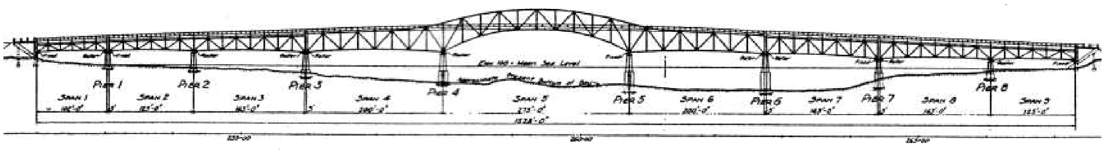

ELEVATION
LITTLE BAY BRIDGE

NATIONAL HISTORIC CONTEXT AND SIGNIFICANCE OF THE GENERAL SULLIVAN BRIDGE DOVER, NEW HAMPSHIRE

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NATIONAL HISTORIC CONTEXT AND SIGNIFICANCE OF THE GENERAL SULLIVAN BRIDGE

Summary

Research has identified and defined the early development period of continuous truss highway bridges in the United States as being from 1927 to 1937. This period was preceded by a ten-year period beginning in 1917 during which time the continuous truss railroad bridge was developed.

The General Sullivan Bridge is one of four major bridges of the same type, style and time period designed by the firm of Fay, Spofford and Thorndike, that as a group significantly influenced future continuous truss highway bridge design in the areas of technology, aesthetics and construction methods. Fay, Spofford and Thorndike (FS&T) remains in business today and since forming in 1914 established itself as a bridge engineering firm of national importance.

A significant advancement in the technology and aesthetics of continuous truss highway bridge design came with the building of the Lake Champlain Bridge and the three other bridges in which the original design was refined and improved upon.

The Lake Champlain Bridge, completed in 1928, was the third major continuous truss highway bridge built in the U.S. It was a highly innovative and aesthetic design that placed the roadway above the side trusses and through an arched center truss. The design was called "ingenious" for its deck layout that "provided the necessary clearance at mid-span with such economy in the approaches." [1]

The second bridge of the group was the Little Bay Bridge, completed in 1934 and later renamed the General Sullivan Bridge. It represents an important step in the evolution of the continuous truss highway bridge for three reasons: it incorporated special features of the lake Champlain prototype that were proved economically sound; the practical application of a new technology for weighing bridge reactions was demonstrated in its construction; and it established, or helped establish, a markedly reduced economical span length for the continuous truss.

The third and forth bridges of the group were identical and built to span the newly widened Cape Cod Canal. The Bourne Bridge (1934) and Sagamore Bridge (1935) utilized high-strength silicon steel to establish a new long-span length for their design, just 11 feet shy of the U.S. record. The longer span required a deeper truss and taller arch from which the roadway deck was suspended.

The unique three-span deck/thru-arch/deck continuous truss design pioneered by FS&T proved to be a highly successful solution for large and small highway bridges around the country where aesthetics and the cantilever construction method were necessary factors and was copied for years to come.

The General Sullivan Bridge is an important early example of a continuous truss highway bridge in the U.S. and its design and construction contributed significantly to the advancement of 20th century American bridge technology.

Continuous Truss Railroad Bridges

The use of continuous trusses for highway bridges in the U.S. did not begin until the mid-1920s. Prior to that time, only a few large continuous truss bridges had been constructed to carry railroads over large rivers and with one exception, all dated from 1917 or later. For obvious reasons the great advances in American bridge technology during the late 19th and early 20th centuries were primarily the work of the railroads.

Most historical engineering texts and papers credit the introduction of the continuous truss bridge to America to 19th century railway bridge engineer, Charles Shaler Smith. The Lachine Bridge, designed by Smith and built 1887-1888 to carry the Canadian Pacific Railway over the St. Lawrence River near Montreal, was a monumental structure with two central thru-spans of 408' each and two side spans of 269' each.[2] The Lachine Bridge was considered to be the only continuous truss of "any importance" built in America until 1915 when construction began on the Sciotoville Bridge to carry the Chesapeake and Ohio Northern Railroad over Ohio River.[3]

The Sciotoville Bridge was designed by Gustav Lindenthal, a brilliant Austrian-born engineer who came to America in 1874, built several of the country's greatest bridges including the highly acclaimed Hell Gate Arch Bridge, and ultimately became known as the "Dean of American Bridge Engineers."[4] When completed in 1917, the Sciotoville Bridge - with two continuous spans of 775' each – was the longest and heaviest fully riveted truss in the world, a title it retained until the building of the 839' Duisberg Bridge in Germany in 1935.[5] Through his works and his writings, Lindenthal became a leading authority and proponent of the continuous truss bridge right up to his death in 1935.

