# 19TH CENTURY IRON STRUCTURES IN GREAT BRITAIN

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I am interested in this subject mainly as an architect, i.e.,I am fascinated by the coming up of architectural shapes. Since it is one of the purposes of architecture to assign some system to aspects in our invironment, buildings are also indicators of the powers in being at the time those buildings were erected. In his book "Logik der Baukunst" Norberg-Schulz writes: "... architecture is a system of symbols. It is distinguished from other systems of symbols by its incorporation of technical implementation as part of the system." The importance assigned, for instance, to engineering and materials aspects in a building structure is particularly evident whenever technical conditions change, new problems to be solved loom large, and possibilities are limited.
This was true of structural engineering during the first industrial revolution. I should like to mention a few examples to describe the way in which new architectural problems, or problems with new significance, and the development of iron construction imply each other and how, out of this close relationship, new building structures evolved.

Iron was the necessary prerequisite for this development. Whenever used in accordance with its different physical properties, it also established new types of buildings. But only the designs initiated by new architectural problems provided the new bases for building on which our present-day architecture rests.
In the new, or re-evaluated, architectural problems of the 19th century, which were classified as monumental architecture and were mainly the responsibility of architects, i.e., national monuments, public museums and libraries, theatres, the conflict became apparent which exists between the forms of iron structures and traditional design concepts.
The new architectural problems which mainly caused the emergence of an independent iron architecture, such as bridges, railway stations, exhibition halls, market halls, department stores, industrial buildings, however, produced a thesaurus of forms in line with the new building technology. In his book "Verlust der Mitte" Hans Sedlmayr confirms that these buildings "... exceed modern buildings in the harmonious equilibrium between modern functionality and human dignity which was never to be reached again." These were the functional requirements connected with the new architectural problems: roofs without any supports covering large free spaces; lightness and transparency of the outer boundaries of rooms; variability of floor plans in multi-storey buildings. Structures made of such traditional materials as stone and wood were unable to offer optimum solutions. This was possible only with iron.

All major improvements in iron smelting since the early 18th century emerged from Britain and are closely connected with the Darby family and the Coalbrookdale ore and coal mines. They were the first, in 1709 and after 1735 at the latest, to convert hard coal into coke and in this way replace charcoal, which became increasingly less abundant, in iron smelting.
The steam engine invented by Newcomen and first set up in a Cornwall mine in 1712, which was further improved by Smeaton, Watt and Boulton in the years to follow, allowed coal to be extracted also from deep underground shafts at low cost. This laid the basis for an enormous increase in coal and cast iron production in the following years.



The production and processing of wrought iron in large quantities became possible only after the invention of the puddle process by Henry Cort in 1784 and the possibility to roll sections of wrought iron, which was developed around 1820. Road construction and the construction of waterways in Britain, which were begun in 1761, following French examples which included 3000 miles of waterways in 1830, created the necessary infrastructure for the distribution of iron and coal. Since the Paris Treaty of 1763, in which Britain was assigned the North American colonies, she became the country determining the arts and culture on the continent. This remained true until the early 19th century. The historic repercussions of iron structures built in Britain at that time extend right into our present (rediscovery of galleries, public rooms covered with glass, Centre Pompidou of Paris, etc.). The basic design principles underlying the development of self-contained iron structures were created in a first phase approximately between 1760 and 1830.
The first phase of iron construction includes such engineers as John Smeaton, Thomas Telford, Samuel Brown, George Stephenson, the architects John Nash, John Soane, and the smelters Abraham Darby and John Wilkinson. This phase is characterized by a substitution of such traditional materials as stone and wood by cast iron.
Before 1770, the walls of buildings consisted of timber posts with infills or massive brickwork, ceilings and roofs made of timber beams, girders or stone walls. Roofs were covered with straw, slate, tiles or lead for protection against the weather.
These structures were mainly able to withstand compression forces. Iron structures offered fundamentally different possibilities.
Bridge constructions are the most spectacular milestones in the use of iron. After Gouffon and Monpetit in 1755 failed to erect a cast iron bridge over the River Rhone near Lyons, Abraham Darby III and John Wilkinson, following a design by the architect Thomas Farnolls Pritchard in 1777-79, erected Coalbrookdale Bridge with a span of 30.5 m. In this way the Darbys had introduced cast iron as a structural material.
The use of semicircular arches with the roadways on top is derived from stone structures; the way in which the five arches situated side by side are interconnected and connected with the abutment, and the whole appearance of the structure, are reminiscent of a timber structure: cast iron thus proved to be a more efficient substitute of traditional building materials.
This "carpenter's work" made of cast iron turned out to be very complicated and unsafe, with respect to statics, foundry techniques and assembly alike, and was found to be unsuitable for larger spans.
Exemplary designs of large spans implemented in cast iron were developed by Thomas Telford in his bridges over the River Spey near Craigellachie in 1814, with a span of 150 feet (45 m) ans Mythe Bridge at Tewkesbury, 1823-26, with a span of 170 feet (approx.51 m).
The four arch ribs composed of subunits in the bridge near Craigellachie are spanned into arch segments by horizontal reinforcements. An interesting feature is the connection between the diagonal braces in the spandrels with the arch and the roadway supports by ridge-and-furrow systems.
In 1963-1964 the iron structure, except for the arch, had to be replaced by steel components, but the original appearance was preserved.
The solution found by Telford, which he also applied in building Mythe Bridge, with minor modifications, proved to be important for later bridges. Here is one example: a road bridge over the River Spey near Carron, 1863, built by McKinnon and Company, spanning 153

