Multi-Storey Buildings in Steel

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Contents

Detailed contents lists are given at the beginning of Part Two, 'Examples of Multi-Storey Steel-Framed Buildings', and at the beginning of the individual sections of Part Three, 'Principles of Design and Construction'.

Preface to English Edition

In present-day building a bewildering array of planning, constructional and aesthetic opportunities is available. Notwithstanding, in most cases the following considerations are of great significance.
1. The quest for economy; this opens up the possibility for the widespread industrialisation of building methods and, hence, rationalisation of the design processes.
2. The quest for simple assembly methods; these demand the application and provision of constructional systems which will facilitate the erection, alteration and enlargement, or even the dismantling, of a building. These considerations explain the progressive trend in all kinds of multi-storey buildings towards prefabrication and towards structural steelwork.

Like every other constructional material, steel has special individual properties which must be understood if it is to be used to best advantage. These determine the design of the building, as well as its details, and affect not only the skeleton but also the carcase of the building. Many well-tried, functional and inexpensive solutions are available nowadays for multi-storey steel-framed buildings but, as the use of structural steelwork has not always kept pace with the possibilities available, it must be concluded that the advantages of structural steelwork have not been brought to the notice, in particular, of building owners and their architects.
It is therefore the object of this publication to fill these gaps in knowledge. Although originally prepared by German authors and published in Germany, with the financial support of the European Coal and Steel Community, it has been translated into a number of other European languages.
This present translation was prepared at the suggestion of the British Constructional Steelwork Association and with the support of the Constructional Steel Research and Development Organisation (CONSTRADO). Despite the fact that the contents of the publication relate to European and North American practice, the publishers expect that the material will appeal wherever the English language is understood.

This publication is in three parts. The first part gives a brief historical glimpse justifying the rather late appearance of structural steelwork in the development of multi-storey buildings, then describes the evolution some fifty years ago of a true architecture in steel and, finally, the many possible concepts of design offered to the architectural profession today.
The second part gives a representative international cross-section of steel-framed buildings which were erected during or since the 1960s. With the aid of 62 carefully selected structures, design concepts and structural forms are presented for all the most important groups of buildings, the adaptability of structural steelwork to all kinds of constructional problems being very clearly demonstrated.
The third part, which specifically constitutes a construction atlas, gives a systematic description of the structural possibilities which are available within the statutory regulations. After a general description of the decision-making criteria for structural steelwork and the present position of modular co-ordination and its operation, the various kinds of structural systems are treated from the point of view of planning considerations and architects' requirements. The development of details within the structural framework and the interrelationship of the structural floors and staircases are demonstrated in theory and in practice. Then the correlation of the loadbearing structure with the claddings, partitions, roofs and technical services is carefully explained. In view of its special importance, an individual chapter is devoted to fire protection. Then there are sections dealing with the preparation, fabrication and erection of steelwork and, finally, a chapter on steel as a material.
In considering future editions of the publication it is the intention of the original German authors and publishers, in collaboration with other interested national organisations, to review the contents and, where necessary, to bring the material up-to-date. This applies particularly to the 'Examples of Multi-Storey Steel-Framed Buildings' in the second part and, to a lesser extent, to the 'Principles of Design and Construction' in the last part.

January 1978 G B Godfrey

One Hundred Years of Steel-Framed Structures Developments and Achievements

Forerunners of multi-storey steel-framed buildings, 1790–1872

The greater part of this book was written in 1972, exactly one hundred years after the construction of Saulnier's factory building at Noisiel-sur-Marne, which can be regarded as the first steel-framed building in continental Europe. Viewed in the context of the overall development of iron technology and structural steelwork, however, 1872 is quite a late date. Let us briefly review some important earlier events. In 1720, at Coalbrookdale, Abraham Darby began to smelt iron successfully in a blast furnace using coke, instead of charcoal, and thus established the conditions for the mass-production of pig iron. The technical improvement of the puddling process made it possible in 1784 to use coke also for the conversion of pig iron into wrought iron, thus reducing the lead that cast iron had gained. With Henry Bessemer's invention of the converter in 1855 and the introduction of the Siemens-Martin or open-hearth process in 1864, the era of mild steel began.

In addition to the tremendous expansion in the production of iron there was progress in the further processing and shaping of the metal. As early as the eighteenth century, iron plates were being rolled in Britain and, by 1830, rails for railway lines were being manufactured by rolling, while 1854 saw the production, in France, of the first I-sections of wrought iron. The I-beam, the basic element of modern structural steelwork and also the first strictly standardised structural component, is the direct descendent of the old iron rail, the product which can be regarded as the hall-mark of the emergent industrial era and on which, as it were, all the driving forces of that age are focussed: commerce and transport, steam power and mechanical engineering, heavy industry, metallurgy and applied science.

The most significant iron structure is the bridge over the Severn at Coalbrookdale, completed in 1779. With its span of just over 100 ft, it is the structure in which iron first came into its own as a constructional material for long spans. The cast iron arch bridge, however, was soon outclassed by bridges designed to exploit the favourable properties of wrought iron in tension and flexure: suspension bridges, girder bridges and truss bridges.

Among the early British and American chain suspension bridges, the most outstanding is Thomas Telford's bridge over the Menai Straits in North Wales, opened to traffic in 1826, which has a main span of 173 m. Subsequently, when the chain had given way to the cable, the record span for such structures had reached 300 m by 1850 and almost 500 m by 1870 with the construction of the Brooklyn Bridge in New York. The daring Britannia Tubular Bridge over the Menai Straits, having twin wrought iron box girders, 9 m deep, with a maximum span of 140 m, was completed by Robert Stephenson in 1850. The truss bridge was particularly suited to the requirements of railway engineering and remained the dominant type from the middle to the end of the century. Representative examples of such bridges are the Cathedral Bridge in Cologne, with spans of 100 m, and the Royal Albert Bridge at Saltash, designed by I. K. Brunel, both completed in 1859. In fact, all the most significant structural systems which have shaped the evolution of steel bridges had already emerged by the middle of the nineteenth century. In 1851, the construction of large iron-framed single-storey buildings reached a spectacular level of achievement in the Crystal Palace, London. About the same time, with the construction of Kings Cross Station in London and the Gare de l'Est in Paris, the series of large railway stations characterised by the arched iron-ribbed roof began to evolve. In 1867, St Pancras Station, London, established a European record with its span of 78 m.

How can it be explained, in a period marked by such major achievements in bridge engineering and the construction of enormous single-storey buildings, that the application of iron to multi-storey buildings failed to proceed beyond rudimentary beginnings and that framed construction did not at that time manage to establish itself wholly and permanently? The reasons may be summarised under four headings and these are in principle the same inhibitions which have until now impeded, or still impede, the general acceptance and efficient application of structural steelwork by architects.