Articles on the Sciotoville Bridge in engineering journals led to further interest in the continuous truss type.[6] A detailed series of articles on the building of the bridge by C. B. Pyle, field engineer for McClintic-Marshall Company, the fabricator and erector of the bridge, furthered the understanding of the practical technicalities involved in their construction.[7] The American Bridge Company, McClintic-Marshall's larger competitor, embarked on their own continuous-truss research and development project, and in 1918 designed and completed the second major bridge of the type in the U.S. to carry the Bessemer & Lake Erie Railroad over Allegheny River at Pittsburgh.[8] The Bessemer and Lake Erie Bridge consisted of two 3-span continuous units, the longest span being 520 feet. Also in 1918, Canadian engineers completed the Hudson Bay Railway Bridge over the Nelson River in Manitoba with a 400' center span and two 300' side spans.[9]

Discussion of the economical applications of continuous bridges and the analysis of indeterminate structures and secondary stresses followed these pioneering structures and continued through the 1920s and into the 1930s. Papers and textbooks on the subject were published by many of the leading engineering professors and practitioners.[10]

Lindenthal's detailed account of the design of the Sciotoville Bridge in the *Transactions of the American Society of Civil Engineers* garnered comments from such learned engineers of the day as C.A.P. Turner, J.E. Greiner and D.B. Steinman.[11] Most debate hinged on the economy of continuous versus simple span truss designs because Lindenthal had not only advocated the continuous span in place of the long-span cantilever, but also as an economic alternative to simple truss spans in many lesser-span situations. After a lengthy and detailed argument, Professor Turner found that while Lindenthal "discloses meritorious details in advance of current practice," his conclusion on the economical virtues of the continuous truss for moderate spans "differs from the majority opinion of American bridge engineers because of lack of demonstrated economy on a scientific mathematical or design basis."[12]

Lindenthal effectively rebutted Turner's economic argument by explaining that the added stiffness and greater resistance to impact and wind loads afforded not only by the continuous girders, but by the continuous lateral bracing, produced a better bridge better suited for high levels, high wind areas and high speed traffic, and would prove economical in that respect not only for moderate but shorter spans as well.[13]

Steinman was squarely in Lindenthal's camp, calling the continuous truss "an excellent bridge type, offering decided advantages (under suitable conditions) over practically all other forms of construction…its general adoption for fixed spans has long been retarded by prejudices based on erroneous notions…a proper comparison with corresponding simple spans will generally show a substantial saving of material in favor of the continuous structure."[14]

Another landmark paper which provoked extensive discussion and much acclaim was entitled "Secondary Stresses in Bridges" by Cecil von Abo published in 1926.[15] Abo compared the various methods pertaining to secondary stresses, applying each to a 150' Warren truss railroad bridge. The ensuing discussion again showed fundamental and complex disagreement among engineers as to the preferred method of solving for secondary stresses and even the importance of doing so.

Continuous Truss Highway Bridges

Lindenthal again led the way with what is apparently the first modern continuous truss highway bridge of indeterminate design in the U.S. of significance, the Ross Island Bridge over the Willamette River in Portland, Oregon completed in 1927 (**Figure 1**). The Ross Island Bridge incorporated an arched center span of 535' and half-arched side spans of 321' with a concrete slab roadway carried above.[16] Lindenthal completed another continuous truss highway bridge over the Willamette in Portland in 1927 as part of the same commission, the Sellwood Bridge. It was also a deck bridge but with parallel-chord trusses and a maximum span of 300 feet. Lindenthal built two continuous truss highway bridges of determinate design in 1880 and 1890 based on the counterweighted funicular principal, see note.[17]

The Ross Island and Sellwood bridges did not receive major coverage in the engineering literature at the time of their completion. One small article discussed the unique method of closing the arch of the Ross Island Bridge without jacking that instead utilized the careful calculation of the expansion of the steel truss due to the daily temperature change.[18]

Lake Champlain Bridge

Following right on the heels of Lindenthal was the engineering firm of Fay, Spofford & Thorndike (FS&T) who in 1927 began the design of a long-span continuous arched truss bridge to span Lake Champlain. The bridge was an innovative and highly aesthetic design with the roadway deck carried above the side trusses and through the arched center truss (**Figure 2**). The bridge was called "ingenious" for its deck layout that "provided the necessary clearance at mid-span with such economy in the approaches."[19] Frederic H. Fay, Charles M. Spofford, and Sturgis H. Thorndike were all highly accomplished bridge engineers and their firm's bold design must have been partly driven by a desire to establish prominence in the rapidly expanding field of long-span highway bridge design.

It was agreed at the outset by both the engineers and the owner (Joint [Bridge] Commission of New York & Vermont) that the bridge "should have as pleasing an appearance as possible" due to its conspicuous height and the historic importance of the site.[20] In designing the Lake Champlain Bridge, Spofford states that he "found it impossible to sketch any simple span design that was at all satisfactory in appearance."[21] He also considered cantilevered and suspension bridges, but discounted each for various reasons, settling finally on the continuous type, which he decided "can be given a more pleasing appearance, consistent with economy, than any of the other types of truss bridges."[22] Design of the Lake Champlain Bridge was begun August 2, 1927 and the final plans accepted November 15, 1927.[23] This places the FS&T design at the very forefront of continuous truss highway bridge construction in the U.S.

Steel Bridge Aesthetics & Further Development

The innovative and highly successful integration of aesthetics into long-span truss design by Fay, Spofford & Thorndike was a significant development. American bridge engineering treatises have included extensive sections on the aesthetic design of bridges since the late 19th century. Bridge designers were instructed to consider the fundamental principles of artistic design in the order of their importance: symmetry, style, form, dimensions, and ornamentation. Occasional commentaries on the elements of good aesthetic design and beauty as it pertained to bridges appeared in the engineering press in the early 20th century, but it was during the 1920s that the movement picked up considerable speed, coinciding with the larger societal movements toward aesthetically designed public spaces like the City Beautiful movement.

