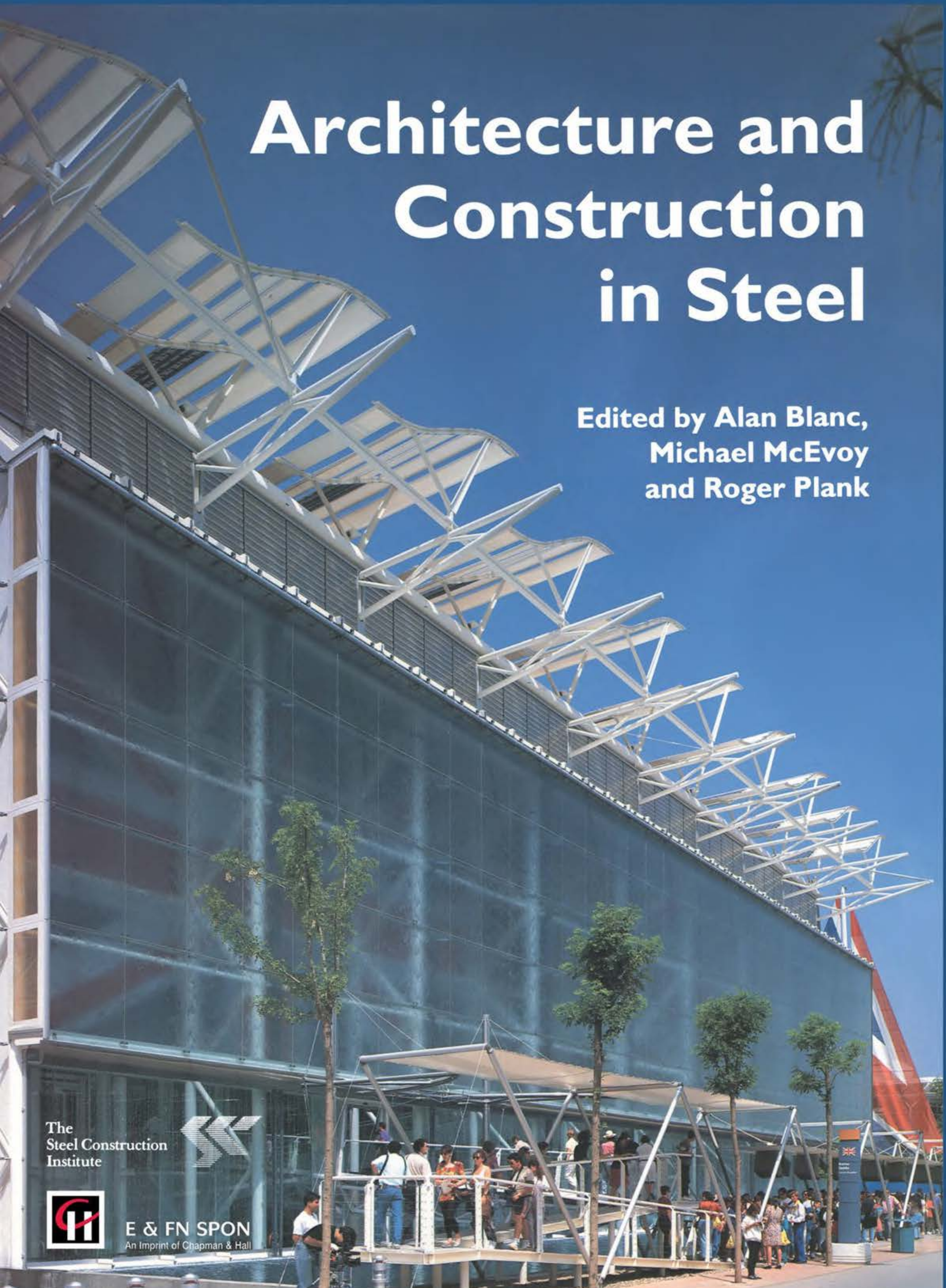

Architecture and Construction in Steel

Edited by Alan Blanc,
Michael McEvoy
and Roger Plank

The
Steel Construction
Institute

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Architecture and Construction in Steel

is the Steel Construction Institute. Its overall objective is to promote and develop the proper and effective use of steel. It achieves this aim through research, development of design aids and design approaches, publications and advisory and education services. Its work is initiated and guided through the involvement of its members on advisory groups and technical committees. The Institute is financed through subscriptions from its members, revenue from research and consultancy contracts and by sales of publications.

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Julian Ryder-Richardson is a chartered architect, and was elected a member of the British Academy of Experts in 1992. He joined GMW Partnership in 1960, becoming a partner in 1971, and has been a senior partner since 1981. Among key buildings he has been associated with are the Commercial Union HQ and Banque Belge (both steel framed) and Barings Bank in the City of London. He wrote 'An Integrated Approach to the Design of Steel Framed Office Buildings of Medium Height' for Constrado, published in 1972

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Spent 14 years with consulting engineers in south east England working on new buildings and refurbishment. Joined British Steel in 1981 and subsequently manager of Structural Advisory Service.

Preface

The genesis of this book stems from British Steel's architectural teaching programme, released in January 1990. Many of the authors engaged in that project have participated in preparing this textbook with the continued benefit of Professor Derek Sugden as honorary editor. My role has been to weld together the disparate elements and to expand the architectural content. The discipline of reducing turgid prose and guarding against repetition has been the role of my co-editors Dr Roger Plank and Michael McEvoy. The end result would never have been completed without the constant advice on content and style by Derek Sugden. The day-to-day work of editing the various contributions has led my colleagues to rewrite some sections to bring matters fully into line with the 1990s. The gestation time of five years is a long one but is needed when running a stable of around 30 writers.

Earlier periods that followed a building boom have seen the publication of books that attempt to summarize the state of the art of steel construction. The present time is perhaps similar to the early 1970s which saw such classics as *Multi-storey Buildings in Steel* (by F. Hart, W. Henn and H. Sontag), and *Buildings for Industry* (by W. Henn). Both were published originally in West Germany to cover post-war construction in the 1950s and 1960s, and English language editions were subsequently published by Granada and Iliffe respectively. This new book is intended to address current developments and to discuss ways of building that are now commonplace in Britain and North America.

Encyclopaedic volumes like *Fundamentals of Building Construction Materials and Methods* by Edward Allen, published by John Wiley and Sons in the USA are excellent teaching manuals but fail to provide a really wide range of up to date case studies to interest the general practitioner. The editing team for *Architecture and Construction in Steel* have aimed at a collation of writing which delves into contemporary practice but provides sufficient historic reference to interest the conservationist whether architect or engineer.

The main readership is seen as practitioner or student from architectural and design disciplines related to building. Engineering concepts of design differ from those cherished by architects, and the texts that follow may help to resolve the misunderstandings. Derek Sugden's introduction seeks to build many bridges to the 'art of construction'. This latter description is perhaps the most valuable concept that the editing team have developed.

The warmest appreciation needs to be expressed for the valuable support from British Steel plc and in particular for the funding granted to The Steel Construction Institute that enabled writers to be commissioned. British Steel also furnished specialist advice from their Structural Advisory Service and from Strip Products, whilst staff, both present and retired, contributed to a number of key chapters.

The personal enthusiasm engendered by Robert Latter, Marketing Manager for British Steel (Structural Steels Division) and by Dr Graham Owens, Acting Co-director of The Steel Construction Institute ensured that the momentum was maintained despite the lengthy process of satisfying a critical editorial board. That board was drawn from the writers involved and reinforced by outspoken outsiders like Dr Bill Addis and Chris McCarthy.

The penultimate thankyous must be awarded to the fellow writers that have given of their expertise and time to ensure success to the venture. . . Professor Bill Biggs, Bryn Bird, Peter Brett, Ken Chandler, David Cochrane, Yvonne Dean, Anthony Gregson, David Harriss, Eric Hindhaugh, Hal Iyengar, Ian Liddell, John Le Good, Michael McEvoy, Keith Moores, Patrick Morreau, Dr Roger Plank, Jef Robinson, Julian Ryder-Richardson, Richard Saxon, Tom Schollar, Dennis Sharp, Professor Derek Sugden, Robert Taggart, John Thornton, Stefan Tietz, Bjorn Watson, Peter Wright and Mark Whitby.

The final words of appreciation are for the work of Ruth Lush and Sylvia Blanc in converting unruly scripts into the tidy realm of computer discs. Special thanks are also due to Susan Boobis, the lively copy-editor engaged by E. & F. N. Spon who grappled with awry spelling, last minute corrections and wild captions to convert all and sundry into printable and readable format. To E. & F. N. Spon, John Saunders and to everyone else involved my heartfelt thanks for a task well done and for the patience of the SCI since Easter 1987.

Alan Blanc, April 1993

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Introduction

Derek Sugden

From the early days of the iron and steel frame there have been manuals, treatises and text books written primarily for the engineer and constructor. For the UK and the English speaking worlds they stretch from William Fairbairn's classic of 1854, *On the Application of Cast Iron and Wrought Iron to Building Purposes* (second edition 1857–8 to which is added 'A Short Treatise on Wrought Iron Bridges') to the *Steel Designers' Manual* of 1955 by Gray, Kent, Mitchell and Godfrey. The last edition of the manual appeared in 1972 and a new edition was published in 1993. Since the first edition of the *Steel Designers' Manual* there have been many books and pamphlets ranging from the erudite, analytical paper to those publications verging on the 'coffee table genre' on the subject of the steel frame in building, but they are invariably written for the engineer. One of the most successful was the book prepared for the Deutscher Stahlbau-Verband *Multi-Storey Buildings in Steel* by the three Profs Dr-Ings Hart, Henn and Sonntag. An excellent book in every way but predominantly a German/American view of the multi-storey steel frame and its development.

Following the publication and success of the *British Steel Teaching Programme* for Engineering students in 1985 and its subsequent publication in the book *Structural Steel Design* (Dowling, Knowles, Owens, 1988) A British Steel Teaching Programme for architectural students was prepared and issued to the architectural departments of all the UK universities and polytechnics in January 1990. The Architectural Teaching programme has some 28 authors, many of whom prepared more than one paper. The editorial work and organization of the whole enterprise was carried out by Dr Roger Plank, Dr Brenda Vale and Robert Vale at Sheffield University with an overview from Dr Graham Owens and Alan Blanc of the SCI. The teaching programme is divided into six sections, the 'History of Iron and Steel', 'Steel Technology', 'Design and Analysis in Steelwork', 'Element Behaviour and Design', 'Non-Structural Uses of Steel' and 'Architecture of Steel'. The lectures are supported by slides, videos and software and are structured in such a way as to provide a continuous teaching programme, although each section and unit is a complete discrete teaching package and may be selected in any order. *Architecture and Construction in Steel*, like *Structural Steel Design*, is a natural consequence of the teaching programme. Because of its unique nature, this first text book on steel construction, aimed specifically at architects, was expanded to cover every aspect of the use of steel and iron in building construction.

The iron and steel frame had a radical, if not revolutionary effect on the way designers thought about buildings. The skeletal frame could be described as the 'armature' of the modern movement because it released building from the inhibitions of the loadbearing wall and trabeated construction. As a natural consequence it changed the way that architects and engineers thought about building and was a great influence on the development of architectural theory. There were historical precedents for thinking and theorizing about an architecture based on a skeletal frame. The two outstanding examples are the Sung Dynasty Building Standards or 'Ying-Tsao Fa-Shih' which dominated Chinese official building for nearly 1000 years and was last defined in an official publication of 1078 pages (Figs 1 and 2)

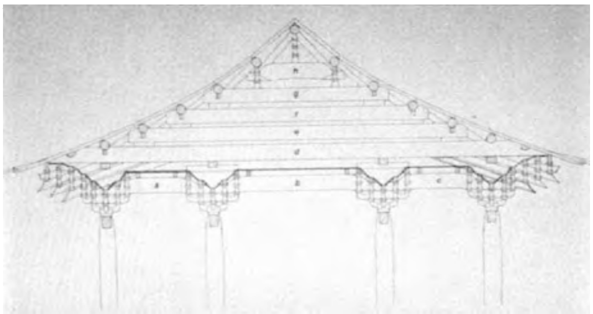


Fig. 1 *Six tiers of beams in Chinese Temple.*

Fig. 2 *Temple gateway, Canton (three tiers of beams).*

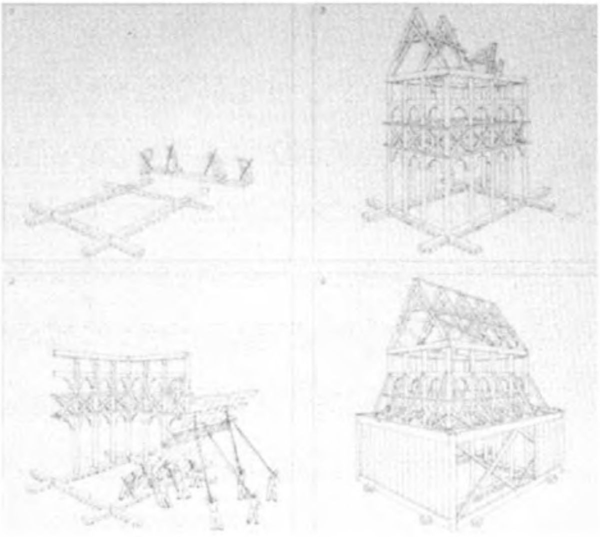


Fig. 3 *Construction of a small stave church, Norway (11th century).*

presented to the throne in 1100 AD; and the 11th century stave churches of Norway, perhaps the first European prefabricated industrialized building system (Figs 3 and 4). They are isolated examples, however, and had little effect on the development of building technique and architectural theories which remained rooted in the trabeated tradition for the vast majority of buildings with the exception, of course, of the arches, vaults and buttresses of the Gothic tradition and the domes of the Byzantine and the Romanesque tradition.

If there is one system that has revolutionized our thinking about ways of building it is the skeletal frame, and if there is one material that has dominated frame construction it is mild steel. It is also the material on which, following the example of Mies van der Rohe, many architects have continuously developed their own philosophy of building. These architectural ideas are still very potent and in the last 20 years have become the driving force behind some of the world's most distinguished buildings.

There are examples of timber skeletal frame construction in the early silk mills and frame and cross wall construction in the buildings of the Hanseatic League, but fire soon became the dominant factor in the design of these timber frames. The first person to tackle the problem in a vigorous way was William Strutt, son of Arkwright's partner Jedediah Strutt. William Strutt's first essay in fireproof building was the Derby Cotton Mill 1792–3 (Fig. 5). This mill had brick arches spanning between heavy timber cross beams supported by cast iron columns. The exposed soffits of the beams were protected against fire by plaster. It was Charles Bage, however, who first introduced cast iron beams into the frame of the Shrewsbury Mill (Fig. 6) of 1796. This followed a correspondence between Strutt and Bage on the suitability of cast iron for beams, William Strutt being rather

Fig. 4 *Fantoff Stave Church, Norway (c. 1200).*

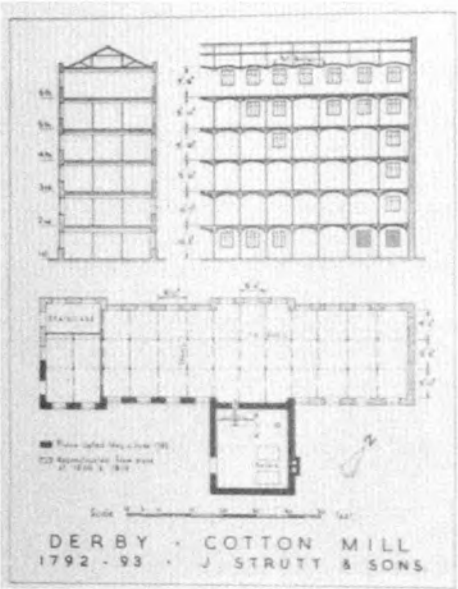


Fig. 5 *Derby Cotton Mill 1792–3 (engineer William Strutt).*

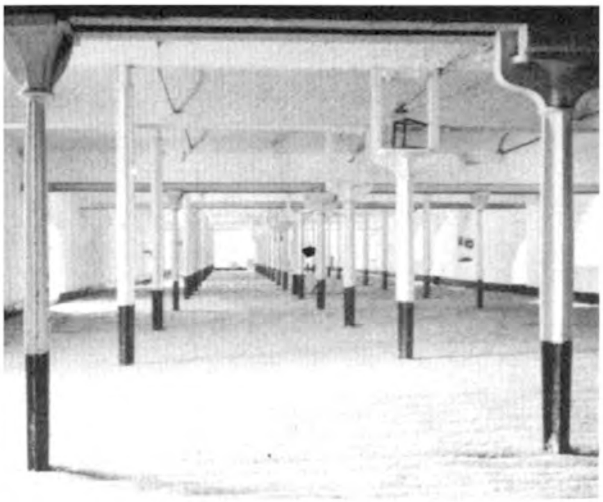


Fig. 6 *Shrewsbury Mill 1796–97 (engineer Charles Bage).*

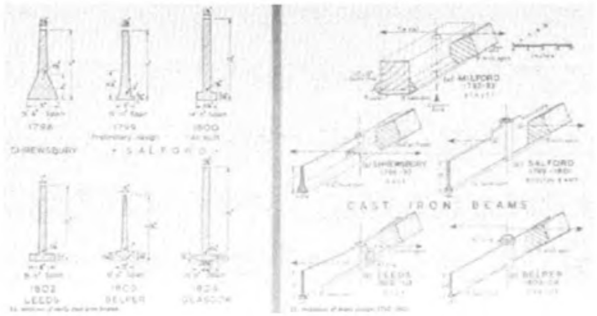


Fig. 7 *Evolutional cast iron beam design 1792–1803.*

cautious because of the brittle nature of the material. Bage however, carried out tests and produced calculations to support this development and after the Shrewsbury Mill cast iron beams became almost standard. Figure 7 shows the development of the cast iron beam section for the early mills. Boulton and Watt made a great contribution to this development but one of the most outstanding examples was William Strutt's Belper North Mill (Fig. 8), a brilliant early example of the rigorous integration of an industrial structure with its energy distribution system. Following this early 'structural revolution' the evolution of the mill and warehouse building was slow; cast iron was gradually replaced by riveted wrought iron. From the middle of the century the style was dominated by the Fairbairn-type wrought iron frame (Fig. 9) with the columns remaining in cast iron but with the development of main beam and secondary beam construction.

The external stabilizing walls were retained throughout the 19th century, together with the cast iron columns. There was one notable exception, and that was the Boat Store, Sheerness 1858–60 in cast and wrought iron described in

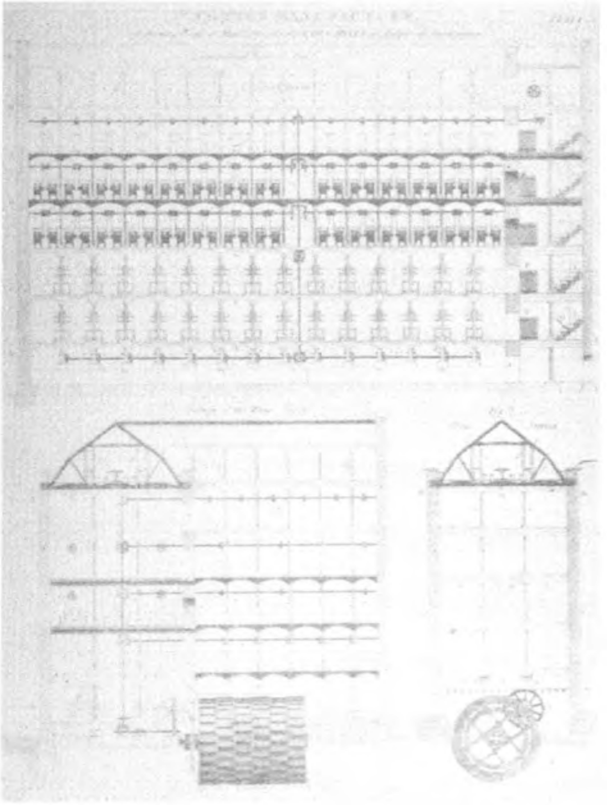


Fig. 8 *Belper North Mill 1803–4 (engineer William Strutt).*

Fig. 9 *Fairbairn-type wrought iron frame LNWR warehouse, Manchester, 1869 interior after conversion (engineers LNWR company).*

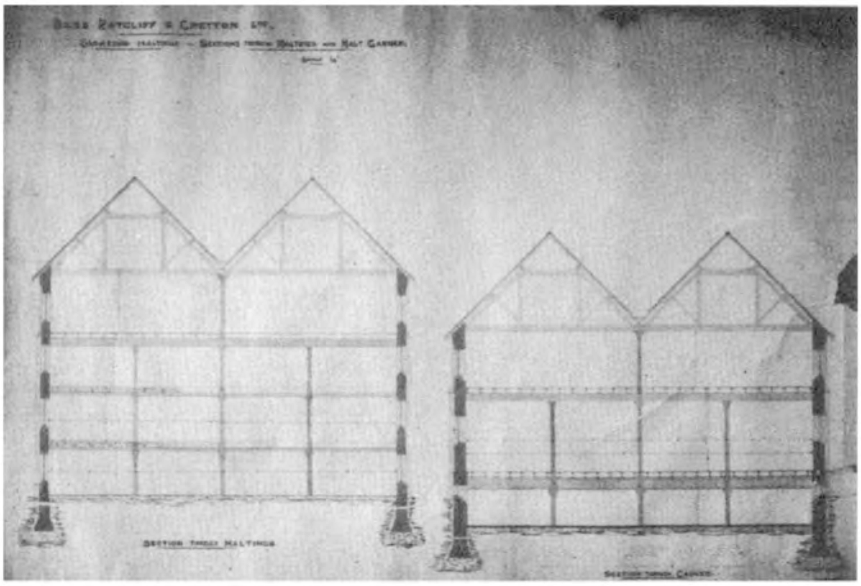


Fig. 10 *Sleaford Maltings 1897–1903.*

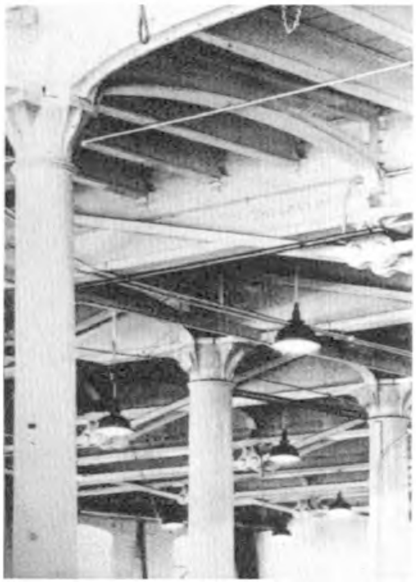


Fig. 12 *Royal Navy Dockyard, No. 6 Boathouse Portsmouth 1843–5.*

Fig. 11 *Albert Dock, Liverpool 1848 (architect Philip Hardwick: engineer Jesse Hartley).*

detail by Dennis Sharp in the first chapter of this historical survey. For me it is perhaps the UK's most seminal building of the modern movement. Its influence at the time seems to have been very small. The heavy loadbearing and stabilizing external walls remained and an example as late as the turn of the century, Sleaford Maltings 1897–1903 (Fig. 10) shows how, despite the adoption of the mild steel frame, the cast iron columns and the external wall are retained in a virtually identical cross section to the 'Fairbairn' frame of 50 years earlier.

