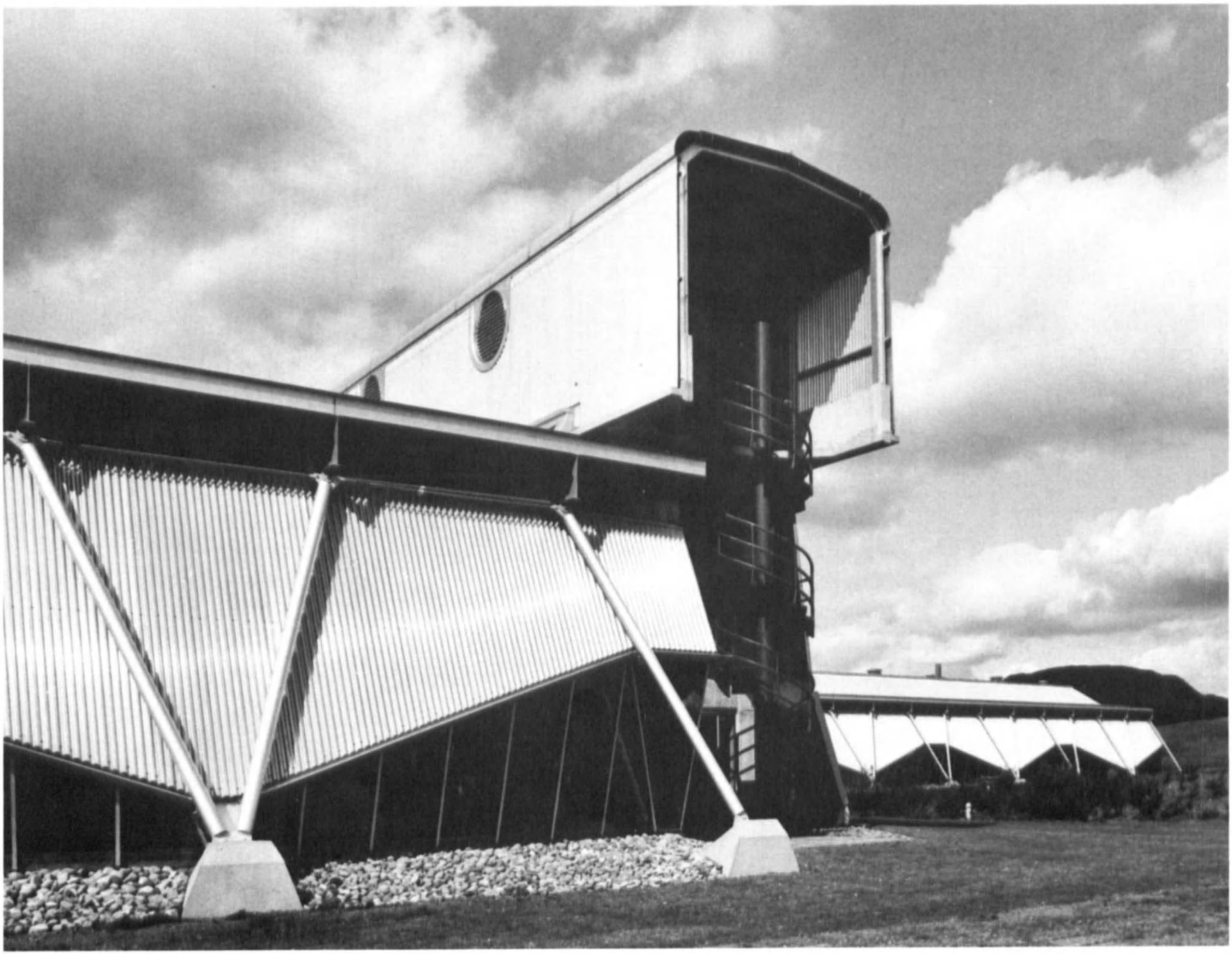

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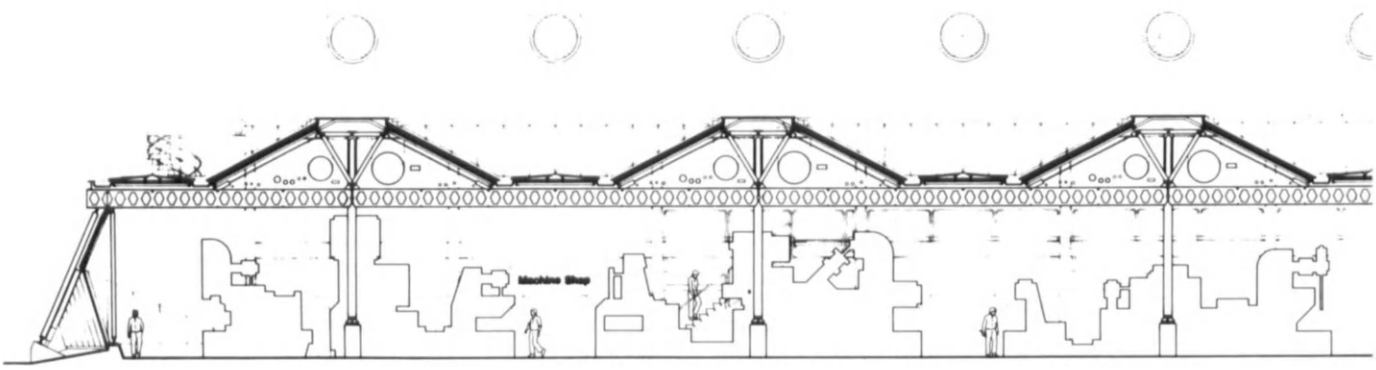
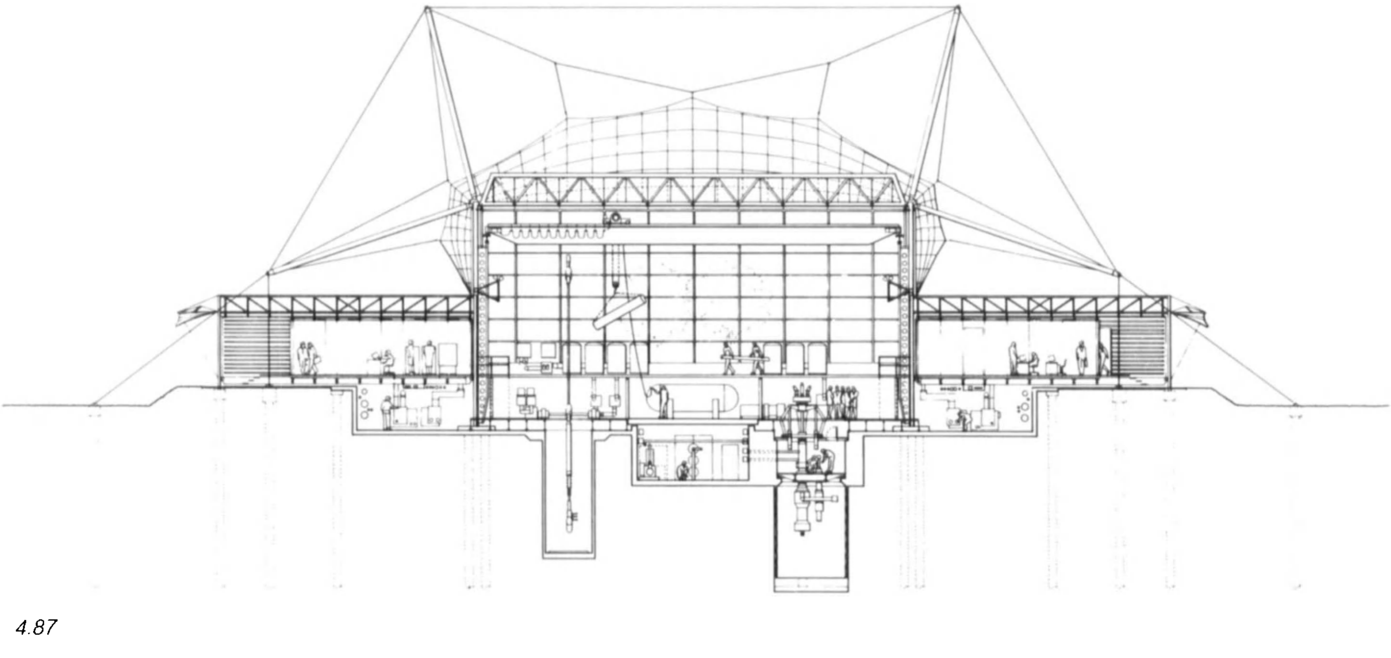


4.84
Schlumberger Cambridge Research Centre, 1985, designed by Michael Hopkins Architects with masted structure and Teflon coated fabric membrane in rural setting

4.87
Cross section with offices and laboratories on either side of the test drilling rig

4.84



4.87

4.85
View of test drilling rig under construction below the fabric roof

4.86
The translucent membrane creates a 'winter garden' housing the reception area and staff restaurant


4.85


4.86

Cummins Engine Plant at Shotts, Scotland

The Cummins Engine Plant at Shotts in Scotland designed by Ahrends Burton and Koralek, is another highly serviced building with the same requirement for wide column-free spaces (Figures 4.81, 4.82). Here the process to be accommodated is of a heavier more industrial nature. A steel structure of primary delta trusses span in one direction and with secondary castellated beams supported from them in the other, on a column grid of 15 × 15 m. The roof sits on the castellas and rises up over the primary trusses to create a services distribution zone clear of the main space. It is a clear, workable solution which is reminiscent of Kenzo Tange's printing plant at Haramachi in Japan, where a concrete box girder runs at high level above the roof and distributes services through the triangular structural beams running in the other direction from which the roof is supported (Figure 4.83). In fact, Tange's innovative building could also have a been a source of inspiration for the Rogers' Inmos and Patscenter spine layout.

The Shotts building has a similar clarity to the zoning of structure, services and circulation, where in this case the pedestrian routes across the production space are in bridges above the main roof structure.

Schlumberger Cambridge Research Centre

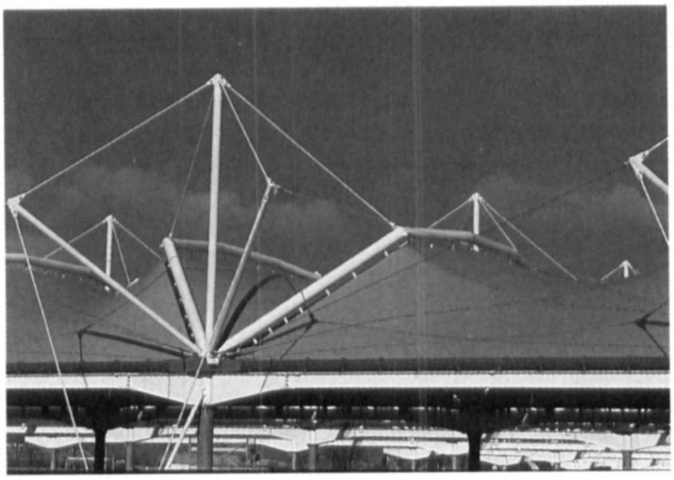
Another exciting new building form with a strongly expressed structure was developed by Michael Hopkins Architects for Schlumberger's research centre at Cambridge, using a masted structure again but this time incorporating a fabric membrane. Here the brief called for offices, laboratories, staff facilities and a drilling test station. The architects chose to group all the activities together with the laboratories either side of the test drilling station, restaurant and visitors reception area. This gave views into the test drilling station from the laboratories, views out over the surrounding countryside for the offices and central meeting place for the restaurant (Figures 4.84–4.87).

This clear approach to planning is followed through in the form of the building where the offices and laboratories are housed in a single storey steel frame structure whilst the test drilling rig is enclosed in two 18 × 24 m bays under a tension supported fabric structure. It makes perfect sense, for the test drilling rig requires only basic shelter with minimum environmental control, which is economically provided by the fabric roof and which also provides natural daylighting through its 15% translucency. The entrance reception and restaurant are also housed in another 18 × 24 m bay under the fabric roof which forms a sort of winter garden, facing south and benefitting from views of the test rig on one side and of the countryside through the glazed end wall on the other. There is a tremendous quality and vitality to this space which comes from its billowing shape and the muted light emanating through the fabric.

It is an exciting and innovative design which is economical in all respects, and shares the quality of architectural detail with the buildings from the Foster's and Rogers' practices. There is a consistency throughout the design and a high level of refinement in the detailing of each of the elements which comes from an understanding of the materials and the painstaking process of 'getting it right'.

4.88, 4.89
Le BOP, Charles de Gaulle Airport: 30,000 m² Air France freight distribution centre with fabric roof designed by Groupe Arcora

4.88



4.89

Freight Terminal, Charles de Gaulle Airport, Paris

There is enormous potential for the use of fabric membrane roofs in big shed construction due to fabric's lightness in weight, its spanning capacity and cost, but there are still only few completed examples. In France, however, the Arcora Group have designed a 30 000 m² canopy in polyester pvc for an air freight distribution centre at Charles de Gaulle Airport (Figures 4.88, 4.89). Here the fabric membrane is suspended from a tubular frame on a semi-regular orthogonal grid of 18.75 m span with a combination of 11.0 m, 16.0 m and 18.75 m bays. The lightness of the covering material has enabled the designers to produce a most elegant lightweight steel supporting structure within an ecomonic budget.

5 More with Less

'To accomplish a task with the minimum of material is finally the only interesting problem' (Bernard Lafaille).

'Rational action in a rational world requires, in every social and economic activity, the maximum net performance per gross energy input' (R. Buckminster Fuller).

A major theme in the development of large-volume buildings has been the engineer's preoccupation with achieving greater spans with less material. This has been facilitated by progressive developments in structural materials, design and methods of construction. In recent times, computer-aided stress analysis has inspired confidence to pare down the size of structural members in conventional systems, to the absolute minimum, whilst exciting innovations with tensile fabric structures and pneumatics have enriched the vocabulary for lightweight structures.

