IRON BRIDGES - SOME ASPECTS OF DEVELOPMENT

Ernst Werner

Considering that iron already existed before the 19th century, it is really surprising that it suddenly began to play such an important role also in building construction in the first half of the past century. Sufficient facts can be assembled, however, to make this development understandable.

Let me briefly sketch some of the most important data. First of all, daily outputs of iron production in former centuries were simply too low. Without going into too many details, I should like to mention that an iron producing plant in Styria had the highest outputs which roughly amounted to the following quantities:

in the 15th century, 12oo - 15oo kg/day
in the 16th century, 17oo - 18oo kg/day
in the 17th century, 18oo - 21oo kg/day.

These are truly small quantities which, in turn, made iron a relatively precious material. At any rate, it was too precious to be used in buildings als long as

(1) sufficient other, conventional building materials were available and
(2) there was no need or demand for new building designs.

As long as charcoal was used for iron smelting it was not possible, for process reasons, to improve the performance of iron smelting furnaces. But even increasing the number of iron furnaces in the 17th century did not help to raise iron production beyond a certain limit because it had become impossible in some regions to procure sufficient quantities of charcoal. Forests had been cut down too severely for iron smelting and other uses, as is evidenced by a picture of the environment of the Sayner Hütte ironworks.

Only in the mid-18th century it became possible, after lengthy and discouraging experiments, to use coking coal, which had been known for a long time, also in iron smelting. This, in turn, allowed the production of iron to grow.

In the same century the world's first iron bridge was built in England, Coalbrookdale Bridge completed in 1779. The bridge was built near the ironworks where the decisive experiments had succeeded in smelting iron ore by means of coking coal.

The overall weight of this bridge, which spanned some 30 meters, is roughly 380 tonnes. This is said to have been the annual output of the Coalbrookdale ironworks. As we all know, the bridge still stands.

Construction of the first iron bridges was a particularly fascinating art. For the first time after many centuries a building material not considered hitherto was employed in building construction. On the one hand, this invited emulation. On the other hand, the state of the art demonstrated by the first few iron bridges by far had not reached the level of knowledge necessary to learn about all technological implications. It took roughly another decade and a half for this learning process to be completed elsewhere, and only then were the technical implications of the first iron bridge put to practical use for transport purposes. There were earlier successful attempts to follow up on this technical novelty, less by technical application than by displays of something not known before. Numerous bridges in parks were built on a reduced scale, merely for use by pedestrians, but closely resembling some grandiose examples.

Thus, also Coalbrookdale Bridge found its miniature scale imitations. In 1791, a park bridge of this type was built in the palace garden of Wörlitz. Unfortunately, I do not have a photograph of this bridge,but I can show you the picture of another park bridge, that of Quarenghi built 1782 to 1786 in the park of Tsårskoe Selŏ. The resemblance to Coalbrookdale Bridge is really striking. Please, bear in mind that the construction of this park bridge was begun merely three years after the completion of Coalbrookdale Bridge.

The first iron bridge serving general transport purposes in Germany, another arched bridge, was built in 1796, i.e., five years after the Wörlitz park bridge, over the Striegauer Wasser near Laasan in Lower Silesia. I have not been able to find out whether it still exists. At any rate, it is mentioned as existing in an article published in a technical journal in 1930. Only after 1820 more iron bridges were built in Germany.

Iron production in larger blast furnaces with cheaper coking coal, compared with the production in smaller furnaces with increasingly more expensive charcoal, made iron a cheaper material. This transition had been enforced by the scarcity of fuel. However, in the process of iron smelting it was not forgeable bloom, as in the old process, but cast iron which was produced as the final product. This material was not at all received with undiluted satisfaction, for it could not be treated in the usual way. Cast iron cannot be forged.

In addition cast iron, very much like stone, has considerable strength under compression loads, but hardly any strength under tension loads. Accordingly, cast iron could be applied as a material in building construction only in structural members which, because of their very stress distribution patterns, generated only compression loads in their sections, which means that only arched structural members could be built. It is therefore not surprising to find the first iron bridges follow the customary forms of stone bridges, at least in their outlines, because they were still made of cast iron. Because of the higher strength of iron compared with that of stone, the sections used for load distribution could be concentrated on a few lines and did not require the whole sectional area, as in stone bridges.

As late as in 1784 the so-called puddling process was introduced as a refining technique by means of which cast iron could be converted into technically useful quantities of forged iron. This brought back the old forgeable iron. It is interesting to note that the first iron suspension bridge of which data can be found, i.e., structural members preferably subjected to tensile stresses, was built only in the last years of the 18th century, which is some 15 or 20 years after the introduction of the puddling process.