1. In comparison with other applications of manual skill and industrial technology, building construction has always been conservative. The architect's conservatism is in itself a critical factor. It is bound up with the fact that people expect their dwellings, their religious structures and their public buildings to provide more than mere protection against the weather and a functionally adequate interior. Man strives to perpetuate himself in his buildings, thus proclaiming his aspiration to culture and his sense of history.

2. 'Architecture' in the historical sense of the word, the grandiose permanence with which architects through the ages have transformed the Greek temple or the mediaeval cathedral from a simple timber structure or a humble assembly hall into works of art expressing tremendous power and highly developed craftsmanship, has ceased to be possible since the advent of technology. The building owners and architects of the nineteenth century developed a sort of artificial tradition with their historical eclecticism. Nowadays, we no longer look with disdain, as we used to do even twenty years ago, upon the architecture of the last century as on a sort of historical fancy dress pageant. But the fact is that the pursuit of historical styles has long obscured the truth (or, at any rate, the practical consequences of this truth) that with the introduction of iron as a constructional material the old concepts of architecture – support and load, anatomy and space – and its structural features – post and lintel, arch and abutment – were superseded or challenged.

3. The architects' historical prejudice increasingly widened the gulf between architect and structural engineer. The division that occurred in the traditional profession of architecture, resulting in the rise of the engineer as a professional man in his own right, and the emergence of modern structural theory were developments that began concurrently with the industrial revolution and constituted an important distinctive feature of the new age that had dawned in building construction. The rapidly progressing refinement of the methods of structural analysis

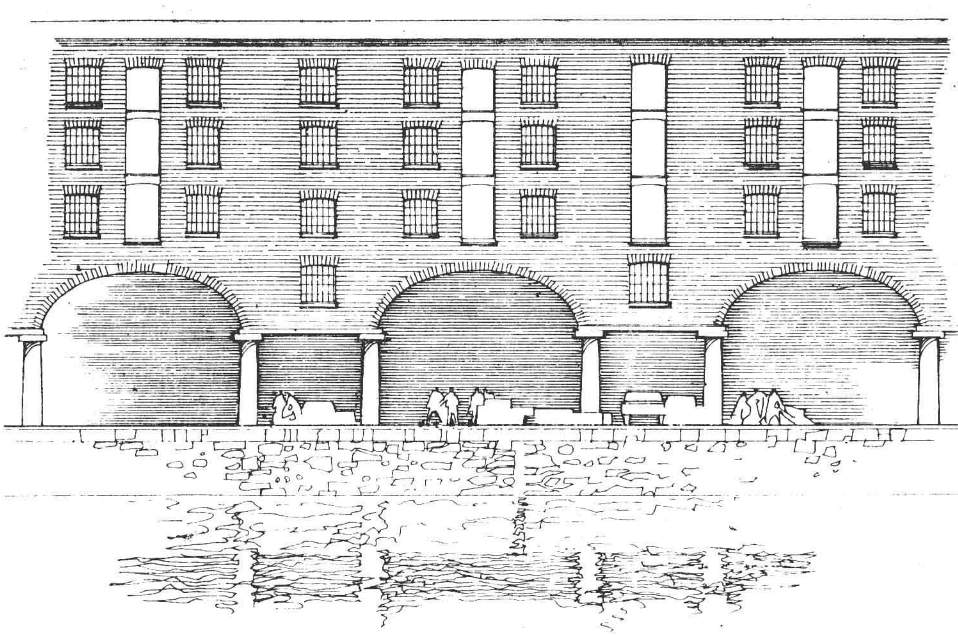
and strength of materials soon carried them beyond the range of most architects and so it is hardly surprising that they returned to the study of historical buildings as the supposed prerequisite to 'monumental architecture' and left 'industrial building construction' to the engineers. Big bridges and wide-span buildings, examples of which were mentioned above, had already become virtually the province of the civil and the structural engineer. Although the engineers were also influenced by the concepts of their time, as is exemplified by their persistence in using the arched girder as a feature of design, they possessed the necessary breadth of vision when the greatest demands were made on their technical judgement, namely, the development of new constructional forms suited to the use of iron.

4. In multi-storey buildings, which had thus become the exclusive field of the architects, the external pressures driving the designers of bridges and single-storey buildings to increasingly daring achievements were largely lacking. Neither the number of storeys nor the floor spans and loadings went beyond the familiar concepts traditionally established in the construction of major public and private buildings. Even when, in certain more ambitious buildings, the incombustible floor slab comprising iron joists – an innovation of the early days of industrial architecture – was installed in lieu of timber joists or the vault, this did not involve any significant change in the general structural pattern of multi-storey buildings. In their external appearance the traditional architectural features of elevational treatment remained unchanged. That is why, in the great cities such as Paris, Milan and Rome, the majority of buildings dating from the latter part of the nineteenth century harmonise so well with the older and more priceless architectural creations.

The relationship indicated here perhaps emerges even more clearly when one considers the celebrated exceptional cases where architects of those days tried to design wide-span iron roof structures. An example is provided by H. Labrouste's meticulously detailed two-bay cast iron arched structure for the Ste Geneviève Library in Paris, yet this ironwork is kept concealed, so that it does not appear on the exterior of the building. Actually, the enclosing wall with its unusually shaped features is even more impressive; evidently the architect felt himself to be on safer ground with this. Even in the big railway stations built towards the close of the nineteenth century, for example at Frankfurt-am-Main, this contrast between the airy iron arched roof spanning the platforms and the massive monumental entrance building rising in front of it is striking.

The first steps towards the development of the structural steel frame for multi-storey buildings had been taken at quite an early period. In order to gain more space and increase the loadbearing capacity of the floors for the installation of machinery in the British cotton mills, the timber posts were replaced by cast iron columns and subsequently floor beams of the same material were substituted for timber beams. The best known of these early multi-storey industrial buildings was erected for the firm of Philip and Lee at Salford in Lancashire in 1801. The designers were Boulton and Watt of steam engine fame. Similar textile mills with internal cast iron frames had in fact already been built in the 1780s, but the one at Salford surpasses them in its daring dimensions and its mature structural design, which made it a prototype for the further development of this form of construction. The building is 42 m in length, 14 m in width and exceptional for its time in having no fewer than seven storeys. Cast iron girders spaced at 2.7 m centres span in the transverse direction, supported at the third-points by a double row of cast iron columns. Here for the first time the floor girders are a kind of I-section with a flat brick infilling.

