The International Conference
PRESERVATION OF ENGINEERING HERITAGE - GDANSK OUTLOOK 2000
Gdansk, Poland September 7-10, 1999

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EVALUATION OF STRUCTURAL RELIABILITY OF HISTORICAL METAL BRIDGES

Abstract

Historical bridges, even quite recent ones, are precious historical records worthy of study from the point of view of industrial archaeology. Indeed, because of both the high level of scientific and technological knowledge and the variety of structural concepts and details they contain, bridges do offer an important synthesis of the prevailing trends in the civil engineering of their period.
In Italy, there is growing interest in the historical analysis of theories and techniques of construction, with particular attention paid to putting intuitions and theories of construction science into practice. Early metal bridges, mainly built in the second half of the nineteenth century and in the first decades of the twentieth century, are of special interest because of their close links with the world of science and construction technology in a period of rapid innovation and theoretical development and consolidation.
In addition, a large number of metal ancient bridges are still used for roads and railways. The problem of their preservation and rehabilitation is very felt and starts from the need of measuring their structural reliability. For this purpose an expert system to be used for the automatic evaluation of the state of conservation of metal bridges has been developed and here presented.
For proceeding with systematic data gathering, it has been necessary to choose a powerful and versatile method for cataloguing the data. Such a method had to be able to facilitate both a general and a more detailed examination of all the structural deficiencies of the elements of iron bridges and offer a system of interconnected data which can be interrelated to give an overall evaluation of the structure.
This automatic method allows then for an inventory of metal bridges with the aim of encouraging projects of rehabilitation for the conservation of historically interesting bridges.

1. INTRODUCTION

In many countries of Europe, as well as in many states of United States (in particular in the New England), there is a very large heritage of bridges built at the turn of the nineteenth century. There, transport departments have set up systems for cataloguing historical bridges, which are of large interest because of the contribution they make to the landscape. In addition, there is growing interest in the historical analysis of theories and techniques of construction, with particular attention paid to putting intuitions and theories of construction science into practice.
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of science and construction technology in a period of rapid innovation and theoretical research.
The development of metal bridge typologies during 19th century was characterised by great transformations, due to the introduction of the new materials: cast iron, wrought iron and steel. A particular attention must be paid to metal arch bridges, which allowed combining the strength of the material with the lightness of the structure.
As is well known, the first iron bridge is across the *Severn River* at *Coalbrookdale*, in the plan of *Shropshire*, 30 km at North West of *Birmingham*. It was built between 1775 and 1779 by *Abraham Darby III* (1750-1791), who was the owner of the foundry at Coalbrookdale, where the elements of the bridge were fabricated, with the co-operation of the *architect Thomas Farnolls Pritchard* and of *John Wilkinson*. The bridge consists of five semicircular arches, 30m in diameter. Each arch is made of two parts, which were cast in horizontal sand moulds.
Soon after, around 1780, the Frenchman *Vincent De Montpetit* faced the problem of building metal arch bridges at locations far from the foundries. To be solved for the first time was the crucial problem of metal construction: to divide the structure in many elements, to be transported and assembled in-situ. The experience of stone masonry arch bridges was present and it suggested the method of separation of pieces. The first cast iron bridge of this type was built in 1796 by the Englishmen *Wilson* and *Burdon*, at *Sunderland* on the *Wear*, with a 72m span. It became a model used for over 20 years for cast iron arch bridges in Europe.
At first, the connection between the elements was achieved by means of wrought iron bolted joints. A large number of more economical solutions were soon proposed for this connection, in order to reduce the quantity of wrought iron elements.
The *Southwark* bridge in London, built by *John Rennie* in 1819, represents the last important step for cast iron construction, with the introduction of flanged joints between cast iron box elements. This solution was used for most succeeding cast iron arches.
Among the early cast iron arch bridges built in Europe, the following must be mentioned: the *Pont du Jardin du Roi* (5 spans) and the *Pont des Arts* (9 spans) across the *Seine* in *Paris,* the *Pont sur le Crou*, near *St. Denis* (one span), and later (1833-36) the *Pont du Carousel*, across the *Seine* in *Paris* (three 47m spans) designed by *Antonie Remy Polanceau,* and the bridge on the railway line *London-Birmingham Railway* (1840), by *Robert Stephenson*, characterised by circular elements in the spandrels. A reproduction of this bridge is included in the collection of didactic models made by Prof. *Pio Chicchi* between 1890-1899 and conserved at the Department of *Costruzioni e Trasporti* of *University of Padova* [11]. The first cast iron arch bridge built in the U.S. is *Dunlap's Creek* bridge in *Pennsylvania*. It was designed by *Richard Delafield* and completed in 1838. It has a span of 24m and consists of five arches formed by bolting together hollow elliptical cast iron voussoirs. It remains in use today.
A crucial design problem for early metal arch bridges was how to reduce deformations and vibrations under variable loads. *Thomas Telford* was the first engineer to propose the possibility of using the deck and spandrels stiffening elements, for his design (1800) of the *London Bridge.* This bridge was not built, but about ten years later, Telford used rigid truss spandrels for the bridges at *Bonar* (1811-1812) and *Craigellachie* (1812-1815). Other notable examples of this type are the bridge of *Sregadin over Theiss*, by *M. Cézanne* and *M. Maniel* (1856-1859) with eight fixed arches, the bridge on the channel of *St. Denis*, designed by *M. Couche* and *M. Mantion*, 45 m span, which was probably the first two hinged arch bridge (1858), the bridge over *Cellina at Montereale,* by *G.B. Biadego* (1878), the railway bridge designed by *J. Palme* (1880), all reproduced in the already mentioned collection of didactic bridge models at Padova.
Another very important problem was how to resist the horizontal thrust of arches (a similar problem was present in suspension systems). This was a stimulus for the evolution of metal arch types. Stephenson provided an original solution in 1836, with the building of the first