With the continuing threat of economic recession, the soaring cost of energy and the accelerating depletion of our natural resources, the essence of Buckminster Fuller's Dymaxion concept for achieving 'more with less' seems ever more relevant, and the future for lightweight structures even more promising.

The development of cast iron for structural framing in the nineteenth century was the first major breakthrough for lightweight structures, which resulted in such tremendous achievements as the arched roof of St Pancras Station built in 1868 with a clear span of 73 m. Here the 1.8 m deep arched ribs weigh only 55 tons each, which is a considerable advance on the stone vaulting of the previous era. This was closely followed by developments in the use of structural steel, which made it possible for the French engineer Contamin to construct the Galerie des Machines in 1889 with the incredible span of 114 m and a steel weight of 24.28 lb per ft^2.

More recently with the advantages of computer analysis, the Louisiana Superdome was constructed with steel lamella domed roof spanning almost twice this length with a diameter of 210 m and a total steel weight of only 26 lb per ft^2, whilst in bridge design, the long-span steel suspension bridge built over the Humber Estuary has achieved a clear span of an amazing 1410 m with a carefully analyzed maximum efficiency in the use of steel.

Technically there is almost no limit to the length of span which can be bridged, or the volume of space which can be enclosed. The actual limits are set by financial considerations, and it is here that economy of means becomes the crucial factor. In the pursuit of structural economy, the primary aims have been to achieve lightweight structures with minimum use of material which can be erected quickly for the minimum cost. There have been a number of developments recently which offer significant advantages and these can be broadly grouped into three categories: space structures, suspended roofs and air-supported structures.

Space structures are three-dimensional assemblies of linear members in which the interconnections are such that a load at any point is distributed in all directions throughout the assembly. They can take the form of flat double-layer grid structures, or braced domes and vaults.

Suspended roof structures use the principles of the suspension bridge and the tent in which loads are distributed directly in tension.

Air-supported structures are flexible, space-enclosing membranes which are stressed by the differential pressures of air within the space or membranes. They are characterized by double curvature shapes and there are hybrid forms which use tension cable support and restraint.

Space Structures

The use of three-dimensional structural systems in building is a comparatively recent development which has emerged with computer programmes for stress analysis, and with progress in jointing techniques. Previously, in a conventional two-dimensional structure such as an ordinary roof truss or portal frame, all the elements lay in the same plane and could only resist loads in that plane. With a three-dimensional structure, loads are spread in all directions and forces are balanced out. With peak loads diminished, inner stresses are reduced and cross sections of compression and tension members are decreased, with the result that less material with less weight is required.

It can be seen therefore, that in theoretical terms, space structures provide a more economic solution for long spans and in practice this has been borne out by the proliferation of proprietary systems marked for the construction industry.

Dr Alexander Graham Bell, popularly known as the inventor of the telephone, was one of the first people to realize the enormous potential of space structures. As early as 1907 he carried out a series of important experiments with tetrahedron-based structure for kites/aeroplane designs and for building structures, which illustrated their tremendous versatility, strength and potential for industrialized prefabrication (Figure 5.1). The development of space structures proceeded with

5.1
Experiments with tetrahedron-based structures by Dr Alexander Graham Bell in 1907

5.2
The Mero System designed by Dr Max Mengeringhausen in the 1940s

early aircraft design, but it was some time before the principles were applied to the building industry.

Mero System

One of the earliest space grid systems was the Mero System introduced in Germany by Dr Max Mengeringhausen in the 1940s and is still one of the most popular in use today (Figure 5.2). The system consists of prefabricated steel tubes which are screwed into forged steel connectors. This connector known as the Mero ball is capable of joining up to 18 members without any eccentricity, and massive skeletal structures can be easily constructed merely with this screwed connection.

In the USA, Konrad Wachsmann was one of the great pioneers of space structures with his research work as professor of Advanced Building Research at the Illinois Institute of Technology in the 1950s. He developed a tetrahedral system for large-span aircraft hangars (see Chapter 2) in which up to 20 members could be joined in a single node using no tools more complicated than a simple hammer.

Also at that time, Buckminster Fuller's research into 'geodesics' effectively progressed the basic form of space structure into the construction of lightweight domes and renewed popular interest in this ancient form of enclosing space.

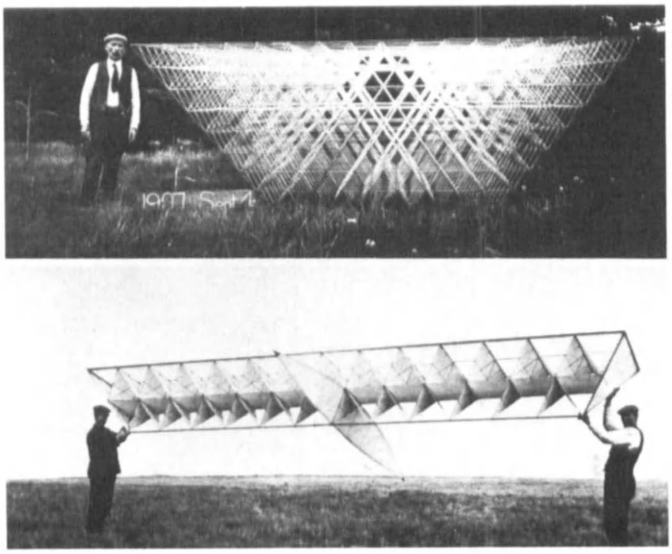
There are therefore two basic forms of space structures in common use, the flat skeletal grids, and the curvilinear forms of barrel vaults and braced domes.

Flat Skeletal Double-Layer Space Grid

With flat skeletal double-layer grids, two parallel-plane grids are interconnected by vertical inclined web members and different patterns are formed if these grids are laid directly over one another (direct grid) or if they are offset from one another in plan (offset grid). Further differences are achieved if differing grid patterns are overlaid on each other which still co-ordinate to form a regular pattern (differential grid). The different geometrics can each have special advantages to suit varying situations of span, load and building shape. In addition to these forms there are two-way lattice grids which are more like a conventional grid of beams, but where the beams are three-dimensional in form.

McCormick Place Convention Centre, Chicago One of the largest two-way lattice grids ever erected forms the roof over the McCormick Place Convention Centre in Chicago built in 1970 (Figure 5.3). Here the total roof area is 410 × 180 m and the total weight of steel is 9500 tons. It covers two large exhibition halls and a theatre complex which are enclosed by glazed walls set back 27 m from the edge of the roof.

This impressive structure consists of 4.7 m deep steel trusses at 45 m centres, supported on 36 steel plate cruciform columns. The structure is immaculately detailed and exposed throughout, it forms a powerful aesthetic for this huge building, designed by C.F. Murphy Associates. Here the structure was designed to suit the one specific application, but double layer space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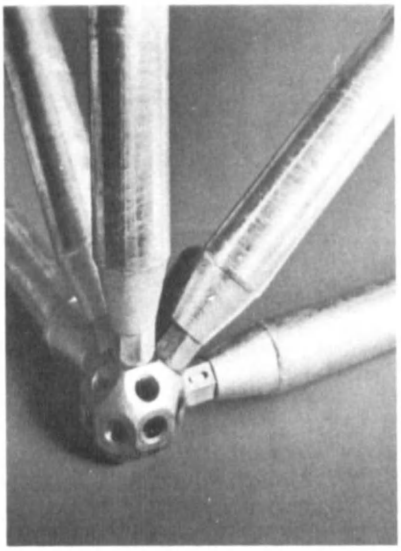
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5.3
The McCormick Place Convention Center, Chicago, designed by C.F. Murphy Associates has one of the largest two-way lattice grids with a roof area of 410 x 180m

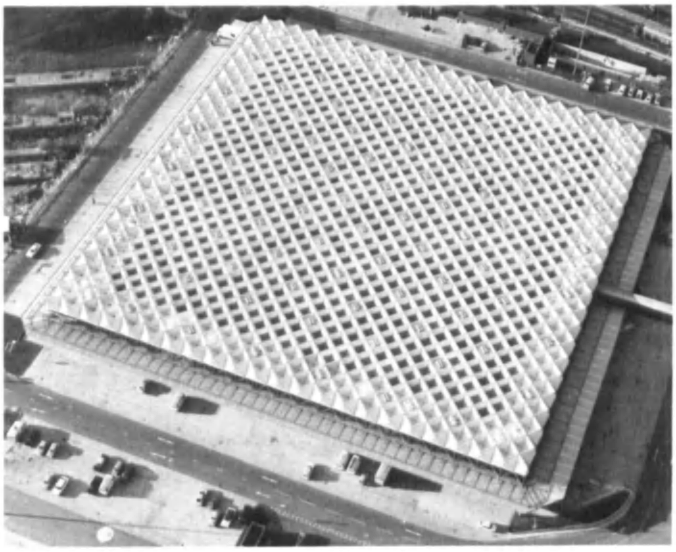
5.4
New Covent Garden Market at Nine Elms by Gollins, Melvin, Ward & Partners has a 3m deep space frame roof covering an area of 109 x 109m

5.3

grids are inherently easily prefabricated and there is an extensive range of proprietary systems available.

New Covent Garden Flower Market A typical example of a simple prefabricated double-layer space frame structure is the New Covent Garden Flower Market at Nine Elms in London, designed by Gollins Melvin Ward and Partners (Figure 5.4). It has a 3m deep steel space frame roof covering an area of 109 x 109m with an overhang on all four sides. It is supported by 36 tree-like columns on a diagonal grid, with repetitive pattern of translucent rooflights. The light tubular steel members of the space frame create a delightful tracery effect echoing a botanical structure which is in sympathy with the delicacy of the flowers traded beneath.

Similar structures are fabricated out of aluminium for even lighter weight construction, and in fact one of the



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5.5
A glazed space structure encloses 1.2 hectares of recreational facilties at Summerland in Japan by Ishimoto Architecture and Engineering Inc

largest space frame roofs in the world is of aluminium tubular sections. This covers the exhibition hall in Anhembi Park, São Paulo, Brazil, which measures 260 × 260 m with a span of 60 m between columns. Aluminium has the advantage of weight, ease of maintenance and transportation but tends to be more expensive than steel for the same spans and loadings.

The scope of space structures is not restricted to just its simplest forms of flat roof supported on a forest of columns. Systems have been developed to suit more complex requirements, such as the British Airways 01 hangar at Heathrow Airport for Jumbos designed by Z.S. Makowski (illustrated in Chapter 2). Here the roof consists of a continuous two-way grid folded to a Z-form and supported by girders on the fold lines and only eight columns along the perimeter. It provides a clear span of 135 m and a height of 34 m at its maximum with an overall high strength-to-weight ratio capable of supporting high equipment loads.

A hangar of even larger proportions and with a similar roof construction was built for Japan Airlines in 1972 at New Tokyo International Airport with a clear spanning space grid roof with tied portal trusses measuring 190 × 90 m overall. The world's largest two-way two-layer rectangular steel space frame grid was the roof of the Osaka Expo '70 Theme pavilion by Kenzo Tange which measured 292 × 108 m.

Summerland, Japan Also in Japan, a vast tubular steel space structure has been used at 'Summerland', By Ishimoto Architecture and Engineering Inc., to enclose a 1.2 hectare all-weather recreational environment where thousands of people each day enjoy an eternal summer climate with tropical vegetation and a vast range of leisure activities (Figure 5.5). The steel roof which is 161 m long by 80 m wide can accommodate the population of a small town or village. Its average daily attendance is 8000 visitors but it can house up to 12 000 people at one time. Inside this vast space, the sense of enclosure is almost lost and the rare opportunity is provided to experience the 'Garden of Adonis' environment identified by John Hix in his book *The Glasshouse*. A combination of lightweight long spanning structure and environment control can create the ideal climate regardless of its location in the world. The potential for this is enormous, but the most suitable structural systems is more likely to be of a tensile or pneumatic type with fabric covering for cost effectiveness rather than a space grid structure. The economics in a space grid structure are best achieved with medium spans by prefabrication of a minimum number of elements for ease of handling and erection.

5.5

Braced Domes and Vaults

The dome is one of the most efficient shapes for covering large areas, for it encloses a maximum amount of space with a minimum surface area. The purity of its shape is appealing. It occurs consistently in nature and is one of Man's oldest structural forms.

In theory there is almost no limit to the size of dome which can be constructed, and this provides a constant challenge to engineers. However, in practice the limitations on the size of domes has been closely associated

5.6
Comparison of dome spans: 1. St Peter's Rome; 2. St Paul's, London; 3. Pantheon, Rome; 4. Astrodome, Houston; 5. Superdome, Louisiana

with the development of available materials and construction techniques. Man's earliest attempts were constructed of mud and timber, but it was the Romans who first demonstrated the structural potential of the dome shape. Using a form of concrete cast in horizontal layers they constructed the domed roof over the Pantheon in Rome in the early second century AD with the incredible span of 44 m.

Its span was not equalled for more than 1700 years and it still remains standing to this day (Figure 5.6). During those intervening years when concrete technology was lost, many spectacular domes were constructed of stone and timber, but the limitations of weight and jointing techniques restricted their spanning potential. Brunelleschi's dome over Florence Cathedral in the early fifteenth century was closest to the Pantheon span if measured across the diagonals of the octagon and for further comparison, the dome over St Peter's in Rome 1591 has a span of 41.6 m whilst the dome of St Paul's in London is 30.7 m in diameter.

