Development of Reinforced Concrete Arch Bridges in the U.S.: 1894-1904

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Abstract

In 1894 Fritz Von Emperger presented a paper on concrete-iron bridges at the International Engineering Congress. Von Emperger showed examples of European reinforced concrete arch bridges and extolled the qualities of German cement. He described tests that showed the superior performance of the Melan reinforcing system, which was patented in the U.S. in 1893. Late in 1894, Von Emperger built the first Melan arch in the U.S. at Rock Rapids, Iowa. Although a few reinforced concrete arch bridges had been built in the U.S. prior to 1894, Von Emperger’s efforts in promoting the Melan system as a “permanent”, cost-effective alternative to products of bridge companies initiated a sustained, rapid development of technologies related to reinforced concrete arch bridges. Reinforced concrete systems were enthusiastically adopted and entrepreneurial designers such as Edwin Thacher and Daniel Luten developed and patented their own proprietary systems. Engineering literature of the period contains revealing opinions on the nature of composite action, advantages and disadvantages of various arch forms, “proper” shapes for arch axes and suitable design methods. The evolution of reinforcing systems is followed and pioneering examples of reinforced concrete arch bridges are given.

Introduction

The introduction of reinforced concrete for arch bridges and other parts of the infrastructure at the end of the 19th century required the concurrent development of a daunting number of technologies:

a) Cement technology  

b) Concrete technology  

c) Reinforcement technology  

d) Analysis and design methods for reinforced concrete composite materials and elements  

e) Analysis and design methods for reinforced concrete arches  

f) Construction technologies

Each of these technologies had numerous unresolved technical issues. Appropriate component materials and processes for manufacturing Portland cement were still developing. Understanding of hydration was incomplete. An experimental or

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scientific basis for control and design of concrete mixes did not exist. There was a paucity of data on the properties of hardened concrete, especially creep, shrinkage and freeze-thaw resistance. There were many, often proprietary, reinforcing systems, which used smooth or deformed bars, expanded metal, rolled rail or standard sections, or fabricated, truss-like assemblies. The behavior of steel-concrete composite sections was unresolved. Issues of bond, anchorage of steel, shear and flexural strength of beams were in debate, as well as appropriate modeling and design of arch forms for a monolithic material like concrete. The issues included the proper variation of cross-sectional area and moment of inertia with position, proper shapes for the centroidal axis, proper rise to span ratios, effects of temperature changes, creep and shrinkage, and the relative advantages of different arch forms (fixed-fixed, hinged, tied, etc.). Construction technologies such as forming, placement of steel, placement and compaction of concrete and curing of concrete were being developed.

The breadth of technologies involved in the realization of reinforced concrete arches and the effective race that existed between European and American engineers to develop and exploit them make comprehensive historical assessments on reinforced concrete difficult. In addition to identifying European and American contributions to each technology, identifying contributions of individuals and firms, correctly identifying significant design “firsts”, there are other, broader issues that are important to the history of civil engineering. One is the relative influence of property rights of inventors versus standardization on the exploitation of a technology. Another is the way reinforced concrete bridges were designed and constructed versus the way iron and steel bridges were realized through bridge companies. A third issue is field versus shop control of quality. Finally the issue of the relationships between systems used for buildings and those used for bridges and other objects is intriguing.

This paper does not attempt an overview of the growth of all the technologies nor a study of the main issues that affect their development. Rather, it focuses specifically on the development of reinforcing systems used in the U.S. for reinforced concrete arches and discusses some of the early bridge designs. It discusses primarily the systems of Jean Monier and Joseph Melan and the contributions of Friedrich (Fritz) Von Emperger, Edwin Thacker and William Mueser. It focuses on the period from 1894 to 1904, when reinforcing systems were simplified and pioneering arch bridge designs were done.

Reinforced Concrete Bridges in the U.S. prior to 1894

One of the earliest U.S. patents for a reinforcing system is that granted to Ernest Ransome in 1884 for his twisted or torqued bars. In 1889, Ransome built what is recognized as the first reinforced concrete arch in the U.S., the Alvord Lake bridge in Golden Gate Park in San Francisco. Snyder and Mikesell (1994) describe the span but do not give details of the reinforcement used. Ransome subsequently focused his activities on building systems and his bridge appears to be a singular achievement that did not lead to further developments.