One very important feature influencing the construction of iron bridges and bridge construction in general is the emergence of railways. After James Watt had not invented the steam engine, but brought to technical maturity a lengthy development process of several centuries, efforts were launched soon to use steam engines for transport purposes. Various attempts to operate steam cars on the streets failed, but the use of steam power in shipbuilding achieved a comparatively early breakthrough.

Only when cars were run on special tracks the right combination had been found for steam energy to drive land vehicles, i.e.,railways. The first steam engine to run on iron rails was built by Richard Trevithick in 1804. In the early 19th century George Stephenson succeeded in disengaging railways from their sole use in mining operations thus turning them into independent means of transport. In 1825 the first public railway line was opened between Stockton and Darlington, and when Stephenson's "Rocket" won first prize in

1830 in a competition close to Rainhill, on the line between Liverpool and Manchester, the rapid development of railways started, rapid even from a present-day point of view. The impulses railway systems gave to the budding iron industry were extremely strong. Railway lines spreading by leaps and jumps, e.g., 500 km of new lines were annually commissioned in Germany in the first 15 years after 1835, required the rapid construction of bridges capable of carrying high loads. Bridges for railways and bridges for roads alike soon used iron without, however, forgetting the usual materials, wood and stone. In America and other countries rich in wood reserves splendid wooden bridges were built even when the construction of iron bridges had already reached a high level. Incidentally, the Göltzschtal viaduct in Germany was built when Stephenson already constructed his tube bridges in England.

In 1850 German railway administrations agreed to no longer build any wooden bridges on their main lines. While roads and paths were still adaptable to changes in terrain, railway lines had to meet the technical possibilities of operation. Railway lines and gradients can be varied only within very narrow ranges. Accordingly, more valleys and intersections had to be bridged than for roads. While many roads terminated at the banks of rivers and transport to the other side had to be achieved either through fords or by ferries, efficient operation of railways soon proved to be impossible if lines ended at every obstacle thought to be too large. Railway operation requires fast, uninterrupted runs over long distances.

I think one can agree with Schadendorf who said: "All bridge construction before 1828-29 was just a prelude, and only railways pushed development ahead".

The first iron bridges for railways seem to have been built in the state of Baden. One of them is still used as a road bridge in the city of Staufen where it spans the small river of Neumagen. This bridge was probably built in 1845. It was part of the Baden railway line through the Rhine valley connecting the cities of Frankfurt and Basle. Like many other bridges, also this one was made of cast iron. Aside from the fact that its load carrying characteristics are not very clear, a quantitative assessment of stresses so as to approximate the actual behaviour with sufficient accuracy was not possible anyway, given the state of the art at that time. When this bridge was under construction, the fact that cast iron was not optimally suitable for railway bridges became more and more evident as a result of frequent major collapses. Cast iron, because of its lack of elasticity, will not carry shock-type loads such as are produced by railway operation. Even such famous experts as Stephenson father and son were not spared such collapses.
Anyway, the bridge was removed from the railway line and parts of it were reused later as a road bridge in Staufen.
This is most probably the only bridge existing and still used in Germany with cast iron as the only material of its main structural members. Collapses of cast iron bridges greatly delayed the propagation of iron bridges. As late as in 1846 warnings were expressed in Germany against the construction of iron bridges because the experience available was deemed to be insufficient. These general warnings of iron bridges were probably influenced by the collapses of cast iron bridges.
However, it should not be overlooked that iron constructions involved hazards inasmuch as they abandoned traditional sectional dimensions and, in doing so, expanded into designs and structures previously unknown without being able to replace the resultant lack of experience by some other structural design principle. What was missing was the field now called building statics. At this point it should be mentioned that the historic designs of structural members made of wood, stone and cable-type materials had developed in accordance with pure crafts traditions, albeit on the basis of natural phenomena observed. There had never been any mathematical or mechanical penetration of the subject and, accordingly, no technical or scientific theories and no set of theories had ever evolved which could have been used in the construction of such structural members. In fact, there was never a theory out of which abstract structural members could have been developed which would then have been implemented in practice. Instead, the structural systems developed and completed over many centuries only subsequently initiated some mathematical and physical treatment which not only served to determine the interaction of forces qualitatively, but also to recognize and evaluate it quantitatively.