Liverpool, Albert Dock 1845

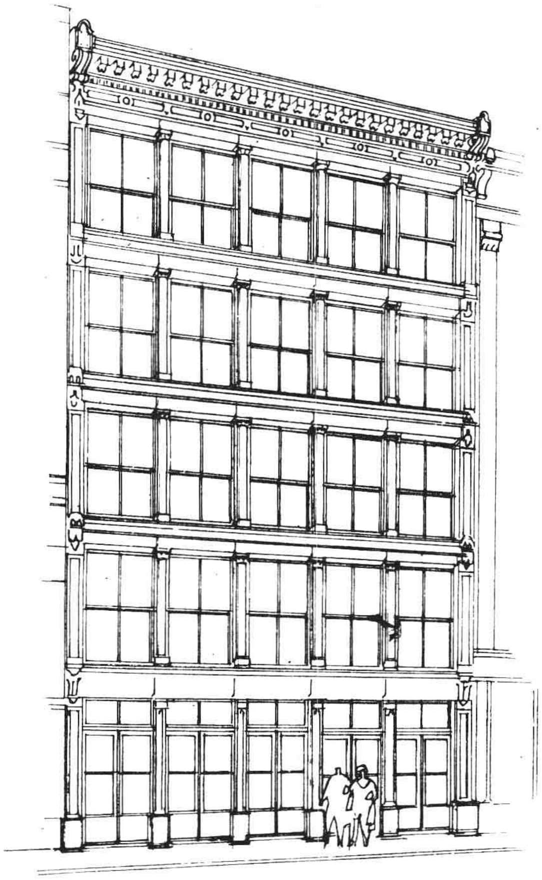


It was not until 1845, when William Fairbairn used wrought iron I-beams in lieu of cast iron in a refinery building, that this type of structure underwent a significant change. In the same year A. Zorès brought the rolled I-section into the construction of residential buildings. From then onwards the wrought iron beam and, later, the mild steel beam came to be more widely used in other types of building, in addition to industrial structures. A number of factors had conspired to help Zorès in achieving this innovation: a strike of carpenters in the building trade, the rise in the cost of timber beams, more stringent fire regulations and the need for floors of greater span.

As developed, the steel beam floor did indeed offer the advantage of better fire resistance and substantially higher loadbearing capacity than the timber beam floor. Also, it was superior to the vault, not only because of the reduced amount of labour involved in constructing floors with steel beams, but especially because of the substantial reduction in storey height and wall thickness. The fact that with the arrival of the iron beam the vault, as a structural system and as the most important design feature of monumental architecture, was rendered obsolete justifies referring to this development as the dawn of a new epoch. The fact that the jack arch held its own for a long time in combination with iron and steel beams in floor construction is a characteristic demonstration of the persistence of the historical approach whereby nineteenth-century architects sought to assimilate or to neutralise technical innovations.

The division between historically orientated romanticism and the realities of technical progress is even more strikingly shown in the structural component which could be said to epitomise the architecture of the Victorian era: the cast iron column, that unusually slender loadbearing member embellished with the historical decorative features of capital, base and fluting. Early cast iron columns of highly original and expressive design were installed in the kitchen of the Royal Pavilion that John Nash built at Brighton in 1821. These are unusually tall and slender tubular members whose capitals are shaped as clusters of palm leaves made of beaten iron plate. Later, the cast iron column was to degenerate into a mass-produced item which could be ordered from a catalogue in any desired height and style: Doric, Tuscan, Corinthian, Gothic or Saracen.

The 'beam construction method' developed by Boulton and Watt dominated industrial architecture throughout the nineteenth century. It cannot, however, truly claim to be called a structural frame in the sense that the iron or steel components formed a skeleton serving as the actual loadbearing system. In these early multi-storey industrial buildings the external walls had to carry a very substantial proportion of the floor loads and also to perform the important bracing or stiffening function, that is, resisting and transmitting the wind loads. This is clearly reflected in the American and European building codes or by-laws of the day. These required the external walls of such buildings to be, on average, half a brick thicker than those of residential and office buildings which were provided with internal loadbearing and stiffening walls. This requirement, which was retained, for example, in the German by-laws up to the Second World War, is astonishingly optimistic. For the permissible loads and stresses on masonry quoted in modern regulations the walls of such buildings would have to be made considerably thicker.



River front, St Louis, Gantt Building 1877

The next step on the road to the steel skeleton, the transformation of the external wall into a loadbearing metal frame, was long in coming, not least because it was inevitably to have a profound effect on the architectural treatment of the façade. Not surprisingly, the first attempts in this direction were again concentrated on that favourite product of the cast iron era, the column. They traced their origins from the arcade, that venerable architectural feature which had played so prominent a part in house construction and in urban architecture generally since ancient times. The wide-spanning arcades in the stark brick fronts of such British dockside warehouses as St Katharine's Dock, London (1828), and Albert Dock, Liverpool (1845), with their thick classical tapered cast iron column shafts of splendid rust colour, surmounted by slim Doric capitals, are indeed most impressive.

Another precursor of the framed external wall which came close to modern construction comprised wrought iron frameworks which were used as far back as the beginning of the nineteenth century to span the increasingly wide shop windows which were coming into vogue more particularly in Paris. These components were a kind of flat arched truss or parallel chord lattice girder enclosed within the masonry. In the United States in the period between 1850 and 1880 a large number of warehouses, department stores and office buildings were constructed whose façades were entirely supported by metal loadbearing members. It would appear that the impetus to this development was given by James Bogardus, a versatile inventor, designer and manufacturer. Among the most important of his creations is the building for the publishing firm of Harper and Brothers (1854). The front of this five-storey building is composed entirely of prefabricated cast iron components; internally it has an iron framework, as used in the British industrial buildings of the period, but applied here in the form of rolled wrought iron beams for the first time in the USA. The architecture of the façade apparently derived its inspiration from Venetian buildings of the High Renaissance and is characteristic of the trend towards heavy, opulent forms, which were subsequently to give way to the eclecticism of the second half of the century.

Of greater appeal to us at the present time are the timeless cast iron façades of the buildings on the river front in St Louis, USA. Here, the traditional architectural features that are used to enliven the façades of historic buildings have been reduced to the barest minimum. The austere cornice mouldings, the elegant plain columns, capitals and bases, really serve only to emphasise the elementary contrast of strong horizontal and graceful vertical features, of prismatic and cylindrical loadbearing members.

In Europe, too, some notable iron façades were built around this time, for example, Gardner's Iron Building, Glasgow (1856). Especially attractive in Oriel Chambers, Liverpool (1864), are the slender sandstone pillars alternating with iron-framed bay windows. Windows of this kind were later to play a major part in the architecture of the Chicago School.