A second reinforced concrete arch is described in the September 7, 1893 issue of Engineering News. The bridge, shown in Fig. 1, was built over Pennypack Creek in Philadelphia. It was designed by Carl A. Frieck, Superintendent of Bridges. The bridge had two 25' spans with rises of 6' 6". The arch was reinforced with "1-1/2 inch mesh wire nets...placed about 2ft apart, horizontally and vertically, throughout the concrete. The diameter of the wire in this netting is 1/8 inch" (Engineering News, 1893). Fritz Von Emperger mentioned the bridge in the November 16, 1893 issue of Engineering News, commenting that "the beginning has been made".

![Figure 1. Reinforced concrete bridge over Pennypack Creek, Philadelphia](Engineering News 1893a)

The Reinforcing System of Jean Monier and his November 22, 1892 U.S. Patent (486,535)

It is well known that Jean Monier, a “Paris gardener”, began fabricating horticultural objects in the 1860’s using concrete reinforced with nets of wire. Monier patented his system in 1867 but it became widely known and used when G.A. Wayss, in about 1878-9, became the owner, or “sole representative” of the Monier system in Germany and neighboring countries. The system is essentially the same as current practices. It consists of one or more grids of reinforcement. The grid dimensions varied from 2” to 10”. The larger, or “carrying” wires, were typically 0.39”, while the smaller, orthogonal, “distribution” wires were typically 0.28”. The rods were wired together at their intersections, much like today.

A Monier arch, built at the train station in Matzdorf, Austria, is mentioned in the February 1, 1890 issue of Engineering News. The bridge had a span of 32.8 ft, a rise of 3.3 ft and an arch thickness that varied from 6” at the crown to about 8” at the abutments. Results of tests on the bridge are reported in the August 2, 1890 issue of Engineering News. An equivalent uniformly distributed load of 1741 lbs/ft² was applied before the abutments “gave way”.

Other Monier arch bridges are described in the May 23, 1891 Engineering News. One consists of three arches, each with a span of about 29'-6", spanning over railroad tracks at Moedling, near Vienna, Austria. It was constructed in 1890-91 and tested in
September, 1890. The same article describes a bolder design at Wildegg, Switzerland. The bridge, shown in Fig. 2, was built in the autumn of 1890 and tested on November 14, 1890. The span was 122ft and the rise was only 11.5ft. Two grids of reinforcement were used, one near the intrados and another near the extrados. The arch thickness varied from 7.9" at the crown to 25.8" at the abutments.

![Figure 2. Melan reinforced concrete arch, Wildegg, Switzerland (Engineering News, 1891)](image)

Engineering News of February 16, 1893 describes three Monier arch bridges, one of 50ft span, one of 65.6ft span and another of 114.8ft span. The article notes that the “principal objections brought forward were: (1) That the wire would eventually corrode by coming into contact with the moist concrete; (2) that the concrete would not adhere to the smooth surface of the iron, and thus the two materials would not act together, and, (3) that the iron wire would expand and contract under changes of the temperature at a different rate than the concrete, and thus cause cracks in the latter material”. The article notes some favorable results from corrosion experiments and states that, according to Bonniceau, a French author, the coefficient of thermal expansion for concrete is “0.0000143 for a change of temperature of 1° C. and that of iron is 0.0000145, or practically the same”.

In his influential 1894 paper in the ASCE, Fritz Von Emperger describes three additional Monier arches, including one of 132ft span, built in 1890 “for show purposes only” for a fair at Bremen. In 1894, Von Emperger was representing the competing Melan system and thus notes that the Monier reinforcement is “not stiff itself”. He cites a failure and “distrust” of the Monier system and notes that “this difficulty has been overcome by the other systems now in use, which use rolled shapes instead of wire netting”. The American discussions of the article clearly reveal that the principal experience in the U.S. to 1894 was with building floors. Many of

The respondents expressed surprise that the coefficients of thermal expansion of steel and concrete were the same.