The divergent opinions that existed regarding bridge "architecture" and aesthetics came to light in 1920 following a story in *Engineering News Record* about a highly decorated concrete bridge built in Philadelphia.[24] A war was waged in a series of articles, editorials and letters over the relationship between art and structures and between architects and engineers, and over who was more qualified to judge what is aesthetically pleasing.[25] Foremost among the causes of the dispute, was the rapid development and adoption of reinforced concrete bridges for the nation's expanding highway network. Moldable into virtually any shape or form, economical, and well suited to arches, concrete at first ushered in a nostalgic return to the classicism and heavy decoration found in earlier bridges crafted of stone. But a symbiotic relationship quickly developed between concrete and the new architecture of Modernism, promoted by Frank Lloyd Wright, Le Corbusier, Mies van der Rohe and others. Functionality meshed with Machine Age philosophy to become Functionalism expressed in Modernistic concrete bridges. The traditionalists and the progressives were at each other's throats.

Longing for the days of stone, “old school” bridge engineer Gustav Lindenthal weighed in with an article in *Scientific American* in 1921 entitled “Some Aspects of Bridge Architecture.”[26] Lindenthal found fault with nearly everything that was happening in the bridge business, but had special vehemence for the current art of steel bridge building: “there is no thought of architecture, or of durability or of pride in the art... the most naked utilitarian considerations are allowed to govern the design... it has become a commercialized trade which has been prostituted, under the pretense of scientific economy, to the production of the cheapest structures that will carry the loads.”[27]

Meanwhile, concrete bridge technology gloriously advanced, stretched into long delicate arches or molded into highly stylized Classical, Art Deco and Modern forms. Each year increasingly stupendous and unarguably beautiful concrete bridges were going up. By 1929 the structural steel industry had had enough. The American Institute of Steel Construction (AISC) established an award to be given annually to the “most esthetic solution to a problem in steel construction.” The first award was given retroactively to the 6th Street Suspension Bridge in Pittsburgh completed in 1928. For 1929 it was decided to give three awards, one for long span bridges, one short span and one honorable mention, the latter given to the Lake Champlain Bridge.[28]

The AISC's director of engineering services, F.H. Frankland, presented a paper to the Canadian Good Roads Association in 1929 in which he noted that the possibilities for continuous bridge design was now recognized by engineers and continued to gain their favor. The bridge type had "generally come to be accepted as the full equivalent of other types where field erection conditions and economy in material permit."[29] Continuous trusses were increasingly being found more economical than cantilevers for long span highway bridges. The first continuous-truss highway bridge over the Missouri River was designed by the firm Sverdrup and Parcel and completed in 1929 at St. Joseph, Missouri.[30] The bridge had two 450' thru-spans and resembled a cantilever design with panels of varying depth increasing to a maximum over the center pier. The next year the Strauss Engineering Company of Chicago spanned the Mississippi at Quincy, Illinois with a parallel chord truss design that incorporated two-spans of 627' each and established a new record for continuous truss highway bridges.[31] The design of these two bridges demonstrated the potential economy afforded by the type when aesthetic considerations are removed from the equation.

In 1930 the AISC decided to give three awards based on a bridge's cost: Class A, over $1 million; Class B, $250,000-$1 million, and Class C, less than $250,000. The press coined the term “most beautiful steel bridge of the year award” which stuck. The Class B award went to a short-span continuous arched truss deck bridge in Delton, Wisconsin, similar in design to Lindenthal's Ross Island Bridge.[32] Two more continuous arched truss deck bridges received the AISC's awards in 1932: the French King Bridge in Massachusetts (Class B) and the Byran Bridge in Nebraska (Class C).[33]

With all this attention and awards being heaped on continuous trusses, Lindenthal came forward to set the historical record straight on his priority and preeminence in the business with an article in *Civil Engineering* (1932) entitled "Bridges With Continuous Girders; Reviewing Half A Century of Experience in American Practice."[34] Lindenthal described his experiments with funicular bearing bridges in the 19th century (see note 15) but made a special point of mentioning Spofford's 1931 article on the Lake Champlain Bridge, noting, "A similar structure, the Ross Island Bridge, having arched continuous girders, was built under my supervision in 1925-1927."[35]

Little Bay Bridge, later named General John Sullivan Memorial Bridge

The contract for design and construction supervision of the Little Bay Bridge was given to FS&T by the New Hampshire Toll Bridge Commission on April 11, 1933 and by July 27 the plans for the superstructure were complete and advertised for bids (**Figure 3**). Foundation construction began July 27, 1933 and on September 5, 1934 the bridge was opened to traffic.[36] *Engineering News-Record* called the General Sullivan Bridge and the companion Ballamy River trestle bridge "exceptional structures, which are notable in design and particularly for the construction methods employed."[37]

The design mimicked the acclaimed Lake Champlain Bridge with the same innovative arrangement of deck side trusses and arched center thru truss that reduced the height and cost of the approach grades while achieving the necessary high-level channel clearance. The Little Bay Bridge represents an important step in the evolution of the continuous truss highway bridge for three reasons: it incorporated special features of the FS&T prototype that were proved economically sound; the practical application of a new technology for weighing bridge reactions was demonstrated in its construction; and it established, or helped establish, a markedly reduced economical span length for the continuous truss.