It was not until the London County Council (LCC) by-laws of 1909 that the presence of a steel frame in the external wall allowed for panel construction as opposed to a traditional loadbearing wall. The first public building in England to use a fully framed steel frame was the Ritz Hotel of 1906. The facade, however, did not indicate or even suggest the underlying steel frame. The external wall was still carrying its own weight from the roof to the ground. The frame was still not recognized as a loadbearing element in the facade as exploited by Green at Sheerness over 40 years before. The first major building to do this and to exploit the new LCC regulations was Kodak House of 1911 where Sir John Burnet made an innovative attempt to express the underlying steel frame.

Alongside the development of the iron frame in the UK, the new materials of cast iron and wrought iron were used for many building elements and building types, from Gothic revival churches of the early 19th century, prefabricated cast iron churches and sunday schools for export, to the cast iron clad frames of Liverpool and Glasgow. Despite these early developments in the UK of the frame, roof and cladding systems, the potential of the skeletal frame was only fully realized in the USA and particularly Chicago, and well documented under 'Chicago style' in Dennis Sharp's historical review.

During the development of the skeletal frame in the 19th century tensions grew between the architect and the engineer. On many occasions this was supremely well resolved as in Jesse Hartley's Albert Dock (Fig. 11) where he worked very closely with the architect Philip Hardwick using cast iron doric columns to support the great warehouses and cast iron doric columns for the Dock office. When wrought iron began to replace cast iron and the I-section and H-section developed, cast iron was still the preferred material for the column. They were invariably of circular section and influenced by architectural precedents. A Royal Navy Dockyard boathouse (Fig. 12) at Portsmouth shows this influence very clearly. An extreme case of these architectural precedents, particularly prevalent in railway architecture where the engineer's work finished at the eaves level and the architect took over at the head of the column, is the decorated platform column at Malvern Station, 1860 (Fig. 13). It is interesting to look at the standard catalogue of the great iron foundry, Abraham Darby and Co., who built the

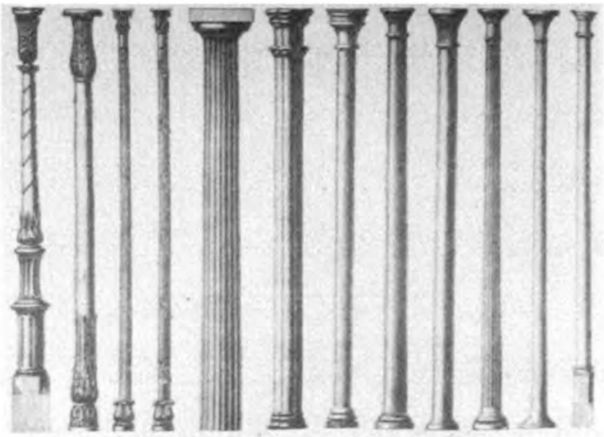


Fig. 14 *Standard structural columns in various styles from catalogue of Abraham Derby and Co 1875.*

Fig. 13 *Architectural design applied to column capital: Malvern Station, 1860.*

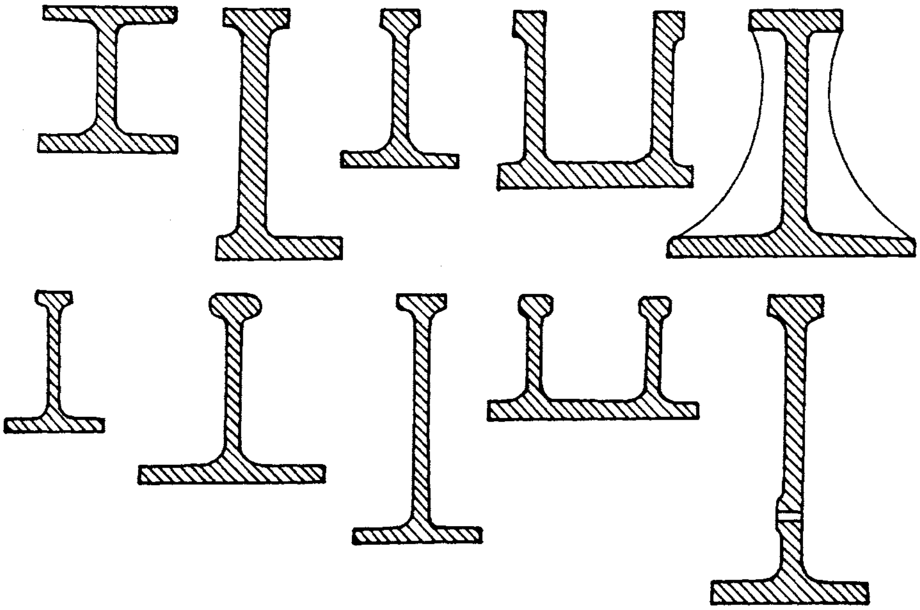


Fig. 15 Early cast iron beam sections.

Fig. 16 *Bibliothèque Nationale Paris 1865–1868 (architect Henri Labrouste).*

first cast iron bridge at Coalbrookdale. In 1875 it showed standard columns (Fig. 14) all decorated in various styles, whilst standard beams were all the result of rigorous testing and calculation and available in forms produced by engineers and constructors alone (refer to Fig. 1.1).

The use of modern materials within established architectural styles contrasts with allowing the architectural form to be influenced by the nature of the material and its construction. There is no better example of this than in the work of a single architect, Henri Labrouste. Twenty years separates his two great libraries in Paris. The first, St. Généviève, 1843–1850 (Fig. 17), is of cast iron throughout, the barrel vaults of prefabricated sections in cast iron reflecting faithfully the Gothic tradition; the second, the Bibliothèque National, 1865–1868 (Fig. 16), is of wrought iron with the domes constructed of plates and flats riveted together in the new tradition, creating a totally new style springing from the material and the process. The columns remain in cast iron inhibited as usual by the Classical tradition.

There are four great examples spanning the 19th century in England which illustrate the theme of engineers working alone and following the disciplines of the nature of the new material and its potential and working in close collaboration with the architect who is still carrying the cultural baggage of previous centuries applying their styles to modern materials and structures. In Telford's magnificent Pont-y-Cysylte aqueduct, built between 1795 and 1803 (Fig. 18) the concept and detailing of the structure springs entirely from the nature of the materials cast iron and stone, the process of their manufacture and of the construction of the great structure. This elegant simplicity is even more surprising when considering that Telford was born in 1757, 13 years before Beethoven, Hegel and Wordsworth. He was

Fig. 17 *Bibliothèque St Généviève, Paris 1843 (architect Henri Labrouste).*

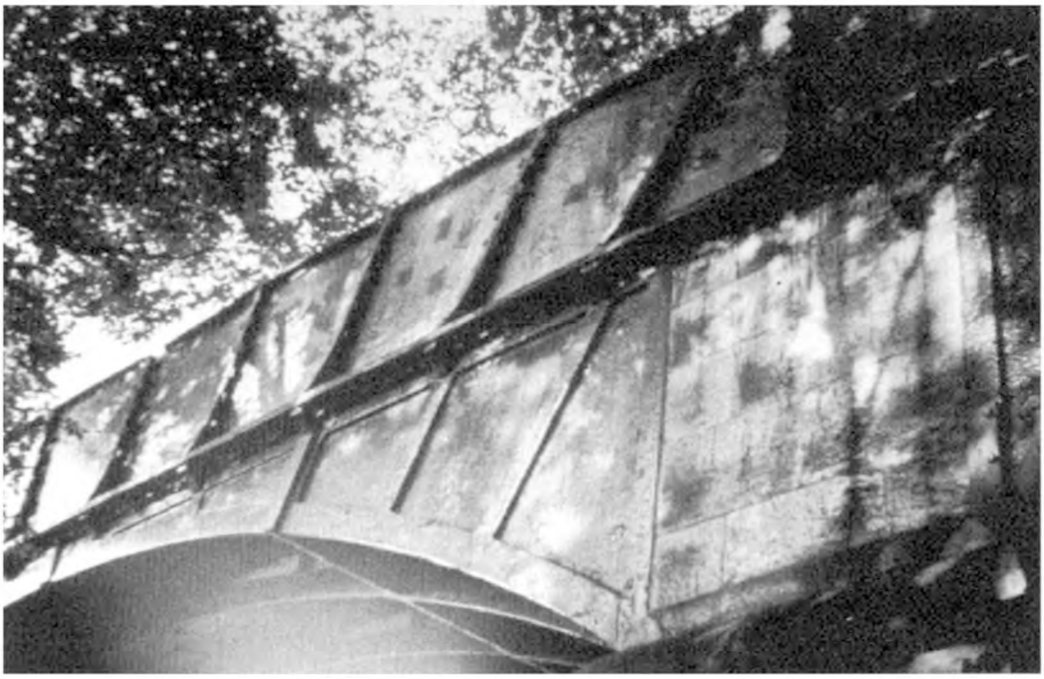


Fig. 18 *Pont-y-Cysylte Aqueduct detail view of cast iron elements.*

Fig. 19 *The Great Stove, Chatsworth 1836–40 (designer Joseph Paxton assisted by Decimus Burton).*

also apprenticed to a stone mason and would have been influenced in his most formative years by the architects of the eighteenth century, and yet this great structure is free from all architectural precedents. The Great Stove at Chatsworth (Fig. 19), built between 1836 and 1840, was the work of Paxton but assisted by the London architect, Decimus Burton. It was one of Paxton's most innovative structures in its combination of cast iron, timber and glass. The portico however, designed by Burton, large enough to take Queen Victoria's carriage, is influenced by Classical and Gothic precedents which would please many of our present day 'post-modernists'. A work of real collaboration, however, was the great tubular bridge over the Menai Strait by Robert Stephenson and the architect, Francis Thompson (Fig. 20). Here this vast engineering concept is cloaked with Thompson's Egyptian architectural style which in no way detracts from the impact of the great structure. The fourth example is Benjamin Baker's Forth Bridge of 1890 (Fig. 21), a masterpiece in the new material of structural steel, totally uncompromising in its 'functional design'. It was attacked by William Morris who claimed that 'there never would be

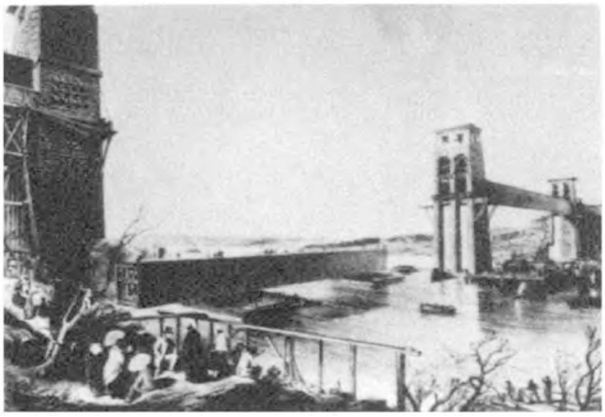


Fig. 20 *Tubular Bridge, Menai Strait 1846–1850 (architect Francis Thompson: engineer Robert Stephenson).*

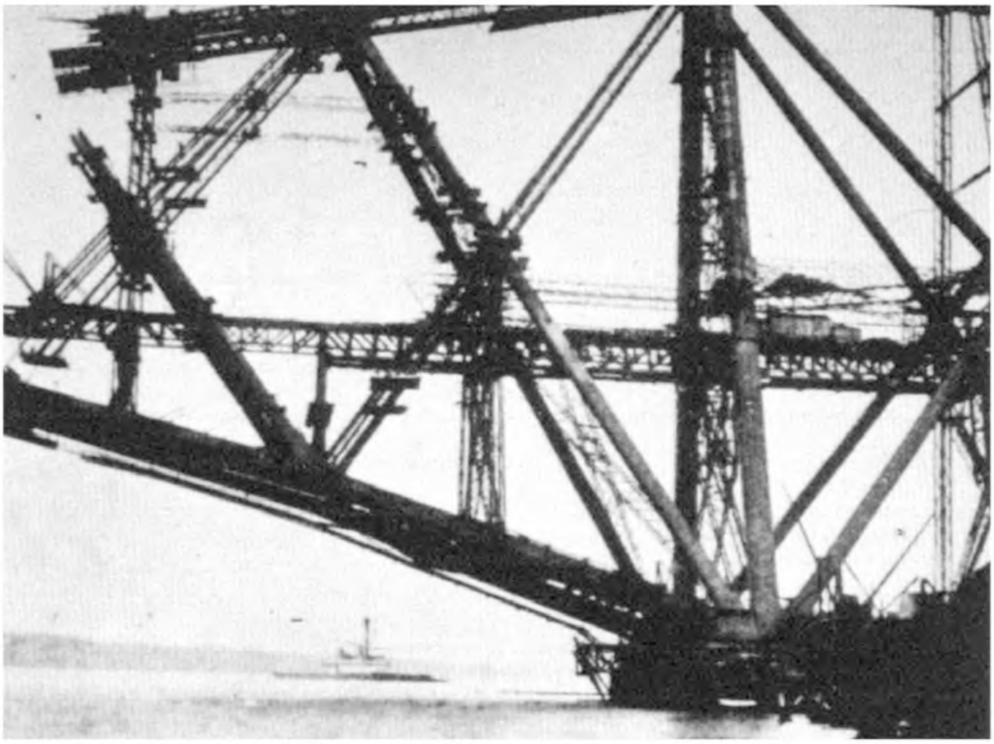


Fig. 21 *Construction of cantilevers to the Firth of Forth railway bridge (refer also to lead-in picture to chapter 7).*

an architecture of iron, every improvement in machinery being uglier and uglier until they reach the supremest specimen of all ugliness – the Forth Bridge'. Less than 100 years separates the Forth Bridge from Pont-y-Cysylte. Sir Walter Scott called Telford's cast iron aqueduct 'the greatest work of art he had ever seen' but since his day a gulf had opened up between the arts and the sciences, between architects and engineers who sadly no longer spoke the same language. The gulf is still with us today.

From these few examples it is possible to generate a thesis that architects and engineers differ fundamentally in their approach to design, with architects working from precedent and engineers working intuitively. Throughout the book the reader will see many examples which both support and question this thesis. No one can escape from his own particular 'cultural baggage' and due to our specialist, numerate and literary dominated educational system the cultural baggage of architects and engineers usually differs very widely indeed. It is hoped that many aspects of this book will introduce architects not only to the intuitive way which engineers work but to some of the precepts developed through their intuitive and analytical techniques. In addition we hope it will appeal to many engineers who should profit by an introduction to the logic behind so many architectural precedents which they will find illustrated and explained within the text.

Architecture and Construction in Steel is in six parts.

Part One 'History of Iron and Steel Construction' by Dennis Sharp, is divided into chapters on the 19th and 20th centuries. *Chapter 1* 'The 19th Century' opens with a general discussion on the influence of materials and techniques on architecture, on iron and steel in particular and the influence of the work on the 19th century engineers. It moves to Chicago, Eiffel and Paris and Vienna, it describes some of the great engineering structures, particularly bridges and railway stations and encompasses the influence of such diverse persons from Abraham Darby and Telford to Loos and Taut and many others. *Chapter 2* 'The 20th Century' is concerned with the scene after 1900. It begins with statistics on steel production and another quote from Adolf Loos. It touches on the inhibiting effect of the by-laws on the development of the steel frame in the UK and describes how the Modern Movement arrived in England 'by the back door'. It traces the development of the Modern Movement and its love affair with technology, engineering and the steel and glass aesthetic, an indivisible trio. It is concerned with the enormous influence which the dialectic of Mies van der Rohe had on the way architects thought about buildings and how strong that influence still is on many of the most outstanding buildings of the last decade.

Part Two 'Materials' has seven chapters which cover all aspects of the properties of steel, its fundamental characteristics, the current techniques of processing, using and protecting the material, particularly within the building industry. *Chapter 3* by Professor Bill Biggs, one of the world's leading experts on materials in the construction industry, is concerned with the basic properties of steel and *chapters 4, 5 and 6* are concerned with 'Structural Steel Components for Buildings', 'Sheet and Strip' and 'Stainless and Related Steels' respectively. *Chapter 4* by the engineer Keith Moores describes the manufacturing process of all the current sections including circular and rectangular hollow sections, cables, ropes, couplings and wire. It also includes a section on components and wire rope fittings which are so widely used in contemporary cable stayed roofs. *Chapter 5* by engineer Eric Hindhaugh includes all those building elements which are processed from strip-steel – a wide range of products, from profiled sheeting to the anchors, connectors and truss plates of the timber trade. The chapter describes their strength, treatment, processing, coating and protection for various applications and environments. *Chapter 6* is a discourse by the engineer D. J. Cochrane on the properties and applications in the building industry of stainless and related steels. The chapter covers their application to structural work, roofing, wall cladding and masonry fixings. *Chapters 7, 8 and 9* are concerned with corrosion and protection. *Chapter* 7 'Nature of Corrosion' by the architect Yvonne Dean, is a survey of the nature of corrosion with particular respect to carbon steel. *Chapter 8* 'Anti-corrosion Measures' by Ken Chandler, includes a review of preparation techniques, painting systems and modern metallic coating systems. In addition, it makes references to design techniques to minimize corrosion. *Chapter 9* 'Fire Protection' by the engineer J. T. Robinson, covers the whole field of fire engineering including design techniques and the full range of passive and active protection systems.

Part Three 'Principles of Steel Framing' could be described as the core of the book. The eleven chapters cover all those aspects of steel frame design which within an architectural concept are concerned with 'choosing'. Choice is at the centre of design, as it is at the centre of all human creativity, and these eleven chapters are essential reading for the student and practising architect in guiding those choices, which are so necessary in evolving a frame which will support and sustain the essential idea of an architectural concept. *Chapter 10* 'The Architecture of Steel' by the engineer Patrick Morreau, sets the steel frame within an architectural perspective. *Chapters 11–14*, all written by practising engineers and one leading academic, are concerned with framing in all its aspects. *Chapter 11* by engineer John Le Good, a practitioner with a wide experience of teaching structures to architects, is concerned with the 'Basic Theory of Framing'. *Chapter 12* by engineer Roger Plank, one of the leading teachers of structures in our schools of architecture writes together with engineer Peter Brett and architect David Harriss on 'Multiple Bay Single Storey Buildings'. *Chapter 13* 'Floor Framing and Services', one of the most important choices in developing the anatomy of a building in these days of complex services, is written by engineer Tom Schollar with architect Anthony Gregson. *Chapter 14* 'Multi-Storey Frames' is the work of engineer Bjorn Watson and is based on his wide experience in Scandinavia, the UK and the USA. *Chapter 15* by Hal Iyengar, one of America's leading structural engineers, is all about 'Tall Structures', an essential primer for a generation of architects who may be involved in the UK's move to the development of buildings over 30 storeys, after the precedent of Canary Wharf. *Chapter 16* by the engineer Roger Plank and architect Anthony Gregson, describes the design and application of 'Composite Floors and Structures' such as the use of reinforced concrete shear walls in combination with a skeletal frame, a knowledge so essential to the emergence of the modern steel frame. *Chapter 17* 'Transfer Structures' by engineer Bryn Bird is concerned not with one of the major elements of the frame, but with a species or offshoot made necessary by the creation of so many multi-storey buildings which exploit the air rights over sites which are usually developments of main line railway termini in our urban centres. These developments create particular problems of transferring the loads of a space divided structure to a space enclosing structure. From these constraints the collaboration of a gifted architect and an innovative engineer may create a dominating and exciting image. *Chapter 18* 'Foundation Structures' by Stefan Tietz makes some necessary references to simple footings and deep basements, but is mainly concerned with all aspects of piling which is invariably necessary for multi-storey steel framed building construction. *Chapter 19* by the architect Richard Saxon is concerned with the design of atria which are now associated with any and every office development within the last 10 years. In addition to covering every aspect of the anatomy of atria it also addresses the problems of climate, fire protection, thermal movement and all the physical problems of this demanding structure. Part Three is brought to a brilliant conclusion in *chapter 20* by the two engineers John Thornton and Ian Liddell who take us through 'Tensile Structures' with all their attendant complications and contradictions.

Part Four 'Steel Construction' has four chapters and is concerned with the detailed aspects of designing, making and erecting a steel frame. *Chapter 21* 'Structural Connections for Steelwork' by Tom Schollar is a review of that part of a steel structure which receives a great deal of 'lip service' but often scant attention. The chapter includes a classification of connections, the type and magnitude of loads, the important separation of exposed and hidden connections and the ever recurring question of bolting versus welding. It expands on welding techniques which includes a short historical review of the subject. *Chapter 22* covers the subject which is invariably a closed book to the professional side of the industry, 'Fabrication and Erection', a subject which is difficult to teach within the academic tradition and is rarely attempted. Bob Taggart's chapter, well and simply illustrated, is an essential guide to techniques of shop and site. *Chapter 23* 'Tolerances and Movement in Building Frames' by the architect Julian Ryder-Richardson quite rightly describes it as an 'emotive subject'. He develops a clear approach to tolerances and separates out the confusion that exists with allowances for movement due to elastic deflection and other deformations. The chapter also puts the whole problem within the context of the changing pattern of contracting and how this reflects back into our approach to the specifying of tolerances. *Chapter 24* 'Insertion and Strengthening of Frames and Upgrading Facades' by engineer Peter Wright and architect Alan Blanc is a response to that somewhat pejorative term 'Facadism' which, due to the pressures of the conservation lobby, has been the catalyst for engineers to develop techniques for supporting and strengthening some very and some not so very distinguished facades while the entire building is demolished and rebuilt behind them, often in a manner and style totally foreign to the architecture of the facade.

Part Five 'Secondary Steel Elements' includes eleven chapters by Alan Blanc which cover all those elements of building where steel in all its various forms dominates or is among the main materials available. *Chapters 25–27* are concerned with cladding systems and facades. 'Decking and Built up Roofing' are covered in *Chapter 28*: 'Fastenings' and 'Metal Studwork and Laths' in *Chapters 29 and 30.* The four important categories of Windows, Door Frames, Staircases and Balustrades and Gutters and Fittings are included in *Chapters 31–34.* There is a final *Chapter 35* written from the heart by Alan on 'Decorative Iron and Steel'.