The September and December 1899 issues of Cement and Engineering News contain a series of articles by E. Lee Heidenreich on the Monier system. Heidenreich admits that he is a “representative of the patentee for Monier construction in the United States”. Remarkably, he focuses on the uses of the Monier system for tanks, storage silos, building floors and culverts but does not emphasize bridges.

![Figure 3. Joseph Melan U.S. Patent 505, 054](image)
The Reinforcing System of Joseph Melan and his September 12, 1893 U.S. Patent (505,054)

Fig. 3 shows the drawings submitted with the Joseph Melan U.S. patent. They show that the system consists of centrally placed stiff beams, denoted by the letter A, in parallel with "rammed concrete" between them. That is, the system does not rely on steel-concrete bond and composite behavior. The steel is centrally placed, not where tensile stresses occur in the concrete. Rather than a concrete reinforcing system, it is more appropriately steel in parallel with concrete. The Melan system was represented in the United States by Fritz Von Emperger. In his 1894 article in the ASCE Transactions, Von Emperger clearly advocates for the Melan system. He pointedly states that: "The inventor of this system, J. Melan, is, in contrast to J. Monier, a well-known engineer and writer. He ranks in German engineering circles as an expert in arch construction..." He notes that, unlike in the Monier system, the steel beams are stiff and that: "They are a kind of centering itself". He then discusses tests performed for the Austrian Society of Engineers and Architects for evaluating different systems. The test specimens were arches with a 13.5 ft span. The systems compared were a brick arch, a plain concrete arch, a Monier arch with one grid of reinforcement and a Melan arch with 3-1/8 inch I beams 40 inches on center. The half span loading used is shown in Fig. 4. The tests predictably showed that the strength of the melan system was about four times that of the Monier system, which only had one grid of reinforcement.

![Figure 4. Loading used for Austrian tests (Von Emperger, 1894)](image)

Von Emperger cites three completed Melan arches having 23.5 ft, 39.5 ft and 65.6 ft spans. Fig. 5 shows the longer arch, which appears not to have any cover for the steel beams, although Von Emperger, in his closure of the discussions states that "...in the Melan arch all iron is covered... I have to state this definitely, because my designs do not show the coating which is supposed to be applied according to European practice, and are, therefore, somewhat misleading." Von Emperger also discusses his design approach. Letting the total load, Q, be expressed as the sum of that carried by the concrete, Qc, and the steel, Qs, Emperger states:

\[
\frac{Q_{c}}{Q_{s}} = \left( \frac{E_{c}I_{c}}{E_{s}I_{s}} \right)
\]

Emperger's equation is not strictly correct because it is only the ratio of the moments that is dependent on the moments of inertia, and not the ratio of the "loads". Emperger also gives formulas for total steel and concrete stresses that depend only on the flexural stiffness ratio given in Eq. (1). Those formulas are also not strictly correct because in an arch the total axial force is shared in proportion to \(E_{s}A_{s}/E_{c}A_{c}\) and the total moment is shared in proportion to \(E_{c}I_{c}/E_{s}I_{s}\). Von Emperger also gives values for the horizontal thrust for the case of a uniformly distributed live load over half span and over the full span. His formulas are consistent with a statically determinate, three-hinged model of the Melan arch.

In his discussion of Von Emperger's paper, W.R. Hutton gave a very perceptive comment on the Melan system: "The Melan system appears to be an entirely different thing. In it no attempt is made to supply directly with metal the deficiency in tensile strength of concrete. It is a combination in one structure of materials entirely distinct in their characteristics, in which combination the moment of inertia of the sections is inversely proportional to the modulus of elasticity of each material."

The Melan and Monier systems presented American designers with two distinct choices. The Monier system, with its loose bars, relied on adhesion and composite behavior. The Melan system simply used steel in parallel with concrete, with no reliance on bond and composite behavior.