Special features

The special features included the innovative deck layout previously discussed, and the use of a state-of-the-art concrete deck design. The slab was reinforced with "welded bar trusses spaced 6 inches between centers and welded into mats by adding spacer bars across the trusses."[38] This is an early use of so-called "unit trusses" for reinforcement, but exactly how early was not determined. Another deck feature was the two-layer construction with the top wearing surface separated from the structural slab by a burlap "cleavage fabric to permit the top layer to be removed if it wears out without disturbing the floor-slab."[39] The design of the dove-tailed sliding-plate deck expansion joints and the double-stepped curbing were also mentioned in the articles on the bridge as being of note.[40]

Technology

Spofford advanced the method of weighing bridge reactions in the field by using newly developed proving rings of unprecedented accuracy to adjust the end reactions on the General Sullivan Bridge.[41] This was the first time the method had been used on a large continuous bridge. Spofford also used the rings on the later Bourne and Sagamore bridges and brought his findings to his colleagues in a 1935 article.[42]

The determination through field measurement of the actual exact weight that a continuous bridge bears down upon each of its supporting bearings is necessary to confirm that the erected structure conforms with its mathematical design. Spofford states that "the assumed reactions at the piers are seldom if ever attained because of such things as changes in the relative elevation of the piers, variations in the modulus of elasticity of built-up steel members, and differences in length of the various truss members as they come from the fabricating shop."[43]

Weighing and adjusting the reactions of continuous bridges was done by Lindenthal and others with hydraulic jacks coupled to pressure gages and with strain gages. Spofford used hydraulic jacks with gages on the Lake Champlain Bridge but found the method to be unsatisfactory due to the inability to measure the friction in the jacks and to maintain the gages in calibration in the field.[44]

The proving rings used by Spofford were patented in the mid-1920s and consisted of round steel "donuts" with sensitive measuring instrumentation inserted within the ring. When a load was placed on the rings its deformation could be measured with extreme accuracy. The proving rings used to measure and adjust the General Sullivan Bridge were manufactured by Morehouse Machine Company of York Pa., and were of 200,000 pound capacity with an accuracy guaranteed to one-tenth of one percent. The rings were actually sensitive enough to detect differences as small a 2 pounds and the operator found he could detect disturbances due to a man standing on the bridge.[45]

The first use of proving rings in bridge construction was in 1933 when David S. Fine, an erecting engineer with the American Bridge Company, used the devices to measure the reactions of a bascule bridge the company built in New Jersey. Spofford was the second to use the rings, and the first to utilize the method for continuous truss construction.[46]

New economical span length

Although overlooked in the engineering literature at the time, the design of the Little Bay Bridge was particularly notable for its main span length of 275' and continuous unit length of 675'. These lengths approached nearly half the length of the Lake Champlain and French King bridges and may have constituted the shortest continuous arched truss built to date. This is significant because in the case of the continuous truss, the trick was to demonstrate that the type could be economically suited for shorter spans, not longer spans. Each type of bridge has a range of span length for which it can be used to advantage over other types, adjusted for variables such as site conditions and loading. In the overall development of highway bridges during the expansion of the nations highway systems, improving the economy and aesthetics of short-to-moderate spans was far more important than the few record setting long-span bridges that garnered the greatest attention. The addition of a very aesthetically appealing truss design that could be built with the cantilever construction method and prove economical for medium span lengths was an important advancement.

Bourne and Sagamore Bridges

The Bourne and Sagamore Bridges were designed by FS&T for the Army Corps of Engineers to span the newly enlarged Cape Cod Canal (**Figure 4**).[47] The Bourne Bridge opened first in 1934 and received the AISC "Class A" award for most beautiful steel bridge of that year; the Sagamore Bridge opened in 1935 and received honorable mention in the Class A category.[48] The three-span continuous arch unit is identical on the two bridges, with the Bourne Bridge additionally equipped with two simple deck-truss approach spans at each end.

With the economical short-span length established for their trademark continuous truss design by the General Sullivan Bridge, the Cape Cod Canal project now presented FS&T the opportunity to establish a new long-span length for their design. At 616', the Bourne and Sagamore spans exceeded the Ross Island Bridge by 81 feet and were just 11' shy of the record span length for a continuous-truss highway bridge apparently set in 1930 by the Quincy Memorial Bridge over the Mississippi River at Quincy, Illinois.[49] These two long bridges however, were still roughly 150' shy of Lindenthal's 1917 Sciotoville railroad bridge.

In addition to the forty-percent increase in span length that the Bourne and Sagamore bridges represented over the Lake Champlain Bridge, they were designed to use high-strength silicon steel. Although the steel cost was 12.8 percent more than ordinary carbon steel, the stronger steel allowed a reduction in the size and cost of the individual members and resulted in a savings of approximately $50,000 for the two bridges.[50] This was not the first use of silicon steel in continuous truss highway bridge construction, at least two other bridges, the 1929 Missouri River Bridge at St. Joseph and the 1930 Quincy Memorial Bridge over the Mississippi made extensive use of it.[51]

The Cape Cod Canal bridges also differ significantly from the Lake Champlain and General Sullivan Bridges in the profile of the arch and the roadway locations, as shown in Figures 2, 3, and 4. The longer span required a deeper truss and taller arch. In order to keep the roadway grades within prescribed limits, the deck was suspended from the arched truss rather than carried at the level of the lower chord members. This arrangement was dictated primarily by site conditions, specifically the required channel clearance opening of 135' high by 500' wide, and the limitations of the possible approach configurations.