feet (approximately 45.6 m). All bridges discussed so far were road bridges. In Scotland alone 1200 bridges were built under the direction of Thomas Telford in this first phase over a period of 25 years. This gives an impression of the growing importance of transport.
In analogy to the translation into cast iron of stone arches, also domes were made of cast iron. The singularly elegant dome of the Halle aux Blés of Paris made by Bellangé and Brunet in 1811-1812 cannot be compared with anything built in Britain.
The large Conservatory in the park of Syon House should be regarded as one example of early iron dome structures. The dome resting on a drum-like substructure is supported by 12 pillars through elevated arches, independent of the facade walls. All components are made of cast iron. In addition to cast iron arches and cast iron domes, cast iron stanchions and girders emerged even before Coalbrookdale Bridge was built. Following classical examples, these stanchions were first made as round hollow pillars. The first cast iron pillar to be used in Britain stood in St. Anne's Church of Liverpool built 1770 to 1772. The model of iron girders is the cast iron rail. After 1780 cast iron stanchions were mainly used in textile mills, because they had higher strengths than timber and allowed smaller dimensions to be used. In this way, it became possible to set up heavy machinery in several storeys one above the other. Mainly aspects of fire safety promoted the use of cast iron. Besides hollow and round structures, also solid, cruciform stanchions were used.As an example of such a structure I do not want to show you the first cast iron skeleton with massive brickwork, which still exists, i.e. Flax Mill of Shrewsbury, Ditherington made by Bage in 1796-97, but a warehouse in the dockyards of Sheerness, which represents the final point in this style of building.
Quadrangle Store is made all of non-flammable materials, i.e.,it is fireproof.
The doors, windows and the roof structure are made of cast iron, as are the pillars and joists. Typical features of cast iron structures are the bolted and plug connections and the cross sections of the joists. Since cast iron can accommodate much lower tensile forces than compression forces, the tensile area must be broadened relative to the top boom. The girder cross sections correspond to a T upside down.
While already in this very first phase of the development of iron constructions wrought iron was used in France chiefly for structural elements subjected to bending stresses (Paris iron frames built in 1785 by Ango; roof structure covering the staircase of the Louvre, 1779-81, built by Soufflot; ceiling of the Théâtre Français,built by Victor Louis in 1786), cast iron had replaced wrought iron in skeleton structures in Britain up until the sixties of the 19th century.
The physical properties of wrought iron were known quite well also in Britain in that early phase. Wrought iron was naturally used as auxiliary material in wooden roof trusses or in trusses for stress relief in timber beams and cast iron girders (for instance, Paxton groove). From his trip to England Karl Friedrich Schinkel in 1826 brought home some sketches of trussed iron roofs showing the typical English trusses. The structural members are clearly distinguished by function. The rafters and struts subjected to compression have rectangular cross sections; suspended pillars and horizontal girders are designed as tie bars. A trend can be felt in this design which recurs in many other structures, especially in the second phase, between 1830 and 1870, and which is characteristic of one face of 19th century architecture: a reduction to a minimum of all structural