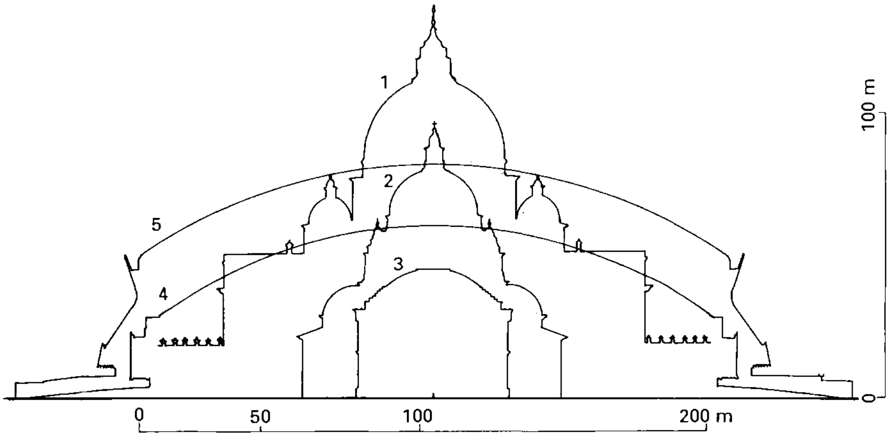
In the nineteenth century the use of iron for roof structures widened the potential for domes and there was a proliferation of their use in public buildings. The Bourse de Commerce in Paris, which had been the Halle au Blé before its timber dome was destroyed by fire, is believed to be the first large iron-framed dome, constructed in 1806–1811, and it was followed by many iron-framed domes throughout the world. Later in the century wrought-iron framing was used as in the 56 m spanning dome of the Albert Hall by Captain Fowke in 1867–1871.

The introduction of steel towards the end of the century brought with it the potential for much lighter weight structures and the possibility of wider spans.

In the twentieth century the development of domed structures has continued to progress with the introduction of concrete shells, lamella steel frames, geodesic and air-supported structures. If there is a competition for the largest dome to be built in the first two millenia since the birth of Christ, which I suspect there might be, then it looks as though it is going to be won by the steel lamella Louisiana Superdome by Sverdrup and Parcel Associates constructed in 1976 with a span of 206 m (Figure 5.7). This is the largest diameter dome to date; however, this is a small-fry and could easily be exceeded if the desire and financial budget was there to justify it. Certainly with the use of lightweight air-supported structures the span could be dramatically increased as in the proposed Arctic City project (see p. 110), where a 2 km diameter dome was envisaged.

Lamella Domes The lamella dome consisting of a series of interconnecting steel units gives an extremely even stress distribution which leads to considerable savings in material and it is for this reason that many of the large stadia domes have been constructed in a lamella form such as the Louisiana Superdome and the Houston Astrodome. Their use is not restricted just to domes and can be economically used for vaulting. An exciting example of this can be seen in the Foster Associates Frankfurt Stadium project, which was designed over the period 1981–1986 but unfortunately never constructed (Figure 5.8).

The competition winning design proposed an extremely elegant, low profile vault to house a 200 m running track with other sports and back-up facilities, together with seating for 3000 spectators. The building was partially dug into the site to reduce its visual impact and the structure spanned between the bermed buttresses. Maximum use was derived from the interesting visual appearance of the trussed lamellas with diamond-



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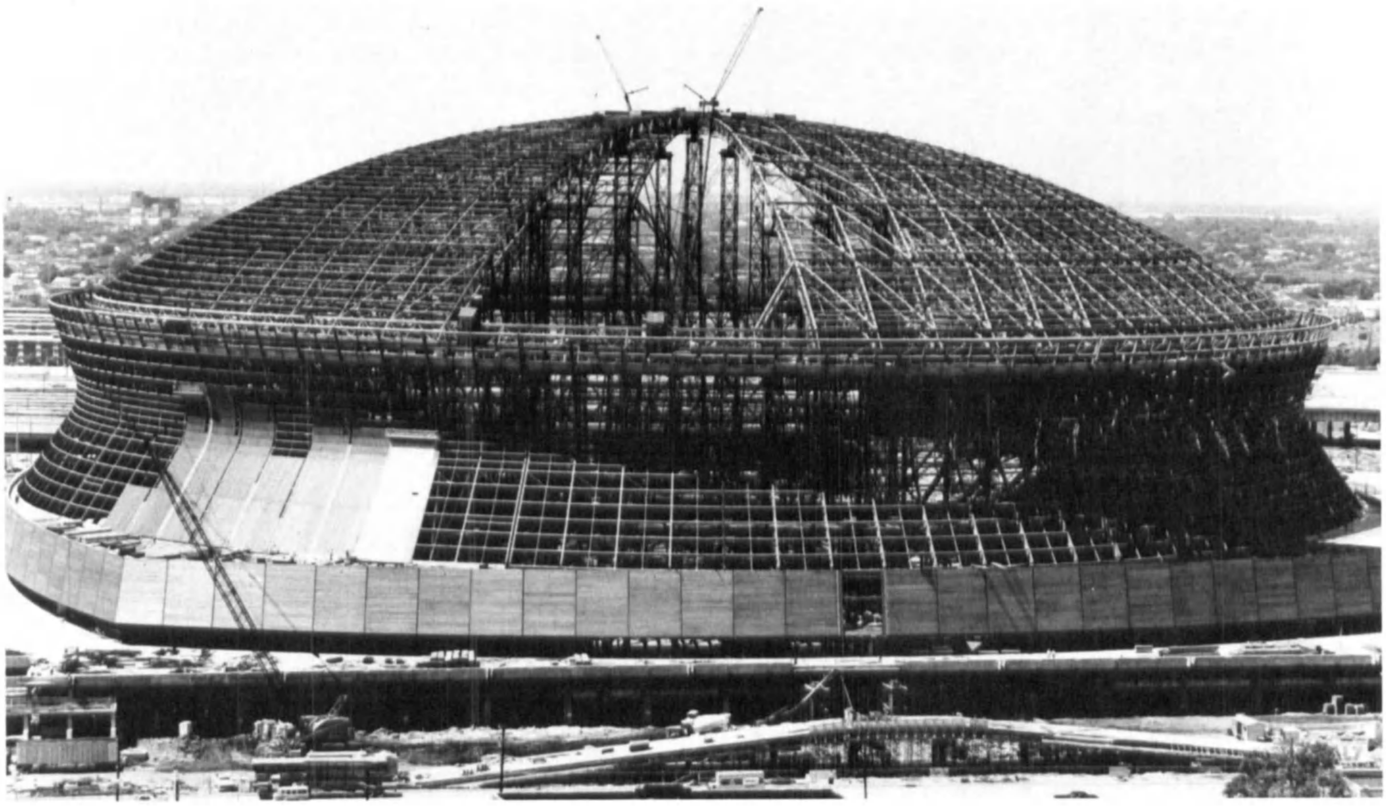
5.7
Louisiana Superdome. Steel lamella with a clear span of 206m designed by Sverdrup and Parcel Associates

5.8
Frankfurt Stadium project by Foster Associates proposed a low profile steel lamella vaulted roof structure



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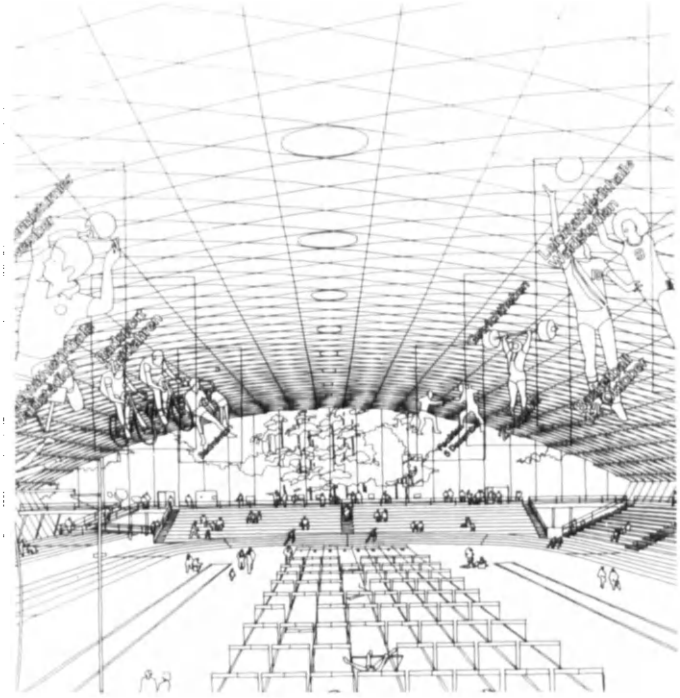


5.8

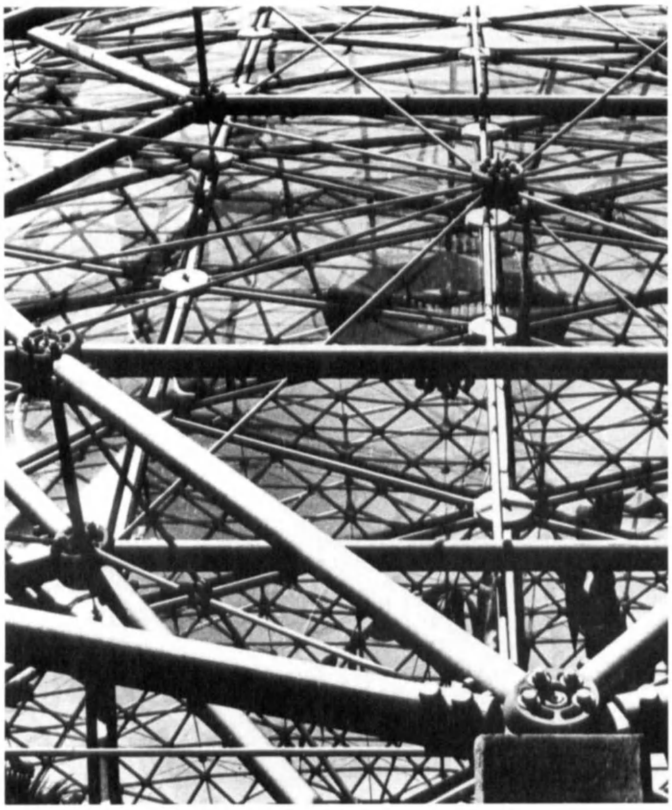
shaped rooflights set into the structure. The services were also integrated within the structure giving maximum efficiency.

Geodesic Structures The other most important form of dome structure is Buckminster Fuller's geodesic structures, which through their ease of prefabrication, have contributed much to the popular use of domes. The geodesic dome uses the regular icosahedral division of the spherical surface divided into 20 equilateral spherical triangles each of which can be subdivided into six triangles by drawing medians and bisecting the sides of each triangle. This complex geometry called 'energetic and synergetic geometry' by Buckminster Fuller has made it possible to construct quite large domes out of prefabricated linear units.

The two most interesting domes of this kind are the Climatron at St Louis, Missouri, and the US Pavilion at the Montreal Expo '67. The Climatron was built in 1960 in the Missouri Botanical Gardens as a kind of special conservatory, where different climates are maintained within the single large space by the use of water sprays to heat

5.9
Detail of structure and external skin of the St Louis Climatron

5.10
Drawing of the Climatron in St Louis, Missouri, designed by Buckminster Fuller



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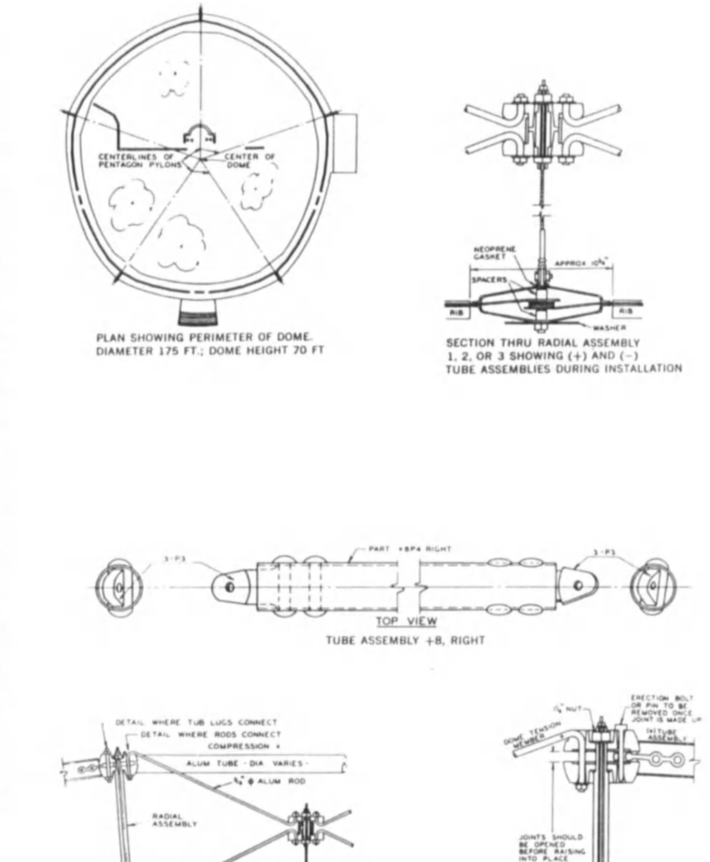