On the other hand, the basic principles of present-day building statics have an old tradition.
Already Archimedes, and probably Aristotle before him, dealt with the phenomenon of the lever, defining and explaining causes and effects. This means that the early days of mechanics date from the third and fourth centuries before Christ. This old mechanical experience was available. Also the interaction of forces, the balance of several forces acting on one point, had been known for a long time.
But buildings were created out of a deep sense of harmony which also included the harmony of forces, that is, the balance of forces. This more emotional approach to building, on the one hand, and the stringent requirement of science, on the other hand, to remain free from common utilitarian ideas, may have been the reasons for scientific findings being incorporated in building construction at a relatively late date.
Till the Middle Ages mathematics and geometry were applied to building construction only to the extent in which they helped to establish simple relationships between rules of composition and proven dimensions of building structures. This was done either numerically or by means of geometry. But the extensive knowledge of mechanics was never used to calculate static conditions of a building, i.e., to determine sectional dimensions as a function of loads and material qualities. Builders in those times were able designers; this is borne out by the monuments that have been preserved to this day.
Indeed, those who laid the scientific foundations of building statics and the theory of strength were concerned more with precise theory than with practical application. With a few exceptions, hardly any of them ever collaborated in the practical implementation of building jobs. The great examples of building construction of which we know were made by builders who happened to be contemporaries of scientific discoveries which also affected building construction, but which they never used.

For many centuries, roughly up until the mid-18th century, building was exempted from any theoretical coverage which tried to recognize and assess forces. This condition persisted and prevailed where, and as long as, the effects of Greek culture and, hence, its concept of science to be cultivated for its own sake remained viable.
This kind of science not burdened by any aspects of practical implementation did indeed exist. As far as the development of building statics, especially the bending problem, is concerned, a few steps might be recalled here:

- Already Leonardo da Vinci worked on the bending problem, arriving at a comparative assessment of the load carrying capacities of different supported spans and sections.

- Galileo for the first time applied the laws of mechanics known at that time to study the stability of solids. In the static problem bearing his name he investigated a beam with one end fixed in a wall and loaded at its free end, thus trying to derive information about the stresses occurring at the fixed end. Even if his basic approach was wrong, he was still the first scientist to establish a relation between external loads and internal stresses.
- The Englishman Hooke in 1675 published the law named after him, according to which strains are proportional to stresses.
- Mariotte and Leibniz improved the studies of fixed-end beams. Leibniz achieved great merits in introducing the infinitesimal calculus in these studies.
- Jakob Bernoulli in 1694 stated the interdependence of the radius of curvature and the bending moment, a theory the Dutchman Huygens regarded as a nice bit of intellectual game, but without any use, which was bound to be the outcome if people didn't know where to apply mathematics with more sense.
- In the late 18th century work on the bending problem had been carried far enough to allow the problem as such to be regarded as solved. However, all this work was subject to a purely mathematical goal and was not extrapolated to practical building construction.
- In the meantime, the first technical education centres were established in France, the Ecole des Ponts et Chaussées in 1747 and the Ecole Polytechnique in 1794. This initiated major impulses to the development of adequate technical and scientific theories for the pragmatic interests of technology.
- Hence, it is almost logical for Navier, a teacher at these colleges, to summarize the numerous studies available on the bending problem, add some work of his own, attempt to apply them to practical building construction and publish them as a book in 1826. This is called the birth of building statics.

This is the first introduction into building construction of a technique relating stresses to loads in structural members, even if only for specific ones, i.e. beams subjected to bending stresses. Yet, this had some impact, especially on structural members in bridge building. This bending theory was applied as a substitute to girders subjected to bending stresses and to such structural members as close-meshed lattice girders developed from timber structures. Although this was not entirely correct, it represented a rather useful approximation under certain conditions. In order to optimize this approximation,

- either the meshes between the lattice bars were neglected,
- or the thickness of the material of the lattice bars was reduced to a theoretical solid plate,
- or the lattice bars were neglected altogether and only the chords were considered in calculation.

Iron was still a very precious building material and, then as now, had to be used very economically. This compelled builders to assess the forces arising and dimension cross sections as precisely as possible. On the other hand, the uniform structure of this new material, which was highly independent of external influences,unlike all earlier materials allowed the rules of building statics to be applied clearly and firmly.

The strength properties of iron, which could be planned with a high degree of reliability already during fabrication, soon resulted in very high permissible stress levels being adopted. Of course, this was only possible by further refinement of the tools of building statics so as not to jeopardize the residual safety margin. Bending theory had provided such a tool.