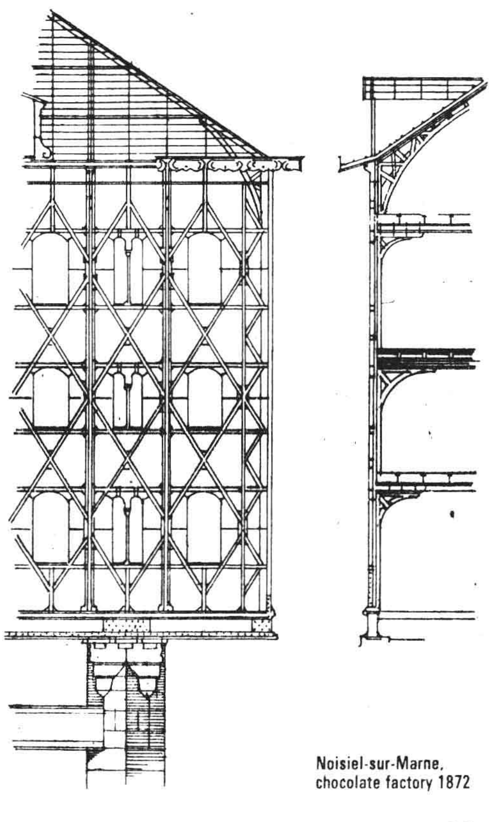
The big fires which occurred in Chicago and especially also in Boston in the 1870s shattered the illusion of the indestructibility of iron structures. The sobering discovery that an incombustible material is not necessarily fire-resistant resulted, in Europe even earlier than in America, in more stringent fire protection regulations and thus effectively killed this first emergence of a purely metal-based architecture.

The first multi-storey building in continental Europe entirely designed as a steel-framed structure is the Menier chocolate factory at Noisiel-sur-Marne, near Paris (1871–1872), by Jules Saulnier. Here again, as in the earlier British cotton mills, it was the operational demands of industrialised building that compelled the engineer to take full advantage of the structural possibilities and the strength of iron as a constructional material.

The factory is built out over the Marne, being supported on four massive piers shaped as cutwaters. The external framework stands on a peripheral sill beam, designed as a deep box section which transmits the entire load of the building and the wind forces to the eight points of support. There are no internal stiffening walls, nor are the end walls, because of the cantilevered construction of the building, able to transmit horizontal forces. Therefore, a rational solution for bracing the structure had to be devised. The exposed framework is stiffened in the longitudinal direction of the building by a network of diagonal members inclined at 60°, forming a system of diamond-shaped meshes which reduce in size in a narrow strip at each corner to form a kind of wind-bracing. To stiffen the building transversely, the floor beams are rigidly connected by means of lattice brackets to the main stanchions of the external frame.

These stanchions, located in pairs over the supporting piers, stand out somewhat because of their heavier section, but otherwise the façade with its thin infilling of brick is entirely smooth. The window dimensions are exactly defined by the diamond network of diagonal members. A subtle differentiation in the height of the windows has been obtained by slightly shifting the position of the joints in the first and the third storeys.

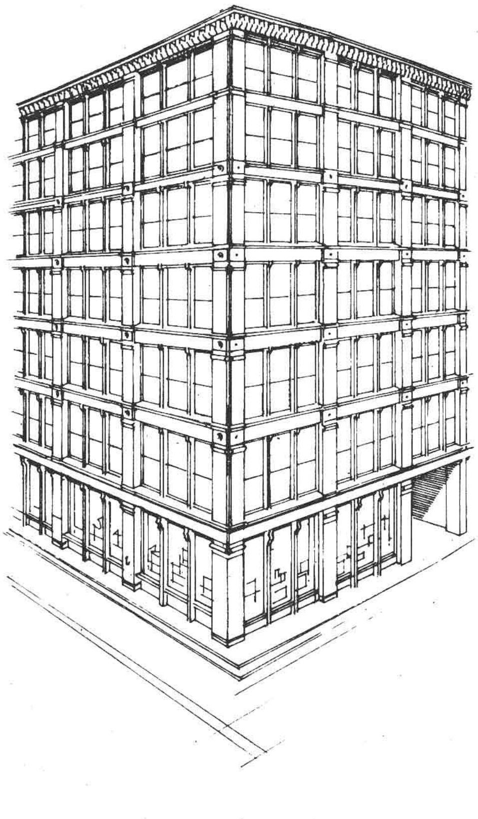
The Menier factory anticipates modern structural steelwork in several respects: the cantilevered corner and especially the diagonal network of bracing, which nowadays still plays a major part in the wind-bracing of skyscrapers. On the other hand, its framework is unmistakably inspired by mediaeval timber-framed buildings, a splendid confirmation of the doctrines of Viollet le Duc, which will be mentioned later. Saulnier's system had no direct imitators of any consequence. The principle of the metal frame was able to make a more lasting impact only when high-rise commercial building became an urgent constructional problem demanding new structural solutions. This development started in Chicago about 1880.



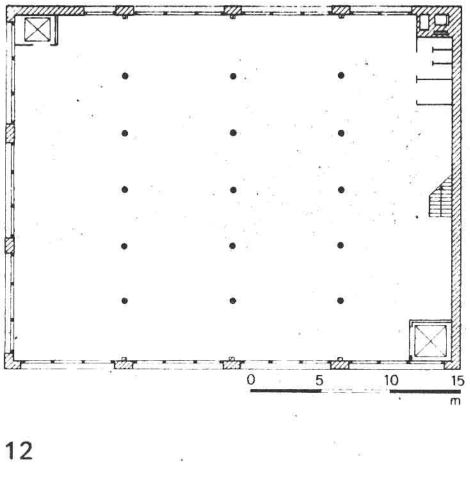
Noisiel-sur-Marne, chocolate factory 1872

The Chicago School, 1880–1910

The modest pioneering settlement at the mouth of the Chicago River where it flows into Lake Michigan attained township status in 1830. By 1871, its population had risen to 30 000. In those days Chicago consisted almost entirely of timber houses of the so-called balloon-frame construction, which is still used in the USA. In that year, however, the town was almost entirely destroyed by fire. Initially, the work of rebuilding the town proceeded in fits and starts. Nevertheless, about the year 1880 there was an unparalleled burst of building activity.
The opening-up of the Middle West, the expansion of the railway system and waterways and the exploitation of the country's mineral resources, had made Chicago the transfer point and production centre of a vast hinterland, the world's largest grain market, the focal point of the timber trade and the food industry, of machinery manufacture and machine tool production. The building industry was scarcely able to cope with the heavy demand for commercial and office buildings, warehouses and shops. The cost of land rose sharply, the density of building within the pre-established street network increased and soon multi-storey structures evolved into skyscrapers. Only with the aid of structural steelwork was it possible to achieve maximum utilisation of the sites and the floor space inside the buildings and also to increase the speed of erection. As early as 1895 the new constructional method had become firmly established in all the major American cities, but at that period Chicago had more high-rise steel-framed structures than all the other cities put together.
There were also often special requirements and circumstances which made structural steelwork possible, influenced it and enforced it. First, there was the topographical situation which, together with the traffic problems, long prevented any extension of the Loop, Chicago's central commercial area. From the outset, importance was attached to open plan buildings with scope for subsequent modification of the internal layout. Several of the early framed buildings alternated in function between warehouses and office premises. Even at that time, subsequent upward extension by the erection of additional storeys was envisaged at the planning stage and often carried out.
The high-rise commercial building would not have been a practical proposition, however, if the mechanical engineers had not managed to produce the necessary service installations at the right time. The first and most important prerequisite was the passenger lift. The safety lift had been invented by Elisha Graves Otis, who demonstrated it at the Crystal Palace Exhibition in New York in 1853. In 1857, he installed the first lift for public use in a department store on Broadway. From then onwards, New York gained a certain lead in the construction of tall buildings and indeed claimed the distinction of having produced the first skyscrapers, nine- or ten-storey commercial buildings of masonry construction, which were erected in the mid-1870s. While the lift was evolving from a steam-powered via hydraulic operation to an electrically operated piece of machinery, the other technical services were also being developed: telephones, pneumatic despatch system, central heating and air conditioning. Apart from the technical prerequisites, one must not lose sight of the imagination and courage which created the first modern steel-framed buildings in Chicago. The architects were inspired by the still active pioneering spirit, which gave their buildings their distinctive power and freshness and also an unmistakable family likeness.