elements. Lightness and transparency are the reasons why these structures are still of so much interest to architects today.
But: Skeleton structures of cast iron had proved to be reliable; section beams and stanchions were cheap and available in large numbers. Even roof frames could be made all of iron, as we have seen. Accordingly, there was no reason for British iron industry to develop wrought iron structures. Why change? This is the only explanation why, as late as 1851, a building such as Crystal Palace, which was such a shining example of building design, contained lattice girders 7.30 m long all of cast iron.
Sutherland summarizes the differences in development on the continent, especially in France, and on the British Isles by saying that, in France, iron was tantamount to wrought iron, whereas in Britain it meant cast iron. The most spectacular constructions in this early phase undoubtedly are the suspension bridges: chain bridges, link belt chain bridges, cable bridges. For all these architectural problems there was only one material to be used: wrought iron, employed most efficiently whenever it had to transmit only tensile forces.
Wrought iron was available in sufficient quantities only after the puddle process had been invented by Henry Cort in 1784. The first chain bridge was built over the River Tees near Winch, Durham, in 1741. The road bed was placed right on top of the taut chains, which were protected by additional chains against excessive oscillations caused by load or wind stresses.
The different systems of suspension bridges developed at that time are mainly characterized by the attempt to come to grips with that problem.
The oldest suspension bridge in Britain still existing and used as a road bridge is Union Bridge near Norham Ford, which was opened on July 26, 1820. It spans 449 feet, which is approximately 134.7 m, and was built by the engineer Samuel Brown. The chains consist of round wrought iron bars with lugs at both ends. Union Bridge has remained unchanged in principle to this day. Two additional steel cables have meanwhile been installed to relieve the chain. Menai Bridge is the first large suspension bridge. It is still the most important road connection between the British continent and the Isle of Anglesey with the port of Holyhead as the point of departure for the trip to Ireland. Thomas Telford designed the bridge in 1817-18. Construction was started in 1819, the bridge was dedicated on January 30, 1826. It spans 580 feet, which is approximately 180 m.The chain links made of flat iron are major innovations since Union Bridge. They are 9 feet, approx. 2.70 m, long, 9.2 cm high and 2.5 cm thick. They were supplied by William Hazeldine from Shrewsbury. Except for the piers the whole structure was renewed in 1939. It had not been possible until then to achieve, by additional structural members, the longitudinal reinforcement of the roadway not planned by Telford. Moreover, the old structure had no longer been able to withstand the constantly increasing stresses. In the process of renewal the outward appearance was largely retained. New features added to Telford's design are the longitudinal reinforcement girder and the footpaths protruding right and left of the bridge.
Above all, the original 16 chains arranged in fours one above the other were reduced to two strands with two steel chains each, one above the other. The suspension bridge over the River Conway built by Telford at the same time, 1822-26, incorporates the principles embodied in Menai Bridge, but has a span of only 327 feet, i.e., 89.10 m. It has been preserved in its original state and shows the original chain arrangement of Menai Bridge.
This survey, which extends approximately up to the year 1830, was meant to show in a number of examples the groping attempts needed in

Great Britain for iron to be used in accordance with its properties, as a material for arches, domes, stanchions, girders, triangular trusses and suspension structures. As has been shown by the examples of industrial buildings and suspension bridges, this development proceeded particularly rapidly, logically and successfully whenever problems were grave and clearly defined and solutions could be found largely independent of established design concepts, from the very needs of the problems at hand.
In this phase of searching and development the foundations were laid for new architectural shapes which fully emerged in the following phases, between 1830 and 1850, and in a second period till 1870.

All remarkable structural achievements in the 19th century were based on iron. Novelties in the uses of timber, stone and, towards the end of the century, concrete had only little effect.
The second phase is characterized in particular by the development of iron lattice work structures and self-supporting skeleton structures. Designs of a new quality were developed, mainly as a consequence of architectural problems associated with railway construction:

1) The forerunners of cast iron girders were rails; the first rails were cast by the Darbys of Coalbrookdale as early as in 1767.
2) The first rolled sections of fundamental importance for structural engineering again were rails developed around 1820.