End of the Development Period

The mid-1930s appear to mark the end of what can be considered the development period of the continuous truss bridge in the U.S. The type began to see broad use in a wide range of spans and the AISC continued to give the type awards nearly every year. Referring to bridge developments in 1937, A.L. Gemeny, senior structural engineer for the U.S. Bureau of Public Roads said "in the field of steel bridges multiple simple spans have almost gone into discard…continuous beam and girder spans are being generally adopted for intermediate lengths …for long spans continuous trusses and cantilevers are used."[52]

In 1935 two major bridges designed by the firm of Waddell and Hardesty were completed over the north and south branches of the Niagara River to Grand Island (**Figure 5**). The south bridge was a near copy of the Cape Cod design with a center thru-span and a suspended deck, the north span was a deck bridge. Both Grand Island bridges had more deeply arched side spans than the FS&T designs, which were essentially flat. The north bridge with the deck truss won the AISC "Class A" award for 1935, beating the Sagamore Bridge which received honorable mention.[53]

Non-arched two-span thru-trusses like the 1929 St. Joseph Bridge over the Missouri River and the 1930 Quincy Bridge over the Mississippi continued to be the preferred design for continuous truss bridges over the big mid-west rivers. Two examples are the mile-long Missouri River bridge at Omaha with a 2-span continuous truss of 1050' overall, completed 1935 **(Figure 6)** [54] and the Mississippi River bridge at Hannibal, with a two-span continuous truss 1125' long, completed in 1936.[55] Continuous deck trusses were also seeing more widespread use in approaches to the big river bridges, as shown by the three-span continuous-truss deck units of 222' span that were used as approach spans to the 740' suspension span of the Mississippi River Bridge at Davenport, Iowa.[56]

State highway departments continued to gain confidence in designing continuous bridges in-house. The Kansas Highway Commission adopted continuous spans and built rolled-beam, plate-girder and continuous truss bridges with an estimated savings of 10-30% over simple spans.[57] The Montana Highway Department also "turned definitely to continuous spans" and in 1938 extended the possibilities of the short-span arched continuous truss highway bridge with a three-span deck truss (84'-168'-84) over the Middle Fork of the Flathead River at Belton Montana. The bridge was built at an amazing cost of only $74,815 and won the AISC Class C award for 1938.[58]

The unique three-span deck/thru-arch/deck continuous truss design pioneered by FS&T was copied for years to come for major and minor highway bridges around the country where aesthetics and cantilever construction were necessary factors. As new bridge technologies and design concepts developed they were integrated into the design type to create hybrid forms of continuous arched truss bridges. The monumental 53-span Susquehanna River between Havre de Grace and Perryville, Maryland, designed by J.E. Greiner and completed in 1941, used two 3-span units identical in appearance to the Cape Cod Canal bridges, but supported by pinned Wichert rhomboid panels over the piers to make them statically determinate structures.[59] The 1949 Julien Dubuque Bridge over the Mississippi at Dubuque, Iowa established a new world's record for a continuous truss by using the deck structure in tension to tie the 845' main arch span. The tie allowed a 25% reduction in the height of the arch resulting in significant savings in material and erection costs (**Figure 7**).[60]

Engineers of the General Sullivan Bridge

The engineering consulting firm of Fay, Spofford & Thorndike was established on July 1, 1914 by Frederic H. Fay, Charles M. Spofford, and Sturgis H. Thorndike. All three men were classmates and graduates of the Massachusetts Institute of Technology civil engineering program and studied under George F. Swain. Fay and Spofford graduated together in 1893, Thorndike graduated in 1895 and they remained in contact thereafter. Fay and Thorndike worked together as engineers for the City of Boston for over fifteen years, and Thorndike taught occasional courses at MIT where Spofford was a full time professor.

Frederic Harold Fay

Frederic Harold Fay was born in Marlboro, Mass. on July 5, 1872 and died at his home in Dorchester, Mass. June 5, 1944. Following completion of his Bachelor's degree at MIT he was accepted to the school's new graduate program. In 1894 he became the first person to receive a Master of Science in Civil Engineering from MIT. Fay worked briefly for Boston Bridge Works and then in 1895 joined the engineering department of the City of Boston where he rose to the position of Engineer in Charge, Boston Bridge and Ferry Division, Department of Public Works.

In 1909 Fay authored a paper with Spofford and another city engineer, J.C. Moses, on the reconstruction of the Boylston Street Bridge over the Boston and Albany Railroad, a major undertaking for the city.[61] He resigned from the City in 1914 to join in partnership with Spofford and Thorndike. Fay took an interest in large scale planning projects and became the firm's expert in that field. Among his many projects one of the largest was the design of the $25 million Boston Army Supply base at South Boston built 1918 to 1919. He was chairman of the Boston Planning Commission from 1922 to 1939, a member of the State Planning Board, and a president of the Boston Society of Civil Engineers.[62] In 1948, to commemorate its 100-year anniversary, the society asked several of its leading members to write articles on the outstanding contributions to engineering made by former members. Spofford was asked to write about those who contributed the most to the field of structural engineering and chose three: George F. Swain (1857-1931), Joseph R. Worcester (1860-1943) and Frederick H. Fay (1872-1944).[63] Spofford pointed to the Lake Champlain Bridges (FS&T also designed the Rouses Point Bridge over the lake in 1937), his port and maritime studies and designs, and his grade crossing elimination project designs including the massive Syracuse project completed by the New York Central Railroad.[64]

Charles Milton Spofford

Charles Milton Spofford was born in Georgetown, Massachusetts on September 28, 1871 and died in Newton, Mass. July 2, 1963 at the age of 91.[65] Like Fay, Spofford also did post-graduate studies in civil engineering from 1893-1894, but it is not clear if he completed his Masters degree. He co-authored a thesis in 1893 for his B.Sc. degree entitled "An investigation into the action of elliptical car springs."[66] Spofford worked for the Phoenix Bridge Company from 1895 to 1899, but only summers from 1897-1899 when he taught in the MIT engineering program as an assistant instructor during the school year. He taught at MIT full time as an assistant professor from 1903 to 1905, then accepted a professorship in civil engineering at Polytechnic Institute of

Brooklyn from 1905 until 1909. In that year he returned to MIT to accept the position of Hayward Professor of Civil Engineering where he remained until his retirement in 1954.