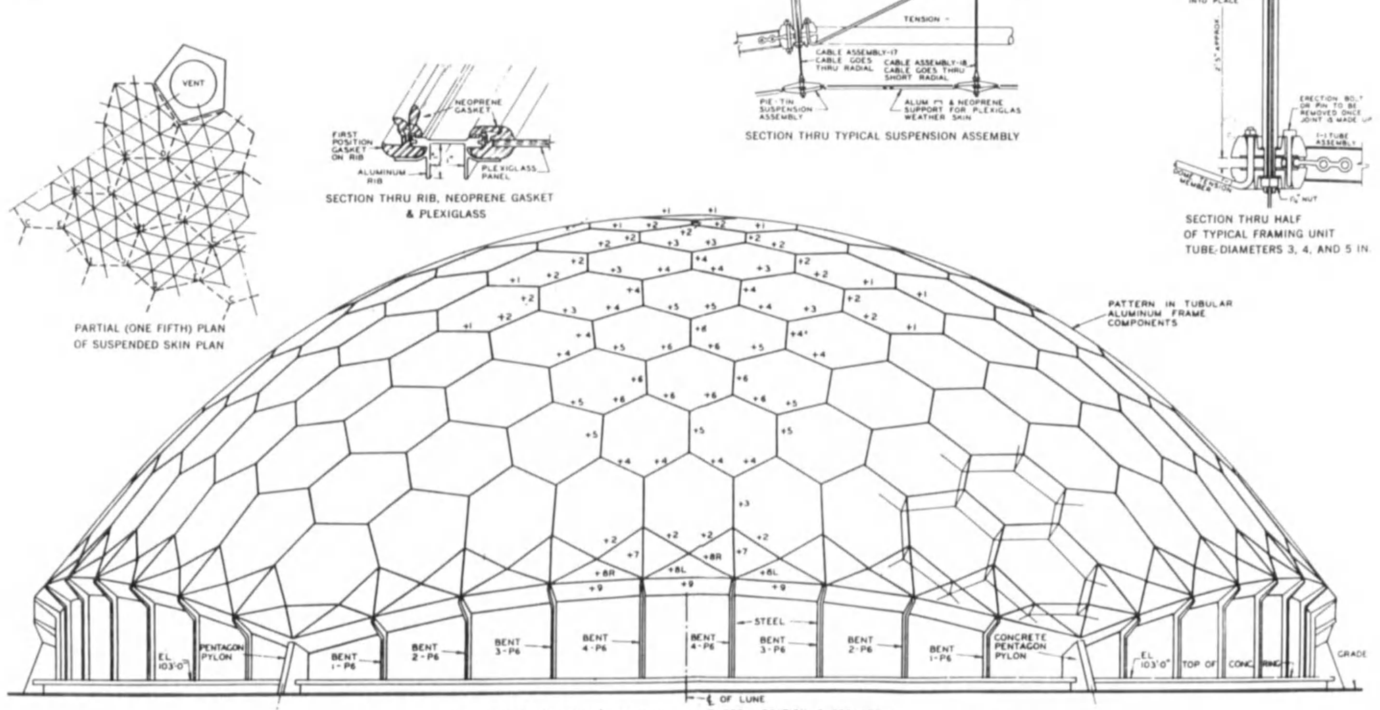

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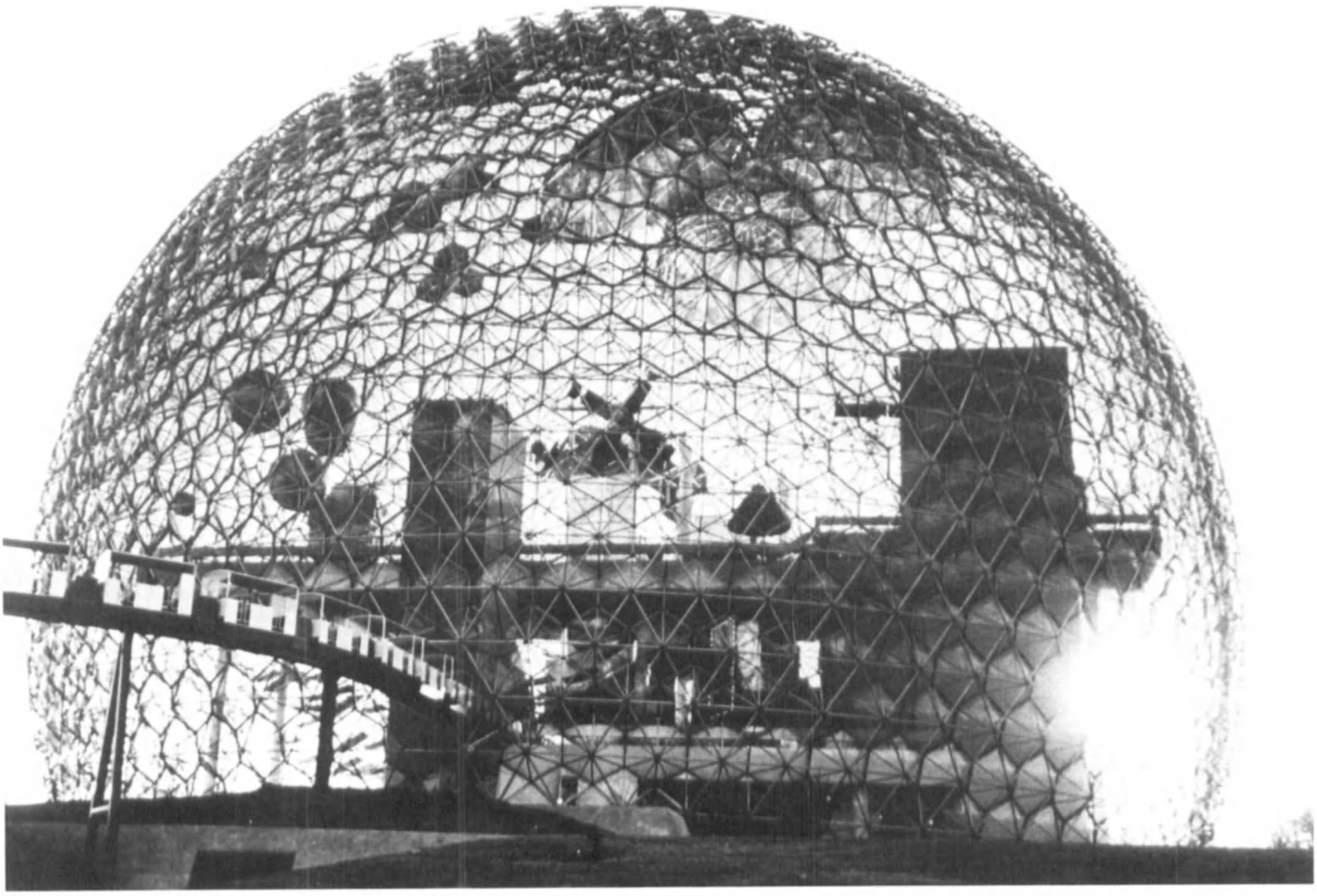
5.11
The USA Pavillion at Expo '67 by Buckminster Fuller with Geometrics Inc. and Cambridge Seven Associates was one of the first environmentally responsive buildings



5.11

or cool the air in different parts of the dome (Figures 5.9, 5.10). They range from the tropical rainforests in one part to dry tropical and Oceanic climates, each with its indigenous vegetation. It is incredible that such variety can be created within the 53 m diameter structure under an acrylic skin and it offers some interesting possibilities for the future.

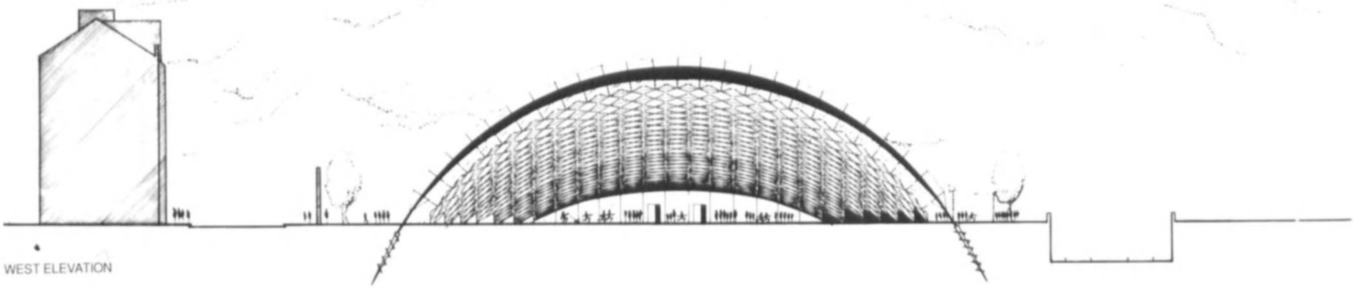
At Expo '67 the dome envisaged by Fuller with Geometrics Inc. and Cambridge Seven Associates was to be one of the first environmentally responsive buildings (Figure 5.11). The 60 m high dome with a diameter of 76 m was provided with solar activated blinds which closed into the centre of each hexagon or would have done if it had worked. Unfortunately it was thwarted by mechanical failures which created an interesting patchwork pattern but failed to control the internal climate. However, this is an aspect of technology and there is no doubt that buildings should be more responsive to their environment.

The McCarthy Whalley Truss A group of young British designers have been experimenting with the design for a structure which will respond to changes in load by changing its shape. To achieve this the architects Andrew Whalley and Fiona Galbraith working with Chris McCarthy of Ove Arup & Partners have designed a structural system based on an interlocking 'star' element of die-cast magnesium, in compression balanced by prestressed chains (Figures 5.12, 5.13). The tensions in the upper and lower chains are connected through a vertical axle and are consequently always in equilibrium for all loading situations.

This innovative structural concept was proposed for a large hall and performance space of 4500 m^2 with a triple layer pneumatic cushion of polyester pvc and entered in the Glasgow Eurodome Competition, for which it was short-listed. The team is continuing to explore alternative structural possibilities generated by the system and a prototype truss has been constructed for analysis at the Robert Gordon Institute of Technology, Aberdeen.

5.12
Glasgow Eurodome competition entry with 'responsive structures' incorporating the McCarthy-Whalley truss

5.13
The McCarthy-Whalley truss in a controlled mechanism consisting of an interlocking 'star' element in compression, balanced by prestressed chains in tension



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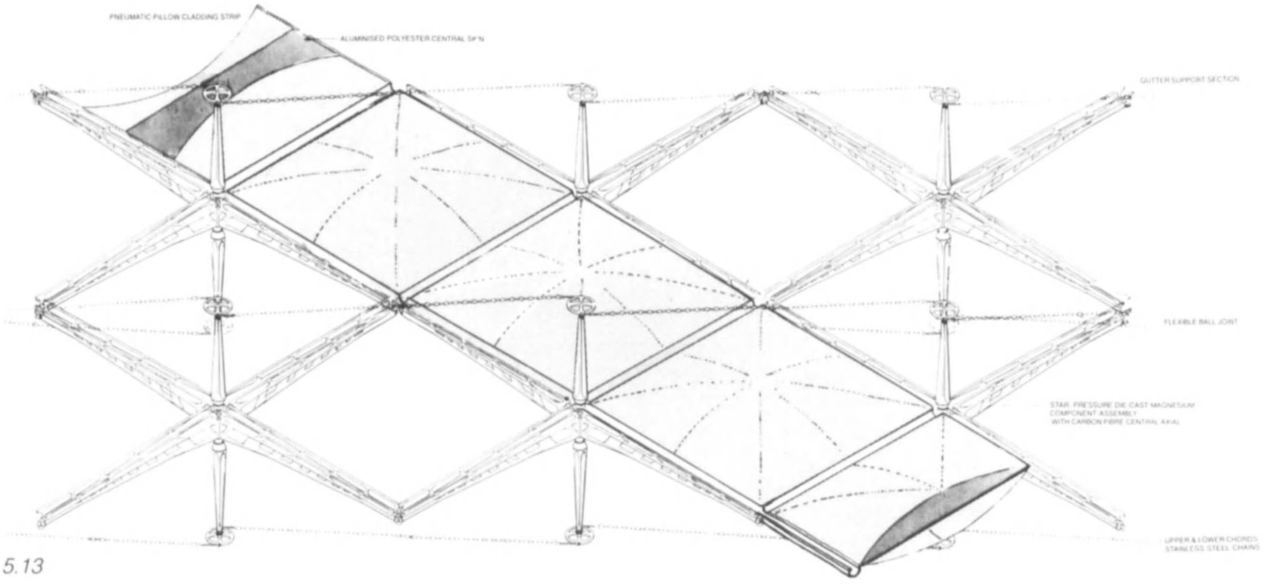


5.13

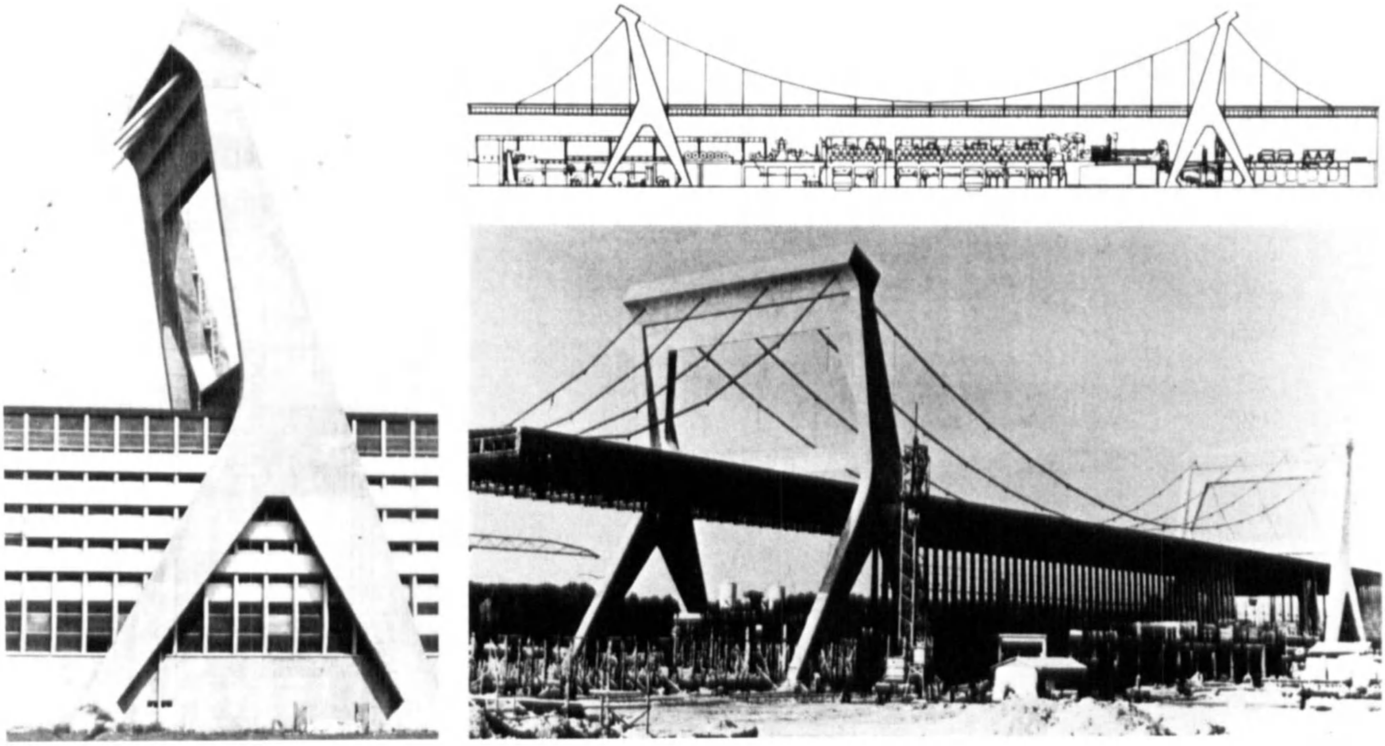
Suspended Roof Structures

Tension structures offer the 'lightweight' solution to long-span, column-free spaces, with the advantages of economy in the use of materials and the visual quality of slenderness. It is for these reasons that their popularity with both architects and engineers has been rapidly increasing in recent years.