Chicago, Leiter Building I 1879



The founder and leader of the Chicago School was William le Baron Jenney. In 1868, he opened his architectural design office in Chicago and with the construction of the Leiter Building I in 1879 his first gamble proved successful. The determination with which this structure was realised within the confines of its formal expression has hardly ever been surpassed since that time. In its sheer strength and power the building is reminiscent of ancient Roman architecture. Structurally, this five-storey building, to which two storeys were added later, was still something of a hybrid: timber beams on wrought iron girders, carried by cast iron columns in the interior and by masonry piers along the perimeter. The daring slenderness of these piers and the great width of the window openings, necessitating a wrought iron girder to act as lintel and edge beam, were novel features. That the masonry is supported and stiffened by the internal iron framework is clearly shown in the prominently featured bearing plates for anchoring the main beams to the top of the piers. Even more advanced is the layout adopted for the Leiter Building I: a clearly conceived planning grid, an open layout and a reduction in the dimensions of the structural components. In these respects it remains unsurpassed, for example, by any reinforced concrete building. This becomes even more strikingly evident when we compare it with the ground plan of the Monadnock Building, the last high-rise building of conventional masonry construction.

Chicago, Reliance Building 1894

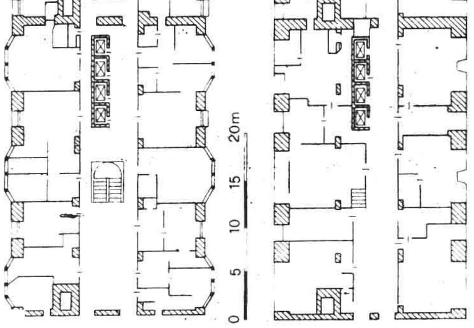
In Jenney's next major building, constructed for the Home Insurance Company (1883–1885), each external pier encases a loadbearing steel column. In its elevational treatment, this building offers nothing like the unity and structural clarity of the Leiter Building I: the prominently featured ground floor, the enclosing round arches in the top storey, the balustrade surmounting the

cornice, these are eclectic architectural motifs which are at variance with the character of steel-framed structures.
Jenney's two main achievements, the Leiter Building II (1889) and the Fair Building (1891), strike a more modern note. Here the historic reminders of the architectural features of bygone days have been reduced to a minimum: only very delicately moulded bases and capitals raise the piers to the status of pilasters; indeed, they could be quite readily omitted, and one cannot help feeling that Jenney himself would have preferred to have omitted them. These two buildings are complete steel-framed structures. It is evident that the masonry pier has no loadbearing function to perform, not even that of supporting its own weight, merely forming a casing around the structural steel column within.
The natural transition from the external wall to the loadbearing structural steel frame had first been achieved by Holabird and Roche in the 14-storey Tacoma Building, erected in 1884 and, unfortunately, subsequently demolished. In this building the bay windows extending all the way up the façade were particularly distinctive, an architectural feature which was to be continued in Chicago until beyond the end of the century. In their most important work, the Marquette Building (1894), Holabird and Roche achieved something very akin to the clear-cut horizontal and vertical arrangement exemplified in the Fair Building and Leiter Building II; indeed, they even surpass them in the reduction of traditional ornamentation.
However, one should avoid rating the work of the architects of the Chicago School the higher the more it conforms to present-day ideas about framed construction. They were not out to develop a new architecture for its own sake: their assignment was to erect tall buildings of stable and fire-resisting construction. To what extent they were able to utilise or adapt the architectural repertoire of their own time depended largely on the client's requirements. Indeed, those architects would have had no time to indulge in much theoretical speculation. It is particularly the spirit of ebullient unconcern with which they took advantage of favourable circumstances and overcame difficulties that characterises their work and links them to one another.
This is very clearly revealed when one examines more closely the two structures in which the spirit of the Chicago School appears to display itself most powerfully: the Reliance Building and the Monadnock Building. The former does indeed deserve the prize for streamlined slenderness of its façade elements and the extremely high proportion of glazed surfaces. Here, framed construction is immediately recognisable. Its bay windows are twice as wide but much flatter than usual. They do not create the impression of mere embellishment, but are instead an integral part of the façade structure, so that we have in effect a folded surface. The actual loadbearing system is largely concealed: each bay window element comprises three external columns of the steel frame, the middle one being hidden behind the protruding window front, whereas the two outer ones are half covered by the mullions. The structural columns are exposed only at the corners of the building and in the bottom storeys. All these refinements would not have been at all effective, however, if an additional ten storeys had not been added to the Reliance Building beyond the five storeys originally intended. Thus, the progressive character of this architecture, the open form, the succession of completely identical units (the principle which had, for large single-storey structures, already been given form and substance in Paxton's Crystal Palace), was highlighted more by a fortunate coincidence than by deliberate design.
The Monadnock Building, which is the most original of Chicago's multi-storey buildings and the one which has since gained the most credit for its monumental value, is not a steel-framed structure at all. In its time, it was in fact the world's tallest structure having loadbearing brick walls. The conservative building owner had brusquely turned down the first designs submitted by the architects Burnham and Root (a steel-framed structure with terra-cotta cladding) and insisted on an all-brick structure with no adornment. Root, at first dismayed by his client's reaction, gradually worked up a genuine interest in this brick creation and devoted special effort to it. The bold concave batter with which the external wall rises from the bottom storey, which protrudes to form a kind of plinth, the gently curved overhang in lieu of a cornice at the top, and especially the rounded corners flaring out at the upper extremity, are features that give this building its incredible dynamism and enhance the impression of tremendous strength suggested by the deeply recessed window reveals.
By means of the bay window, arranged at every third grid line on the plan, Root did in fact manage to introduce some steel framework into the structure, bring relief to its massiveness and also enhance the effect. More particularly, he harmonised his building with the adjacent contemporary buildings and achieved this so effectively that the basic structural difference is not perceived at first sight.