For cost reasons, used rails were often directly employed as girders for textile mills.

3) The bridges that had to be built for railway construction were the sourced of important principles of iron lattice work structures.
4) Railway station halls, workshops, locomotive sheds raised a number of architectural problems in structural engineering.

The steam engine, originally developed by Newcomen in 1712 as a pump to keep the deep shafts of mines free from water, was converted into a prime mover for processing machines independent of location, due to the improvements made by Watt.
In 1802 Richard Trevithick applied for a patent for "a steam engine to draw carriages". On February 13, 1804 the first steam locomotive was operated on cast iron plates.

In 1825 the first public railway line mainly reserved for goods transport was opened between Stockton and Darlington. With the dedication of the Manchester - Liverpool line in 1830 also regular passenger traffic was taken up. Unlike roads, railway lines are unable to follow more or less satisfactorily the shape of the country, especially on hills and in the radii of curves. The large number of bridges which therefore became necessary for optimum routing generated decisive impulses in iron construction when it came to spanning large widths. Rolling wrought iron, a technique which had been developed for rail fabrication in 1820, had led to the mass production in 1830 of angular and T-sections. They were riveted together in a great variety of types of girders. The leading example of a bridge composed of such girders is Britannia Railway Bridge over the Menai Straits built by Robert Stephenson, the son of George Stephenson, with the assistance of Fairbairn and Hodgkinson in 1846-1850. The main spans of the box girders were 460 feet, which is approximately 140 m. What had been the world's longest railway bridge for a long time had to be dismantled after a fire in 1970.
The second box girder bridge of the same type was built by Stephenson over the River Conway, very close to the chain bridge by Thomas Telford, with a span of 412 feet, which is approximately 124 m. This second bridge was completed in 1848, a test case for the much larger Britannia Bridge.



Stephenson's design was preceded in 1845 by a series of tests by Fairbairn and Hodgkinson which were conducted to determine the strength properties of cast iron and wrought iron and define the optimum tube cross section. This is the first time that scientifically based findings were applied to an engineering construction in Great Britain, 100 years after the foundation in Paris in 1747 of the Ecole des Ponts et Chaussées. Cullmann criticized the belated experiments by British engineers as being unnecessary, accusing the authors of a lack of theoretical knowledge. The results, he said, were not too different from what could be found in any textbook of mechanics anyway.
In my mind, this is rather characteristic of the different approaches by British engineers and their continental colleagues. Despite the absence of theoretical knowledge, Robert Stephenson, even if unconsciously, designed the first continuous girder in building Britannia Bridge when he riveted the series of four pipes into one. The static possibilities of the box girder he had developed were successfully applied in bridge building only 100 years later.
The development of self-supporting wrought iron structures around 1850 was largely due to the use of rolled sections for structures with spans as wide as that of Britannia Bridge.
The next step towards lattice girders to be taken in bridge building in Britain was prevented by Robert Stephenson by his personal vote. Only the 1862 International Exhibition of London, at which a model of Dirschauer's lattice girder bridge was displayed, revealed that this system could have reduced the cost of Britannia Bridge by fifty percent.
The first girders with parallel top and bottom chords developed mainly by the American engineers Whipple, Howe and Pratt date from the forties of the 19th century. As is documented by the wrought iron lattice girders of Crystal Palace in Great Britain, the magnitudes and directions of the forces occurring in such lattice girders were known and could be determined in that country at least after 1850, which is inexplicably late, considering Palladio's description of a German lattice work structure in 1570.
Another problem of architectural engineering connected with the rapid development of railways, which greatly furthered the development from cast iron arches to wrought iron arched trusses and from timber trusses to lattice work structures, were railway station halls.
George Stephenson, whose steam locomotive called "Rocket" operated on the Manchester - Liverpool line, built the first railway station together with J. Forster in Liverpool in 1830, Crown Street Station. It consisted of a building erected parallel to the rails which contained waiting rooms, ticket counters, offices and residential apartments. The platform was roofed over by a timber truss structure with a span of 9.10 m. Right into the forties of the 19th century such timber trusses remained the roofs over station platforms in England: besides the roof of Crown Street Station there were the roofs of Lime Street I of Liverpool, 1836, Nine Elms of London, 1837-1838. Afterwards, iron suspension structures, mostly designed as "English trusses," replaced the heavy timber structures: Euston Street Station of London, 1835-39; Curzon Street Station of Birmingham, 1839; Trijunct Station of Derby, 1839.
The most efficient triangular truss design on the continent was developed by Wiegmann and Polonceau between 1836 and 1839. While this type of truss was mainly used for French railway station halls, British engineers preferred arched trusses for their halls. Although these arched roofs allowed for much greater spatial variability, they were less economic than the smaller and lighter French structures. Arched designs certainly met the historizing design concepts of the