The economy of material is critical for reasons of cost and more importantly the reduction in self-weight, which is essential to the achievement of long spans, whilst the slenderness is important to the visual appearance of the structure which benefits from the filigree effect of the lighter weight tensile members. As Phillip Drew said in his book *Tensile Architecture*: 'An exposed tensile member communicates its task with remarkable eloquence compared with heavy compressive members because of the identity of force and form'. For example, spiders' webs and yacht masts both convey this quality of strength and lightness in contrast to the heaviness of traditional forms of buildings.

The first tension structures built by man were probably tent-like forms constructed of animal skins and later their potential was improved with the introduction of woven materials. Ships' sails have been fabricated since the time of early civilization and it is known that the Romans covered their stadia with 'velum', fabric awnings to provide shelter from the sun. Suspension bridges in a simple catenary form are also known to have existed in China and Tibet for centuries before Christ, using plant fibre ropes, but progress was limited until the introduction of iron cables in the early nineteenth century. This made long spanning bridges possible for the first time, so that in 1826 Thomas Telford was able to construct the Menai Suspension Bridge with a span of 147 m followed by Brunel's Clifton Suspension Bridge with a span of 285 m and John Roebling's Brooklyn Bridge with a span of 523 m. The spanning capacity of these suspension bridges has continued to increase with the 1378 m span of the Golden Gate Bridge in 1937 up to the 1410 m span of the Humber Bridge of 1978.

5.14
Nervi's Paper Mill at Burgo provides a 147m column-free production space with a cable-supported roof



5.14

The first major building to use a suspended roof system is generally accepted as being V.G. Shookov's series of four steel tent pavilions at the Nijny-Novgorod Industrial Fair of 1896 in which steel lattice mast structures supported suspended net roofs of thin steel strips. This was an extremely sophisticated system way ahead of its time and it anticipated Bernard Lafaille's French Pavilion at Zagreb, Yugoslavia in 1935 in which a suspended steel saucer-shaped roof was used with a diameter of 36 m. However, it was not until the 1950s that tension structures started to become more widely used, their appearance being highlighted by Powell and Moya's 100 m high 'Skylon' tensile sculpture at the Festival of Britain in 1951 and Matthew Nowicki's pavilion at Raleigh, North Carolina, in 1952.

From this time interest in tensile structures escalated with major input from both engineers and architects such as Eero Saarinen, Lev Zetlin and Kenzo Tange on a complete range of buildings from exhibition halls to aircraft hangars and stadia roofs.

Tension structures can be categorized into those which use *linear* elements such as rods or cables to transmit the tensile forces and *surface* forms such as membranes and cable nets. The former being based on the suspension bridge offers the suspended roof form to buildings and the latter which is based on the tent provides the full range of membrane structures, including prestressed concrete and fabric structures of either cable-guyed or pneumatic form.

Linear Suspended Roof Structures

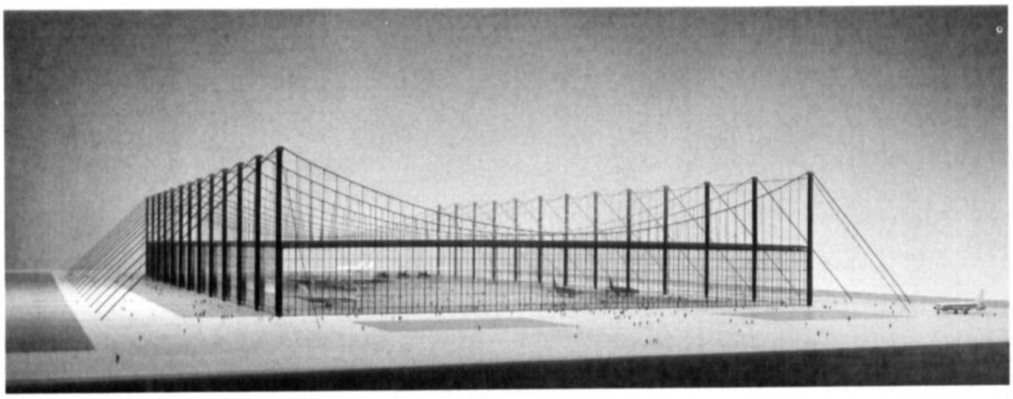
The linear systems use the suspension bridge principle of masts supporting a roof from rods or cables. One of the most dramatic examples is Nervi's Paper Mill at Burgo where the brief called for a long column-free space to house the production process and the resultant building provides a 147 m long hall with a prefabricated truss roof deck suspended by flat steel chains from two enormous concrete towers (Figure 5.14). The building has a beautifully expressive structure but one cannot help thinking that the form is over-elaborate for its purpose.

The cable-supported roof, however, is an extremely efficient means of providing large column-free spaces. The lightness of the cable reduces dead weight and surpasses all other known systems in terms of structural efficiency for long spans.

5.15
Project for an Exhibition Hall/ Aircraft Hangar by Peter Pran at the Illinois Institute of Technology in 1960s with Myron Goldsmith and Fazlur Kahn, proposed a span of 304 m with a cable-supported roof

5.16
Table of comparative weights of long-span steel structures, prepared from research at the Illinois Institute of Technology in 1960s

5.17
Model of the structure for the new East Croydon Station by Alan Brookes Associates with 55 m span



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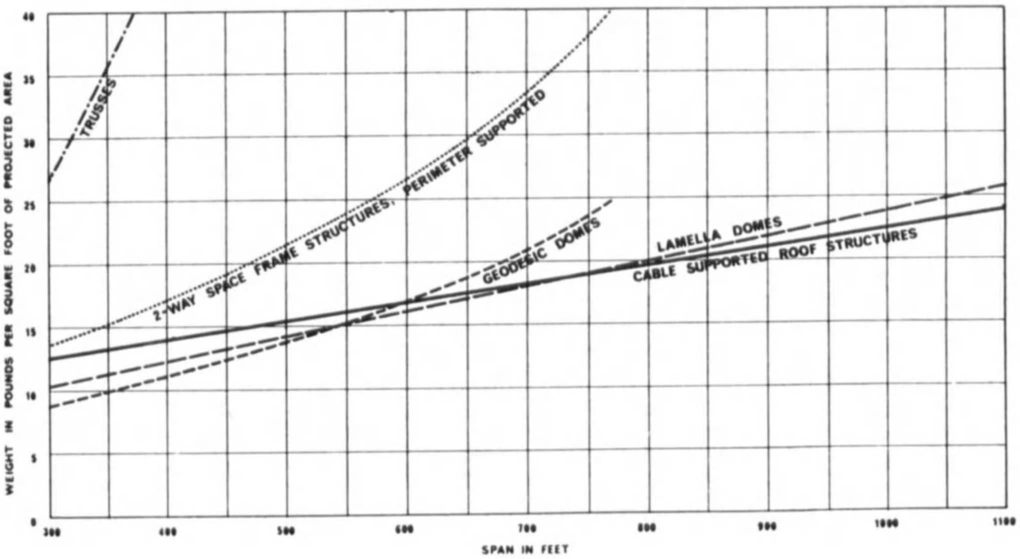

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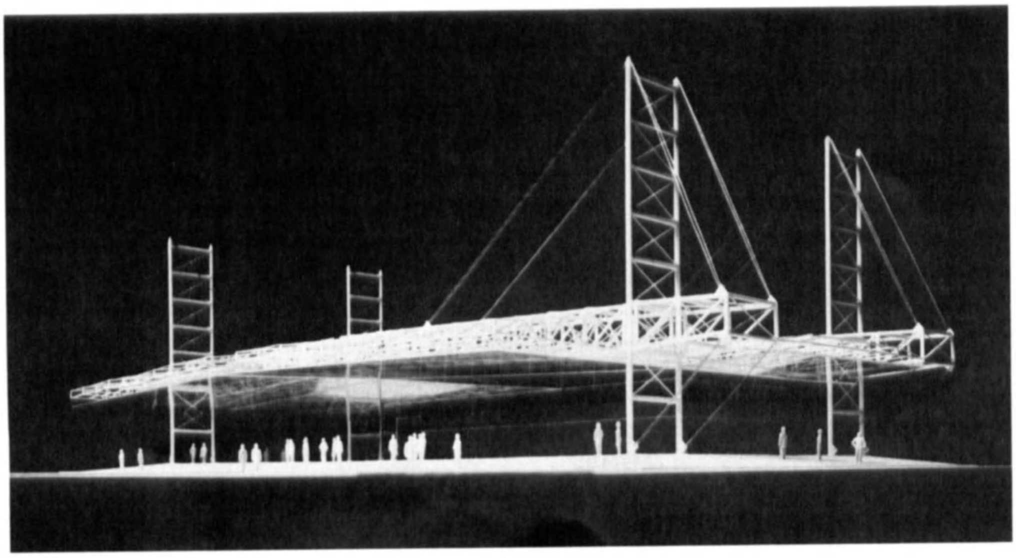
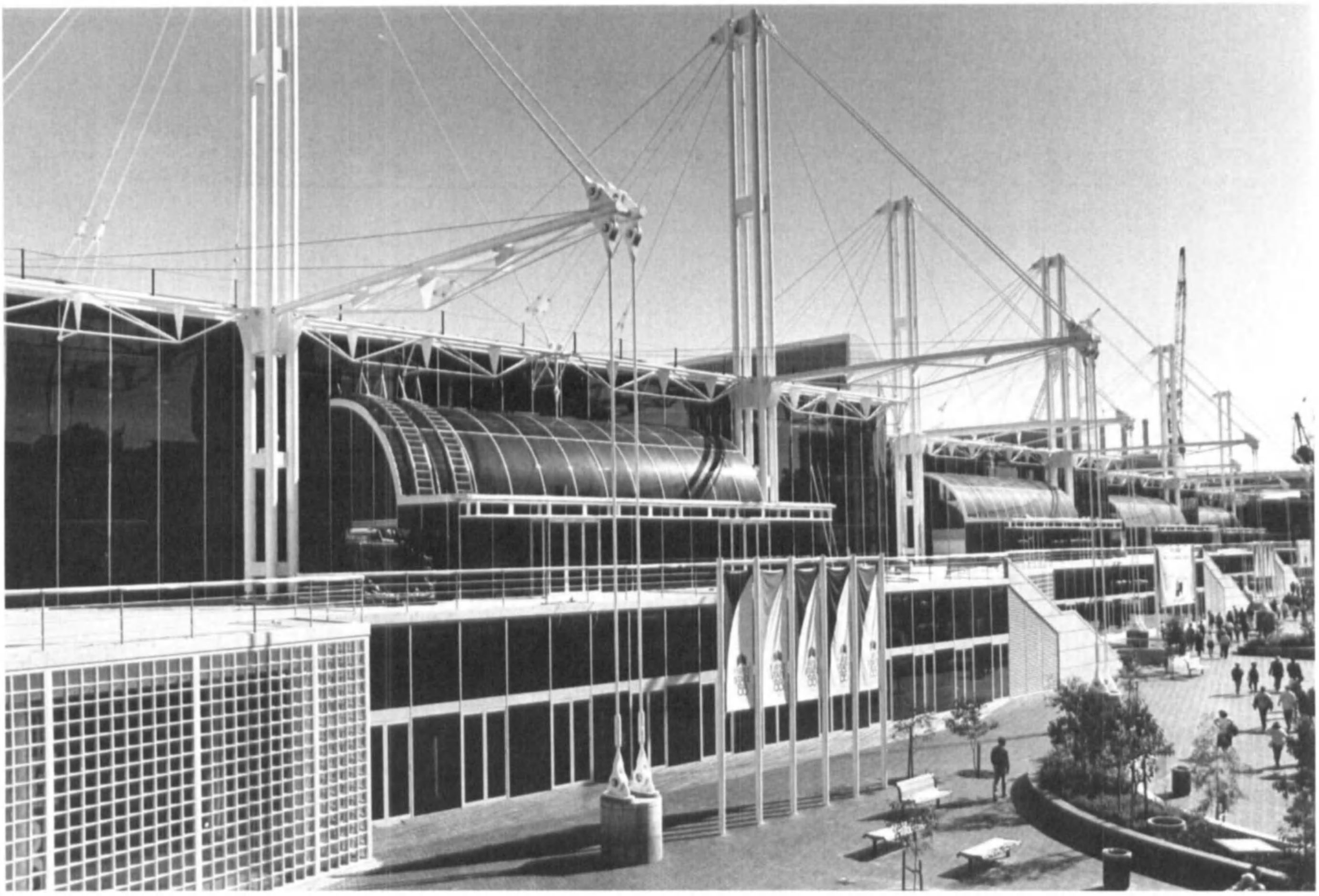


5.17

5.18
Darling Harbour Development Exhibition Centre, Sydney, Australia, by Phillip Cox, Richardson, Taylor & Partners. The cable-stayed structure with prismatic trusses provides a series of clear span enclosures each measuring 87 × 60 m

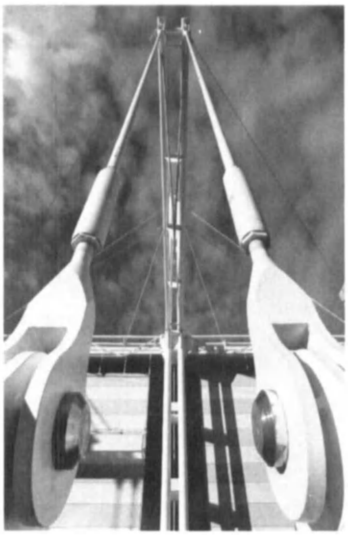
5.19
Detail of the holding down rods pin-jointed connection



5.18

Research undertaken by Peter Pran at the Illinois Institute of Technology in the 1960s, with advice from Myron Goldsmith and Fazlur Kahn, demonstrated this efficiency with a project for an Exhibition Hall spanning 304 m (1000 ft) by 609 m (2000 ft) in length (Figure 5.15). Comparative studies were undertaken with the structural weights calculated for the different structural systems (Figure 5.16). From this it was found that the cable-supported roof with 60 m high masts at 15 m centres provided the most economical structure with the lamella dome structure being closest in weight, although of course, the dome would have had severe restrictions on the shape of the space provided.