Other European Reinforcing Systems

The November 16, 1893 issue and the April 12, 1894 issue of Engineering News describe the reinforcing system of R. WuenSch, of Budapest, Hungary, patented in 1884. Fig. 6 shows a 16.6 ft model of the system used for a Hungarian government test. Von Emperger also describes the WuenSch system in his 1894 paper. He lists six highway bridges, with spans ranging from 13.5 ft to 55.9 ft that were built using the system. Fig. 6 indicates that WuenSch embedded a rigid frame of reinforcement within the concrete. Therefore the system probably behaves as a rigid frame with a hunched girder.
Figure 6. Test model of R. Wenscch reinforcing system (Von Emperger, 1894)

Of course the most widely used reinforcing system in Europe was that of Francois Hennebique, patented in 1892 (Cusack 1984). The Hennebique system, however, was used principally for buildings and reinforced concrete girder bridges, and had less influence on reinforced concrete arch bridges.

Reinforced Concrete Arch Designs in the United States from 1894 to 1904

Perhaps because of Von Emperger's influence, U.S. arch bridge designs of this period were dominated by Melan-type reinforcing systems. The Monier system of tied individual bars was largely relegated to other applications, although, over time, there was a gradual acceptance of composite behavior and systems similar to that of Monier evolved in the United States. In this period, four engineering firms were prominent in the design of reinforced concrete arches in the U.S.:

a) F. Von Emperger, William Mueser and the Melan Arch Construction Company of New York
b) Keepers and Thacker
c) William Mueser, Edwin Thacher and the Concrete-Steel Engineering Company
d) Daniel B. Luten and the National Bridge Company, founded in 1902

The first three constitute a continuity of ideas and designs whereas the work of Daniel B. Luten represents an independent direction.

The first two Melan arches in the U.S. were built by Von Emperger in 1894-5. The first was a 32-ft span arch built in Rock Rapids, Iowa. The second was the 70-ft span, Eden Park Bridge in Cincinnati. The Rock Rapids Bridge is extant but has been moved to a park and no longer serves as a bridge. Its history and structural behavior have been documented by the Historic American Engineering Record (HAER). These studies are contained in two reports, IA-63 and IA-89, which are in the permanent HAER Collection in the Library of Congress. The Eden Park Bridge is also extant, in very good condition, and remains in service. The Rock Rapids arch is reinforced with either 1 or rail sections having 3" flanges, spaced 3 ft on center. The Eden Park Bridge is reinforced with 9" I beams also spaced 3' on center.

Von Emperger describes another Melan arch, also built in 1895, in Engineering News (VOL. XXXIV, No. 19). It is a footbridge in Stockbridge, MA with a span of 100 ft. Fig. 7 shows the very elegant design, which has a 9" arch thickness at the crown. The bridge is reinforced with 7" deep, 135 lbs/ft, I-beam sections, 28" on center. William Mueser tested the bridge by applying an equivalent distributed load of 75 lbs/ft².

Figure 7. Melan arch for footbridge at Stockbridge, MA (Von Emperger, 1895)

In 1897, Von Emperger received a patent (No. 583,464) for a reinforcing system that used two reinforcement ribs, either trussed or simply spaced, one near the intrados and the other near the extrados. Von Emperger reasoned that: "The use of solid ribs for reinforcing the masonry arches has not given satisfaction in small spans where the iron should be at a smaller distance than four inches, which is the smallest I-iron in the market, while in larger spans the I-iron could not be well bent. The use of metal in the core of a vault or arch is useless, as only those portions of the ribs are called into action which are located near the intrados and extrados of the vault or arch, and as a correctly-constructed arch should increase in cross-section toward the haunches, the reinforcing-ribs should follow the shape of the arch in the same manner."