Spofford published a college engineering textbook in 1911 entitled "The Theory of Structures" which became a standard and was republished in four editions, the last being in 1939.[67] He was not a prolific writer or engineering theorist however. His only other major work was his 1937 textbook *The Theory of Continuous Structures and Arches* which joined several other in an increasingly crowded field. He wrote about ten articles for journals. Useful contributions are the Boylson Bridge article he wrote with Fay, a detailed investigation of highway bridge floor types, a historical piece on Thaddeus Hyatt - an early American inventor of reinforced concrete, a method for the division of bridge costs between street railways and cities, and his report on the use of proving rings that resulted from his work on the General Sullivan Bridge.[68] His other half-dozen articles reported on the salient features of important bridge design work done by FS&T, but did not really add materially to the greater body of engineering knowledge.[69] In 1942 he chaired the American Society of Civil Engineers (ASCE) in-house sub-committee that reported on the Tacoma Narrows Bridge collapse.[70]

Sturgis Hooper Thorndike

Sturgis Hooper Thorndike was born June 11, 1868 in Beverly, Massachusetts. He received a B.A. from Harvard in 1890 and a B.Sc. in civil engineering from MIT in 1895. Following graduation he entered the employ of the City Engineer of Boston where he spent the first 18 years of his career. His work for the city involved a large amount of bridge design, and in 1906 he was made assistant engineer in charge of bridge design. He had a major role in many of the city's prominent bridges including the Longfellow Bridge over the Charles River to Cambridge. Between 1904 and 1906, he was granted a leave of absence from the City during the school terms to teach engineering courses at MIT. In 1911 he was promoted to Designing Engineer of the Bridge and Ferry Division of the Department of Public Works, but later in the year resigned the position to establish a private consulting practice. In 1914 he formed a consulting partnership with fellow MIT alums Fay and Spofford. Thorndike remained a principal of the firm until his death February 16, 1928 at the age of sixty.[71]

Howard James Williams

Howard James Williams, of Fay, Spofford & Thorndike, served as "assistant engineer in charge of detailed design" on the General Sullivan Bridge project.[72] Williams was born in Kingston, Canada in 1895, received his B.Sc. in civil engineering from Queens College, Kingston in 1917, and his M.Sc. in engineering from MIT in 1920. He worked for several firms as an engineer on hydropower developments at Niagara Falls, Quebec and Maine until 1926 when he joined FS&T as a senior engineer. He became a partner in 1947 and an officer/director of the firm in 1956. His obituary was not located but he was still with FST in 1964. In addition to his bridge design work, Williams was chiefly responsible for design work on the New Jersey Turnpike and the Port of Portland, Maine.[73]

Andrew Peter Ludberg

Andrew Peter Ludberg, was employed by the Lackawanna Steel Construction Corporation as Resident Engineer in charge of the steel superstructure on the Little Bay Bridge.[74] Ludberg was born in 1889 in Ostersund, Sweden and immigrated to the U.S. when he was four. He received a B.Sc. in civil engineering from the University of Wisconsin in 1911 and after graduation joined the engineering department of the Chicago, Milwaukee, St. Paul & Pacific Railroad. He worked for the American Bridge Company as a structural draftsman from 1913 to 1921. Between 1921 and 1927 he was associate professor of civil engineering at the University of Idaho.[75] He briefly returned to American Bridge Company, but soon accepted the position of chief draftsman the Lackawanna Steel Construction Corporation. Ludberg possessed a "remarkable skill in mathematical analysis and insight into the elastic behavior of structures, especially those of the 'higher' and indeterminate type," and it likely because of those abilities that he was assigned resident engineer on the Little Bay Bridge project.[76] On April 11, 1934, during his routine morning inspection of the steel work, Ludberg stepped on an unattached section of concrete formwork on Span 3 and fell to his death. He was the only fatality resulting from the construction of the General Sullivan Bridge.[77]

General Sullivan Bridge Stress Analysis Methods

The question has been raised regarding the significance of the mathematical methods used in the design of the General Sullivan Bridge and whether they constituted relatively new or sophisticated methods to analyze stresses in continuous structures. The analytical methods chosen were not new or sophisticated and were apparently chosen due to their familiarity, ease in checking, and suitability to be divided among a staff of calculators. Spofford's 1911 textbook was not the first to bring these methods to light, and no evidence was found that his treatment of the subject was considered exceptional by his peers.

Spofford states that the Method of Least Work was used to calculate the stresses in the continuous trusses of the bridge and explains the procedure: "A preliminary design was first made using reactions as determined by the 'Three Moment Equation; this was followed by a more accurate determination of the stresses applying the least work principle and revising the section areas accordingly."[78] There was nothing particularly novel or significant about this mathematical approach to the problem at the time, it was one of the oldest mathematical methods for solving elastic theory problems. Spofford and his "calculators" who performed the laborious and repetitive calculations used the same methods for the design of the Lake Champlain Bridge six years earlier. In discussing the Lake Champlain project, Professor Robert Abbett questioned the immense labor of using the method of least work, when better methods were available.[79] Spofford replied that he found the least work method preferable when the computations can be divided among several staff members.