It is this lightness and economy of structure together with the exciting visual appearance which prompted the design of the masted structures by Richard Rogers for Fleetguard at Quimper and Norman Foster's Renault



5.19

Centre in the early 1980s, illustrated on pp. 83–84.

Since then many other interesting designs of this form have emerged, one example being the new station at East Croydon by the architects Alan Brookes Associates with Anthony Hunt Associates as the structural engineers (Figure 5.17). This elegant structure achieves a 55 m span with trusses of only 1.8 m depth supported by cables from 20 m high masts of double column assemblies. The weight of structure at only 130 tonnes demonstrates the economy of this kind of structure.

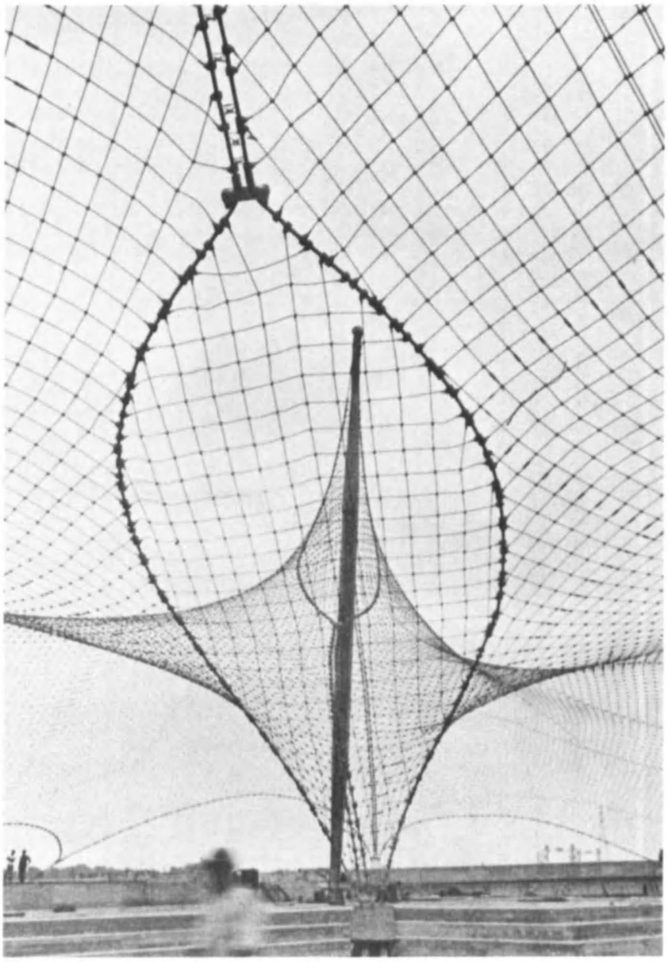
Another interesting use of masted structures on a much larger scale can be seen at the Darling Harbour Development Exhibition Centre in Sydney, Australia, by the architects Phillip Cox, Richardson, Taylor and Partners where 25 000 m^2 of flexible column-free space is provided in five interlinked halls (Figures 5.18, 5.19). A cable-stayed structure with prismatic trusses supported from 32 m high masts with MS rods provides a clear-span enclosure of 87 × 60 m for each hall. All structural connections are pin-jointed using stainless steel pins and the primary and secondary trusses are exposed internally. The structural engineers for this building which was completed in 1987 were Ove Arup and Partners.

Fabric/Membrane Structures

The form of tension-loaded structures changed dramatically with Frei Otto's work in the development of cable-net and prestressed tensile membrane systems. From 1959 onwards he used models to investigate the sort of shapes that could be used for tensile membrane structures. By stretching nets, soap bubbles and elastic membranes he generated a whole new language of exciting double curvature shapes which he was able to demonstrate through a series of live projects such as the German Pavilion at the Montreal Expo in 1967 and the 1972 Munich Olympic roof structures.

At Montreal, a prestressed cable net of 12 mm diameter steel cables supporting a pvc membrane was suspended from masts of varying heights, pulled down at restraining points and bounded by edge cables which transferred the stresses to the anchor points in the ground (Figures 5.20, 5.21). The resulting form provided a spectacular array of interrelated anticlastic surfaces providing environmental enclosure with the minimum weight of material. It is said that Frei Otto's team took 20 000 man hours on the design of this pavilion which was erected in only three and a half weeks. The spans of about 45 m were not great but a new and effective system for providing lightweight large volume enclosures had been clearly demonstrated.

5.20
Montreal Pavilion



5.20

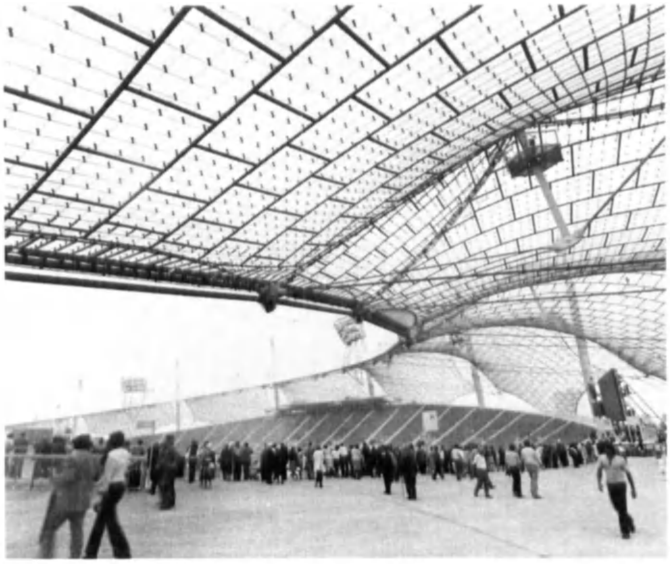
The same system was used for the Munich Olympic roofs five years later, on a much larger scale, where a space of 22 000 m^2 was covered (Figure 5.22). Here the spans were increased to 135 m but it is generally thought that the quality of the shapes and the detailing of the subsystems was inferior to the Montreal Pavilion.

Since that time, the important introduction of Teflon-coated glass fibre fabric has resolved the problems associated with having a separate weatherproof fabric and structural cable net. The material provides a durable waterproof membrane which can be highly prestressed, is relatively lightweight and translucent. New forms and applications are being developed which take advantage of these qualities such as the winter garden and environmental enclosure to the test drilling rig at Schlumberger Research Centre in Cambridge by Michael

5.20, 5.21
German Pavilion at the Montreal Expo in 1967 by Frei Otto with pvc membrane suspended from prestressed cable net

5.22
Cable net Munich Olympic roofs by Frei Otto

5.21



5.22

Hopkins Architects, previously covered on p. 90. Here the true qualities of a durable modern tent are realized with exciting form and wonderful quality of light.

The opportunities for the use of fabric structures are immense, and the full potential has yet to be realized. The applications range from the formal stretched cladding panel, as used by Michael Hopkins Architects on the Services Tower in Ipswich to the proposed covered piazza in Foster Associates' Hammersmith Centre. The former demonstrates the use of fabric as a cladding material in a traditional way in place of a panel or masonry construction (Figure 5.23). Here the fabric is stretched over a 2 m square steel frame and pushed out with a bicycle wheel type structure of stainless steel rods to create a curved tension-loaded shape. The panels, which are fitted to the inside of a tubular steel structure, form a translucent envelope to a stair and lift tower which was added onto the face of an existing car parking

5.23
Prestressed fabric membrane panels 2 m^2 provide the cladding to a Service Tower in Ipswich by Michael Hopkins Architects

5.24
Foster Associates proposal for a fabric membrane roof over the large public space at the Hammersmith Centre Development

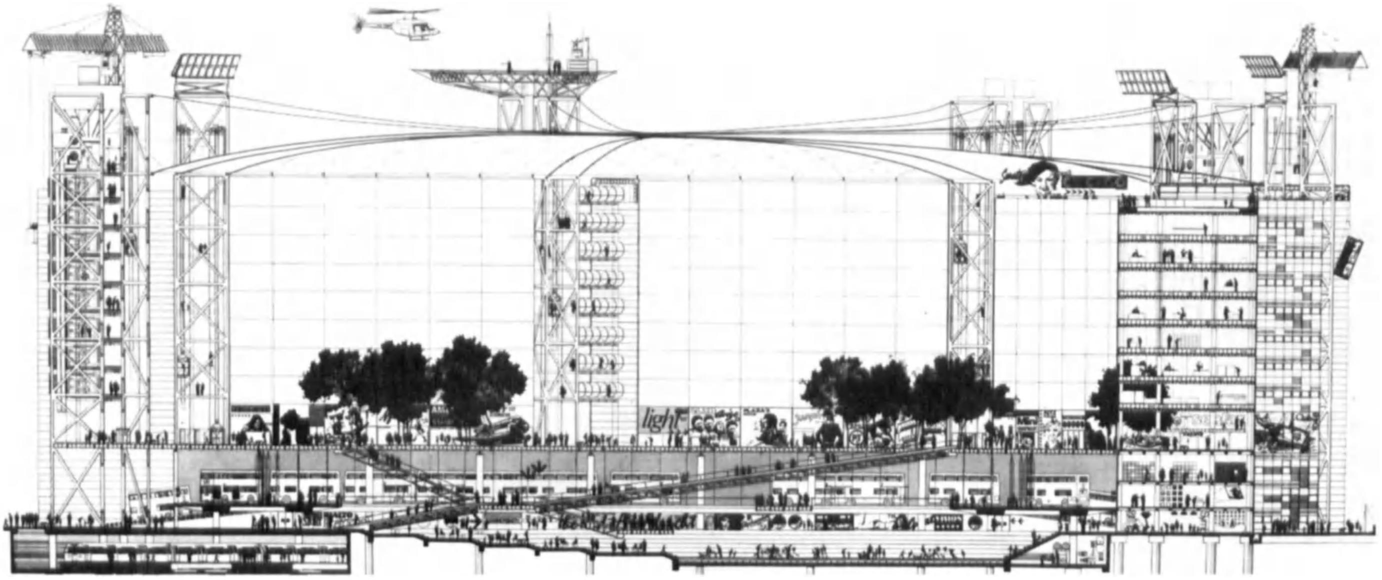

5.23

building. In this way it provides an economical solution to a weather-tight enclosure where the control of temperature was not important.

Foster's proposal for the Hammersmith Centre used a fabric roof to cover the huge area of public space at the centre of a shopping, office and transport interchange (Figure 5.24). It respected the need for a public space in this situation and addressed the problems that inclement weather creates on the use of such spaces. The fabric canopy would have provided an economical solution to this and might have found many other similar applications, had the project not been abandoned. The idea for the roof had been based on the Uni-Centre in Atlanta, the US Pavilion at Expo '70 and the proposed Norfolk Gardens project in Norfolk, Virginia where 48 000 m^2 of space was enclosed in a fabric roof.

In Munich, a large membrane roof has been used for an open ice rink in the Olympic park designed by Professor Ackermann (Figures 5.25, 5.26). Here the membrane is suspended from a single catenary arch of tubular steel membranes with a strong, clear form. The tent-like space inside has a light, open quality with the secondary structure of timber joist and cables defining a grid.

In conclusion, it is clear that the fabric membrane offers an extremely lightweight form of enclosure and its low self-weight makes long spans achievable with the minimum amount of structure. The obvious shortcomings on thermal and acoustic performance can to some extent be remedied by the use of a double-skin construction. It is possible to incorporate insulation into the cavity and to


5.24

5.25
Ice rink in Munich designed by Professor Kurt Ackermann, with fabric membrane roof

5.26
Interior of Munich ice rink, showing timber and steel rod secondary supporting structure

5.25

5.26

control solar gain by the use of reflective surfaces as proposed by Dr Laing at the first International Colloquium on Pneumatic Structures in Stuttgart 1967. Furthermore, it ought to be possible to produce lightweight fabric membranes which are directly responsive to weather conditions by control of solar radiation and it is likely that this is an aspect where innovation will take place. It also seems likely that we will see wider use of air-supported or partially air-supported membrane structures for large-span column-free spaces which first proved their potential at the Expo '70 at Osaka.

Air-Supported Structures

The principle of the balloon is so simple and its application to lightweight structures can be easily appreciated. F.W. Lanchester was one of the first to see it and he submitted a patent in 1917 (Figure 5.27) for 'An Improved Construction of Tent for Field Hospitals, Depots and like purposes' in which he states:

'The present invention has for its object to provide a means of constructing and erecting a tent of large size without the use of poles or supports of any kind. The present invention consists in brief in a construction of tent in which balloon fabric or other material of low air permeability is employed and maintained in the erected state by air pressure and in which ingress and egress is provided for by one or more air locks'.