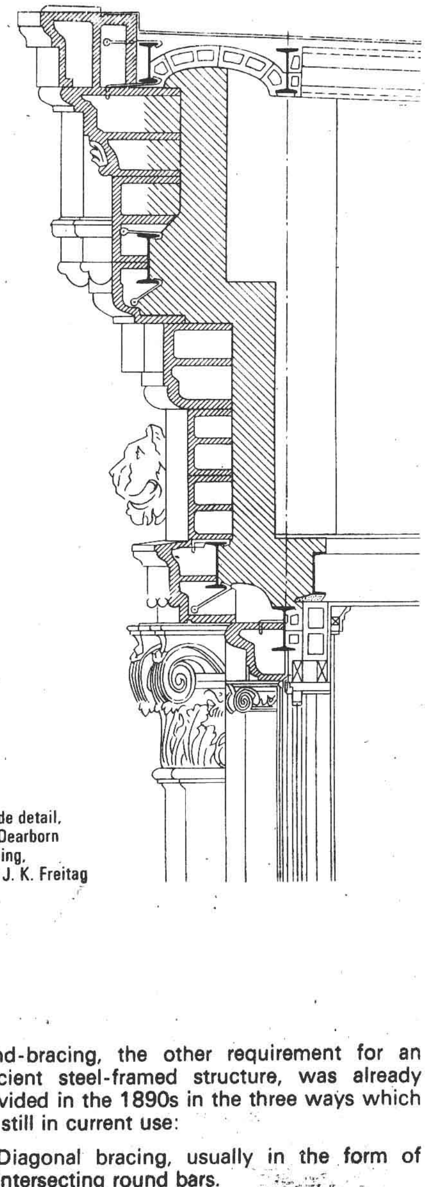
The buildings that have survived from those days do not in themselves tell us very much about the development of structural steelwork. Among the technical publications of the period, only *Architectural Engineering* by J. K. Freitag (New York, 1901) gives detailed information, its aims being approximately the same as those of this present book. That the engineer, as distinct from the architect, has played an important part in American high-rise building construction is evident even from the title of that book, which could be amplified as indicating 'the application of engineering methods to the structural design and construction of buildings'.
With reference to 'Chicago construction', Freitag distinguishes two types embodying two stages of development. First, there is 'skeleton construction', established by Jenney and given mature application in the Tacoma Building: a completely interconnected structural framework which receives all floor, roof and wall loads and transmits them to the footings of the columns, but which is still dependent on the stiffening effect of the masonry walls for the transmission of wind loads. This 'skeleton' was, however, soon superseded by the second type of structure: the 'cage'. Here the structural frame is a self-contained rigid system in which the wind-bracing has become an integral part of the supporting framework of the building. Since, in this case, the frame is virtually independent of the enclosing walls, it is possible to form large window areas, use interchangeable partitioning for internal layout and reduce the wall thicknesses and loads. More particularly, there is a considerable speeding-up of construction: the erection of the infilling or cladding for the external walls can now be carried out in a number of storeys simultaneously.

Chicago, Monadnock Building 1891

Typical floor plans, Monadnock Building



The present-day structural engineer may be surprised to learn that fire protection figures very prominently in the above-mentioned book. The Chicago engineers and architects were disposed to regard 'fireproofing' not merely as a necessary evil, but as something deserving particular attention. The consternation caused by the disastrous fire of 1871 must have made a lasting impression. Freitag gives statistics of fire damage; he reports experience gained with fires which attacked steel-framed buildings in the 1890s and describes in detail the measures for providing fire protection around all loadbearing components.



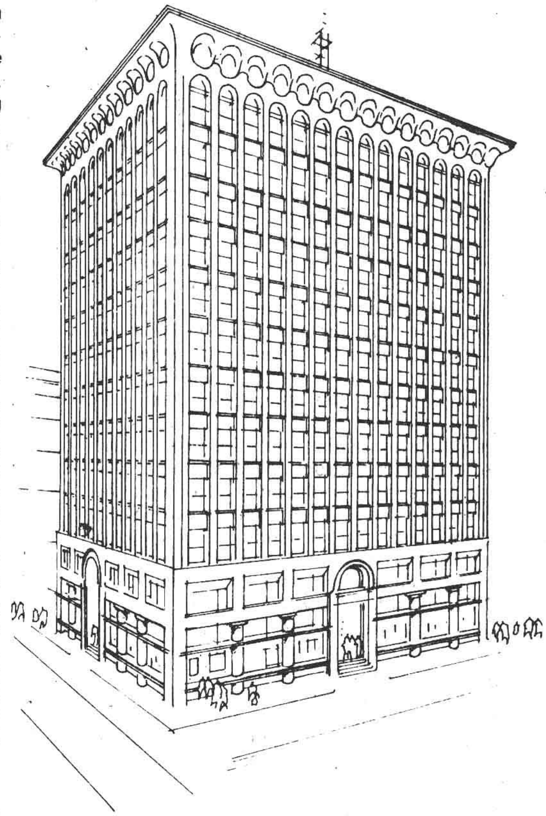
Façade detail,
Fort Dearborn
Building,
after J. K. Freitag

Wind-bracing, the other requirement for an efficient steel-framed structure, was already provided in the 1890s in the three ways which are still in current use:

1. Diagonal bracing, usually in the form of intersecting round bars.
2. Portal frames, which were used where large openings in walls were required and when diagonal bracing could not be accommodated.
3. Lattice girders or trusses of the greatest possible construction depth, rigidly connected to the loadbearing columns.