19th century in a very special way.
Arched trusses were used in three basic types:

1) as plate trusses,
2) as trussed arches,
3) as lattice arches.

A rolled arched truss was used for the first time by John Dobson in building the railway station hall of Central Station, Newcastle, 1846-55 with a span of 17 to 20 m.
A comparable building was erected in York in 1871 by Prosser who had also worked at Newcastle. Colours, larger glass areas and ornaments on the trusses resulted in the comparatively much more elegant and lighter appearance compared with the hall of Newcastle. Kings Cross Station of London, built by Lewis Cubitt in 1851-52, is surprising above all because of its facade, which is determined by the two halls. The original semicircular timber beams made up of bolted boards joined by the Emy system were replaced by wrought iron trusses in 1870 without changing the outer appearance. Other impressive examples of the use of these timber engineering structures are the Central Hall of Smithfield Market, London, built by Horace Jones in 1867-68, and the Royal Scottish Museum of Edinburgh built by Matheson. Also Paxton had used arched board trusses in his Crystal Palace.
One of the most impressive station halls, which was arched over with rolled plate trusses, was built by Isambard Kingdom Brunel for Paddington Station II in London in 1852-54. In his father's office Brunel had already worked on the first tunnel under the River Thames, had won a competition over Thomas Telford for the Clifton suspension bridge in 1831, which bridge was completed only in 1859 after his death, had supported Robert Stephenson in building Britannia Bridge, had constructed a railway bridge over the River Wye near Chepstow in 1852 and completed the design of a bridge over the River Tamar near Saltash. He was able to win the architect Mathew Digby Wyatt as a collaborator on this railway hall who was made responsible for ornaments and decoration. Moreover, Owen Jones, who had been responsible for the colourful variety of Crystal Palace, the colour concept of which unfortunately has been lost, cooperated in the project. Fox and Henderson were responsible for the iron structures after having successfully completed construction of Crystal Palace. The centre aisle of the original three-nave building has a span of approximately 31 m, the two aisles each span 21 m. Two transepts cutting into the longitudinal barrels like lunettes are parts of the longitudinal reinforcement. The glass roofing makes visible the vault-type structure.
In 1916 the fourth nave was added over the cab stands. Plate trusses were no longer suitable for the continuously increasing spans.
For this application it was much better to use the second type of arched structures, trussed arches. They constituted advancements of the principles of triangular lattice girders. Such arches shaped like crescent trusses were used for the barrel shaped roof of London Bridge Station in 1844 and the roof of Bethnal Green Museum, built as a Museum of Science and Arts by C.B. Young and Son at Kensington in 1853-54 and brought to Bethnal Green in 1871.
Fenchurch Street Station of London, built by George Berkeley in 1853-54 with a span of 32 m, also has a crescent shaped truss which is very closely related to the famous truss of Lime Street Station II. It was constructed in 1847 by the Dublin iron founder Richard Turner with the enormous span, for that time, of 47 m. Turner in his greenhouses of Belfast in 1839, Dublin in 1843 and, above all, Great Palmhouse of Kew Gardens, 1845-48, besides Joseph Paxton with his