His ideas were sound, but unfortunately, at that time there was not a suitable membrane material in existence so his designs were never realized.

Research into suitable fabrics for blimps and barrage balloons during World War II brought significant advances in membrane materials and the first use of air-supported structures for shelters and anti-aircraft gunnery training. In the 1950s the two American firms Birdair Structures and Cidair Structures started to market the first air structures for military and commercial use, then in 1962 Frei Otto's book on tensile structures brought the subject of pneumatic structures to a wider audience. An

5.27
Patent for air-supported tent by F.W. Lanchester in 1917

5.28, 5.29
The American Pavilion at the Osaka Expo '70 by Davis Brody Associates was an innovative, low profile air-supported dome measuring 142 × 83 m

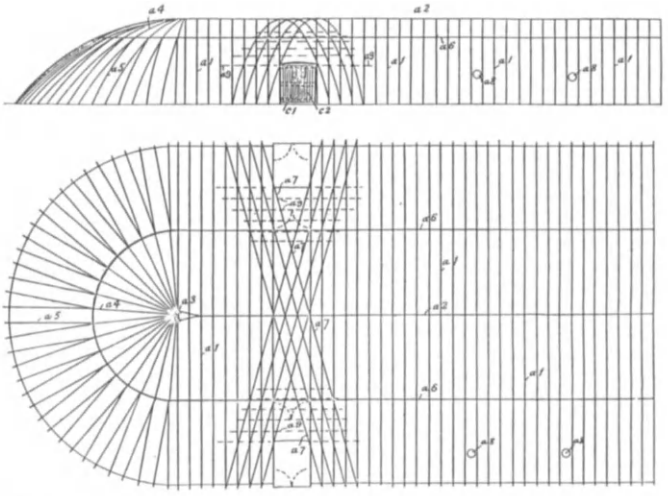
international colloquium was organized in 1967 at Stuttgart and the first significant pneumatic structures were constructed three years later for the Osaka Expo '70.

The American pavilion designed by Davis Brody Associates was a low profile oval shaped membrane dome measuring 142 × 83 m seated on a saucer-shaped bowl partly dug into the ground and mounded around (Figures 5.28, 5.29). It was the largest spanning air structure attempted up to that time and demonstrated the tremendous economy of this form of structure. It was constructed with a net of 48 mm diameter cables anchored to a concrete ring and a pvc-coated high frequency welded glass fibre fabric, which with a total weight of 60 000 kg, could be sustained with an internal pressure of 27 mm of water pressure. It was a sophisticated and restrained design which to some extent had resulted from a massive budget cut-back from the government, but its size and elegant shallow curve with a rise of only 6 m made it a landmark in the design of air structures.

Following the Osaka Expo '70 there was an increased respect for air structures and a range of new applications throughout the world. Perhaps the most popular of these has been the enclosure of leisure activities, from swimming pool covers to sports stadia, which have been particularly popular in the USA. One of the largest of these installations is the Silverdome at Pontiac, Michigan which was completed in 1975 (Figure 5.30). Covering 4 hectares, it houses an 80 000 seat covered football/multi-purpose stadium used by the Detroit Lions and extensively for concerts. The structure by Geiger Berger Associates is domed by a single membrane translucent cable-restrained air-supported roof with a maximum cable span of 228 m and a total structural weight of less than 4.8 kg/m^2 (1 lb/ft^2).

With the low self-weight of the membrane, it is technically possible to enclose much larger spaces still, including possibly a whole city. One such study was carried out by an international design team lead by Frei Otto and Ewald Bubner with Ove Arup and Partners and Kenzo Tange, to investigate the possibility of erecting a city in the Arctic under a transparent inflated skin covering an area of 3 km^2. The main object was to create an artificially controlled climate corresponding to European conditions for up to 45 000 inhabitants in areas where the natural climate is extreme and inhospitable.

The design proposed a cable-net of high-strength polyester fibres with cables of 270 mm diameter at 10 m centres spanning 2 km with a height of 240 m. Anchoring was by means of a ring foundation. Figure 5.31 shows



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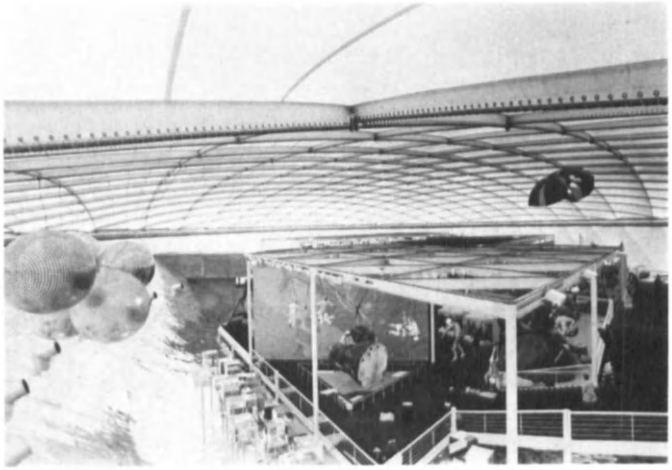


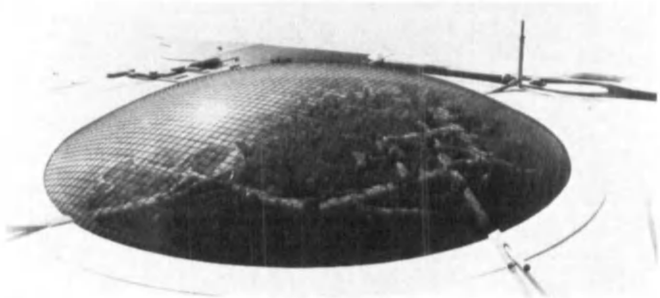
5.29

5.30
The Pontiac Silverdome with a span of 228 m is one of the largest air-supported cable-restrained fabric roof structures

5.31
Arctic City Project by Frei Otto, Ewald Bubner and Ove Arup and Partners, proposed a transparent inflated skin covering an area of 3 km^2 to house a community of 45 000 inhabitants

5.32
Buckminster Fuller's project in the 1950s for a 2-mile diameter tensegrity dome over Manhattan

5.30



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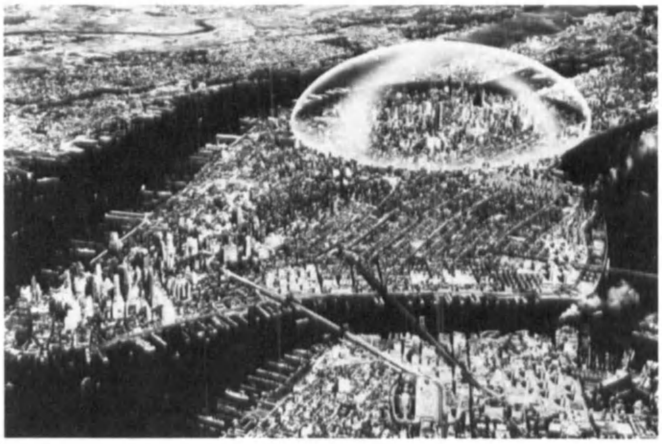

5.32

the stages of the construction process for the membrane which uses balloons to assist inflation which would take approximately 50 hours. Once the membrane had been erected, the City could be constructed under ideal weather conditions. Houses, streets and gardens would be created with natural vegetation, birds, animals and man all provided with healthy fresh air. It sounds idyllic and quite feasible if the desire is there and the economics can be made to add up.

This concept relates back to the proposal by Buckminster Fuller in the 1950s for a 3.2 km diameter tensegrity dome over Manhattan with the Empire State Building at the centre (Figure 5.32), and to a similar scheme proposed by him for St Louis. It is what John Hix describes as the 'Garden of Adonis' concept, a dreamlike artificial environment of perfection which could be made to work in reality.

We have seen the splendid achievements of the Victorians in enclosing 7.3 hectares of exhibition space under glass for the Crystal Palace, followed by the development of wider spans with more efficient structures, vast steel sheds such as the Boeing Assembly Building which encloses 5.8 million m^3 in one space and the Louisiana Superdome which covers 3.2 hectares under its 207 m diameter roof. We have seen the vast clear-span glazed space structure for the Japanese 'Summerland', the environmentally responsive geodesic domes of Buckminster Fuller for the Montreal Expo and the Climatron followed by Frei Otto's lightweight cable-net roof structures for the Munich Olympic stadia, and the superlight air-supported roofs for the US Pavilion at Osaka and the Pontiac Superdome.

Here is proof of innovation and the advancement of building technology. With it has come the opportunity for longer spans and the enclosure of larger column-free spaces with more efficient lighter weight structures. This process will continue with the development of new materials and structural types. Surely we as architects and members of the design team cannot afford to ignore it. It is our task to process the new technology: we must make architecture out of it.

6 The Future

'Modern architecture offers architects an extraordinary opportunity to evolve new forms and materials. The computer, microchip, transputer, biotechnology and solid state chemistry could lead to an enhanced environment, including more rather than less individual control and fewer uniform spaces.

The best buildings of the future, for example, will interact dynamically with the climate in order to meet the users needs better. Closer to robots than to temples, these chameleon-like apparitions with their changing surfaces are forcing us to rethink again the art of architecture. Architecture will no longer be a question of mass and volume but lightweight structures whose superimposed transparent layers will create form so that architecture will become dematerialized.

To date (and here I include Early Modernism) concepts have been founded on linear, static, hierarchical and mechanical order. Today we know that design based on linear reasoning must be superseded by an open-ended architecture of overlapping systems. This 'systems approach allows us to appreciate the world as an indivisible whole; we are in architecture, as in other fields, approaching a holistic ecological view of the globe and our action thereon.

In architecture, invisible micro-electronics and biotechnology are replacing industrial mechanical systems. We shall soon be living in a non-mechanical world which will make buildings such as our Lloyd's of London, which is generally considered too innovative to be outdated, seem old-fashioned. Buildings, the city and its citizens will be one inseparable organism sheltered by a perfectly fitting, ever-changing framework. Post, beams, panels etc., will be replaced by a seamless continuity. These walking, changing robots will contain many of the characteristics of living systems, interacting and self-regulating, constantly adjusting by electronic and biotechnological self-programming. Man, shelter, food, work and leisure will be connected and mutually dependent so that an ecological symbiosis will be achieved.

Present-day concerns for single objects will be replaced by concern for relationships. Shelters will no longer be static objects but dynamic objects sheltering and enhancing human events. Accommodation will be responsive, ever-changing and ever-adjusting. Cities of the future will no longer be zoned as today in isolated ghettos of like activities; rather organizationally they will resemble the more richly layered cities of the past, living, work, shopping, learning and leisure will be housed in continuous, varied and changing structures.

In the case of architectural structures, dynamic responsive systems, acting much like flexing muscles in a body, will reduce mass to minimum by shifting loads and forces with the aid of an electronic nervous system which will sense environmental changes and register individual needs.

If all this sounds too far out, let us remember that futurologists and writers of science fiction have in the long-term proved to be conservative in their dreams. Only a hundred years ago Jules Verne fantasized about trips around the world that took only 80 days.

Michael Davies, one of my partners, has described the experience of living in a responsive building of the future:

"Look up at a spectrum-washed envelope whose surface is a map of its instantaneous performance, stealing energy from the air with an irridescent shrug, rippling its photogrids as a cloud runs across the sun, a wall which, as the night chill falls, fluffs up its feathers and turning white on its north face and blue on the south, closes its eyes but not without remembering to pump a little glow down to the night porter, clear a view-patch for the lovers on the south side of level 22 and to turn 12 per cent silver just before dawn".

The globalization of political power, trading and technology is taking place, we can either withdraw into an inner world hoping to find support in nostalgia or face up to and try to solve what is a social, technical and most importantly, a cultural crisis. This revolutionary change requires as part of a new global understanding a radical architectural response.

Research and innovation is inherent in man's search for improvement. Innovation is seldom popular – it challenges our preconceived ideas'

Richard Rogers

'Arthur C. Clarke has observed that "any sufficiently advanced technology is indistinguishable from magic". This magic has appeared several times during the twentieth century; when the Wright Brothers first demonstrated the feasibility of sustained flight; when the first Apollo astronauts stepped on the surface of the moon; with the announcement of the first home computer by Apple; when a human life was first extended by the use of the Jarvik heart. The impact of technology on our everyday lives is unquestionable and we take much of it for granted. To exist without it would be extremely inconvenient, if not unthinkable. We spend a great deal of money on it and frequently become totally dependent on it, particularly in the First World. When new technology appears we often rush to acquire it.

Future Systems believes that borrowing technology developed from structures designed to travel across land (automotive), or through water (marine), air (aviation) or vacuum (space) can help to give energy to the spirit of architecture by introducing a new generation of buildings which are efficient, elegant, versatile and exciting. This approach to shaping the future of architecture is based on the celebration of technology, not the concealment of it.

As far as building applications are concerned, specific opportunities for the introduction of structures derived from marine or aviation technology include the following examples: whole and partial roof or wall elements for housing utilizing aircraft wing technology; total enclosure panel systems for industrial buildings utilizing aircraft wing technology; full vehicle enclosures for mobile homes utilizing aircraft fuselage technology; sectional or modular enclosure systems for manufactured housing utilizing aircraft fuselage technology and yacht hull technology; full or sectional shell enclosures for earth-shielded or underground homes utilizing systems for large earth-shielded or subterranean public enclosures utilizing ship hull technology; lightweight climatic (sun/rain) protection devices and superstructures utilizing ultralight/human-powered aircraft technology and small/experimental yacht technology.