Part Six 'Outstanding Contemporary Steel Architecture' is a coda in sonata form. *Chapter 36* 'Oustanding Steel Buildings Worldwide' by Dennis Sharp is an interesting and erudite selection of buildings from the 'Centre Le Corbusier' in Zurich and Arup Associates' Stockley Park to Philip Johnson's 'The Garden Church' in California and Philip Cox, Richardson and Taylor's Football Stadium in Sydney. There are always certain buildings another contributor would choose or exclude. Some well known icons of the last few years have been overexposed and this perhaps persuaded Dennis Sharp quite rightly that other lesser known but important buildings should be included. His examples with their individual analyses will make us all look more carefully at the way architecture is made and what it has to fulfil rather than for the current obsession with its surface appeal. *Chapter 37* 'Structural Steel Design Awards' by Alan Blanc speak for themselves but are additionally illuminated by Alan Blanc's commentary. All the examples are by definition by UK designers and are a striking example of the architectural quality of so many recent British buildings and particularly the outstanding contribution being made by the current generation of British structural engineers. *Chapter 38* 'Futures' is by Mark Whitby and Alan Blanc. Mark is one of Britain's most distinguished and inventive young engineers who typifies the current generation's concern with the primacy of design in their approach to building engineering. He has contributed a broad brush view about the social and technological influences which he sees in the shaping of man's creativity in the future with Alan Blanc providing the 'last word' in his own inimitable way.

Mark Whitby's chapter is a grand overview which begs the question 'but what about the next generation of buildings?' Perhaps we should try and look a little closer at architecture and steel construction over the next few years. During the 1940s when, following the Second World War, the building industry began to be revitalized, the steel frame was again the preferred solution for the single and multistorey building. It followed the pattern involved in the early days of the 20th century and apart from the development of welding techniques and lip service to plastic design theories, the approach to design and construction was very static. The 1950s and 1960s saw the rapid development of in situ and precast concrete for building frames, accelerated by architectural theories, local and central government policies and the rise of industrial building with its closed and open building systems.

The late 1970s saw a return to the steel frame stimulated by an overall improvement in service from the constructional steel industry combined with the emergence of new forms of management contracting and construction management. On a visit to Finsbury Avenue during the erection of the steel frame, nearly 40 years since my first involvement with steel frames, I felt 'just where I came in'. The only explicit difference was the use of composite construction for the floors, universal beams replaced rolled steel joints and there were more sophisticated drylining fire protection systems. What of the next generation? For the multi-storey frame there will be more sophisticated holistic analyses which will be integrated into the CAD systems for the architecture and building services. More attention arising from the holistic analysis will be paid to composite construction with a more sophisticated approach to dealing with lateral forces and elastic and thermal movement. The frame and floors acting with the cladding and partition system will be part of the total energy analysis and physical analysis of the building in its creation, life span and demolition.

The single storey building will give even greater scope for the innovative engineer working with a creative architect to use structural steel and steel products in the most radical and one hopes 'outrageous' ways which are yet integrated in a realistic way with the building physics. The opportunity is there to design and build stunning buildings which may also be described as 'Triumphs of Technology' rather than 'Triumphs over Technology'.

Part One

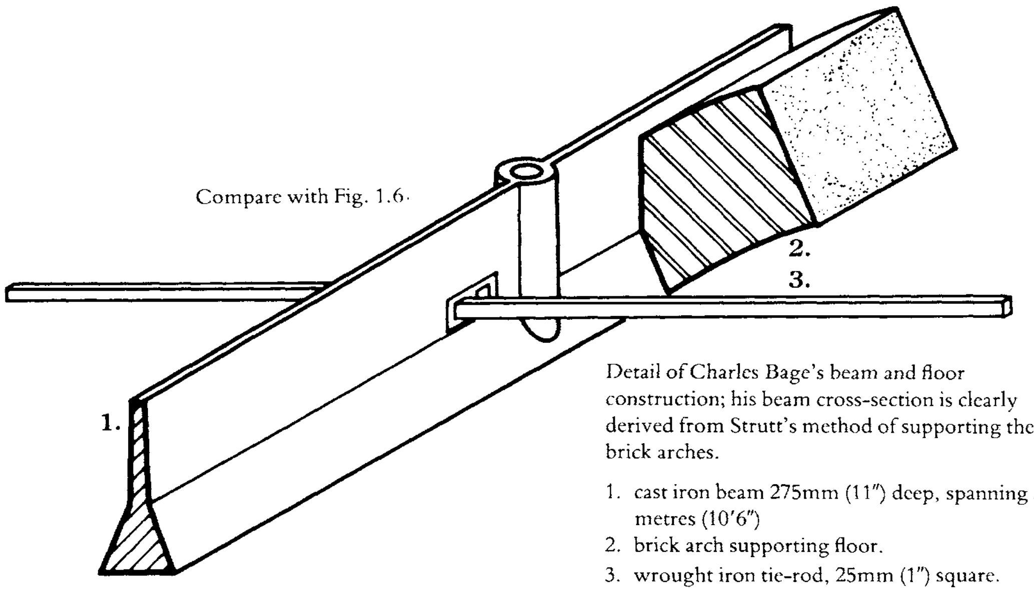
History of Iron and Steel Construction

Isambard Kingdom Brunel, 1806–59

George Stephenson 1781–1848

Gustave Eiffel, 1832–1923

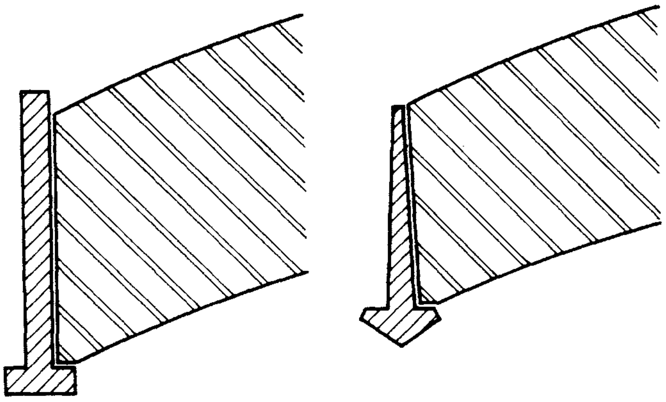
Sir William Fairbairn, 1789–1874



Compare with Fig. 1.6·

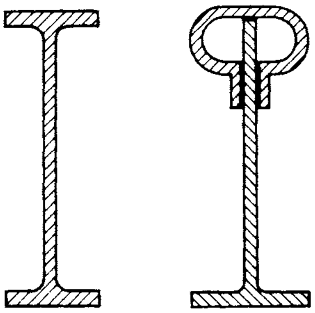
Detail of Charles Bage's beam and floor construction; his beam cross-section is clearly derived from Strutt's method of supporting the brick arches.

1. cast iron beam 275mm (11″) deep, spanning 3.2 metres (10′6″)
2. brick arch supporting floor.
3. wrought iron tie-rod, 25mm (1″) square.

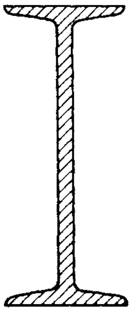


(Left) Cast iron section supporting brick arches for the Salford Mill by Boulton and Watt, 1799–1801.

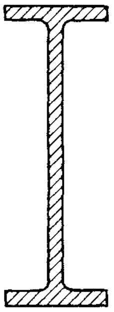
(Right) Cast iron beam section, supporting brick arches for the Belper Mill, by William Strutt, 1803–04.



Early wrought iron beams by Fairbairn and Zores, c. 1850.



Mild steel, tapered flange beam, c. 1885.



Mild steel, universal beam c. 1955.

The development of cast iron and wrought iron beams in the 18th and 19th century. By kind permission of Alan Ogg.

1

The 19th century

Dennis Sharp

1.1 INTRODUCTION

It has often been claimed that the new spirit in building of the 19th century had little to do with architecture. Architects, it has been argued, were in the main preoccupied with stylistic matters rather than technical ones, producing architectural cloaks for public buildings such as the new town halls, opera houses, theatres, libraries and museums. The less stylistically inclined engineer was conversely building (and often inventing) new systems of construction and the structural shapes of bridges, furnaces, warehouses, derricks, workshops and factories as well as other utilitarian structures of the time.

Although this myth is not entirely true, substantially it remains a valid summary. The exceptions, it is now more readily acknowledged, provided the 'contact points' in the growth and development of new techniques, skills and means of expression in the construction industry. Having previously enjoyed both creative and technical freedoms in the construction of cathedrals, churches, cloth halls, towers and barbicans, architects and master masons had never really experienced the coincidence of untrammelled possibilities for a series of new materials, unprecedented social, political, economic and speculative opportunities. The lack of a consistent architectural style for a whole panoply of new building types was a constant embarrassment, even in the early years of the 19th century: 'Architects harangued each other, laymen harangued architects, and the only point on which almost everyone . . . agreed was that the architecture of the immediate past, of the first years of the century was at the best boring and at the worst common' [1].

It is perhaps too easy to chart the course of innovation and speculative prototypes as if they were themselves part of some great Darwinian scheme, as if a casual plan was at work in which an inevitable course was gradually being uncovered by curious, brilliant and inventive people. It was hardly that. Revolutionary yet simple means brought about the rapid growth of events that led to the introduction of lighter materials into the building industry. The industry had taken centuries to master the weightiness of stone, the massive nature of brick and the solidity of the surface volumes that result from the combination of these natural materials. Iron offered a multitude of new possibilities in a constructional sense, not the least of which was the desire to prefabricate and site assemble complex structures. To create wide spans and to form simply supported but transparent envelopes as shelters for activities and as protections against nature were somewhat simple minded design aims, they formed but the basis on which the new technology got underway. In the later medieval period stained glass windows were often strengthened by wrought iron framing members. Wrought iron cramps were also later introduced to reinforce masonry.

As designers reached for the sky in their efforts to create bigger and larger structures they pushed the possibilities of wrought iron to the known limits of the material. The 19th century saw some of the boldest experiments in comprehensive constructional techniques since the introduction of the arch. The experiments began with revisions to the simple elements of building. In Europe, iron roofing members were introduced in the 18th century in buildings for fire reasons also, particularly for theatres and warehouses. Victor Louis constructed a wrought iron roof for his *Théâtre Français* in 1786; other designers followed his methods with interest.

It is, however, bridges that provide a key introduction to the topic of historic cast and wrought iron. The earliest known examples that employed iron in their construction seem to be the Chinese chain bridges which are represented in the famous 'Bridge (magic) myths'. An 'iron bridge' on a suspension principle crossed the Kin-Sha river in China in the 8th century. Chain bridges were common in Yunnan much earlier [2]. Iron was also employed in Pagoda construction certainly from the Sung period and perhaps earlier. Later examples are better known and significant advances in the early use of iron can be illustrated by reference to such famous British engineers as Brunel, Telford, the Stephensons and Rennie.

1.2 CAST AND WROUGHT IRON

The modern story in fact starts with the work of the Darby Brothers at Coalbrookdale. They brought the new smelting process into common use, forming rough bars of 'pig' iron. However, cast and wrought iron had been used in a number of Gothic buildings. The concurrence of coal and iron ore measures at Coalbrookdale led to the most rapid advances in iron casting culminating in 1777–9 with the construction of the famous clear span 'Ironbridge' at Coalbrookdale over the River Severn (Fig. 1.1). The assembly of the cast iron components for this semi-circular bridge resembled the spokes of a gigantic wheel, with the elements put together using pins and bolts rather in the manner of an oak truss assembly with metal fastenings. There were technical limitations in making long lengths of cast iron, so the bridge comprises a whole series of short compression elements. The technical ingenuity in putting together the components to achieve a 100 ft span (30 m) was a remarkable achievement in terms of accuracy and workmanship. The designers understood the compression attributes of cast iron which, coupled with its low corrosion risk, achieved a viable arched bridge structure in the new material. It still stands today, the noble father of a family of cast iron bridges that covers the elegant Mythe Bridge at Tewkesbury (1823–6) to the climax of wrought iron suspension bridge construction over the Menai Straits (1819–26), both by Thomas Telford (1757–1834).

The reputation of West Midlands ironfounders was enhanced by their collaboration with the canal engineer Telford in developing solutions for wide span cast iron aqueducts, such as Pont-y-Cysyllte (1795–1805), carried on masonry piers. Flanged castings were used in this project, bolted together to form a box-like channel to support the water trough with flange arched elements below. The combined span of the 19 arches was 1001 ft (302 m) with a height of 120 ft (36 m) above the valley floor; each arch spanned 45 ft (13.5 m).

Telford saw the great potential of iron as a structural material but his background was that of a skilled stonemason. His approach was therefore largely empirical in the constructional use of cast iron, although he was one of the first engineers, together with John Smeaton (1724–92), to appreciate the scientific basis of structures and their European origins [3]. His confidence, however, was such that a proposal for a 600 ft (180 m) clear span bridge was made for London in 1800, a simple development of the arched span components used on canal bridges.

The engineering achievements in the early 19th century were fuelled by the post-Waterloo boom in Britain's economy and led to extensive road construction, many fine bridges, and finally to even greater engineering works linked with the expansion of the railway which included viaducts, railways sheds and stations as well as more bridges of a revolutionary design.

The engineering practice of Isambard Kingdom Brunel (1806–59) and his father Sir Marc Brunel (1769–1849) brought scientific principles to bear on engineering construction. Besides introducing mathematical calculations into structure, the skill of the Brunel partnership was also directed to the use of forged wrought iron using steam hammers to achieve structural sections with a wide range of applications such as bulbous 'I-bars' for ships and tees for rail tracks. These former were developed for building beams with extended webs and additional forged members to the lower flange.

The inventiveness of Brunel can be seen in the first proposals for the Clifton Suspension Bridge (1831 but completed 1864, five years after his death) (Fig. 1.2). It had a 702 ft span and a width of 31 ft. Wrought iron chains and suspenders carry the cross framed road deck between the masonry towers. It is anchored back to the cliff abutment 245 ft above water level. The great Royal Albert, Saltash railway bridge, by contrast, was a tubular arched girder bridge raised off masonry towers, with a slung lattice for the rail deck below. It was partly built with ironwork reserved for Clifton but made up of 17 land spans and having a total length of 2220 ft (Fig. 1.3). Another wrought iron tubular bridge was constructed by Brunel over the Wye at Chepstow.

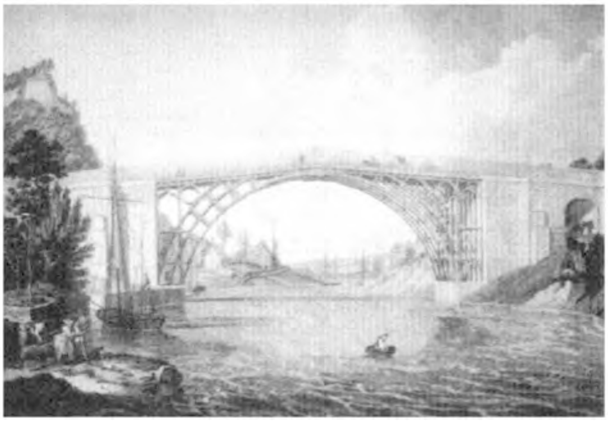


Fig. 1.1 *Ironbridge, Coalbrookdale 1777–9 (engineer Abraham Darby).*

Another remarkable advance made by the Brunels was in ship construction (Fig. 1.4). Here they developed the first screw propeller driven iron ship capable of crossing the Atlantic. The ship's construction comprised iron rib and deck beams and iron plating and rivets which were used for the first time in its construction instead of conventional timber planking. The *Great Britain* made her maiden crossing in 1845 and was followed within 10 years by a ship that was 680 ft (204 m) long and not exceeded in size until the launching of the *Titanic*. The wrought iron used by the pioneer engineers was produced in relatively small furnaces and prepared and worked to achieve specific shapes and strengths.

1.3 FORTH RAILWAY BRIDGE: FIRST STEEL STRUCTURE

The production of mild steel followed the adoption of the converter process from 1856 onwards. The first large scale use of modern day steel in Britain was in the construction of the Forth Railway Bridge (Fig. 1.5), a fine, elegant tubular cantilever structure designed by Benjamin Baker and completed in 1890. Here the work embodied the latest technology with steel tubular trusses put together by riveted and

Fig. 1.2 *Clifton Suspension Bridge, Bristol 1831–64 (engineer I. K. Brunel).*

Fig. 1.3 *Royal Albert Railway Bridge, Saltash 1852–9 (engineer I. K. Brunel).*

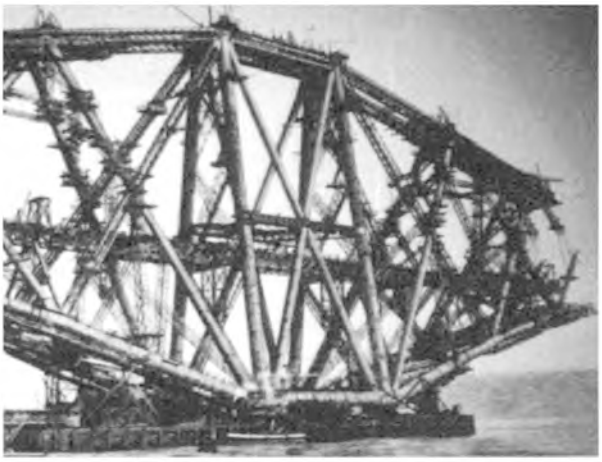


Fig. 1.5 *Forth Railway Bridge under construction, late 1880s (engineer Benjamin Baker).*

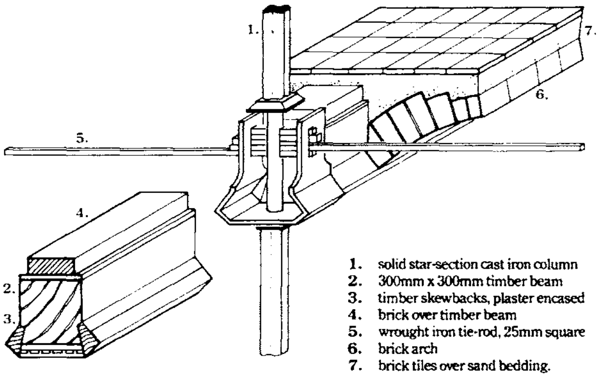


Fig. 1.6 *Strutt's use of wooden beams and brick arches with cast iron columns. Courtesy Alan Ogg:* Architecture in Steel.

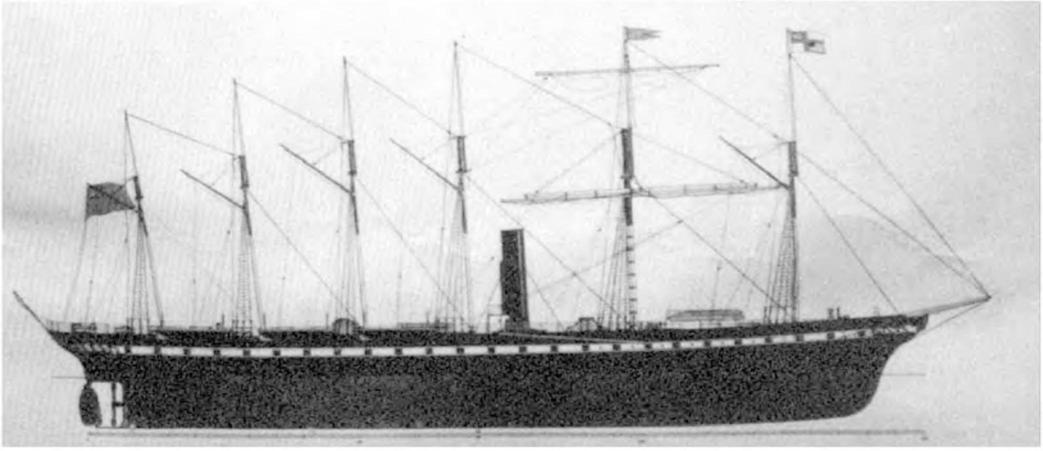


Fig. 1.4 *SS Great Britain 1845 (engineer I. K. Brunel).*

bolted work to achieve the tapered cantilevered trusses with multiple spans, max: 1710 ft (523 m). The advance to modern day steels meant that bridge designers finally had a mass produced material available of proven strength. Like wrought iron, it had the ability to be bolted, riveted or forged together to form the composite elements needed in this kind of large scale bridge construction.

1.4 MILL BUILDINGS IN BRITAIN

Cast iron was extensively used in mill buildings in Britain from 1780 onwards with the growing need to protect premises and stored goods from fires. The early mills however had wood beams carried by cast iron columns as detailed in Fig. 1.6. The cotton mill for Phillips, Wood and Lee was erected in Salford in 1801 and, according to Giedion, 'surpasses all others of its time in the boldness of its design'. Considerable refinement took place at the end of the 18th century under the influence of Charles Bage and William Strutt; as shown in the lead-in illustration. Salford represents the first experiment in the use of iron pillars and beams for the whole interior framework of a building [4]. It set the precedent until William Fairbairn turned his attention to more sophisticated fireproof methods at mid-century (Fig. 1.7).

The Industrial Revolution saw the development of new types of buildings for manufacturing and assembly purposes, many of which demanded new technical solutions for their construction. These technical requirements led to innovations that in turn had a significant effect on the determination of the architectural result. But, it has to be said, that up to the 1840s '. . . builders, engineers, and more rarely architects (were) constructing mills according to the structural and architectural traditions that had developed in the latter part of the 18th century' [5]. This meant following, often quite crudely in some of the early mills, the Palladian pattern books of the period, for the main facades of these new buildings. But coincidentally the buildings themselves were growing to awesome sizes, and minor emphatic facades became of less importance in the face of large repetitively patterned walls of brick and iron framed windows and the vast interiors that had to provide large uninterrupted spaces for the vast new machines and the hundreds of workers employed in them. Light had to be provided internally and, increasingly, the need for overall fire protection became a critical issue. The technical part of this story, particularly as it becomes more concerned with ferrous metals, takes on a special significance: first cast iron, then the growing awareness of the better structural strength characteristics of wrought iron emerged, and then steel, the full architectural possibilities of which were not grasped until the end of the 19th century. Thus the rise of iron as a prime building material can be traced sequentially in its initial partial application in mill buildings such as those erected by William Fairbairn, the Manchester based engineer, in the northern industrial cities [6]. An interesting side issue in Britain was the adoption of a neo-classical vocabulary for some of the exteriors of mill, works and dock buildings. Stuart and Revett had drawn the attention of connoisseurs and collectors to the virtues of the pure Greek

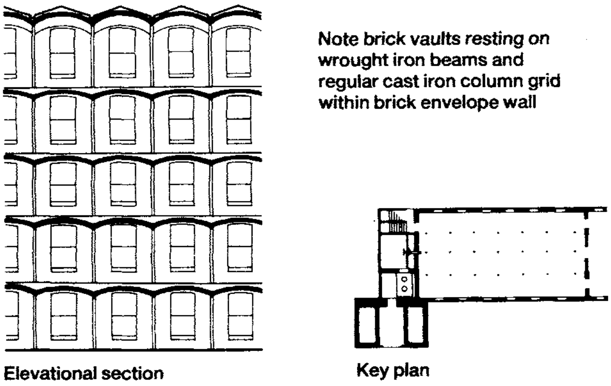


Fig. 1.7 *Typical construction by William Fairbairn c.1845. Courtesy Alan Ogg:* Architecture in Steel.