Edwin Thacher embraced the Melan system and quickly executed prominent, innovative designs. In the autumn of 1895 and spring of 1896, Thacher designed what very likely was the first reinforced concrete arch railroad bridge, the crossing of the Michigan Central Railroad over Southern Boulevard, in Detroit, MI. The bridge, shown in Fig. 8, had a skew span of 48 ft and was reinforced with 41 "ribs" spaced 30" on center. The "ribs are built up of four angles 4 in by 4 in by ½ in, with a solid web 12 ft long at the center, and laced with 2½ in bars between the center web plate and the end. They are 15 in. deep at the crown and 24 in. deep at the springing" (Railroad Gazette, 1899).
In 1896, Thacher patented a design for an open spandrel reinforced concrete arch (U.S. Patent No. 570,239). From March 27, 1896 to January 12, 1898 the firm of Keepers and Thacher designed and built the great five-spans reinforced concrete Melan bridge over the Kaw River at Topeka, Kansas again using latticed steel trusses, centered on the arch axis, as reinforcement (Engineering Record 1898). On January 10, 1899 Thacher received U.S. patent No. 617,615 for a reinforcing system which recognized that fabrication of trussed reinforcing was not necessary. He simply separated the intrados bar from the extrados bar. "The bars act as the flanges of beams to resist bending moments, whereas the shearing stresses, which are small, are taken by the concrete alone." He devised bars that were "readily bent" "readily and cheaply spliced" and "can be stored or shipped in straight form". On September 1899, he published a very long and detailed article in Engineering News on "Concrete-Steel Bridge Construction". Thacher discussed practically all the issues on arch construction, including the relative benefits of open and closed-spandrel forms, hinged arch forms, shapes of arch axes, proportioning of reinforcement, cement and concrete technology and construction. Thacher included the Keepers and Thacher Specifications for Reinforced Concrete Construction. In 1902 he received another U.S. patent for improved reinforcing bars (U.S. Patent No. 714,971). At about this time (Simmons, 1993), he also entered a partnership with William Muejer and founded the Concrete-Steel Engineering Company. The Melan-Von Emperger-Muejer-Thacher lineage is beautifully illustrated by Fig.9, an advertisement appended to Homer Reid's 1907 concrete textbook. The flyer also illustrates a Melan arch built on the Vanderbilt estate in Hyde Park in 1898 and the modern reinforcing bar, patented by William Muejer.

Independently from the lineage culminating in the Concrete-Steel Engineering Co., Daniel B. Luten devised innovative, competing reinforced concrete arch forms and reinforcing systems. Luten founded his National Bridge Company in 1902 in Indianapolis. His reinforcing systems utilized separate round bars, bent to follow the regions of potential tensile stresses, and thus rely on composite action. Luten devised an innovative tied arch system, using a reinforced concrete tie in the bed of a stream. Luten's accomplishments are beautifully described in James Cooper's book "Artistry and Ingenuity in Artificial Stone" (Cooper, 1997).
The VonEmperger and Thacher Papers for the 1904 International Engineering Congress

Von Emperger's and Thacher's contributions to the International Engineering Congress of 1904, published in the ASCE Transactions, provide good perspectives on developments in reinforced concrete arch construction from 1894 to 1904. Von Emperger credits Thacher for his 1897 patent proposing "flat steel bars, independent of each other, near the intrados and extrados of the arch. These bars are subjected to tension and compression only. That part of the steel, which in the Melan system is represented by the web of the arched ribs, is saved, but the concrete must take all the shearing stresses without aid from the steel." Von Emperger then provides a history of the development of reinforced three-hinged arches in Europe from 1898. He states that "one of the most important advantages gained in the use of hinges is the greater independence of the structure from the execution of the work." Von Emperger also discusses the use of reinforced concrete girders for smaller spans.

Thacher, in his article, notes that since 1894, "the Concrete Steel Engineering Company, of New York City, and their predecessors have built, or are now building, under the Melan, Thacher, and Von Emperger patents, about three hundred spans of concrete-steel bridges, distributed over nearly all parts of the United States." He notes that the longest reinforced concrete arch span in construction is 132 ft but envisions open spandrel spans of 500 ft or more.

Observations

Von Emperger's strong advocacy and active design practice after 1894 made the Melan system dominant for reinforced concrete arches in the U.S. The Melan system did not rely on composite action between concrete and steel but rather used steel in parallel with concrete. Edwin Thacher and other designers slowly realized that composite action between steel and concrete was achievable and that reinforcing systems could then be simplified. The new reinforcing systems that evolved essentially approached that of Jean Monier, who used individual rods, wired together to form grids, in the 1860's. Nonetheless, the reinforced concrete arch became common in the U.S., using primarily Melan-type reinforcing systems, in the period from 1894 to 1904. The following decade saw experimentation with hinged arch forms, the development of simpler systems for short span bridges and the use of open spandrel arches for larger spans.

References


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