The foundation is the third problem for which steel-framed construction demanded new solutions or, to be more precise, modifications of the known types: strip footings, piles, caissons. That Chicago played a leading part in developing the 'floating foundation' was due to the soil conditions encountered there: plastic clay of great depth, but offering the advantages of uniform settlement for buildings with correctly designed foundations. The type of foundation usually provided under conventional masonry buildings, wide and not very deep masonry strip foundations, could not be adopted for the individual footings under steel-framed multi-storey buildings. The hugh massive pyramids of masonry which would have been required for such foundations would either have filled up the urgently needed space in the basement or, alternatively, if they had been installed at greater depth, would have involved additional expense and increased risk, as the settlement in the plastic clay would have been greater and more irregular the deeper the foundation penetrated into it. For this reason designers adopted a concrete foundation slab on which, instead of stepped masonry footings, railway rails were laid in alternate directions in several layers which were successively embedded in concrete. In this way the depth of the foundation was halved. Later, rolled steel I-beams were used instead of rails. With the increasing number of storeys a situation was soon reached where groups of columns were installed on a common grillage or where sometimes the entire base had to be designed as one large grillage foundation.
In the early days of steel-framed construction the piled foundation made relatively little headway. It was, however, the preferred form of construction in New York and Boston with their rocky subsoil. With timber piles, the lowering of the level of the ground-water was a source of anxiety, there being several instances of piled foundations coming to grief as a result. Park Row Building in New York, which with its 36 storeys was the world's tallest building around 1900, is still founded on wooden piles. The advanced form of the pneumatic caisson, constructed of timber or steel, was employed to cope with particularly difficult soil conditions and ensure structural safety. These ambitious techniques for foundation construction, which had already been tested in railway bridge building, were further developed to meet the demands of steel-framed high-rise buildings in New York.
Reverting to the technology of structural steelwork, it should be noted that in 1885 the rolled wrought iron beam was superseded by the rolled mild steel beam, which was first produced by the Carnegie Steel Company in the USA. After this innovation, the cast iron column soon receded into obsolescence, as did also the complex shapes for columns composed of curved or chamfered wrought iron sections, these being superseded by standardised rolled steel sections or box sections. In addition, at an early period, the rivet had replaced the bolt for structural connections. Thus, about the turn of the century, all the essential elements of construction had been evolved which were to carry structural steelwork through the next forty years of its evolution.

Perhaps of greater interest to the architect than the above-mentioned technical achievements are the problems of façade detailing presented by steel-framed construction. For one thing, it became necessary to build windows of unusually large width. At first, the architects contented themselves with a simple arrangement



Buffalo, Guaranty Building 1895

comprising three or four vertically sliding windows per bay. From this was evolved the typical 'Chicago window': undivided fixed glazing in the middle, flanked by two narrower horizontally divided side lights. Mullions, were already being utilised as a means of obtaining a differentiated internal layout with movable partitions.
A particularly important and interesting detail is the spandrel, that is, the area between the windows of two consecutive storeys. With the transition to the cage-type structural frame the window lintel, the floor edge girder and the cill of the window above had to be designed and detailed as a single entity. Some of the spandrel sections illustrated in Freitag's book, with their mixture of steel and historical façade details, now strike one as rather odd. On closer inspection, however, it appears that the structural and physical problems – temperature movement of the steel columns, relief of the window construction, compensation for settlement of the cladding and the masonry backing – have been carefully thought out.
Having proved highly successful as a lightweight fireproof infilling for floors and as an internal lining, terra-cotta became very popular as an external cladding material. The ancient technique of facing a building with ceramic slabs offered the architects numerous possibilities for enrichment and colour. The delicate relief treatment that burnt clay demands can provide a finely graded dimensional scale and convey an impression of lightness which is appropriate to

framed construction. Terra-cotta ornamental features confined to cornices, window surrounds and cills harmonise very well with brick facing on a high-rise building such as, for instance, the Marquette Building.
Finally, for prestige buildings a whole range of materials was available: natural stone for the bottom storeys and brick facing for the main upper part of the building, with terra-cotta features for lintels, mouldings and cornices. The fact that natural stone facing, despite its disadvantages, inadequate fire resistance, difficulties of fixing to steelwork and backing, had always managed to hold its own on commercial high-rise buildings and was especially popular towards the close of the last century is due to that century's fundamental sense of history, which although thrust into the background by the Chicago School was not entirely extinguished.
As steel-framed construction was perfected and spread throughout the United States, a change in architects' attitudes took place with a movement towards the academic historical approach. The first historians of modern architecture, Giedion for example, blame the 1893 Chicago international exhibition for this, more particularly the ornate decorative style which was imported from the Ecole des Beaux Arts, France, and which reigned supreme at the exhibition. It was considered to have nipped in the bud the upsurge of new architecture and to have held up progress for the next fifty years. At the present time, this interpretation no longer appears acceptable. It has since been recognised that the exhibition of 1893 was not the origin of the neoclassicist movement, but a symptom of it. The Chicago School's achievement and the architectural forms it stood for were too spontaneous to provide the basis for a new convention in design which would be accepted by the public and the architectural profession throughout the country, to meet the increased and more exacting demands in terms of size and prestigious character of buildings. The time was not yet ripe for functional steel-framed architecture without historical antecedents.

Chicago, detail from front elevation of Carson, Pirie and Scott store 1901

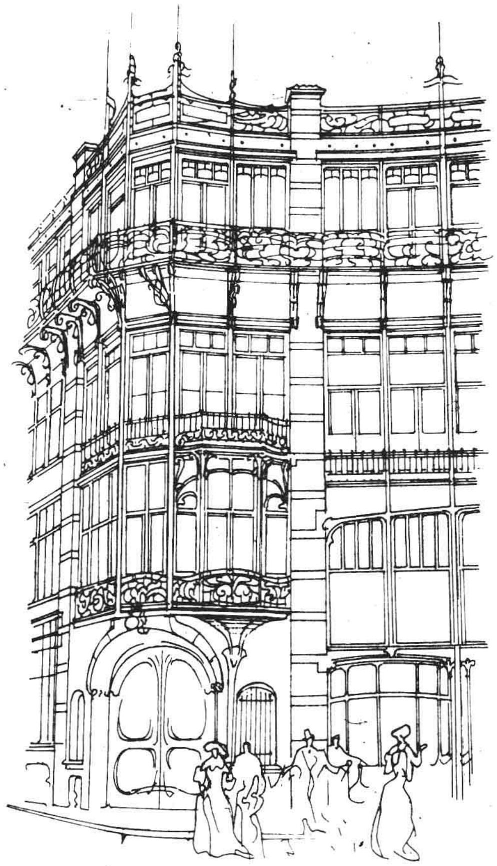
The problems that skyscraper architecture had met in the 1890s are forcefully demonstrated in the work of Louis Sullivan. After completing his studies in Paris he had joined D. Adler's architectural practice and worked with him until 1895.
The first high-rise commercial building designed as a fully developed steel-framed structure by this firm is the Wainwright Building at St Louis (1890–1891). Here Sullivan attempted to solve the architectural problem in the sense of a self-contained visually well-balanced composition. In conformity with the classical arrangement, substructure surmounted by walls terminating in a cornice at the top, he subdivided the building into three zones: three plain bottom storeys of masonry construction, followed by the office storeys in brickwork, with closely spaced protruding piers and recessed ornamental spandrel walls, the whole being crowned by a powerful richly-ornamented frieze with a widely-projecting top slab. The piers are much wider at the corners than at the intermediate points; the actual loadbearing system is revealed in the wide spacing of the columns on the ground floor.
In the Guaranty Building at Buffalo, built in 1894–1895, Sullivan not only refined this principle of architectural articulation, but also enhanced the scale effect of the vertical treatment of the façade: here, the marked divisions between the three zones and the solidity of the corner piers and cornice are much less obvious, all the elements being combined into one organically harmonised entity. At the base of the building, however, the loadbearing columns are more distinctly expressed; on the ground floor some of them are round columns, early forerunners of the pilotis which Le Corbusier was later to postulate as a component of modern framed structures.
The ornate architectural treatment of these two skyscrapers failed to catch on – it was too personal and too ambitious. Sullivan must have felt this himself; at any rate, in his last famous building, the Carson, Pirie and Scott store in Chicago (1899–1901), he reverted to a simple elevational treatment closely following the pattern of the structural framework. The ornamental features are confined to the two bottom storeys and to delicately moulded window surrounds. Here, the classical principles of architectural design have been superseded. For Sullivan himself, the building proved to be a bitter disappointment; his contemporaries failed to understand him and saw in it a relapse into the primitive beginnings of framed construction. In the last 24 years of his life he received no more major assignments.