Fig. 1.8 *Boat Store, Sheerness 1858–66 (engineer Col. G. T. Green).*

Fig. 1.9 *Menier Chocolate Factory, Noisiel-sur-Marne 1869–74 (engineer Jules Saulnier).*

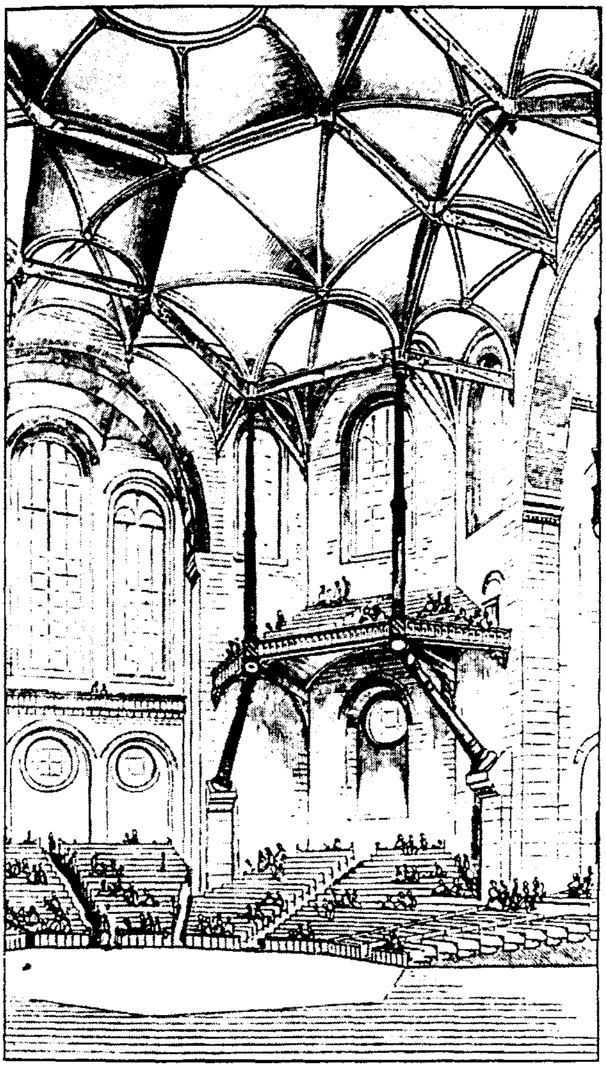


Fig. 1.10 *Iron vaulted construction (architect Viollet-le-Duc). From Entretiens sur l'Architecture 1863–72.*

style through their magnificent delineations of the Attic monuments in their five volume work, *Antiquities of Athens* (1762–1830).

The fully framed Boat Store erected for the Royal Navy in the Naval Dockyard at Sheerness in 1858–66 and designed by the Admiralty Engineer Col. G.T. Green (1807–86) was the first of a long line of multi-storey iron structures (Fig. 1.8). It was a mixture of cast and wrought iron and four storeys in height. It served as a foundry, a fitting out shop and boat store. It had a single storey central nave some 210 ft long and transverse cast iron columns and beams supported timber joists whilst wrought iron longitudinal plate girders spanned the 30 ft between. It is claimed to be the first 'portal action' structure. Externally the striated bands of windows were separated by surface panels of corrugated iron, thus completing a simple and very 'functional' looking facade. This simple elevational treatment of the innovative cast iron structure fascinated the apologists of the Modern Movement in architecture [7].

William Fairbairn's faith in the structural nature and ability of cast and wrought iron was maintained well into the second half of the 19th century. Sir Henry Bessemer's conversion process of 1855 took a long time to develop, although it eventually heralded the introduction of mild steel as a constructional material. It possessed many of the same properties as iron but as a 'new' material required some adaptation in its use both by architect and engineer. Essentially it was a better quality material and much more consistent in its manufacture. It was more ductile and could withstand considerable deformation before failure and was equally strong in tension and compression. It exhibited great inherent qualities as a skeletal framing material for high buildings, although it was not necessarily an easier material to erect than iron. Side by side with other technical developments, methods of analysis, constructional regulations and new inventions – including most importantly the refinement of the earlier invention of the lift or elevator – steel construction was soon to provide the basic bones for a generation of new glazed and framed buildings onto which were fastened a whole variety of building cloaks.

Initially steel framed construction was introduced to replace iron for increasingly higher public and commercial buildings in rapidly expanding town centres, largely in the US. Later it did become economical for use in the construction of tall residential blocks there. In Europe it was used extensively for railway stations and factories. Its first extensive use there was as a large scale multi-framing material at Saulnier's Menier Chocolate Factory at Noisiel-sur-Marne near Paris, 1869–74 (Fig. 1.9).

This building is considered to be the first one in Continental Europe to have been composed in its entirety of a wrought iron frame with non-loadbearing masonry external walls. In reality, it was like a great bridge resting on piled foundations driven deep into the River Marne which it used for hydraulic power purposes. It was indeed an industrialized Old London Bridge with its lightweight framework above infilled with decorative brickwork and tiles which caused the great French architect and archaeologist Eugene Viollet-le-Duc to eulogize in his *Entretiens* (Fig. 1.10) on its 'progressive medieval appearance'. The repeated frame was so arranged that the uppermost floor was suspended from the roof structure, leaving the floor below completely free of columns.

Otherwise the material was only slowly introduced into the building industry during the following 25 years. As it became cheaper to make, its use was more widely accepted in the 1890s. In London it was not introduced until the early part of the new century and then for the new steel-framed Ritz Hotel in 1904 and two years later the east wing of Selfridges in Oxford Street.

1.5 CHICAGO STYLE

In Chicago after the great fire of 1871 an opportunity arose to rebuild most of the central area of the old city. The great 'garden city' of the American mid-west – the grain centre of the world at the time – was rebuilt with grand boulevards, huge lakeside parks and promenades and later grew up the tall stone clad and iron – later, steel – framed blocks characteristic of this great regional centre. For a time Chicago was a cauldron of ideas for these new materials. Apart from one or two significant and notable exceptions, the use of ferrous metals for high building was *de rigueur*. However, there is the 16 storey high brick masonry-bearing Monadnock Block of 1891, erected when complete skeletons were becoming standard practice. Indeed, there is evidence to show that it was intended originally to be built entirely in steel but John Wellborn Root (1851–91), the energetic architectural partner of Daniel Burnham, who was largely responsible for the planning of Chicago, decided upon a tapering brick slab with such subtle refinements that the eminent 19th century American critic Montgomery Schuyler pronounced it 'the best office building of the day'. It still remains a much admired landmark. Its walls, however, were some 6 ft thick at their base. Elegant it may have been from an architectural point of view, but it was overtaken by events.

There was a certain degree of inevitability it seems about skeleton construction developments in America. Certainly in Chicago it was seen as a positive response to the city's unstable soil conditions and many of the early skyscrapers were supported on isolated pier foundations before caisson foundations were introduced in 1894 at the Stock Exchange in North LaSalle.

Larger window sizes, of course, were another inevitable outcome of the new framed construction aesthetic, although architects were still keen to shower ornament and decoration onto their unacceptably simple functional and economic steel frames. By the turn of the century it was claimed that Chicago had more tall buildings – many artistically considered – than all the other cities of the world put together! The initiative with the new high building was to stay with Chicago for many years. New York was not to lag too far behind in terms of individual building examples, although the great boom in high-grade skeletal structures in the centre of Manhattan was to take place between the wars. For a time New York was even to take the lead as the city with the highest building in the world when the Empire State Building was topped-out in 1921, but what was high in those days can hardly be considered so today. When the Sears Tower, Chicago, designed by SOM, reached its epoch-making 1700 ft it reduced its neighbours to mere pygmies, although it could not hold a candle to the quality of architecture, engineering and urban comparability of its earlier relatives. One example is the Adler and Sullivan Auditorium Building, completed in 1889, which now accommodates Roosevelt University as well as the great 4000 person plus auditorium from which it derives its name. Perhaps this building demonstrates more clearly than any other Chicago structure of the end of the 19th century an effort to bring about a unity between uses and materials. The brick-built theatre auditorium was entered from street level, whilst the hotel was situated at the top of the building, served by a bank of lifts and looking out across the lake and, at the time, enjoying a unique view of the Columbian World Exposition. Sullivan, whose masterpiece the Auditorium most certainly was, modelled its exterior to a very large extent on the earlier Marshall Field store (built in 1884 but demolished in 1929), designed by his mentor H.H. Richardson (1838–86). A similar rough textured finish was given to the stonework of the lower storeys to the Auditorium and a consistent Romanesque motif used for the windows on the great facades. The iron structure situated on the edge of the lake soared to a height of 270 ft (17 storeys to the top of the tower) above ground level; it reputedly weighed 110 thousand tonnes deadweight. In 1888, the year it opened, it was the tallest structure in the city.

Fig. 1.11 *Portrait of Louis Sullivan 1856–1924.*

The Auditorium block differed materially in many respects from other commercial buildings of the time. It was one of the first major custom designed multi-purpose buildings on the new American skyscraper pattern. Although it housed an auditorium of sumptuous proportions with clubrooms and hotel, it also served as a central location business address, thus providing theatre patrons with places to stay and dine as well as to work. The idea had been conceived by the building's owner Mr Ferdinand Peck, who, developing his profit opportunities as they arose, altered his requirements and the architect's plans time and time again. Sullivan (Fig. 1.11) brought about a cultural masterpiece with decorative patterns the like of which the mid-west had only seen before in the swirling patterns made by nature on the waters of the Lake or on the wind-swept prairies. But it was his engineer-trained German Jewish architect partner Dankmar Adler (1844–1900) who was responsible for tying this unique iron structure together from an engineering point of view and for introducing complex steel elliptical trusses to span the 117 ft across the Auditorium (Fig. 1.12).

Burnham and Root's Reliance Building was designed in 1890 but completed in 1894 some three years after John Root's death and still remains an important articulate example of the sheer glass, open-walled skeletal building (Fig. 1.13). In its general treatment it anticipated by decades the Modern Movement glass tower and in the detail treatment of its flat cornice (removed c.1948) also seems to anticipate Frank Lloyd Wright's bold oversailing roofs.

The building had an unusual constructional history. It has been referred to as perhaps the ultimate refinement of the 19th century skeletal frame skyscraper. Its site was hemmed in by existing leases: the leases on the lower floors ran out in 1890 and the upper storeys in 1894. The first stage – designed by Root – saw the demolition of the ground floor and the construction of the beam and rail foundations for the high-rise tower, whilst the upper floors were supported on screwjacks.

Charles B. Atwood, a New York architect, entered Burnham's office after Root's death to redesign the upper storeys. He put the screwjacks back temporarily in order to support the old building before its final destruction and then added 13 bay-windowed floors over the present ground floor shop.

The steel skeleton went up in just over a fortnight and the whole exterior was completed in less than six months. The beautiful full length bays were totally incorporated into the body of the building and are today still the building's most characteristic feature. Set close to the surface (cf Belluschi's Equitable Savings and Loan Association Building, Portland, Or., 1948, see chapter 27) the full width 'Chicago Windows' give the building the appearance of a tightly sealed yet transparent membrane. All structural support is provided by the internal skeleton, and the window walls as well as the floors were contained within the building envelope.

How high, how far, how big? That was the numbers game. Just how far could these extraordinary new materials go? Prior to the great engineering monuments of the 19th century, there had been many exceptional wonders in the world of an engineering kind, many of which had exploited the use of materials; some defied gravity.

The psychology of size has always held a fascination for mankind. Today, books set out the league tables of the well known – and even the more obscure – items in this record breaking world. In a sense they show the same sort of enthusiasm that the builders of the Colossus of Rhodes must have felt, or the constructors of the colossal Qutub Minar in Delhi or even for that matter the designers of the great obelisks of Egypt and Washington, DC. It is a puzzling but

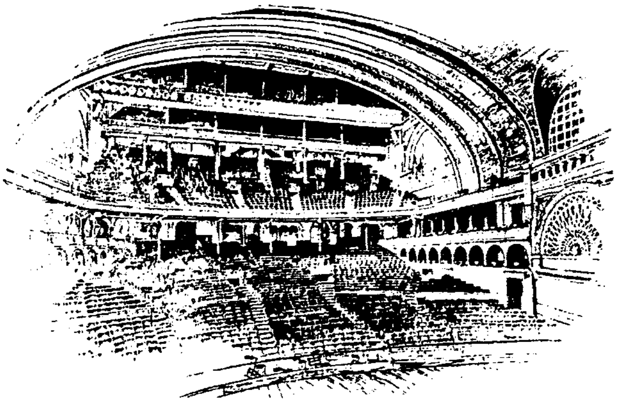


Fig. 1.12 *Interior of the Auditorium Theatre, Chicago 1887–89. The two upper galleries and much of the first balcony could be closed off to reduce the capacity to 2574 seats (architects and engineers: Adler and Sullivan).*

Fig. 1.13 *Reliance Building, Chicago 1890–94 (architects and engineers Burnham and Root).*

compulsive tendency to achieve great structural and engineering feats, and iron and steel offered almost limitless opportunities, it would appear.

Sometimes the creative existentialism operates on a more mystical plane and record breaking desires are subordinated to spiritual or symbolical goals. Who knows, for example, where the ideas and the technical knowhow came from that produced the massive iron Ashoka columns of North India, the great rebuilt (1835) iron trusses at Chartres of the 1870s (370 ft high above the floor) or the interwoven and interlocking patterns of the stonework lintels of the chief Cairo mosques? Perhaps it is that atavistic spirit that is part of one's make-up that motivates the creative process to seek the ultimate answer.

In the modern steel age Frank Lloyd Wright had no doubts at all that his design for a 1 mile high tower could be built, and, lest we forget it too easily, engineers have more recently flung a great bridge across the Bosphorus achieving success where before such a structure was considered to be a complete impossibility. Konrad Wachsmann's enormous tubular steel projects for aircraft hangers and Buckminster Fuller's great dome constructions are all part of this exciting story.

1.6 IRON'S GREAT SYMBOL: THE EIFFEL TOWER

It is no wonder sensing the challenges of the Modern Age that Gustav Eiffel (1832–1923) – a man in his late 50s and an engineer who had grown increasingly confident of his abilities with the use of iron – should seek the judicious use of the new material to create a world record. Through the use of special techniques and innovative methodologies he created the tallest structure in the world – 300 m (or 986 ft) – to crown the 1889 Paris Exposition (Fig. 1.14). It took 2 years to complete. It was prefabricated and site riveted. His tower exemplified the 'new' industrial age of the second half of the 19th century. In a sense too the tower brought to a head the results of his experiments in straight girder bridge construction, for the kind of iron framed rigidity he had developed for Bartholdi's New York *Statue of Liberty* and for inventing ways of conveying heavy materials on a slope. Le Corbusier called it the 'Fruit of intuition, of science, of faith, daughter of courage and of perseverance' [8].

Erecting the world's tallest *structure* – it can hardly be described as a building in any conventional sense – was a challenge as big as walking on the craggy surface of the moon was in the mid-20th century. Certainly at the time no-one got a closer view of the moon than from the top of Eiffel's own prefabricated iron tower. Although of hard iron, it became a romantic dream. His detractors claimed he was mad and that the tower would surely topple within a short period of time. It was described as 'unrealisable, useless and senseless'.

Fig. 1.14 *Eiffel Tower, general view of 300 m shaft 1887–89 (engineer Gustav Eiffel).*

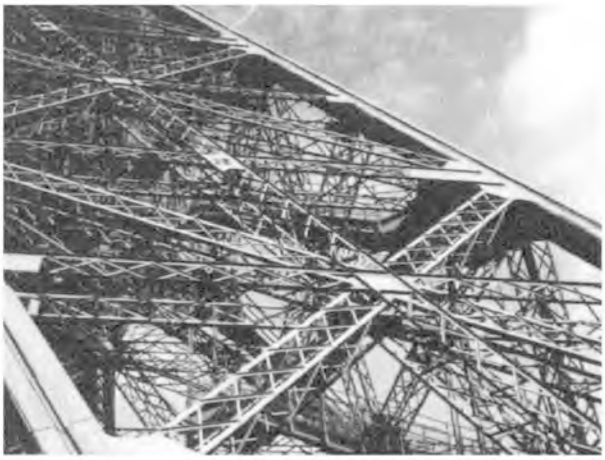


Fig. 1.15 *'The real strength of the Eiffel Tower is in its voids as much as in its iron'.*

One eminent French writer, who abhorred it, dined there every day in order that he should not see it! Wind forces had proved a big problem and to solve it the supporting elements were reduced to a minimum. As Joseph Harriss has written: 'The real strength of the Eiffel Tower is in its voids as much as in its iron!' (Fig. 1.15) [9]. With the accurate pre-punched rivetting the whole structure was assembled on site in a smooth straightforward manner. Even so it was also described at the time as 'a colossus of iron' and compared favourably with the Washington Obelisk (555 ft high), the Great Pyramid of Egypt and Cologne Cathedral (512 ft high). Today the structure has itself become the very symbol and principal marker of the city of Paris; perhaps even of France itself. It has been used as the subject of films, paintings, sculpture and more recently an elegant essay by Roland Barthes [10].

1.7 KINGS CROSS/ST PANCRAS STATIONS

Kings Cross Station, the largest station in London at the time of its construction (1852), was a plain-fronted brick building designed by the architect Lewis Cubitt with the collaboration of engineers Sir William and Joseph Cubitt. It was erected in one of the most dilapidated, squalid and poverty ridden areas of London and opened in 1852, bringing a new kind of elegance into the area. Its plain brick bipartite facade presented two identical semi-circular arches to the road surmounted by a squat clock tower. Its original appearance was not a great deal different from the frontage that can be seen today. Its importance, however, at the time was as one of the more functionally designed train shed structures. Its lengthy arrival and departure platforms were arranged on either side of an arched brick wall topped by two great laminated timber roofs. These proved unsatisfactory and were soon replaced by iron ribbed roofs in 1869–87. It still retains its long, low character, presenting a great contrast to the great open train shed next door at St Pancras built for the Midland Railway Company by their engineers W.H. Barlow and R.M. Ordish. This building represents a peak in iron railroad construction both in terms of its structural ingenuity, with iron ties supporting its single parabolic iron roof under the platforms, and its direct expression of architectural space. Motivated by a desire to express and, one expects, create an ornamental arrival venue for the new noble iron 'horses', this great railway stable was erected to cover a multitude of noisy, hot, sweaty and steamy activities. Long lines of railway coaches discharged their passengers onto simple platforms. They were led from these at one side to a busy road and on the other through elegant doors to the luxurious *Midland Hotel*, a fairytale confection dreamed up by Sir George Gilbert Scott for the delectation of the exhausted traveller, thus providing an entry into the genteel but expensively upholstered world of London business and society. To professional eyes it seemed that these two related but unconnected worlds, of the functional rail shed and the posh hotel, symbolized the division between public decorated architecture and simple mechanical functional engineering. Indeed, it is worth noting that there is a decisive structural gap even today between the last of the train shed's arch bow trusses and the ornamental brick facade of the former hotel's private walls.

For a time, in Europe at least, traditional architectural and innovative engineering solutions did not mix. Unlike the Romanesque and Gothic method of accepting and co-existing side-by-side with alterations, the implementation of stylistic improvements and changes, at St Pancras the lines of demarcation were clearly drawn. More consistent design relationships were to be found in many European railway station examples in places like Paris, Hamburg and, some years later, in Stuttgart and Helsinki. Some of these were the result of architectural competitions that had purposefully sought out new and original solutions for combining all the various elements of great station termini.

Fig. 1.16 *Bibliothèque de Sainte-Geneviève, Paris 1843–50 (architect Henri Labrouste).*

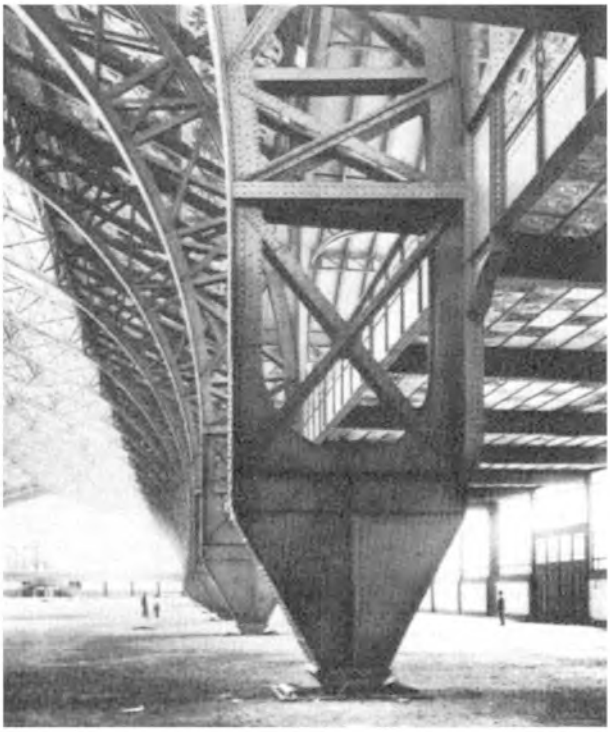


Fig. 1.17 *Galerie des Machines, Paris 1889 (engineers Dutert and Contamin). Courtesy Alan Ogg:* Architecture in Steel.

Fig. 1.18 *Wrought iron balconies of Casa Milà, Barcelona 1905–10 (architect Antoni Gaudi).*

1.8 EUROPEAN PIONEER IRONWORK

Much earlier than Eiffel's epoch making landmark tower, Henri Labrouste's *Bibliotheque de Sainte-Genevieve*, Paris, 1843–50 used cast iron internally in a thoroughly imaginative and sympathetic manner (Fig. 1.16). His building – what Hitchcock has called '. . . the finest structure of the forties in France' [11] – combined two architectural languages, the restrained classical for the facades and the new lightweight, filigree construction for the interior. With the *Sainte-Généviève Library* Labrouste left its metal frame exposed in an audacious gesture towards the Vitruvians. Without such a brave act, Frantz Jourdain wrote in a well known essay on August Perret 'Baltard would probably have not built the *Halles Centrales* or the dome of St-Augustin in iron'; without him it seems unlikely that Sedille would have used this outcast material in the *Au Printemps* department store. He went on to indicate the abhorrence the establishment felt towards the material: 'The Institut treated iron with a pious terror that might have been appropriate for a shameful disease'. In effect it was not until a succession of exemplary world expositions had taken place in Paris culminating in the Exposition 1889 – which of course included Eiffel's Tower as well as Dutert and Contamin's *Galerie des Machines* (Fig. 1.17) – that the virus was eventually killed and then only after a struggle to take land height and width records. At roughly the same time the incursion of craftsmen and artists into the field of ornamental casting led eventually to the establishment of what was to become known as the art nouveau, a playful and highly naturalistic decorative style that was to sweep through France. It reached its apotheosis as a style at the Paris Exposition of 1900. Here iron and wood took on an entirely new significance. They were used in their most original forms in the shaping of sinewy, elegant and often quite beautiful shapes as armatures for furniture, lamp standards, metro entrances – as with the work of Hector Guimard – as well as gable ends and balconies. In the worst possible taste both materials were also employed to outline curves and evocative shapes as if they had been squeezed from a toothpaste tube instead of cast or cut from root or branch. Iron had a particularly important role to play too in its use as a framing material for stained and clear glass used in laylights or for impressive domes of light above grand stairs such as in the brilliant work of Baron Victor Horta in Brussels or Antoni Gaudi in Barcelona. They took advantage of the material, setting it up architecturally to create a filigree effect or as a firm support for a translucent screen.