greenhouse of Chatsworth, 1836, and Crystal Palace, 1851, had fundamentally influenced building with iron and glass. "It should be a large greenhouse tailored to the needs of railways," was an explanation given by Brunel of his concepts of the appearance of the railway halls of Paddington Station then under planning.
Turner's greenhouses are also examples of a close juxtaposition of cast iron and wrought iron with their different physical properties. Cast iron, which was mainly able to bear compression stresses and could be worked to ornamental forms without great expenditure because of its capability to fill moulds, was used for columns or components which needed decorative treatment, whereas rolled T-sections of wrought iron or forged round bars were used whenever tensile or bending forces had to be transmitted. Turner in this way created logically differentiated building concepts evident also to the observer, because they were free from any arbitrary elements. The subdivision of his structures into single elements, which could thus be shaped to meet their specific purposes, made the buildings true to scale in a way corresponding to that of the plants exhibited.

The same concept of design construction is incorporated in the hall of Victoria Station, 1859-66, with a span of approximately 40 m, for which Robert J. Hood used the third type of arch, the lattice arch. Now the most suitable design had been found for arches spanning large widths, a precondition of the construction of the monumental railway station halls in the last third of the 19th century.
The hall of St. Pancras in London, completed in 1868 by the engineers Peter William Barlow and E.N. Ordish, had spans of 71.40 m, which made it the first of these monumental halls and, for a long time to come, also the largest. As previously in the greenhouses of Paxton and Turner, the trusses are directly placed on the floor of the hall, thus abolishing the separation of wall and ceiling.
St. Enoch Station in Glasgow, built in 1875-76 by W. Blair and E.N. Ordish, which was demolished two years ago, and Manchester Central Station built by L.H. Mourson in 1877-78, today used as a parking lot and threatened by disintegration, are direct successors of St. Pancras. The further development of lattice work structures after the mid-sixties began with the introduction on the continent of hinged girders and hinged arches for bridge structures and wide-span halls.

This also applies to the advancement of earlier cast iron dome structures into the lattice work domes with static space effects (such as the Schwedler dome).
In Britain, the system of cast iron or wrought iron ribbed domes continued to dominate architectural designs.
In connection with representative buildings requiring much light or light coming in from the top, such as winter gardens, passageways, exchanges, libraries etc., very delicate structures were built, such as Kibble Palace of Glasgow, built by John Kibble in 1873; Barton Arcade of Manchester, 1871-73; Corn Exchange, Leeds, 1860-63 built by Cuthbert Brodreck; Royal Exchange of London built by Charles Burry in 1880.

At the end of this survey, which was to show the emergence of typical iron structures, I should like to describe the "Boat Store" in Sheerness built by G.T. Greene in 1858-60.
Undoubtedly, the Crystal Palace built by Paxton, with Fox and Henderson as contractors, all design drawings of which were made by Charles Fox within seven weeks, constitutes the first rectangular independent steel skeleton building and has had an extremely stimulating effect on the propagation of iron structures with respect to design, forms, space impression, assembly and prefabrication

However, even at first sight Boat Store seems to be removed from Crystal Palace more than just eight years. The iron skeleton buildings, which had been developed into independent structures even before Crystal Palace and Boat Store, used arches as structural elements on the basis of iron bridges. This was the advent of large, light-flooded halls.
In the field of multi-storey buildings this development took longer. Here the advantages of skeleton structures could be made use of only after the massive enclosing walls were no longer necessary for structural reasons, for instance, for longitudinal and transverse reinforcements. This was achieved, for instance, by cruciform wind braces: In his Boat Store Greene demonstrated the possibility to design an iron frame and make it stand only by means of bending resistant ties between the girders and the principals.
In his lecture "The Boat Store, 1851-60, and its Place in Structural History," London, 1960, A.W.Skempton indicates that Greene got some decisive ideas for his Boat Store from the structure of Bethnal Green Museum. The reasons which caused G.T. Greene to use an iron skeleton structure for the dockyards of Sheerness were the shorter building time, the lower loads on the foundations, for the whole dock had to be piled, and better possibilities of admitting light.
The excellent details, according to A.W. Skempton's opinion of Greene's building in his paper referred to above, compared well with the details of Mies van der Rohe's apartments on Lake Shore Drive of Chicago.
The Boat Store is a culminating point in the development of multi-storey skeleton construction in Great Britain, a point from which the steel skeleton structures of the Chicago School went on.