The "three moment equation" originated with the French engineer Clapeyron who studied a continuous beam with three supports. The load on the center support depends on the length of the beam, but also on its elasticity. Clapeyron discovered a mathematical relationship between the bending moments (three) at each support based on the loads on the beam between each support. He published his theorem in 1857 and it has since been known as Clapeyron's Theorem of Three Moments.[80] The reactions on continuous girders can be accurately determined using the theorem if the entire beam is of constant section and material (constant moments of inertia and modulus of elasticity), if not then the method requires a series of repeated calculations in which the reactions are approximated and results adjusted to obtain the desired accuracy.[81]

The Italian engineer Alberto Castigliano (1847-1884) presented the method of least work theory in his book "Theorie de l'equilibre des systemes elastiques et ses applications" published in Turin in 1879. The first to explain Castigliano's theories in English was MIT (later Harvard) professor George F. Swain in 1883.[82] It was not until 1919 that Castigliano's book was translated in full into English by British engineer E. C. Andrews under the title *Stresses in Elastic Structures*.[83]

The first comprehensive presentation of the method of least work in the U.S. appears to be an 1891 article by William Cain who gave this introduction to the subject:

> The method is found to be of very general application to all structures in which the laws of elasticity have to be considered in finding the stresses; as in every kind of beam or arch, trusses of any shape with superfluous members and all systems where there is a continuity in the members or where there is not free play at the joints, as in nearly all roof or bridge trusses. It further offers an exact method by which we can ascertain the limit of error made in our ordinary approximate computations (which apply only to articulated systems, free to move at all the joints), and thus exposes some of the unknown errors which are usually included in our "factor of safety," though it has more appropriately been termed our "factor of ignorance".[84]

Probably the best simple introduction to the principle and application of the method of least work is that given by British engineer, Harold M. Martin in 1895:

> Every metallic or wooden structure is elastic, and constitutes a spring. If a spring is loaded by a weight, it elongates, and a certain amount of work is done in this elongation. This work is stored in the spring in the form of potential energy, and can be reconverted into mechanical work, as is commonly done in clocks and watches. The stiffer the spring the less it is deformed by a given weight, and hence less work is stored in a stiff spring loaded with a 1-lb. weight than in a light one loaded by the same weight. Thus if 1 ton is hung from a steel bar of 2 square inches in section, less work is done in deforming the bar than if it was hung on a steel bar of the same length and of 1 square inch section. If a weight lies on a platform supported by four legs of elastic material, work will be done in deforming the platform and compressing the legs.
>
> If there had been only three legs, the ordinary principles of statics would suffice to determine the weight taken by each leg, which is then quite independent of the comparative stiffness of the legs and the platform. When, however, we have more than three legs, these statical principles no longer suffice, and to determine how much of the weight is carried by each leg it is necessary to introduce other considerations. The one great principle to which such problems can be reduced is known in dynamics as that of

> least action, and in such problems as we have before us as that of "least work." That is to say that the work stored in an elastic system in stable equilibrium is always the smallest possible.[85]

Martin goes on to describe in simple mathematical terms how to solve for the load carried by each leg with a given weight located at a certain place on the table, and then proceeds into analyzing increasingly complicated frames.

Through the 1890s up to the mid-1930s, a great number of important articles and textbooks were published on the subject of statically indeterminate structures, several of which are discussed below. For a broader review of the body of work on the subject, the reader is referred to the endnote for two excellent historical summaries on the subject.[86]

A paper given in 1899 by Frank E. Cilley discussed the futility of hoping to analyze indeterminate structures with an exactness and provoked contrary discussion by such majors as Lindenthal and Swiss professor C.W. Ritter. Lindenthal called the paper "a contribution to the old controversy as to whether or not statically determinate structures are superior to statically indeterminate ones, and is a scholarly attempt on the affirmative side of the equation."[87] Cilley's paper was a brilliant thesis that argued with sophisticated mathematical reasoning that a determinate structure can and should supplant an indeterminate one in every case, and that structural redundancy therefore equals structural waste. This work had a lasting effect in dividing American engineers into two camps, and as noted in the historical section above, it was not until Lindenthal and several other leaders built major continuous trusses, and new minds reasoned their economic validity, that the merit of indeterminate bridges became generally recognized.[88]

In 1905 Professor Isami Hiroi of Tokyo Imperial University wrote the first textbook in English (published in the U.S by Van Nostrand) on the use of the method of least work to solve for secondary stresses in bridge trusses.[89] Carl Grimm devoted a chapter to using the method of least work in his 1908 book *Secondary Stresses in Bridge Trusses*, as well as chapters on the four other leading methods for solving secondary stresses: Manderla method, Muller-Breslau method, Ritter method, and Maxwell-Mohr method. [90]

In 1911, the two leading college structural engineering textbook authors - Johnson, Bryan & Turneaure and Merriman & Jacoby - came out with new editions of their multi-volume treatises that included sections on the complete application of method of least work.[91] Two more textbooks, C.M. Spofford's *Theory of Structures* (1911) and *Theory of Framed Structures* (1922) by C.A. Ellis both contained sections on indeterminate structures and the method of least work.