The curving, flowing linearity of the early art nouveau, seen in building interiors, in furniture design, book illustrations and graphics as well as in the flowing robes and bodily movements of celebrated dancers like Loie Fuller – herself a minor sensation at the 1900 Paris Expo – was soon followed by an apparent rationalization, a *massen regie* that was to prepare the world for the kind of geometric definitions that produced the early signs of artistic cubism on the one hand and 'functional' architecture on the other.

Around the turn of the century the new materials that had been introduced and ridiculed and attacked as insubstantial and unevocative of cultural values – cast, wrought iron, steel and concrete – were becoming *de rigueur*, at least among the European avant-garde. As well as Baron Victor Horta in Belgium and the individualistic Antoni Gaudi in Barcelona (Fig. 1.18) – the virtual leaders of the *fin de siècle* movement – Hector Guimard and Frantz Jourdain in France, Otto Wagner, Josef Hoffmann and J.M. Olbrich in Vienna and, to a degree, C.R. Mackintosh in Glasgow all saw the potential of the new adaptable materials. They began to use them structurally, decoratively and most certainly organically in their designs. Horta's experiments are among the most interesting. He often introduced lightweight materials to facilitate his supporting problems for complicated building sections. The inventive light wells he designed with domes and laylights were essential for the deep sites of his Brussels apartment blocks (Fig. 1.19). But it was as an adjunct to the new transportation systems then under construction in many European cities that both cast and wrought iron really came into their own. Earlier cast iron had been a feature in the Baroque palaces and town centres for the ornamental gates and park fences, the garden monuments, fountains and balconies (from Versailles, Bath and Nancy to New Orleans and Liverpool). It had all the festive feel of a world fair pavilion, yet as a material it was hard wearing and ductile. It could easily be fashioned to imitate natural forms, and decorated. It offered untold opportunities to an original designer. Numerous permutations of the materials were possible for rolling stock, rails, bridges, entrances, pavilions and canopies for the new Paris Metro around 1900, by Hector Guimard and the new *Bahnhofen* by Otto Wagner for Vienna (Fig. 1.20).

After this peculiarly eclectic art nouveau phase in the 19th century cast and wrought iron began to be employed on a much wider basis in structural and architectural contexts. It was no longer necessary to mimic past stylistic motifs, as Hardwick had done with his cast iron Doric style dockside buildings in London and Liverpool, in order to appear up-to-date and 'modern'. No, that had come about by the application of the age-old mimetic and nationalistic motifs and devices that had given birth originally to the language of architecture – from primitive hut to reed temple – and which, for a time at least, caught Europe eventually in a creative and fashionable storm. It forced to a head the all-important issue of the machine and art, of craft and skill, and, ultimately of quality and inventiveness in architecture. The acceptability, respectability and usefulness of the new

Fig. 1.19 *Staircase in Hotel Solvay, 224 Avenue Louise, Brussels, Belgium 1894–90 (architect Victor Horta).*

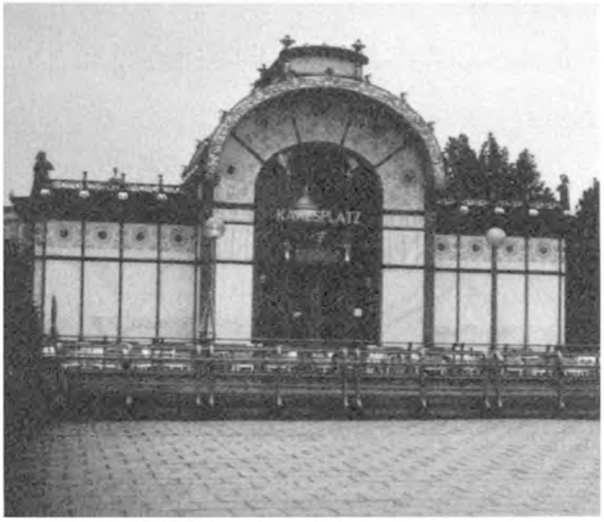


Fig. 1.20 *Karlsplatz Station, Vienna 1894–98 (architect Otto Wagner).*

Fig. 1.21 *Post Office Savings Bank, Vienna 1904–6 (architect Otto Wagner).*

materials was soon established. A whole new propagandist literature emerged in Europe, including Wagner's *Moderne Architektur* (1896) and Loos's early essays, *Spoken into the Void* (1897–1900) and in particular his later attack on 'Ornament and Crime' (1908) which, building on the work of Viollet-le-Duc and others, confirmed the importance and applicability of the new materials as a part of 'Modern' architecture.

The public hall of Wagner's Post Office Savings Bank building in Vienna, 1904–6, is an astonishingly successful amalgamation of iron and glass design (Fig. 1.21). It is a piece of inventive architecture that followed the tradition of the *Länderbank*, with their courtyard-like banking halls as well as the great railway shed tradition (admittedly somewhat scaled down and refined in its aesthetic treatment). Its pure shapes and plastic forms were integrated with the surface elements of the building into a unified and harmonious whole. In the original competition entry design of 1903 Wagner had shown a three-part glazed roof for the banking hall suspended from cables. However, the final design incorporated a kind of double roof with both the actual roof members and the glass ceiling supported on iron beams.

Here in Vienna, whilst Germany was still absorbed with the decorative excesses of the Jugendstil and Muthesius's continuing flirtation with the English Arts and Crafts, the distinctly new: 'Modern' architecture had emerged in the Austrian capital. Wagner had successfully discarded his earlier reference to the French decorative ironwork tradition which was to be seen in the subway buildings for the Hof Pavillion and the Karlsplatz Station, both of 1898. His new architecture was characterized by its flat planes and its restrained detailing.

1.9 THE CRYSTAL PALACE AND ITS SIGNIFICANCE

The 1851 Crystal Palace by Joseph Paxton is often referred to as one of the most important innovative iron buildings in the history of architecture. Paxton's design was unique, as was the way it was selected for construction. Some 233 designs were submitted for the competition for the Crystal Palace, none of which were adopted. However, designs by Hector Horeau, whose design for an earlier adventurous iron and glass market hall for Paris also remained unbuilt, was awarded a special mention. But Paxton came in from the outside, a persuasive horticultural engineer with a flair for getting his own way. He produced his own design (originally sketched on a piece of paper) (Fig. 1.22) in nine days. It was drawn out quickly in Manchester and built in less than four months on the Hyde Park site by Fox and Henderson and Co.

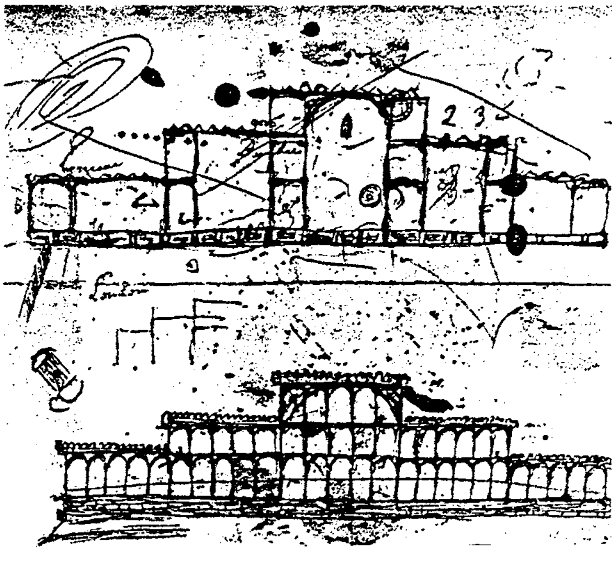


Fig. 1.22 *Paxton's first rough sketch for Crystal Palace 1850.*

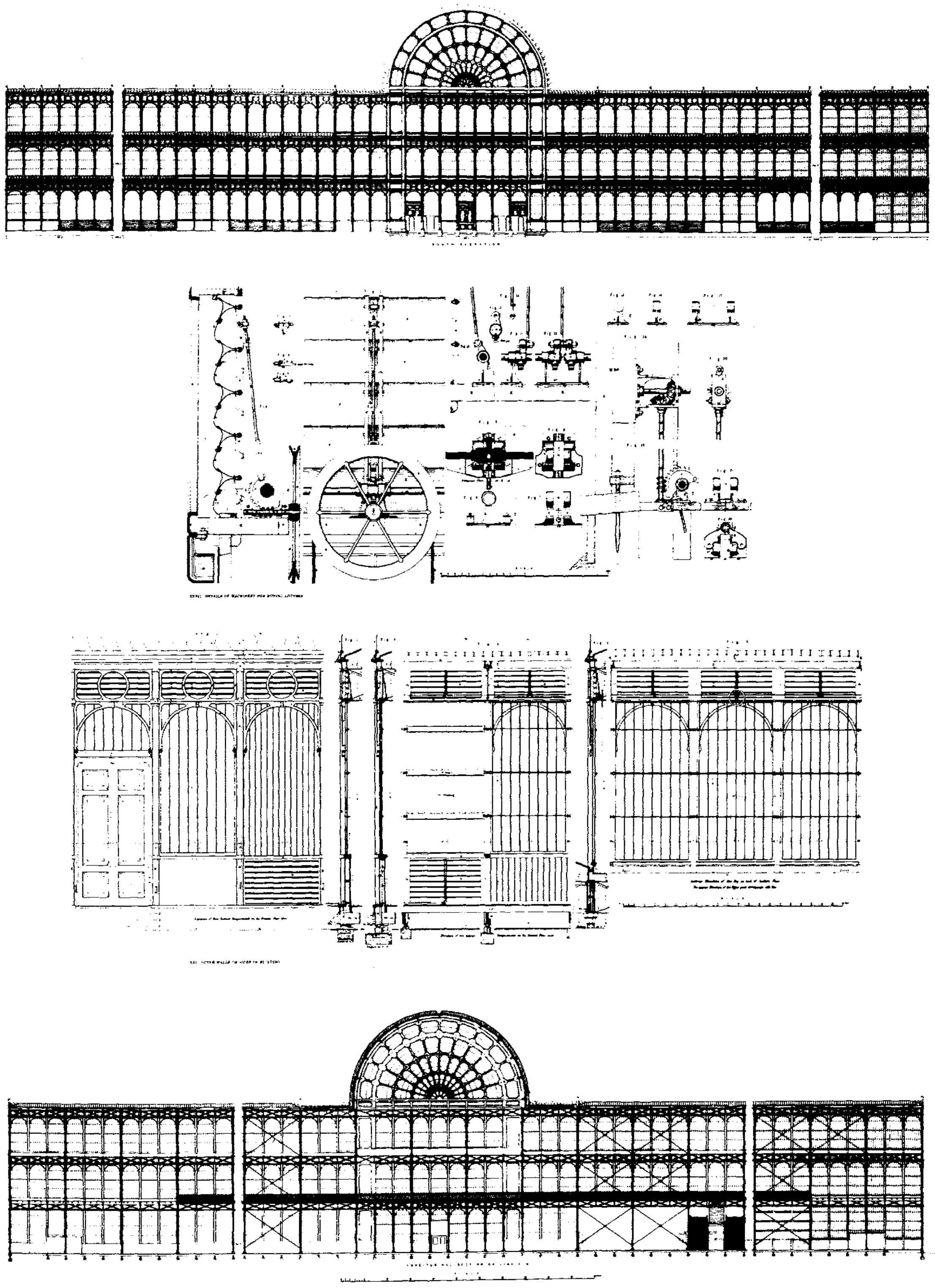


Fig. 1.23 *Crystal Palace elevations, sections and details, Hyde Park, London 1851 (designer Joseph Paxton).*

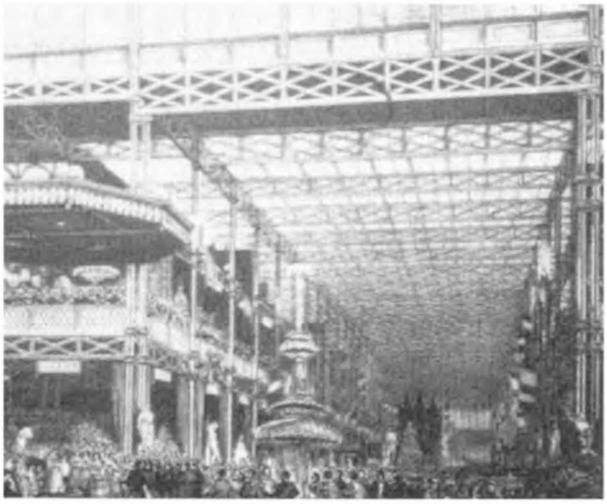


Fig. 1.24 *Interior of Crystal Palace 1851.*

The ground plan was a vast rectangle, sized approximately 1851 ft along the long axis. It was 450 ft wide (with 72 ft broad transepts) and the highest transepts reached 104 ft. The building covered 18 acres. Its magnitude can be appreciated when it is stated that it was four times the size of St Peter's at Rome, and six times that of St Paul's, London. Prefabricated out of moulded cast iron, it set the tone for iron buildings of the next 50 years (Figs 1.23 and 1.24). It employed 3300 cast iron columns, 2220 girders, 1128 girder bearers and 34 miles of guttering tubes as well as 250 miles of wooden sash-bars.

In Britain the use of iron as an 'architectural' material was not exactly popular. Few architects really knew how to use it from a technical point of view. There was at the time no architectural language in iron which could be adopted. What was learnt came from earlier prototypes, principally from timber and stone sources as we have already seen at Ironbridge as well as experiments like those of Horeau and the 'genius' or 'magician' Paxton. However, it was extensively used by Dean and Woodward for their Oxford Museum of 1854–60 (Fig. 1.25). This building came under the close critical eye of contemporary Gothicists such as John Ruskin, who claimed that they could only use new materials such as iron fashioned into some kind of medieval frame. The building eventually went up against a barrage of ridicule and the material used was considered quite unsuitable for its purpose as a museum. Nevertheless, the use of iron and glass construction at the Oxford Museum was singularly innovative. It may well now be assessed as part of a new architectural sensibility. Certainly at the time it must have been viewed as part of a growing new convention of ideas that took into account large scale stores and shops, arcades, galleria, winter gardens, palm houses and floral halls. These sorts of buildings were beginning to appear in fashionable cities throughout Europe, from Gothenberg to Genoa.

As building types, arcades were splendid examples of the everyday commercial application of iron and glass construction. They took up the baton handed on by Paxton's prefabricated iron and glass parts and like the Crystal Palace they offered ease of erection and connection as well as volumetric economy.

Indeed, the arcades of the 1870s and 1880s provided inspiration in other areas of design as both spatial and social structures. Ebenezer Howard, for example, in his diagram for the 'ideal Garden-city' envisaged a wide glazed shopping 'arcade' ring all around his central park fashioned in a kind of circular boulevard plan. Significantly, it was to be called 'The Crystal Palace'. More modest experiments were undertaken such as the remarkably original contribution of architects such as Peter Ellis in Liverpool (Fig. 1.26). His

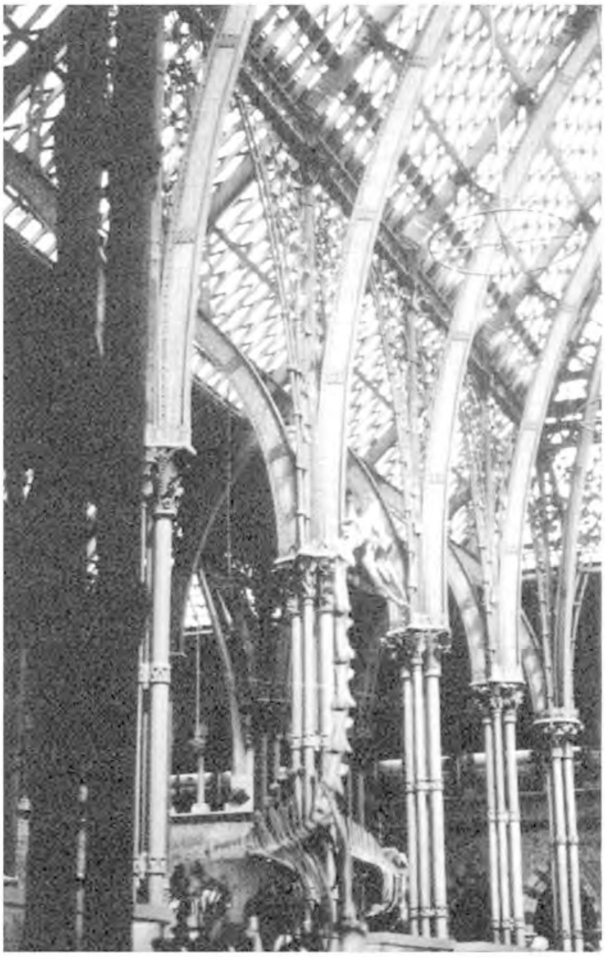


Fig. 1.25 *Oxford Museum 1854–60 (architects Deane, Son and Woodward: metalwork Skidmore).*

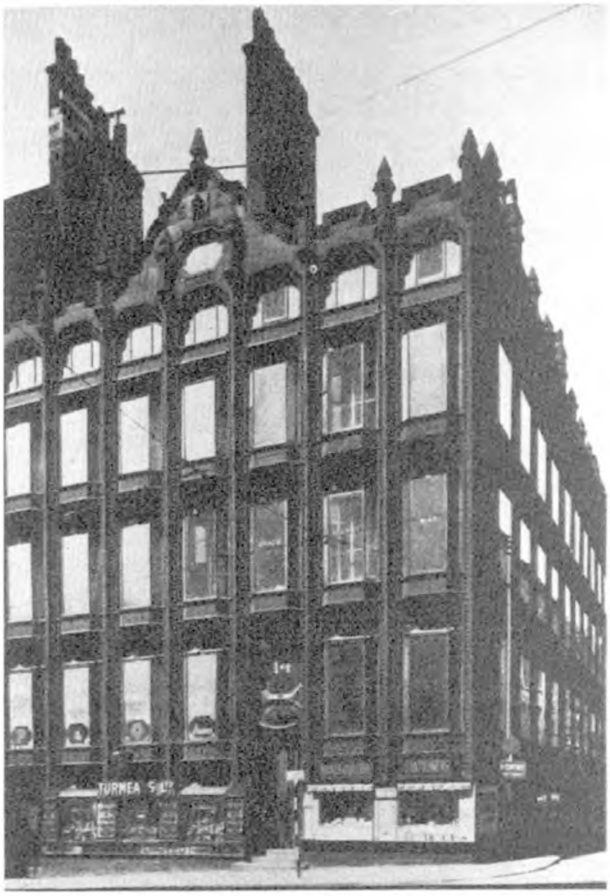


Fig. 1.26 *Oriel Chambers (left), Liverpool 1864–5 (architect Peter Ellis).*

Oriel Chambers (1864–5) located in Water Street has been described as 'the most significant office building in Liverpool' [12]. An impressive iron framed building, it brought together an inventive constructional methodology and a unique means of architectural expression. It relied largely for its effect on a shallow oriel bay elevational treatment. The building's iron frame was clad in stone on the main elevations and the oriel bay window effect also took into account the reflective quality of Liverpool's evening sunlight [13]. The oriel windows seem to be a refined outcome of the great tradition of decorative and structural cast iron that grew out of the early experiments of architects like Thomas Rickman, with his iron framed prefab churches at Everton and Aigburth [14].

Tower Bridge (1894) was a totally different proposition. Built to the design of Sir Horace Jones with J.W. Barry as engineer it epitomized the confusion that existed between architecture and engineering. Here a naked utilitarian steel structure was overhung with a heavy cloak of Scottish style castellated architectural decoration. This effect, as a fairytale fiction, clearly outdid even Sir George Gilbert Scott's earlier Midland Hotel at St. Pancras. It provoked a critic in *The Builder* to write that it was 'The most monstrous and preposterous architectural sham that we have ever known'! In its construction no foundations were required for the great facades as these 'side walls' were hung off gigantic stirrups of steel. *The Builder* critic went on that it was 'a discredit to the generation that has erected it . . . one of the worst and most ludicrous failures we know of' [15].

Such a view, of course – although genuinely shared at the time – palls into insignificance today when one realises the bridge's huge general public popularity. Perhaps this is what was meant by the 19th century phrase 'romancing the stone'? Tower Bridge, with all its stylistic inconsistencies, is certainly an example of the continuing concoction of structural brilliance and architectural exuberance that was to blossom in England around the turn of the century – in this case based on the notion of a national gateway to the capital – when the rest of Europe was beginning to come to terms with the architectural opportunities of the new material.

There are few buildings in Britain which actually fall into the art nouveau category, many of which used iron in order to portray natural forms. The great exception is the work of Charles Rennie Mackintosh, particularly in the two stages of the development of the Glasgow School of Art (1896–1908) along Renfrew Street, Glasgow. In Mackintosh's building there was a close identification with iron as a material, the adoption of natural form metaphors and its structural importance. In the new Library wing the design of the high feature windows in particular indicates the architect's mature understanding of the potentiality of materials like iron. 'Shapes are always derived from the character of the materials', one writer remarked of Mackintosh's building. The famous curvilinear brackets beneath the great studio windows to the main Renfrew Street elevation also provide lateral bracing. Furthermore, they give lateral support to the window cleaner's ladders! Thus the brackets are given a role both as ornamental decoration and as a utilitarian one. In this they share a similar visual interest to that displayed by architects like Antoni Gaudi in Barcelona (Fig. 1.18), with the great swirling iron balcony decoration of the Casa Milà and the much more formal ornamental use of ironwork as it was used by Josef Maria Olbrich at the Artists' Colony in Darmstadt (1901–3). Here the material was converted into repetitive design motifs by local blacksmiths under the careful scrutiny of the architect.

For architects iron and steel offered the opportunity to develop a new means of expression that they largely thought of as a component-based trabeated form of construction and structural innovations like the Eiffel Tower which, as we have noted, had an open framework for wind resistance, provided inspiration both for new spatial compositions with filigree effects and much later for a concern with transparent and translucent building envelopes.