As far as space technology is concerned, it is likely that in the next century structures and systems derived from advanced space applications will initiate a whole new generation of structural concepts for use back on Earth. Certain design concepts or hardware systems already developed and tested for space use have immediate applications: prototype beam-builder machines developed in the 1970s for automatic fabrication of space structures can be used to construct lightweight envelopes in remote terrestrial regions where normal construction techniques are difficult or impossible; pre-assembled, deployable structural systems that have already been developed for potential Space Station main beam applications could be developed for vehicle-mounted extendable structures for mobile travelling building enclosures; advanced crew-assembled structures from stowed kit systems could be incorporated in the design of simple and adaptable building systems for rapid erection of emergency shelters or even 'do-it-yourself' structures.

Here, then, are some new technological ingredients which can be used to construct the future. It is technology which is capable of yielding an architecture of sleek surfaces and slender forms – an architecture of efficiency and elegance, and even excitement. The technology is out there, waiting. The effect of introducing this technology into the built environment will be positive and profound. The decision on whether to use it or not is up to architects and engineers alike. Ultimately, it is likely that the design limits will be set, not by the capability of the technology involved, but by the depth of their creative imaginations.'

Jan Kaplicky and David Nixon of Future Systems

'Current materials in use for primary and semi-structural applications are generally the ones which have been known for the last 100 years with advancements made in quality and strength through development and research. These include steel, aluminium alloys, concrete reinforced with steel in the form of steel bars or prestressed tendons, and stress-graded timber. Framed and surface structures usually use one or a combination of these materials. The last 20 years have seen the development of structural fabrics known as tensile membranes. This advance has resulted from a combination of research into coated woven fabrics and big advances in structural analysis using computers.

Research into other materials for structural use has been carried out for a long period by the aircraft and aerospace industry and developments are now taking place in other fields. These now include not only the car and boat industries but also sectors of the structural engineering and building industries. The quest is for strength, stiffness and weight reduction without an excessive cost penalty.

Unlike those other industries where design and development is for large scale or batch production, the building industry tends to be different in that unless the project is one which involves prefabrication and repetition, every building is a prototype with a choice of structure and materials. It is, however, only a matter of time before certain of the traditional structural materials are replaced by the new ones. These new materials include the following with their likely uses. It is not an exhaustive list but is indicative of the research being carried out:

- Titanium aluminium alloy as a steel replacement.
- The combination of the superfibres – glass, carbon or aramid — with resins to form skeletal and surface structures.
- Combinations of metals and grp to form stiff composite panel ıstructures.
- Kevlar ropes as replacement for steel ropes in suspension bridge cables.
- Further advances in structural fabrics both in terms of engineering performances and environmentally by the use of double and triple layer and 'pillow' forms.

The current and future use of these advanced materials may include whole skeletal systems, cladding, loadbearing panels, masts and towers, bridges and bridge decks and structures in space, and it is possible that the next twenty years may see more advances in new materials than the previous one hundred years.'

Anthony Hunt

'Designers in all ages have sought to use an appropriate technology in response to their clients' requirements. Today the technology related to materials such as glass, silicone, aluminium and polycarbonates offers maximum lightness and economy of use while still maintaining the internal requirements of the building. These materials not only give the opportunity for long-span lightweight assemblies, but also facilitate maximum transparency of the building envelope.

It is now possible to evaluate the potential of these new forms of construction using accelerated testing and advanced calculation methods. Architects can thus infuse their designs with confidence and extend the architectural potential of this new circumstance. It is not just a question of style as some would suggest, but rather the natural consequence of opportunity to take advantage of technological advances for the benefit of built space.

Milan Kundera has referred us to the "unbearable lightness of being". We are no doubt in a moment of change and it is time for designers to take up the challenge to explore and develop these new materials of our time and not to stay cloaked in our past.'

Alan Brookes

'One of the more powerful concepts of the twentieth century is sustainability; the care and maintenance of environmental resources. The aim is to ensure that future generations inherit a world no worse than the one we have.'

The Environmental Appraisal Unit
at Greater London Consultants

'The problem of Modern architecture is not a problem of rearranging its lines; not a question of finding new mouldings, new architraves for doors and windows; nor of replacing columns, pilasters and corbels with caryatides, hornets and frogs; not a question of leaving a facade bare brick or facing it with stone or plaster; in a word, it has nothing to do with defining formalistic differences between the new building and old ones. But to raise the new-built structure on a sane plan, gleaning every benefit of science and technology, settling nobly every demand of our habits and our spirits, rejecting all that is heavy, grotesque and unsympathetic to us (tradition, style, aesthetics, proportion), establishing new forms, new lines, new reasons for existence, solely out of the special conditions of Modern Living, and its projection as aesthetic value in our sensibilities. Such an architecture cannot be subject to any law of historical continuity. It must be as new as our state of mind is new, and the contingencies of our moment of history.

The art of building has been to evolve through time and pass from style to style while maintaining the general character of architecture unchanged, because in history there have been numerous changes of taste brought on by shifts of religious conviction or the successions of political regimes, but few occasioned by profound changes in our conditions of life, changes that discard or overhaul the old conditions, as have the discovery of natural laws, the perfection of technical methods, the rational and scientific use of materials. In modern life, the process of consequential stylistic development comes to a halt. Architecture, exhausted by tradition, begins again, forcibly, from the beginning.

We have lost the sense of the monumental, the massive, the static, and we have enriched our sensibilities with a taste for the light and the practical. We no longer feel ourselves to be the men of the cathedrals and ancient moot halls, but men of the Grand Hotels, railway stations, giant roads, colossal harbours, covered markets, glittering arcades, reconstruction areas and salutary slum clearances.

We must invent and rebuild *ex novo* our Modern city like an immense and tumultuous shipyard, active, mobile and everywhere dynamic, and the modern building like a gigantic machine.

I affirm
That the new architecture is the architecture of cold calculation, temerious boldness and simplicity; the architecture of reinforced concrete, iron, glass, textile fibres and all those replacements for wood, stone and brick that make for the attainment in maximum elasticity and lightness.
That the real architecture is not, for all that, an arid combination of practicality and utility, but remains art, that is, synthesis and expression.
That decoration, as something superimposed on or attached to architecture is an absurdity, and that only from the use and disposition of raw, naked and violently coloured materials can derive the decorative value of a truly Modern architecture.
And finally I affirm that just as the ancients drew their inspiration in art from the elements of the natural world, so we – materially and spiritually artificial – must find our inspiration in the new mechanical world we have created, of which architecture must be the fairest expression, the fullest synthesis, the most effective artistic integration.'

Sant 'Elia – Il Messaggio

Bibliography

Books

Ackermann, K. (1984) *Industriebau*, Deustche Verlags-Anstalt, Stuttgart

Banham, R. (1960) *Theory and Design in the First Machine Age*, Butterworth Architecture, London

Banham, R. (1986) *A Concrete Atlantis; Industrial Building and European Architecture*, MIT Press, Cambridge, Mass. USA

Banham, R. (1985) *The Architecture of the Well-tempered Environment*, 2nd edn, Butterworth Architecture, London

Bauer, M. (1985) *Luftschiffhallen in Friedrichshafen*,

Betjeman, J. (1972) *London's Historic Railway Stations*, John Murray, London

Binney, M. and Pearce, D. (1979) *Railway Architecture*, Orbis Publishing, London

Blaser, W. (1972) *Mies van der Rohe* (adapted from *Mies van der Rohe: the Art of Structure* published in 1965), Thames & Hudson, London

Boaga, G. and Boni, B. (1965) *The Concrete Architecture of Riccardo Morandi*, Alec Tiranti, London

Borrego, J. (1968) *Space Grid Structures*, MIT Press, Cambridge, Mass. USA

Briggs, A. (1979) *Iron Bridge to Crystal Palace: Impact and Images of the Industrial Revolution*, Thames & Hudson, London

Brooks, A and Grech, C. *The Building Envelope*, Butterworth Architecture, London

Architectures D'Ingénieurs Centre Georges Pompidou, Centre de Création Industrielle, Expositions Itinerantes CCI No.8, Paris

Le Temps des Gares Centre Georges Pompidou, Centre de Création Industrielle, Paris

Condit, C.W. (1986) *American Building*, University of Chicago Press,

Dean, C. (1989) *Housing the Airship*, Architectural Association, London

Dent, R.N. (1971) *Principles of Pneumatic Architecture*, Architectural Press, London

Downes, C. (1971) *The Building Erected in Hyde Park for the Great Exhibition 1851* (originally published by John Weale in 1852), Reprinted for the V&A Museum by HMSO, London

Drew, P. (1976) *Frei Otto – Form and Structure*, Crosby Lockwood Staples, London

Drew, P. (1979) *Tensile Architecture*, Granada Publishing, London

Dini, M. (1985) *Renzo Piano, Projects and Buildings 1964–1983*, Butterworth Architecture, London

Eekhout, M. (1989) *Architecture in Space Structures*, Uitgeverij 010 Publishers

Fletcher, B. (1961) *A History of Architecture on the Comparative Method*, 17th edn, The Athlone Press, University of London

Giedion, S. (1979) *Space, Time and Architecture*, 5th edn, Harvard University Press, Oxford University Press

Greif, M. (1978) *The New Industrial Landscape – the Story of the Austin Company*, The Main Street Press, New Jersey

Grube, O.W. (1971) *Industrial Buildings and Factories*, The Architectural Press, London

Grube, O.W., Pran, P.C. and Schultz, F. (1976) *100 Years of Architecture in Chicago*, Follett Publishing Co., Chicago

Guedes, P. (ed.) (1979) *The Macmillan Encyclopedia of Architecture and Technological Change*, Macmillan, London

Hennig-Schefold, M. and Schmidt-Thomsen, H. (1972) *Transparenz und Masse*, Verlag M. DuMont Schauberg

Herbert, G. (1978) *Pioneers of Prefabrication*, Johns Hopkins University Press

Hildebrand, G. (1974) *Designing for Industry – The Architecture of Albert Kahn*, MIT Press, Cambridge, Mass. USA

Hix, J. (1974) *The Glass House*, MIT Press, Cambridge, Mass. USA (first published by Phaidon Press Ltd, London, 1974)

Huber, B. and Steinegger, J.-C. (1971) *Jean Prouvé – Prefabrication: Structures and Elements*, Pall Mall Press, London

Jencks, C. (1973) *Modern Movement in Architecture*, Penguin Books Ltd, Harmondsworth

Joedicke, Jürgen (1959) *A History of Modern Architecture*, Architectural Press (copyright by Verlag Gert Hatje, Stuttgart)

Kahn, A. (1970) *The Legacy of Albert Kahn*, The Detroit Institute of Arts

Kahn, M. (1917) *The Design and Construction of Industrial Buildings*, London Technical Journals Ltd

Kaplan, M.H. *Space Shuttle*, Aero Publishers Inc.

Le Corbusier (1923/1970) *Towards a New Architecture*, Butterworth Architecture, London

MacGrath, R. and Frost, A.C. (1961) *Glass in Architecture and Decoration*, The Architectural Press, London

Mainstone, R.J. (1975) *Developments in Structural Form*, Allen Lane/Penguin Books, London

Makowski, Z.S. (1965) *Steel Space Structures*, Michael Joseph, London

Mallory, K. and Arvid, O. (1973) *The Architecture of Aggression* (reissued as *Walls of War*), The Architectural Press, London

Meeks, C.L.V. (1956) *The Railroad Station*, Yale University Press, Architectural Press, London

Nervi, P.L. (1956) *Structures by Pier Luigi Nervi* (translation), F.W. Dodge Corp., New York

Neuhart, J., Neuhart, M. and Eames R. *Eames Design: The Work of the Office of Charles and Ray Eames*

Ogg, A. (1987) *Architecture in Steel – The Australian Context*, The Australian Institute of Architects

Otto, F. (1969) *Tensile Structures – Cables, Nets and Membranes*, MIT Press, Cambridge, Mass. USA

Pevsner, N. (1968) *The Sources of Modern Architecture and Design*, The World of Art Library, Thames & Hudson, London

Price, C., Newby, F. and Suan, R.H. (1971) *Air Structures*, HMSO, London

Richards, J.M. (1958) *The Functional Tradition in Early Industrial Buildings*, Architectural Press, London

Sharpe, D.C. (1960) *An Aircraft Hangar and the Study of Long Span Metal Structures*, Thesis at Illinois Institute of Technology

Stephens, J.H. (1976) *The Guinness Book of Structures*, Guinness Superlatives Ltd, London

Vaughan, A. (1977) *Great Western Architecture* Oxford Publishing Co.

Venturi, R., Scott-Brown, D. and Izenaur, S. (1972) *Learning from Las Vegas*, MIT Press, Cambridge, Mass. USA

Wachsmann, K. (1960) *Turning Point of Building*, Reinhold, New York

Winter, J. (1969) *Modern Buildings*, Hamlyn Publishing Group Ltd, London

Winter, J. (1970) *Industrial Architecture*, Studio Vista, London

Journals

A + U
Renzo Piano, building workshop 1964–88, 3/1989
Richard Rogers 1978–88, 12/1988
AD (Architectural Design)
Convertible roofs, July 1973
Frei Otto at work, March 1971
The anatomy of the factory, November 1968
Factories, 1974
Architectural Review
Making connections, December 1989
Metal and masonry, July 1988
Architecture of commitment, March 1987
Another low-tech spectacular, September 1985
High tech, July 1983
Skin, July 1983
Roger's Inmos Factory, December 1982
Foster's IBM Greenford, August 1980
Manplan 2+3, October and November 1969
L'Architecture d'Aujourd'Hui
Verre et acier, Dec 1980
Structures, Dec 1968 – Jan 1969
Baumeister
Hallen für die Industrie, April 1983
Building with Steel
(Published by the British Steel Corporation)
Space structures, August 1972
Progressive Architecture
High-Tech design/internal distribution system, July 1978
Techniques and Architecture
Des usines pour des hommes, Juin (343) 1982
Structures spatiales un bilan, (309)
Structures spatiales 2, (320)

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