Finally, attention must be drawn to some projects in which the pioneering spirit of Chicago continued to display itself until the First World War. These were more modest buildings, attracting less notice from the public and the critics, in which, with less architectural pretension and with simpler means, the designers managed to accomplish what Sullivan had, in the Carson, Pirie and Scott building, distilled as the quintessence of the Chicago School. With their plain brick facing, their fine differentiation of vertical features and horizontal bands, they have an almost timeless quality. A characteristic example of these early genuine steel-framed buildings is the Liberty Mutual Insurance Building (1908).

Chicago, Liberty Mutual Insurance Building 1908

Evolution of framed construction in Europe: France, Belgium, West Switzerland, 1890–1930

It is no coincidence that it was in France and Belgium that the first steel-framed multi-storey buildings were developed, because the material and intellectual conditions were particularly



Brussels, Maison du Peuple 1899

favourable there. Even in the early days of ironwork France had, at various times, challenged Britain's claims to leadership in this field. The first wrought iron roof frames were constructed in France before cast iron bridges were built in Britain. With their glass and iron vaulted roofs at the Galerie d'Orléans and the Jardin des Plantes in Paris, the architects Fontaine and Rouhault introduced an innovation of fundamental significance for nineteenth-century architecture.
From about 1860 onwards, France gained a clear lead in building iron bridges and, especially, in the construction of iron-framed single-storey buildings. Nor could the achievements of the great French bridge engineer G. Eiffel, in the boldness of their conception, be rivalled by the work of the contemporary German designers of truss bridges. Following the achievements at the international exhibitions in Paris in 1855, 1867 and 1878, structural steelwork culminated in the 110 m span three-pinned arch structure for the Galerie des Machines at the 1889 exhibition. This building, possibly the most interesting and impressive structure of its kind ever built, would perhaps not have had the misfortune to be demolished in 1910 had it not been over-shadowed by the Eiffel Tower. The latter, initially unpopular, had by then become firmly established as a symbol of Paris and it must certainly have prompted not only artists but also architects to acquire a new sense of space and structure.
In architecture, the French had always been distinguished among the Latin nations for their rational approach, their clear thinking as designers. French architectural theoreticians of the eighteenth century were the first to draw attention to the rational qualities, the constructional and formal logic of the mediaeval Gothic cathedrals, and applied these strict criteria to a critical assessment of modern buildings. About 1850, when the Gothic Revival in Britain reigned supreme, the French architect Viollet le Duc produced his ten-volume *Dictionnaire raisonné*, a comprehensive compendium of the architecture and building technology of the Middle Ages, which made him the leading exponent of what was termed 'mediaeval rationalism'.
He attributes all developments of architectural form to structural necessities and achievements. For him the groined vault, the system of piers and buttresses of the Gothic cathedrals represent the end of a long evolution which moved towards a progressively clearer realisation of the skeleton principle in the structure of the vaulted basilica, the great achievement of the French engineering spirit. 'La construction gothique est ingènieuse', asserts Viollet le Duc in his controversial article, 'Construction'. The passionate polemics with which he championed the mediaeval builders' achievements were directed against his contemporary colleagues of the academic school of thought, who clung to the architectural ideals of the Ancients and of the Renaissance and who rejected the innovations of iron construction.
'The Romans construct in the way that the bee builds its cell; this is marvellous, but it is not progress: the honeycombs at the time of the Romans look exactly like those at the time of Noah. Give a Roman architect cast iron, iron plate and glass and he will not know what to do with them. The modern spirit is of a different kind . . .'. In this context he uses the words 'modern' and 'Gothic' almost as synonyms.
Aided by the movement led by Ruskin and Morris in Britain, the rational doctrines advocated by Viollet le Duc constituted an important precondition for that movement in international architecture which preceded the 'modern' school of thought and which for the first time made a complete break with the 'historical' outlook.

'Art Nouveau', when it arrived, was hailed as something really novel. It provided an artistic impetus which was as intense as it was short-lived, a necessary transition stage. In order to topple the deep-rooted concepts regarding traditional architectural forms, the leading architects evidently had to start with ornamentation. They had to offer a completely new, versatile, self-contained repertoire of ornamental shapes and patterns, derived directly from nature, as already demonstrated in contemporary painting, graphic arts and interior decoration by, among other artists, Edward Munch, Aubrey Beardsley and the British designers of the Morris School.
The structural material that was to provide the realisation of this language of architectural form in the actual structure was iron. The techniques which were employed in making the brittle metal conform to the curving, swaying shapes of plants and which involved, to our way of thinking, a peculiar combination of cast iron, curved sections and sheet metal cut to various shapes, may have been inspired by Viollet le Duc's proposed designs for the embellishment of iron structures. By exploiting and emphasising the slenderness and the malleability of the iron loadbearing component, the Art Nouveau architects reverted to a course of evolution which had started far back in the early days of cast iron construction in the interior of the Royal Pavilion at Brighton, designed by Nash, and which had temporarily come to a halt in the iron façades at St Louis around 1860. Although they did not achieve the true synthesis of the contemporary form of expression with the current loadbearing system, in their best work they did achieve an astonishing harmony of structure and decor. What is more, they kept alive the idea of the externally exposed metal frame.
It is particularly in this respect that the first creations of Art Nouveau architecture, the buildings erected in Brussels to the designs of Victor Horta, are also the most important. With the Tassel Building (1892–1893) he rose to sudden fame. The layout on plan, the flowing sequences of rooms and internal spaces at different levels, was not something fundamentally novel for an urban building in the Belgian capital. What was new was the intense spirit of spatial movement, the flourish and the decorative power of the visibly exposed ironwork in the staircase, the lattice girders for the landings and stair strings growing out from a cast iron central column with the curving tendrils of the infilling members.

Brussels, Magasin à l'Innovation 1901