One of the first major experiments in this area was carried out by the young Bruno Taut in his so-called 'Monument of

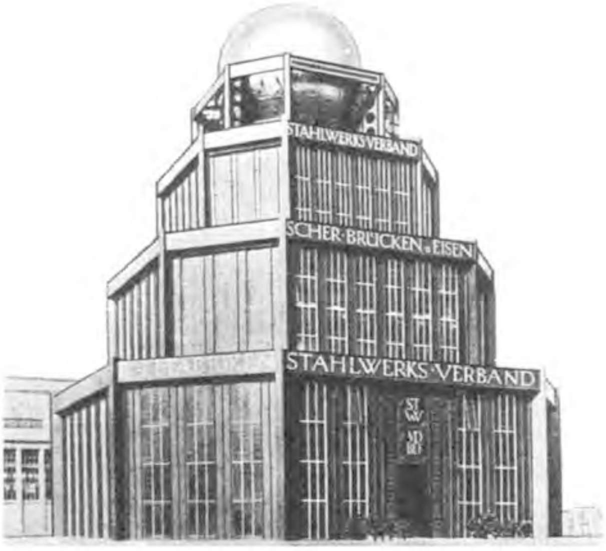


Fig. 1.27 *Steel Pavilion, Leipzig Fair 1913 (architect Bruno Taut).*

Iron' which was designed for the Träger-Verkaufskontor, Berlin in 1910, with its open freestanding metal framework straddling a small, almost classical, *tempieto*. A couple of years later Taut designed his memorable steel pavilion for the Stahlwerks Verband at the Leipzig Fair, 1913 (Fig. 1.27) which had a gold coloured sphere surmounting a steel framed octagonal pyramid with obvious echoes of J.M. Olbrich's Secession House, Vienna of 1896 whose own giant filigree domed structure was dubbed 'the golden cabbage'.

At around the same time the eminent architect/teacher Hans Poelzig also produced his own multi-purpose and monumental water tower site in Posen (now Wroclaw, Poland). This too had an elemental steel frame with huge open filigree columns in its interior. This structure was virtually contemporary with Peter Behrens' turbine hall for the AEG Company situated on the Huttenstrasse, Berlin, a three pin metal arched building which for many people is the first significant example of the new architecture (Figs 1.28 and 1.29).

This first phase of modern architecture saw many efforts to create a valid new means of structural expression and, contrary to the mythology that has built up over the years that it was an episode entirely dominated by white, smooth faced surfaces of reinforced concrete, many architects employed steel construction. Some mixed steel with brick, others with glass panels. Erich Mendelsohn designed his Rudolf Mosse Pavilion for the Cologne Press Show in 1928 in steel and glass and his more permanent Bexhill Pavilion in Sussex, won in competition with Serge Chermayeff, also had a steel frame designed by the London based Austrian engineer Felix Samuely. Arthur Korn's Fromm Rubber

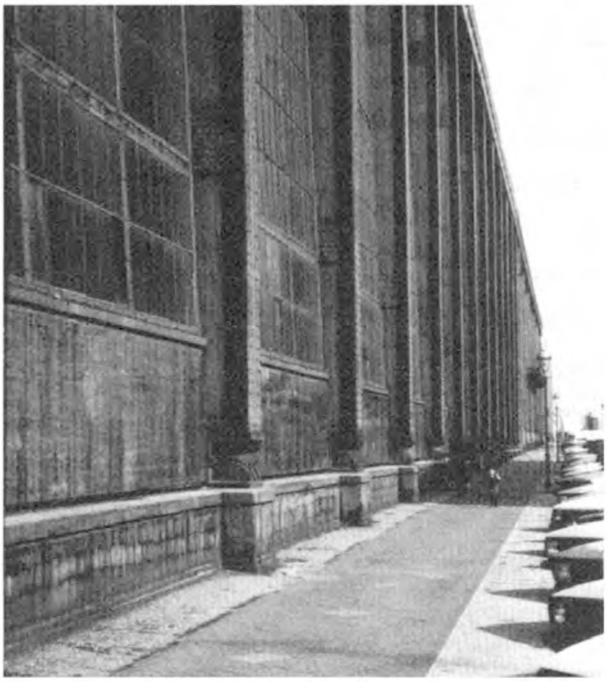


Fig. 1.28 *AEG Building, turbine factory, Berlin 1909. Facade showing vertical legs of portal frames (architect Peter Behrens).*

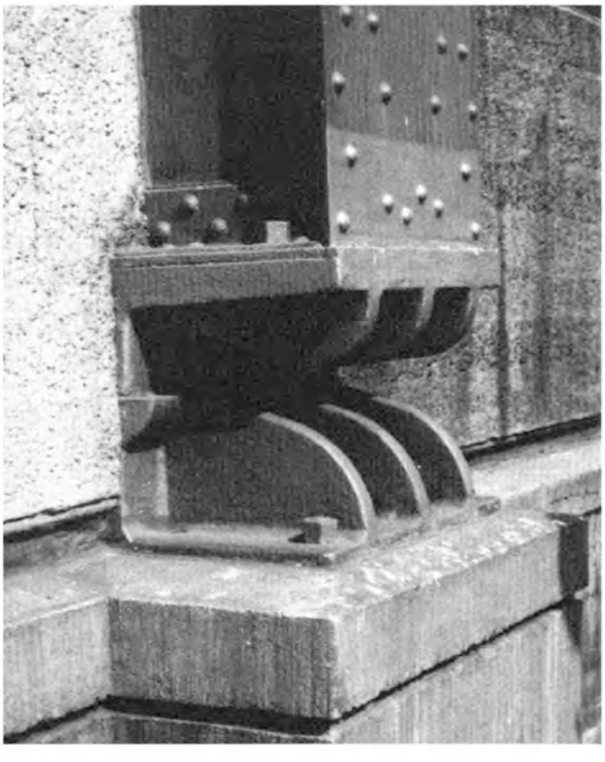


Fig. 1.29 *AEG Building, turbine factory, Berlin 1909. Detail view of base to portal frame.*

Factory of the early 1920s also had a steel frame. Rudolf Schindler, who emigrated to the west coast of the US from Austria in the early 1920s, summed up the contemporary feeling about steel and architecture as follows: 'Architectural forms symbolize the structural functions of the building material. The final stage of this development was the architectural solution of the steel skeleton: its framework is no longer a symbol. It has become form itself.' This 'functional' philosophy was at the root of the developments we call the 'Modern Movement' in architecture. It spread through its 'International Style' phase from 1929 to 1939 but lost its impetus in Europe in the postwar phase due to steel shortages and restriction on the use of the material in housing schemes, as the following chapter indicates.

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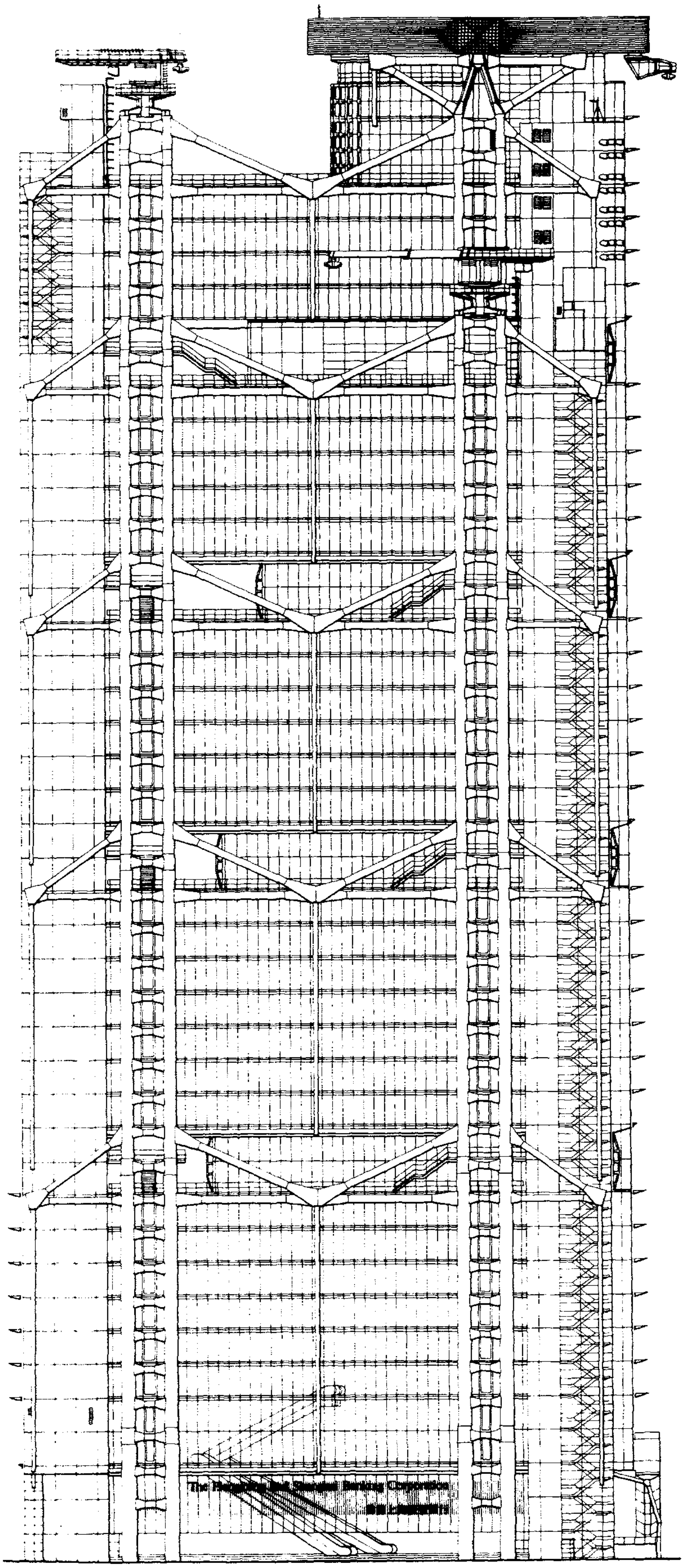


Elevation of Hongkong and Shanghai Bank 1986 (architects Foster Associates: engineers Ove Arup and Partners)

2

The 20th century

Dennis Sharp

2.1 INTRODUCTION

The last quarter of the 19th century saw a meteoric growth in the total world output in steel to around 28 million tonnes. The United States produced almost twice as much steel as Britain, with Germany nearer the US total with 8 million tonnes per year. However, British engineering experience in combination with this plentiful supply of iron and steel enabled the country to gain an unprecedented lead in areas such as shipbuilding. In the 1890s four-fifths of the world's new shipbuilding was in British hands; in 1913 her share was still more than three-fifths [1]. Between 1898 and 1899 some 98.8% of the ships launched were made of steel [2].

Urban life too greatly benefited from the new steels. From lamps, street lights, telephones and typewriters to the startling effects of the flickering projectors of the new cinematography, to the wide use of overground and underground railways the new world welcomed the industrialization and mechanization that steel had brought. It had arrived. Adolf Loos, a prophet of the new architecture from Vienna, soon dubbed the American plumber 'the quartermaster of culture' – at least that culture that was decisive for the modern world. The new machine age was fashioned in steel: the great airship hangars were some of the early symbols of the era.

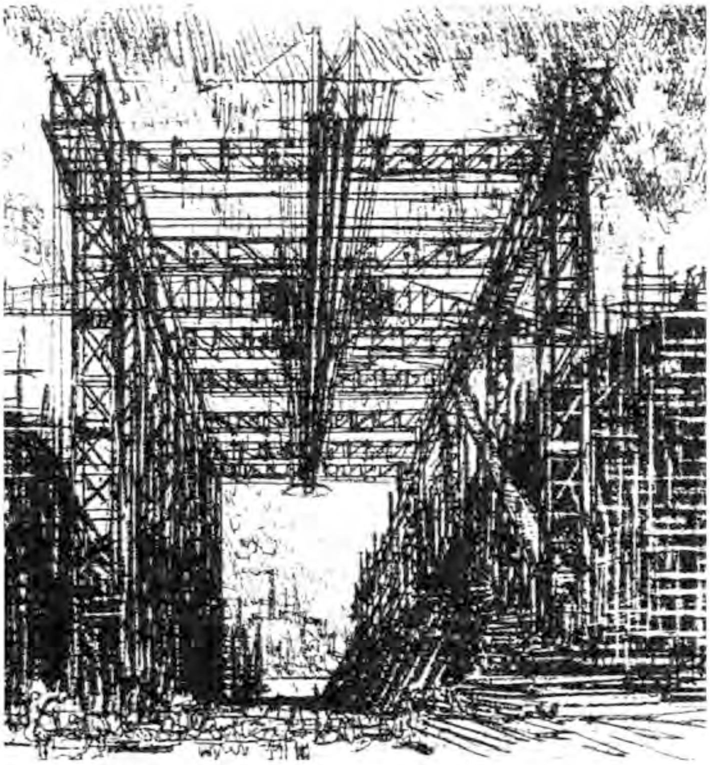


Fig. 2.1 *Pictures of war work by Joseph Pennell.*

Artists, writers, photographers and poets were creatively stimulated by the potentialities of the new age and its materials. Joseph Pennell and Frank Brangwyn recorded the excitement of steel armament manufacturing processes during the period of the First World War with their atmospheric and evocative pictures of war work in Britain and the USA (Fig. 2.1). Fernand Léger, the architect trained Parisian artist of the Purist Group, made a series of drawings and paintings of steel constructors (Fig. 2.2). Robert Delauney depicted the interpenetrating planes of Eiffel's tower in a succession of canvases. Carl Sandburg, the American poet and writer, saw the publication of his 'Smoke and Steel' in 1921. It included such verses as:

Oh, the sleeping slag from the mountains, the slag-
heavy pig-iron will go down many roads.
Men will stab and shoot with it, and make butter and
tunnel rivers, and mow hay in swaths, and slit
hogs and skin beeves, and steer airplanes across
North America, Europe, Asia, round the world.
Hacked from a hard rock country, broken and baked
in mills and smelters, the rusty dust waits
Till the clean hard weave of its atoms cripples and
blunts the drills chewing a hole in it.
The steel of its plinths and flanges is reckoned, O, God,
in one-millionth of an inch. [3]

But above all iron and steel made the skyscraper possible, heralding a new architectural era.

What for some men was seen as poetry to others became a structural and constructional challenge. Having already seen how the use and employment of the new framing materials had precipitated a high building boom in great centres such as Chicago and New York, smaller towns were to share in the new building art throughout the United States. Among the many pioneering advocates of the efficient systematic use of steel was Alfred C. Bossom (later, Lord Bossom of

Maidstone and one of Churchill's aides on postwar prefabrication) who had migrated, temporarily as it turned out, to the USA as a young, promising architect to work on the steel towns designs in and around Pittsburgh for Andrew Carnegie. Bossom did well in the States, marrying advantageously into a banking family. In towns like Galveston, Houston and Buffalo his new tall bank buildings (often the tallest structures) demonstrated the architect's growing organizational skill in producing fast-track, efficient and economic tall buildings (Fig. 2.3). After his return to England Bossom published his own poetic, but essentially practical, eulogy to the new universal building type, the skyscraper, bearing the romantic title *Building to the Skies* (1934). In this book he recorded the sense of adventure he shared with the pioneers of the high building art and emphasized the difference in attitude between North American and British practice. When he was building his 23-storey Liberty Bank in Buffalo, a question arose as to the strength of its steel skeleton. 'It was above the New York City standard of strength, but, oddly enough, below that called for by the local building laws', he wrote, 'I had little difficulty in persuading the authorities that their rules . . . were obsolete. I was not only allowed to build to my own plans, but was virtually invited to rewrite the structural steel building code for the entire city . . . In Britain . . . I should probably have been run in by the police as a public danger.' It was the immense adaptability of the skyscraper 'by virtue of the simplicity of its steel framework' and its concentration of functions and services that Bossom so admired in the 1930s [4]. Structural steel made the skyscraper possible for a number of practical reasons, but it must be remembered too that it had a profound effect on building economics. The cost of a steel frame ranged from 8% to 15% of total building costs in the 1920s [5].

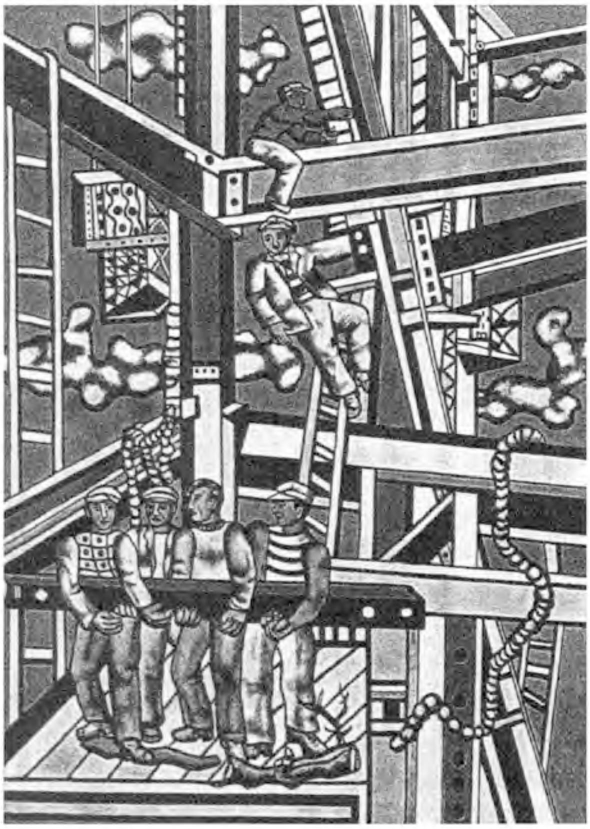


Fig. 2.2 *Les Constructeurs, by Fernand Léger.*

Fig. 2.3 *Liberty Bank, Buffalo, NY mid-1920s (architect Alfred Bossom).*

Fig. 2.4 *Ritz Hotel, Piccadilly, London 1903–6 (architects Mewès and Davis).*

In London in 1905 one of the first steel framed buildings (probably the first in the capital) was the Ritz Hotel, Piccadilly (Fig. 2.4), by Mewès and Davis, although the frame itself was not expressed externally, as the reduction of thickness of external walls was not permitted until 1909 in London.

Steel soon became the commonest structural material in Britain. It took on many shapes in its manufactured states but its main form was as a constructional framework with supports laid out on a grid pattern with trussed or with flat roofs. During the interwar period steel framed single storey factories and warehouses consisting of rows of supporting steel columns carrying sawtooth north light roofs or simply open trussed pitched roofs were to be found along many of the new arterial highways. Gradually, welded portal frames were introduced and as the new high tensile steels were made available longer spans, and north–south monitor roof lights, became possible.

Modern architecture entered British life largely by the backdoor. It was an expatriate movement. In the late 1920s the Russian Berthold Lubetkin arrived from Paris to work in Hampstead. Soon afterwards the German émigrés arrived, fleeing Hitler's purges. Gropius came with his wife Ilse directly from Rome, where he had been giving a paper on theatre design; Erich Mendelsohn arrived with his wife, having fled Berlin in haste. He took up practice with Chermayeff, a Harrow-educated Englishman originally from the Caucasus. Later Breuer, Frankel and Korn arrived (Fig. 2.5). I mention this for one reason only – they were all men committed to the architecture of steel and glass that I mentioned earlier when referring to Otto Wagner. They worked in close collaboration with engineers like Arup and Samuely who knew German but, importantly, were well acquainted with the new techniques of building associated with the modern architectural movement. One of the most successful buildings to emerge from this influx of foreign architects and engineers was the De La Warr Pavilion (Fig. 2.6) won in competition by Mendelsohn and Chermayeff in 1934 for the exceedingly dull geriatric seaside resort of Bexhill-on-Sea. It was the first all welded steel construction building in the UK and part of the plastic design revolution of the 1930s.

The structure was calculated by Felix Samuely, who had known Mendelsohn in Berlin and who, on the strength of this collaboration set up his practice with Cyril Helsby, a New Zealander; Conrad Hamann joined them a little later. Writing in 1935 Samuely remarked that welding had been adopted for economical reasons 'but it also had the advantage of permitting the fabrication of such structural units which left unaltered the lines and overall dimensions of sections desired by the architects' [6]. The building was described at the time as 'a welded steel skeleton with curtain walls of reinforced concrete'. It was meticulously detailed and at times daringly complicated from a structural point of view as the great north staircase cantilever still testifies today. It remains the greatest German building in Britain and one of modern architecture's finest achievements anywhere.

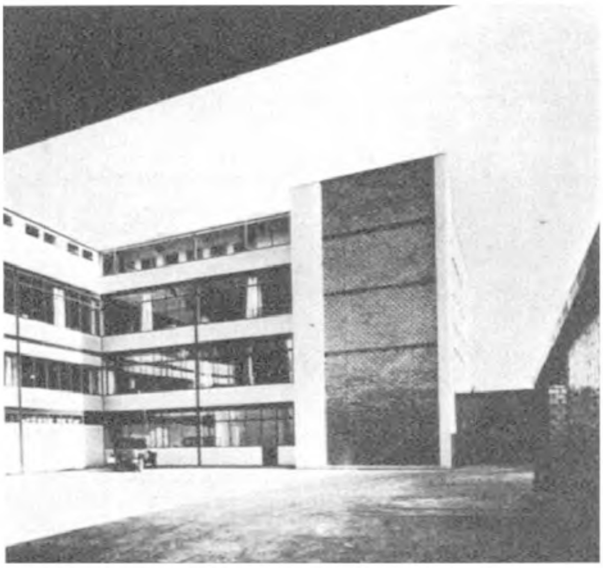


Fig. 2.5 *Fromm Contraceptives Factory, Berlin, 1928–30 (architects Artur Korn and Sigfried Weitzmann).*

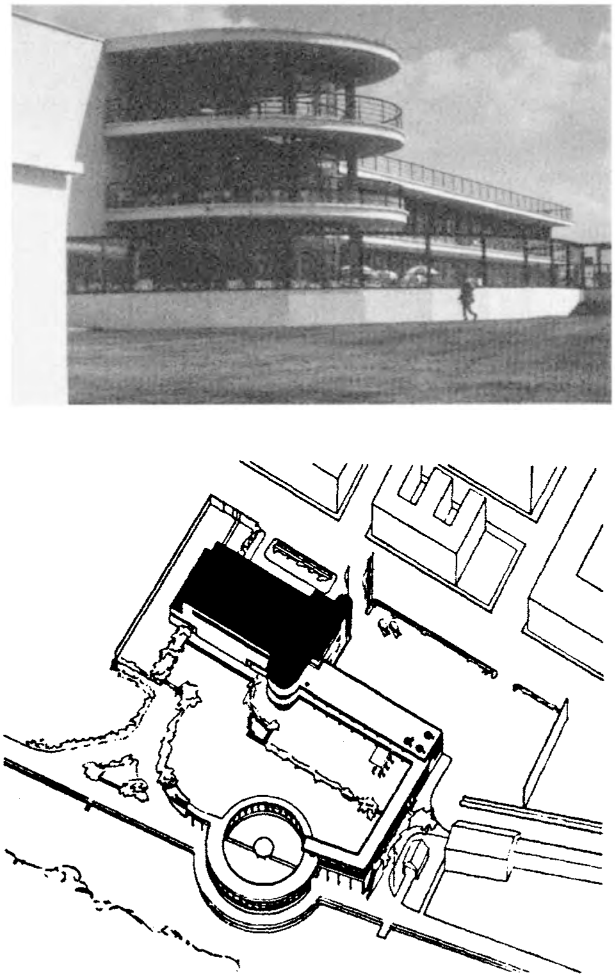


Fig. 2.6 *De la Warr Pavilion, Bexhill-on-Sea 1933–35 (architects Mendelsohn and Chermayeff: engineer Felix Samuely).*

In the postwar period, particularly for industrial and factory buildings, welded tubular construction was used to create even larger spans, give economy in the use of material, accelerate erection, and give added ability to support simple roof coverings. Such developments were of immense importance in the development of new prefabrication techniques. Those designers who were interested in standardization and industrialized components in the years immediately after the Second World War built on this earlier knowledge to forge ahead of other European countries [7].