Bowstring bridge with cast iron arches and iron chains at *Newcastle,* with multiple spans of 38m. *Squire Whipple* in the U.S. and *Isambard Kingdom Brunel* in England improved the bowstring form.

Whipple built the first iron bowstring bridge over the *Erie Canal* in New York State in 1840, and patented his design in 1841. Whipple used cast iron for the compressive arch and wrought iron for the tension tie. Whipple also included diagonal elements so that truss action rather than arch action is dominant for some loadings. Whipple's design and his writings were very influential in the U.S.. By the 1870's hundreds of iron bowstring arch-trusses were manufactured by dozens of bridge companies and shipped throughout the U.S. The bridge companies used a bewildering variety of element cross-sections and joint details. One of the major design concerns was the lateral stability of the arch. Several lateral bracing systems were used, with uneven effectiveness.

In 1849, for the bridge at *Windsor* (57m span), Brunel placed a light lattice of diagonal elements between the arch and the tie chain, to serve the stiffening function of the spandrels designed by Telford. Two year later, Brunel faced a dual problem for the suspension bridge of *Chepstow* (90m span), with a suspension chain corresponding to the arch and a strut (about 3m diameter) corresponding to the tie rod. In 1858, starting with the arch and suspension structural systems, Brunel proposed a very large truss-arch (137m span) in which the arch and the suspension chain were the chords. This was the prototype of trusses with almost constant forces in the chords for a uniform loading condition.

Early railway truss bridges were built in America, in wood, starting about 1831. In the tradition of Burr wooden bridges, *Herman Haupt* designed and built all-iron truss-arch bridges, beginning about 1854. Haupt's designs were the first all-iron bridges used on *the Pennsylvania Railroad*, although the railroad quickly switched to iron versions of *Pratt* trusses. By far the greatest achievement in metal arch construction in the U.S. is *James Buchanan Eads'* magnificent bridge over *the Mississippi River* at *St. Louis*. Eads' bridge consists of three spans (153m, 158m, 153m) and was completed in 1874. Eads made pioneering contributions to foundation technology, material technology, and fabrication/erection technologies.

Several very large iron *truss arches* with bolted joints were built for railways and roads in Europe. Many of them are well known as monuments of industrial archaeology: the bridge across the *Rein* at *Horch-halm* near *Coblenz* (two two hinged arches of 106 m) by *M.M. Altenloh* and *J. Zimmermann* (1876-79); the bridge across the *Rein* at *Coblenz* (two hinged arch) by *M. Hartwich* (1862-64); the celebrated railway bridge of *Garabit* across the *Truyère* (two hinged arch) by *G. Eiffel* and *L. Boyer* (1884-85); the railway bridge of *Paderno* across the *Adda River* (fixed arch 266m span, 80m high) by *Rothlisberger* (1887-1889). Structural details of these bridges are very well reproduced in the mentioned historical collection of bridge models of Padova University [11].

The author has concentrated his attention to the structural evolution and to the problems of conservation of such constructions erected during this period, with particular reference to the metal bridges of Veneto Region [12], where innovating professors and engineers were working at the time. In a previous paper [10] he suggested a powerful and versatile *method for cataloguing the data of historical metal bridges* in order to facilitate both a general and a more detailed examination of the panorama of the production of iron bridges and be able to identify and describe the more important structural aspects. Such a method allows building a system of interconnected data which can be interrelated and, which are easy to manage.