It is difficult to say whether iron promoted the development of bending theory or whether bending theory furthered the use of iron in bridge building. To the extent that these were girders, they were now free from the random facts of experience which were no longer of any use for these constructions. For other structural members, for which such a method with sufficient technical accuracy was not available, a comparatively simple technical remedy was found in dimensioning. Designs were based on established building forms, and for iron structures merely the sectional areas were reduced as a function of the strength of iron versus that of stone, This was done, for instance, in arched bridges. However, for girders such or a similar reference did not exist. This fact illustrates the unsafe ground on which the first iron bridges stood, if they were girders.

Hence, it is not surprising to see that the early years of the construction of iron bridges were disturbed by many collapses,which greatly detracted from the glamour of the new material. Consequently, the establishment of a theoretical basis played a major role in the further development of the construction of iron bridges.

Let me also briefly refer to some other developments leading to the establishment of a theory: I am referring to the theory of trusses.

Starting from the basic designs of trusses and truss frames, a variety of structural systems had evolved in the construction of timber bridges. As spans grew, more and more of these basic designs were superimposed. When wide-span wooden bridges were used also for railway purposes, especially in America, which meant that they would have to withstand much higher loads, the number of structural members superimposed on each other acquired irritating proportions. Yet, many of these bridges collapsed despite the vast expenditure in materials involved.

This was the situation when the Bavarian building official Culmann (1821-1881) took a trip through North America on behalf of his government in 1849 and 1850. He wrote a report about the construction of the wooden bridges he found in great varieties in the USA; the report which was published in 1851, contains a theory of trusses. In the same year also Schwedler announced such a theory. Culmann developed his theory from a penetrating analysis of the load carrying behaviour of the bridges he had seen, whose systems had been put together without any knowledge of their actual load carrying behaviour.

Culmann tried to assess the load carrying behaviour of complex structural members of bridges by initially reducing to some typical basic designs the practical cases of wooden bridges with their sometimes most unclear systems. One such basic design is the parallel-chord truss. The term truss is used by Culmann for the first time to describe structures consisting of top and bottom chords and webs arranged in such a way that all pieces always form triangles. He also made the extremely simplifying, but permissible assumption that all pieces intersect at truss joints.

American and British engineers for many decades implemented the theoretical concept of the articulation of truss members at truss joints by using real bolted connections for their truss joints.

On the European continent this extreme approach was not followed, as a rule, but care was also taken to ensure that the axes of truss pieces intersected at one point, if possible. This takes care of the assumption of intersection joints with a sufficient degree of accuracy. It also provides the geometric accuracy of triangles in theoretical assumptions and practical implementation. The lattice girders now built consequently became much less complicated in design and much more transparent in terms of their load carrying behaviour.

On the one hand, these simplified trusses thus became calculable for the first time; on the other hand, this simple structural principle had recognizable repercussions on the design of established truss systems which gradually and increasingly changed into structural members composed of triangles.
For comparison, just see the examples shown here dating from the period before the publication of the theory of trusses. Both are so-called trusses girders. Their sheer size sometimes grew to meaningless proportions as, in previous times, the variety of forms of trusses and truss frames in timber structures.
This elucidation of the load carrying characteristics of truss girders also led to the so-called lattice girders, of which I showed a few examples, being replaced by wide-mesh trusses. However, up to that point in time some spectacular bridges were made in that structure, for instance, the first iron bridge to cross the River Rhine in Cologne, which people called the "Muusfall" (mousetrap). These lattice girders were the continental European variety of the English tube bridges of which I showed Britannia Bridge. Incidentally, lattice girders were covered neither by bending theory nor by the theory of trusses.
For comparison, I would like to show you another lattice girder bridge in order to indicate the development which had taken place meanwhile.

The transition from cast iron to forged iron, especially the trend experienced early on the European continent to fix the intersections not in precise articulated joints, finally led to junction plates.
In many instances this solution was hard on sensitive eyes. This is a comparatively good example. These frequently ungainly plates were instrumental in destroying the original clear lines of trusses, or at least upsetting them considerably. Consequently, it is not surprising to see such amorphous designs becoming synonymous for ahuman building and the symbols of artists' criticism of technology.

Under the limits imposed by my subject I was able only to discuss a few short aspects of the complex web of conditions surrounding the development of iron bridges. More had to remain unsaid than would be warranted in the interest of the subject matter. Yet, I hope that this paper has been able to provide some ideas.