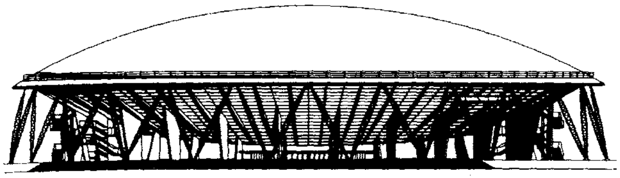
During the war years in Britain the Government had issued an order to prohibit the use of steel for building except under licence by private merchants (contractors); steel licences were already required for the general sale and purchase of steel [8]. Few public, and even fewer private buildings were produced anywhere in the world during the war years. Automation progressed considerably, as did the growing awareness of the advantages of lighter weight metals and plastics. These too were to be absorbed into the programme for industrialized buildings that got underway in the early 1950s. All this activity was supported by a growing awareness internationally of a need for a philosophy of architecture and for new principles of design.

In the immediate postwar period the tenets of the Modern Movement in architecture's white cubic concrete phase were even more closely adhered to than in the 1930s. However, there was also an awareness of the potential of transportable buildings and lightweight components manufacturing. These technologies were transferred from the wartime aeronautical and destruction industries into the peacetime needs of rebuilding industry and society. The Portal Committee in Britain provided the Government of the day with essential information on the applicability of prefabrication closely following American practice [9].

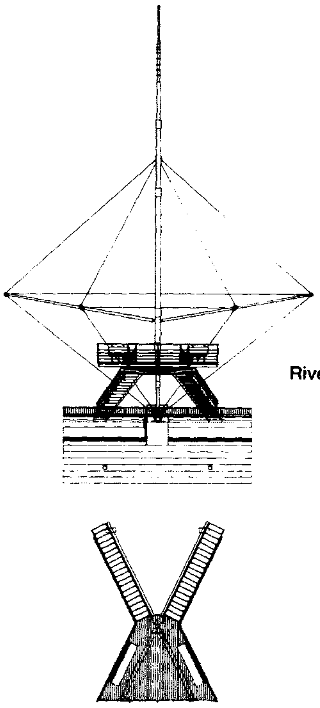
All of this may be seen as part of that formal tradition in architecture and with a firm place in the intellectual apparatus of postwar design theory. In Britain too there was also a quasi-intellectual group of Neo-Georgians whose influence extended well into the public housing programmes whose strong lobbying after the war ensured their preferences were absorbed into postwar reconstruction proposals. Another group, The Empiricists (if one dares to use that term to describe the socially conscious reformers whose legacy derives from Robert Owen via Henry George and Ebenezer Howard) seized the new opportunities offered by an optimistic government to create New Towns and to revert to the informal picturesque tradition and vernacular materials albeit to see their designs set in prairie-like environments. In such places steel as a building material only played a small part in design considerations as the chief component for the prefabricated schools put up in Hertfordshire and Essex in places like Hatfield, Stevenage, Hemel Hempstead and Basildon.

One event certainly stands out as a major statement on architecture: the 1951 Festival of Britain (Fig. 2.7), an experiment in aesthetic values as well as in materials, technologies and supportive national psychology. However it did, at the time, appear somewhat trivial. The completion of the solid Royal Festival Hall at the same time allowed a restatement of architectural values to be made at the Festival. It was a strong building whose imagery earned the title of the New Empiricism.

The Festival Hall was somewhat despised by those who recognized the directness of Mies van der Rohe's cold steely aesthetic. It was seen as relevant and appropriate to the postwar age. Thus the emphasis swung back to Chicago. The city underwent a Teutonic renaissance and Mies, with Holabird and Root and others, erected a series of minimalist structures in steel (with brick panels) between 1940 and 1953 for the Illinois Institute of Technology campus (Fig. 2.8). These buildings were based on a standard bay grid of 24 ft by 24 ft × 12 ft high and expressed externally by an exposed

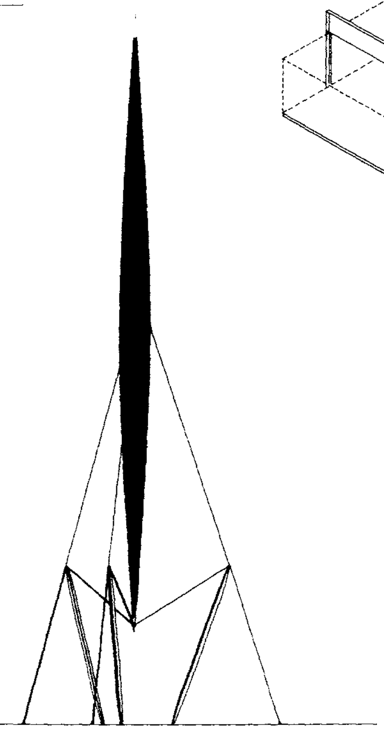


Dome of Discovery (architect Ralph Tubbs)



Plan

Viewing platforms (architects Eric Brown and Peter Chamberlin)



The Skylon (architects Powell and Moya)

Fig. 2.7 *South Bank designs for various buildings, Festival of Britain, London 1951.*

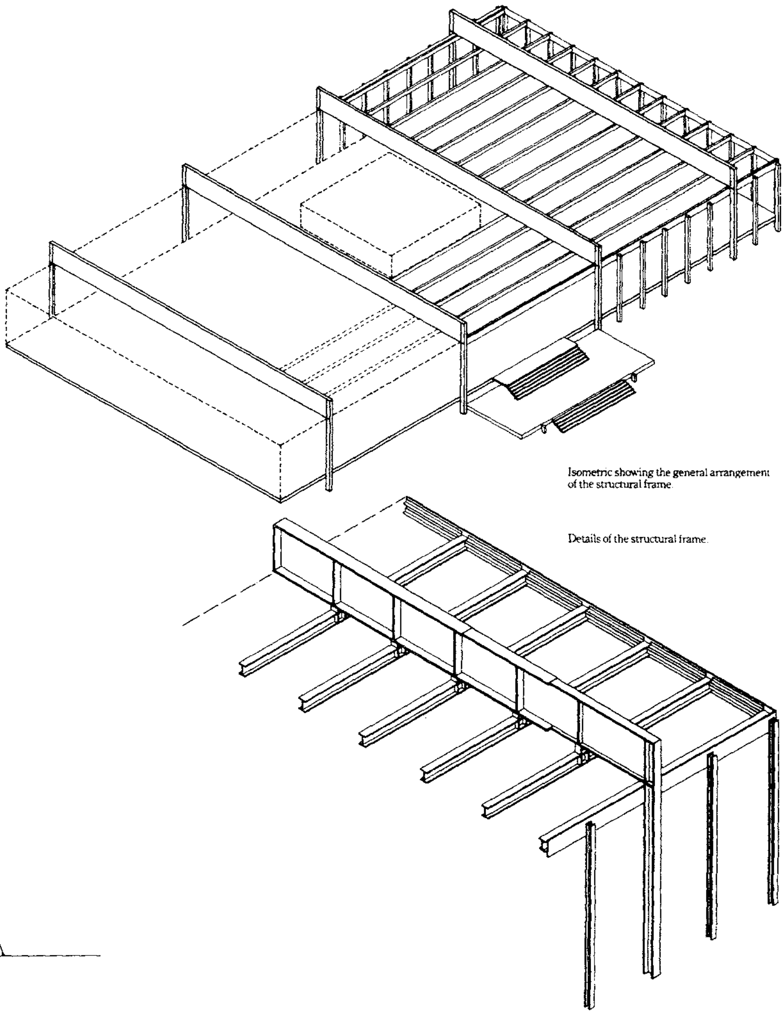


Fig. 2.8 *Alumni Memorial Hall, IIT Campus, Chicago 1945–46 (architect Mies van der Rohe). Courtesy Alan Ogg:* Architecture in Steel.

Fig. 2.9 *Lake Shore Drive apartments, Chicago 1948–51 (architect Mies van der Rohe).*

steel structure. H.P. Berlage's structural honesty argument was taken literally. Mies's structural elements, at IIT, were as clear in their architectural intentions as those admired by Goethe at Strasbourg Cathedral. They had been conceived, as his disciple Philip Johnson wrote, 'in terms of steel channels and angles, I-beams and H-columns, just as medieval design is conceived in terms of stone vaults and buttresses' [10]. Mies's Lake Shore Drive apartments were built at the same time, with planted I-beams to act as stiffeners on the outside as well as columnar devices (Fig. 2.9). The Mannheim Theatre Project, the uniquely beautiful Farnsworth House (Fig. 2.10), the Berlin National Gallery and a succession of well disciplined, if somewhat plagiarized, examples of the Miesian mode followed. The best examples include the Smithson's school at Hunstanton (1954), Eiermann's fine German Pavilion at the Brussels Exposition, 1958 (Fig. 2.11), and John Winter's 'Cor-Ten' house in London's Hampstead (see section 36.2.1). As his legatees soon discovered, a Mies van der Rohe design exhibited many concerns about unity, organic principles, order and the *Zeitgeist* but also, as he reminded an IIT audience: 'everything depends on how we use a material, not on the material itself' [11]. The Smithson's school was important too in its innovative use of 9 inch RSJs as H frames frames welded on site into beams and stanchions, the whole based on the use of plastic theory as a stressing discipline (Fig. 2.12).

Steel may well have worked well for Mies van der Rohe as an appropriate material for apartment construction in Chicago and Detroit. It was not so readily available or acceptable in Europe, or in Britain in the postwar years. The Smithson's school was a notable exception [12]. Concrete construction had largely taken over. Steel was retained for single storey buildings, farms and factories or large complex public buildings dependent on composite construction. It was in the area of single storey lightweight structures that it was to make its most telling advances in the hands of revolutionary designers like Buckminster Fuller, Jean Prouvé and Frei Otto. Before examining their contribution it is useful to examine the influential climate of opinion that grew up as part of modern architectural design theory.

2.2 MECHANIZATION AND NATURE

In his seminal work, *Mechanization takes Command* (New York, 1948) [13], Sigfried Giedion referred to the growth of mechanization as 'a contribution to anonymous history'. In this extensive study he looked at not only a hidden tradition but also at something rather more specific: a collection of ideas that when brought together would show that a fundamental split, in 'our period', as he called it, between thought and feeling came about by mechanization. Whereas his earlier polemical work [14] *Space, Time and Architecture* (1941) attempted to show how a new phase of engineering and architecture had emerged at the end of the 19th century, *Mechanization takes Command* opened up a much larger field of enquiry. Mechanization was viewed from a human standpoint and how far 'mechanization corresponds with and to what extent it contradicts the unalterable laws of human nature' was the theme. He saw questions about the *limits* of mechanization (as far as the human aspect was concerned) as fundamental tenets which should under no circumstances be disregarded. Its subtle effects and influences made it difficult to isolate, thus he dubbed his study an 'anonymous history'. Giedion rightly felt that it was a neglected and under-researched area.

Mechanization has affected all aspects of life and has had an impact on most designed objects, including cities, factories, houses and furniture. His concern was that the reader should understand the tools of mechanization but not merely in a technical sense. With such an understanding we can then begin to assess the wider significance of the mechanized culture into which Giedion's own pioneer generation was born.

Mechanization, as a phenomenon, is marked in its beginning by the elimination of the 'application of handicraft'. This process had begun in the United States during the second half of the last century. This 'assembly line' displays 'the symptom of full mechanization' in Giedion's view. Further, he argued, the problems of mechanization have a typological aspect and that, 'the history of styles follows its theme along a horizontal direction; the history of types along a vertical one'. Such a viewpoint remains valid today and was one recognized by Nikolaus Pevsner in his *A History of Building Types* (1976) [15] where he argued that buildings 'have a use before they have a style'. Also, he wrote that it is pointless to evaluate the second without understanding the first, an attitude that was adopted in the work of the British architectural historian the late Reyner Banham in his book *The Architecture of the Well-tempered Environment* [16]. Banham examined mechanization in a building services 'performance' context. He adopted a somewhat different method of analysis to Giedion, looking at the efficiency and purpose of a work of architecture in relation to its wider environmental considerations, to structure, to form and cultural conditioning factors as well as a technological context.

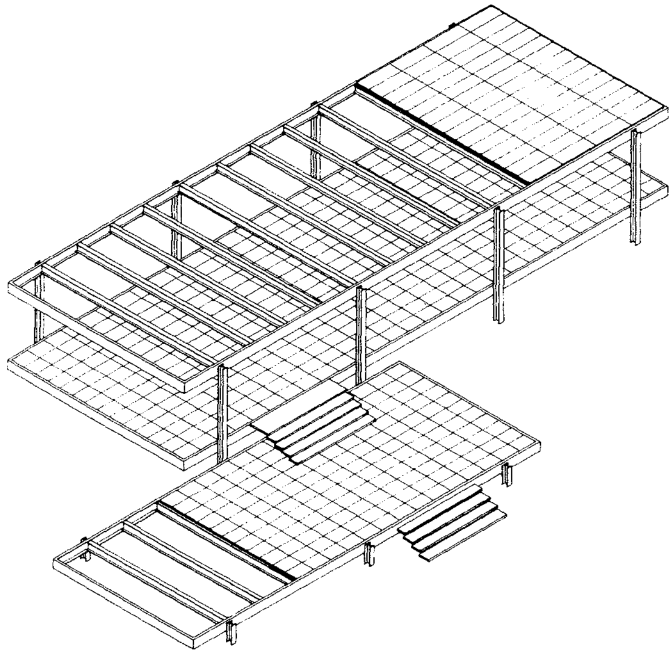


Fig. 2.10 *Farnsworth House, Illinois (diagram of frame) 1946–49 (architect Mies van der Rohe). Courtesy Alan Ogg:* Architecture in Steel.

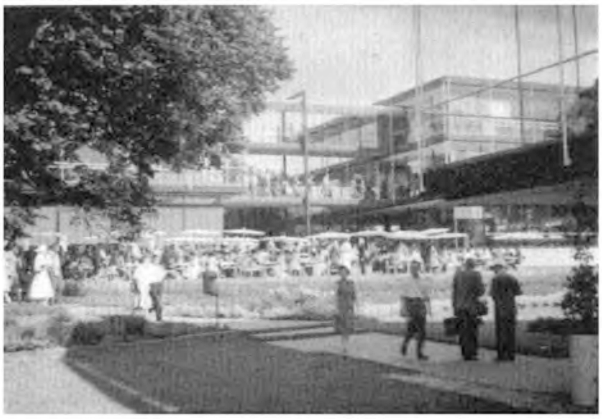


Fig. 2.11 *German Pavilion, Brussels Exposition 1958 (architect Egon Eiermann).*

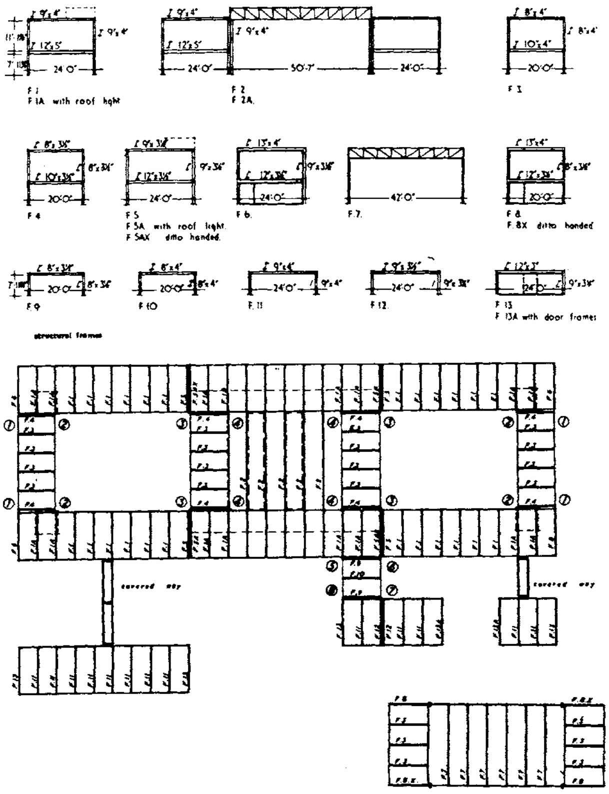


Fig. 2.12 *Hunstanton School, Norfolk 1950–54, diagram of welded frame (architect Alison and Peter Smithson: engineers Ove Arup and Partners).*

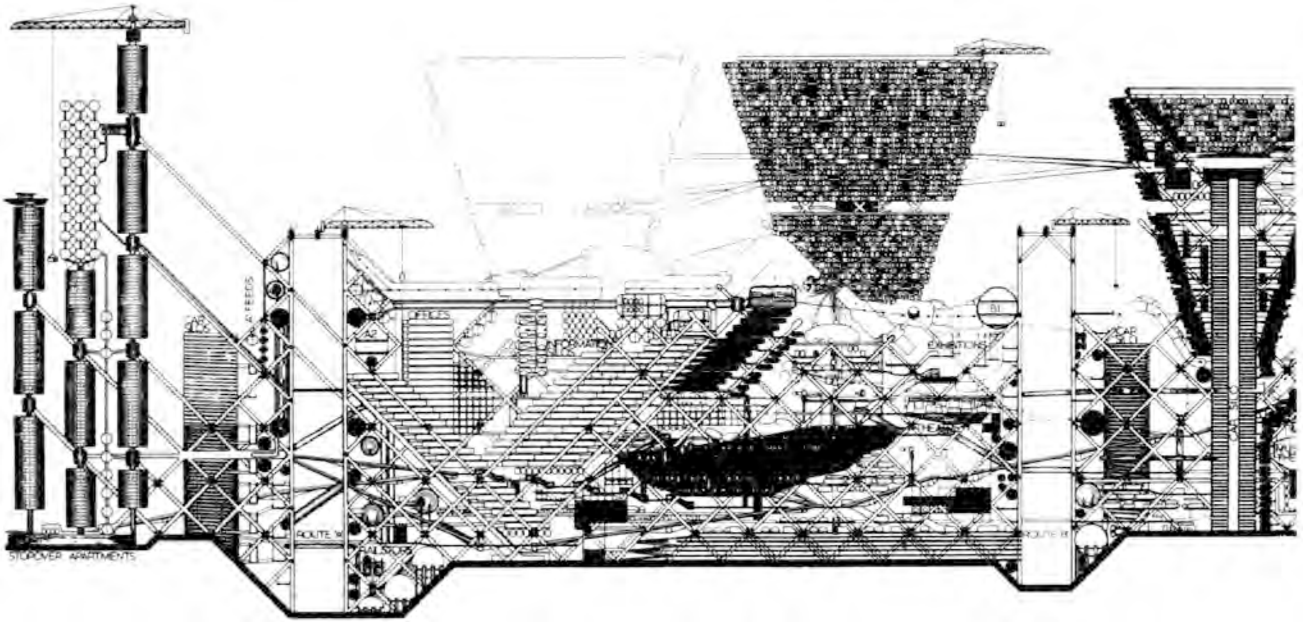


Fig. 2.13 *Plug-in City, 1967 (Archigram).*

Surely it is from these deeply rooted attitudes to cultural and architectural history that the current 'Hi-Tech' architectural attitudes have gained a renewed effectiveness and credibility? Whilst this term 'Hi-Tech' itself is a meaningless and only a currently fashionable stylistic label, the astonishing persistence of this attitude – perhaps one might call it a 'mechanical' or systemic industrially designed architecture – is remarkable. Metal construction has always provided the framework for this approach, from Paxton to Grimshaw. Today it is no longer anonymous but systematic, rationalized high profile design suitable for the fast-track, economic one-off structures required by today's clients.

There are many buildings and structures in the world which owe much to the persistence of this engineering approach and its aesthetic formulation into a 'style' has been one of the most welcome and surprising developments of the past two decades. It has swung the emphasis away from concrete and its attendant solidity.

Recently, architecture has gone through periods of formalism, historicism, so-called 'Post-Modernism', Beaux-Arts and Classical Revivalism, even what the French term 'graphic terrorism', all under the general term of pluralism in current design. Pastiche, and historically referenced remodelling, have dated far quicker than anyone

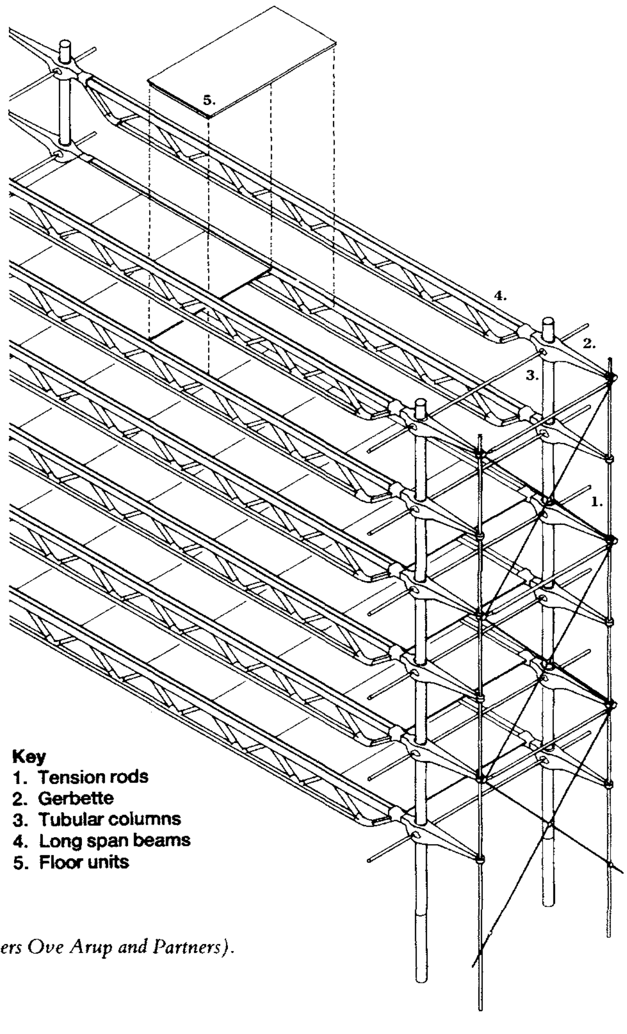


Fig. 2.14 *Pompidou Centre, Paris, 1971–7 (architects Piano and Rogers: engineers Ove Arup and Partners). Courtesy Alan Ogg:* Architecture in Steel.

expected and seem to be as empty as many had predicted. However, those architects who have consistently pursued a line that accepted rational engineering principles and the logical use of structural systems in steel, concrete and glass have created a potent new vocabulary of forms. In some cases techniques from industry have been borrowed and materials have been employed in a way that is entirely consistent with a modern architecture freed from current stylistic clichés. It would perhaps be absurd to suggest that these trends dropped out of the blue. Rather, they have evolved in parallel with major technological advances in the fields of mechanization, engineering and industrial design aided, and indeed only made possible, by the many new computer techniques available to its designers. Whilst many of the architects and designers responsible for the new metal architecture may well view themselves as direct inheritors of the 19th century engineering legacy and of such innovations as dirigibles, lightweight bridges and aircraft construction, there is little doubt that the new techniques have played their part in enabling entirely new structural types to be calculated. This is true for complex roofs like the great concrete sails of the Sydney Opera House as well as for complicated lightweight tensile structures as developed by Frei Otto and others. Their historic pedigrees, however, are unquestionable.

Otto, in the foreword to his first volume of *Tensile Structures* (1967) recorded that: 'The primary impulse for engineering projects employing tensile structures was provided in the past century by Roebling and his suspension bridges followed by those of Ammann, Leonhardt, Steinman and Strauss'. But whereas these pioneers provided the

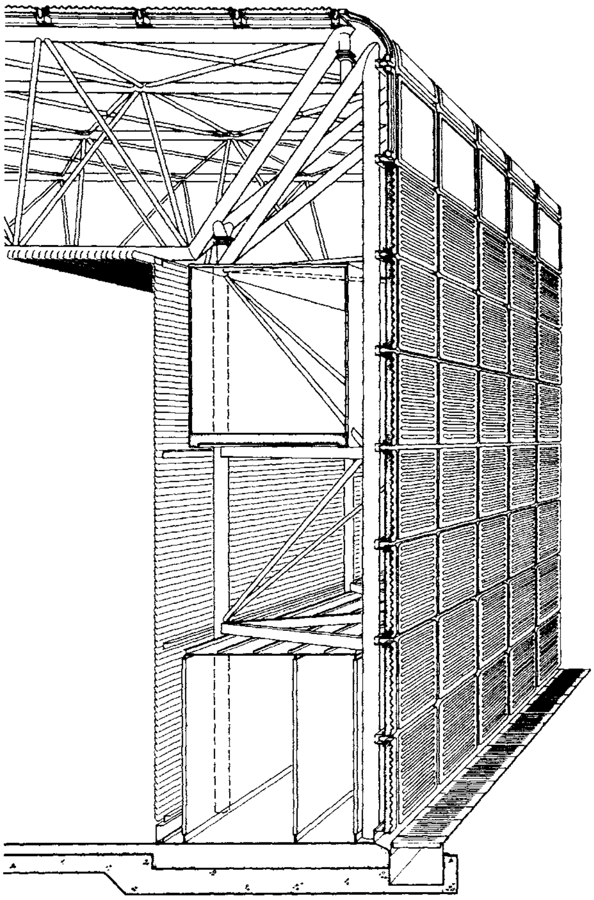


Fig. 2.15 *Roof and wall frames Sainsbury Arts Centre, Norwich, 1974–8 (architects Foster Associates: engineers Anthony Hunt Associates). Courtesy Alan Ogg:* Architecture in Steel.

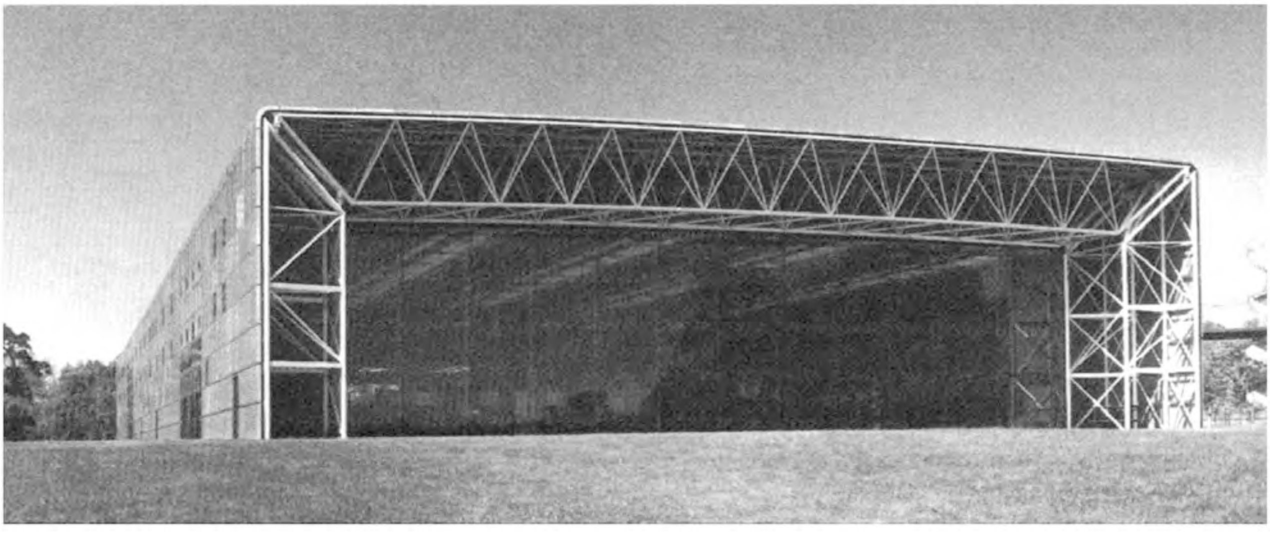


Fig. 2.16 *Gallery end, Sainsbury Arts Centre, 1974–8 (architects Foster Associates: engineers Anthony Hunt Associates).*

fundamental theories the new techniques, new forms and new expressions required for such structures were nearly all developed by later designers. Indeed, in the area of lightweight structures greater possibilities of flexibility occurred in the late 1950s when aerodynamic shapes and light, transportable structural elements were adopted to form a variety of new structural forms and coverings.

In the early 1960s the German architect Rudolph Doernach developed a deformed metal skin into a single curvature structure and Buckminster Fuller continued to develop his extremely lightweight domes of pneumatic sandwich panels. At about the same time new types of air and bubble structures were also being developed.

Parallel to these new engineering inventions ran a series of theoretical, polemical ideas about architecture and the 'spatial city'. Developed by architects, teachers and idealists such as the London-based 'Archigram' group (Fig. 2.13), Otto and the Paris-based Hungarian designer Yona Friedman. A graphic portrayal of a new architecture was depicted requiring unusual methods of engineering and architectural assemblage. These ideas were without issue at the time, but by the mid-1970s buildings like the Pompidou Centre on the Place Beaubourg, Paris, erected to a design won internationally by Renzo Piano and Richard Rogers (Fig. 2.14), bore a close resemblance to the visionary Archigram work and the work of Eames, Ehrenkrantz, Fuller, Wachsmann and to some extent Prouvé. In this kind of architecture the advantages of modern metals were explored, as were the expressive and technical advantages of separating structural supports from services. Foster's Faber building, with its totally transparent facade and mechanized interior, at Ipswich (1975) and the Sainsbury Arts Centre (1978) (Figs 2.15 and 2.16), an industrial shed at University of East Anglia, Norwich, also by Foster, as well as some of the early work of Farrell and Grimshaw were also part of the genre. In such projects as Cesar Pelli's large 'Blue Whale' design store in Los Angeles and the series of industrial capsule projects by Japanese architects such as Kisho Kurokawa and other 'Metabolists' the rapid extension of these experimental ideas took root internationally.

Gradually, these designs and the innovations they represent have led to a whole new line of rational, Hi-Tech, steel framed and finished buildings. British architects and engineers, acknowledging their obvious debt to the pioneering work of 19th century engineers as well as to the anonymous designers of airship hangars and aircraft now clearly lead the world with buildings like 'Lloyds' and 'Inmos', Gwent, by Rogers, Foster's Renault Centre, Swindon and the Hongkong and Shanghai Bank with its great 'coathanger' structure. In Australia, too, with the experience and knowledge of engineers from Arup's working in close collaboration with firms like Cox, Richardson and Taylor, the steel tradition is enthusiastically continued [18]. But it is not just a matter of good, even smart, fashionable, design that expresses technological excitement in the use of materials that have lain dormant for far too long. It provides speedy construction, on and off site, prefabrication and assembly, economy of detailing, finer tolerances and good value for the client.

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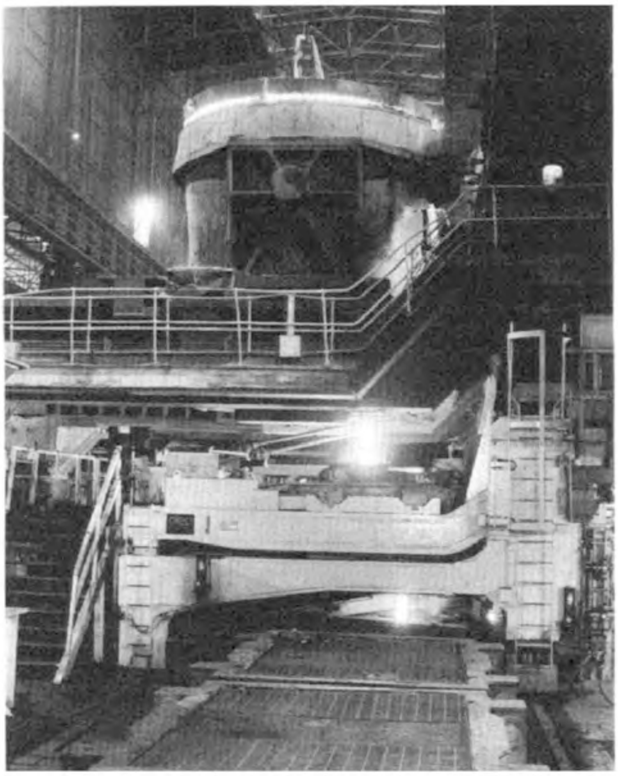
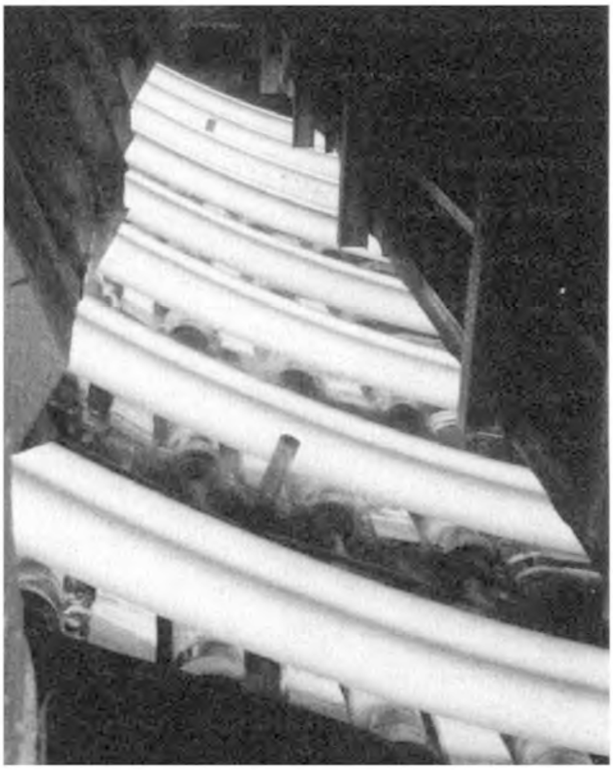
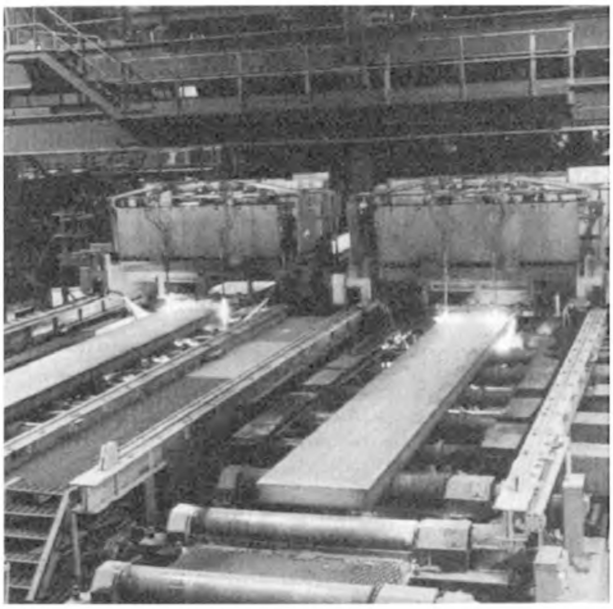
Steel production at British Steel, Redcar, UK.

Part Two

Materials





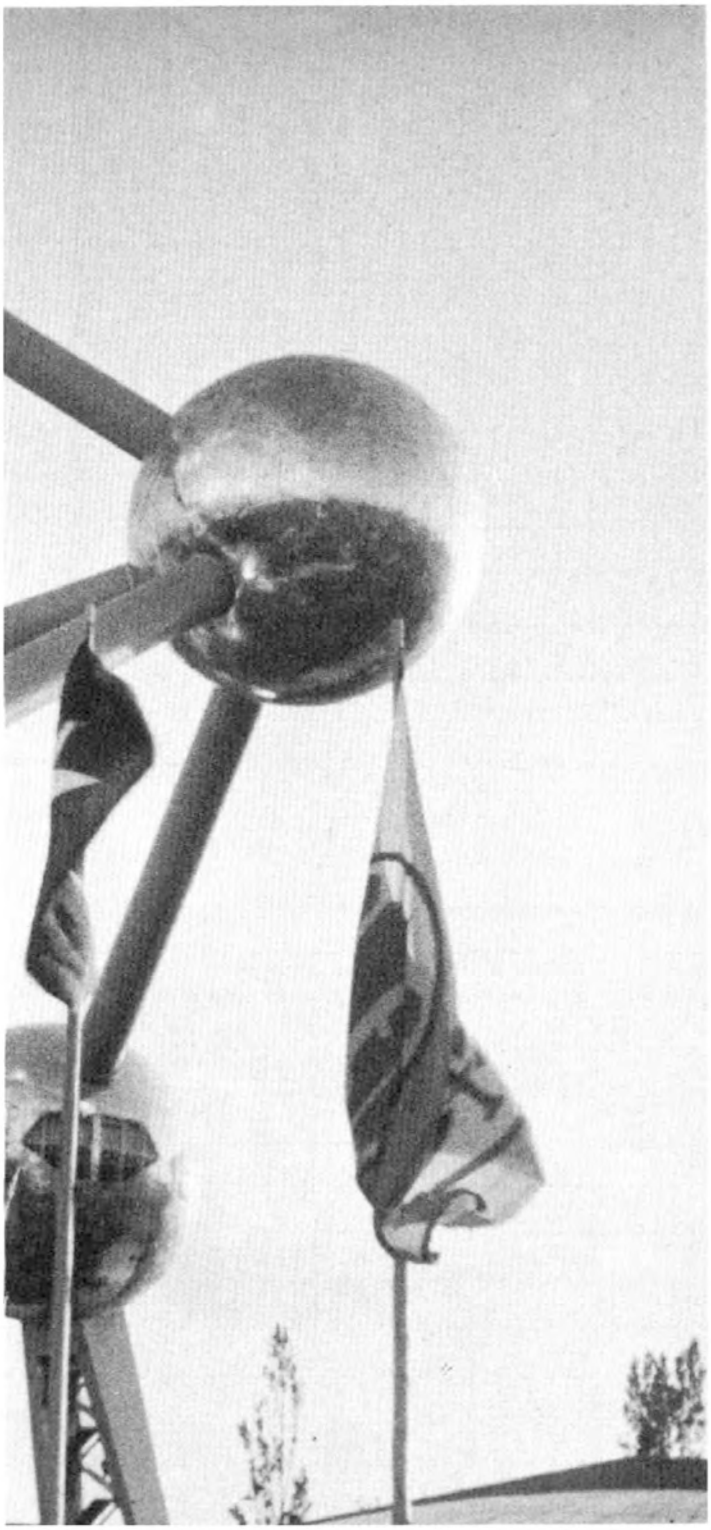


Symbolic molecule of iron. The Atomium, Brussels 1958 (architects A. and J. Polak: engineer A. Waterheys).

3

Properties of steel

W. D. Biggs



3.1 INTRODUCTION

Steel is essentially an alloy of iron and carbon but, despite this apparent simplicity, it is one of the more complex and interesting of all materials. In this chapter the manufacturing process is described briefly. This will enable steel to be distinguished from its close relatives – wrought iron, cast iron and cast steel – and also explain some terms found in specifications. Note that the descriptions are based upon traditional steelmaking practice – nowadays there are many variations. The chemistry, however, remains the same.

Like all metals iron is extracted from naturally occurring ores. These are complex chemical compounds but, for simplicity, it can be assumed that the basic source material is iron oxide (FeO) even though these ores have long since been worked out. Historically iron was late upon the scene – this was largely due to the high temperatures needed (c. 1600°C or 3000°F) to reduce the oxide to the metal. A forced air blast (e.g. a blacksmith's bellows) solved this and the addition of a reducing agent (carbon) achieved the reaction

$$\mathrm{FeO + C \rightarrow Fe + CO}$$

the carbon monoxide gas being released into the air. This first reaction produces *pig iron*. This contains a considerable amount of carbon which exists in the form of the hard, brittle carbide of iron (Fe_3C) and pig iron is only useful for further processing.

By remelting the pig, sometimes with scrap, and by controlled oxidation, again using an air blast, the carbon content is reduced to between 2.4% and 4.0%. This is *cast iron* which, as its name implies, is cast directly into shape in sand or metal moulds. Because of its high fluidity at iron-making temperatures it produces a sharp impression of the mould, and for many purposes no further machining is required. Depending on the composition the carbon can now exist in two different forms – as graphite (grey cast iron) or as iron carbide (white cast iron). Both impart brittleness to the material, although this can be ameliorated by reheating white cast iron to produce *malleable* iron. Its use in structural engineering is therefore limited – manhole covers, pipes etc. Its earlier widespread use for rainwater goods has now largely given way to polymeric materials. Nonetheless it was the predominant structural material in the 19th century and will be found as beams and columns in many rehabilitation and refurbishment projects. For all practical purposes it should be regarded as unweldable and should be handled with great care.

Steelmaking requires even closer control of the oxidation process, since it is now necessary to reduce the carbon content to rather less than 1%, indeed to around 0.2% for most structural steels. This is achieved in one of two ways: by remelting a charge of pig, possibly with scrap iron and steel, in a large open furnace and using relatively pure iron oxide (open hearth process) or by transferring a molten charge into a converter and blowing air (nowadays often oxygen) through the melt (Bessemer or converter process). In order to maintain the reaction a considerable excess of oxygen must be added and the melt is sampled periodically to check the carbon content. When the desired value is reached the reaction is stopped by the addition of elements which 'fix' the surplus oxygen as oxides. After a period of resting, these rise to the surface and may be skimmed off as slag. The elements used for this are generally manganese and silicon, and steels treated in this way are known as killed steels. The addition of manganese is important for another reason. One of the commonest – and most deleterious – impurities in steel is sulphur, originating from the ore or the coke. It causes a defect known as hot shortness in which the steel cracks disastrously and irremediably if it is subjected to any stresses (including cooling stresses) whilst hot. Apart from any other beneficial effects, manganese neutralizes this and specifications often require a minimum content of manganese even in the most pedestrian of steels.

Not all steels are treated in this way, however. Some steels are poured into moulds without 'killing' – in this case the carbon/oxygen reaction continues in the mould and a line of blowholes (the result of carbon monoxide formation) appears just below the outer skin. These are rimming steels and are quite acceptable for some purposes such as steel plate, sheet and strip according to BS 1449 [1], since the rolling needed to produce these products closes up the blowholes and a fully coherent product emerges.

In between killed and rimming steels lie the so-called balanced steels. These contain just enough deoxidizer to suppress the formation of blowholes but are not fully 'killed': BS 4449 permits these to be used for reinforcement bars [2].

In the traditional manufacturing process, steel is cast into ingots which are then subjected to further processing by forging or rolling to produce engineering sections such as angles, I-beams, plate, sheet etc. Some engineering components are, however, cast directly to shape – *cast steel*. The production process is not significantly different but cast steels, in general, contain a higher carbon content than wrought steels of equivalent properties, and this has some consequences if welding is to be used.

Continuous casting (concast) is a rather different process; it is a recent development which combines several of the operations associated with rolled steel products. This, together with other advances such as vacuum degassing, has led to considerable improvements in efficiency and quality.

The traditional terminology for the different types of steel is far from precise – steels with up to, say, 0.3% carbon are described as mild steels, from 0.3% to about 0.6% carbon as medium carbon steels (or often simply carbon steels) and thereafter as high carbon steels. If alloying elements are added (see section 3.5 below) they then become alloy steels.

Wrought iron is a variant of the basic material. Traditionally this was produced by 'puddling', in which pig iron is remelted and oxidized until the carbon content is reduced to about 0.05% and allowed to cool until it is a pasty mass. This is then removed from the furnace and hammered or rolled into bars. The impurities, mostly manganese sulphides, are stretched into longitudinal threads giving wrought iron its characteristic fibrous texture. Although not much is used now except for decorative purposes, wrought iron, with its excellent ductility and toughness and good resistance to corrosion, was the main competitor to cast iron before the introduction of cheap steel (c. 1870). It is still to be found in structures dating from Victorian times, such as the Eiffel Tower (1889) which was contemporaneous with the Queensferry Bridge (1890) of steel construction.

3.2 MECHANICAL PROPERTIES

3.2.1 Introduction

Before attempting to classify the various alloys of iron it is necessary to consider the properties which are important to the designer. In fact, these are not specific to steels but apply generally to all metallic materials.

Metallurgists tend to divide properties into two groups: *structure insensitive* and *structure sensitive*. Structure insensitive properties are wholly invariant – they are associated with the properties of the atoms themselves and the primary forces between them. They do not depend on the arrangement of the atoms. The principal properties here are the *elastic modulus*, the *density* and some chemical, electrical and thermal characteristics. As the name implies, the structure sensitive properties are wholly dependent upon the past history – whether hot-rolled or cold-rolled, whether heated and cooled and if so how. All of these processes disturb the atomic arrangement and these disturbances are reflected in changes in properties. From the designer's point of view the most important structure sensitive properties are the *yield strength* and the *fracture strength*.

3.2.2 Tensile properties

In a tensile test steel behaves substantially as shown in Fig. 3.1 from which the following properties can be defined.

Elastic moduli. These are commonly defined in terms of the relationship between stress, σ, and strain, ϵ, in that region