In 1926, John I. Parcel and George A. Maney published the *An Elementary Treatise on Statically Indeterminate Stresses*.[92] This became arguably the leading text on the subject for decades, coming out in three editions until it was complete revised with a new title and coauthor in 1955 as *Analysis of Statically Indeterminate Structures*.[93] Parcel was professor of structural engineering at the University of Minnesota and later a partner in the firm of Sverdrup & Parcel. He called Johnson, Bryan and Turneaure's 1911 *Modern Framed Structures* "the best and most comprehensive treatment of statically indeterminate stresses in the English language."[94]

The first major American contribution to the analysis of statically indeterminate structures was made by Hardy Cross in 1930 when he described a new method for analyzing building frames that became known as the moment distribution method. When published in the ASCE *Transactions* in 1932, it was followed by 146 pages of discussion from 38 commentators, possibly a record. "Cross was immediately hailed as the man who had solved one of the knottiest problems in structural analysis."[95] His method was later called "probably the most notable advance in structural analysis during the twentieth century."[96] The Cross method was readily applied to solving secondary stresses in trusses, as demonstrated by Professor F.P. Witmer, head of the engineering department at the University of Pennsylvania, who applied it to the same 150' Warren truss example as was used by von Abo in his landmark 1926 paper. Witmer completed the analysis in only six hours, and claimed that the method "will prove to be the simplest and most expeditious method yet advanced for this purpose.[97] Had FS&T used the Cross method to solve the stresses of the General Sullivan Bridge, that would have been a first. Instead, the first to apply the moment distribution method to a continuous truss appears to be Truman P. Young, a structural engineer from Ohio, who designed a 3-span continuous arched truss and published his procedure in 1936. [98]

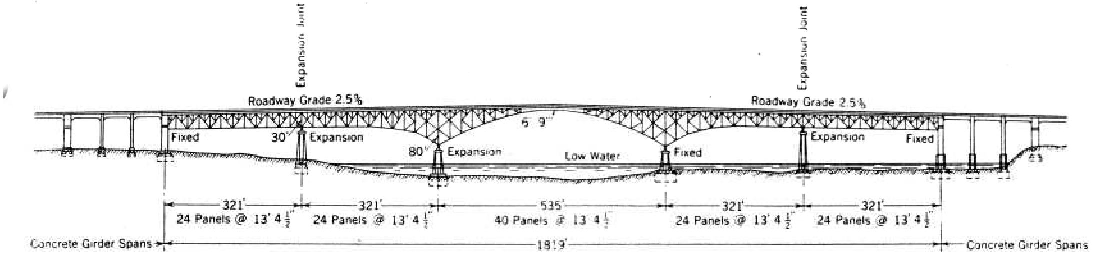

Figure 1: Ross Island Bridge, Portland, Oregon, 1927
main span 535', vert. clearance 100', continuous unit 1177', l.o.a. 1819'

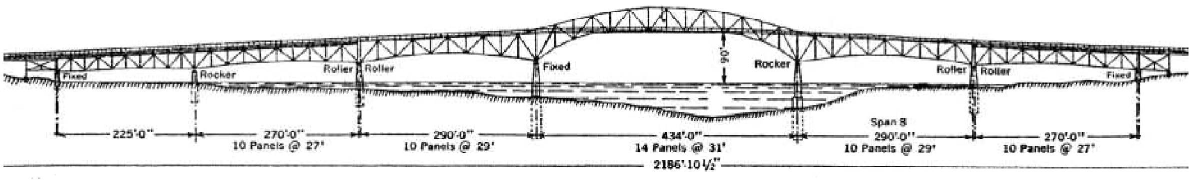

Figure 2: Lake Champlain Bridge, New York to Vermont, 1928
main span 434', vert. clearance 90', continuous unit 1014', l.o.a. 2187'

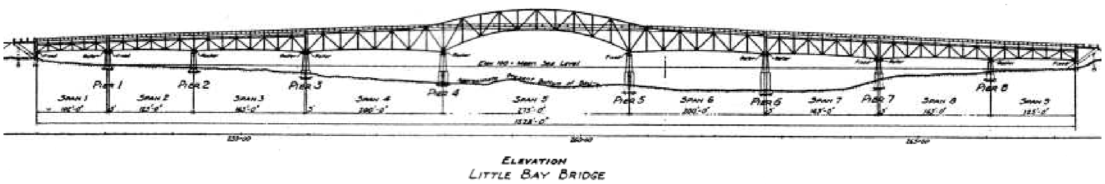

Figure 3: General Sullivan Bridge, Dover, New Hampshire, 1934
main span 275', vert. clearance 40', continuous unit 675', l.o.a. 1528'

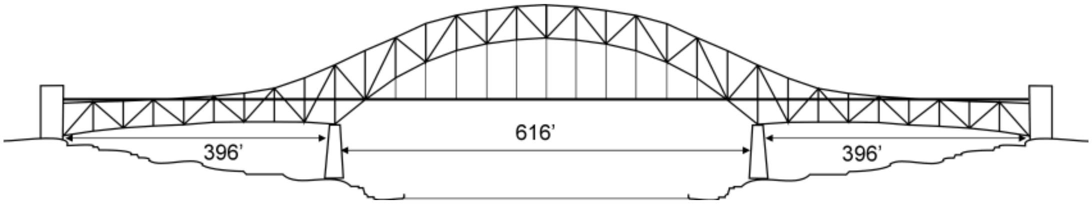

Figure 4: Sagamore Bridge, Cape Cod Canal, Massachusetts, 1935
main span 616', vert. clearance 135', continuous unit 1408', l.o.a. 1408'
Note: Bourne Bridge (1934) identical with addition of two simple deck spans at each end.

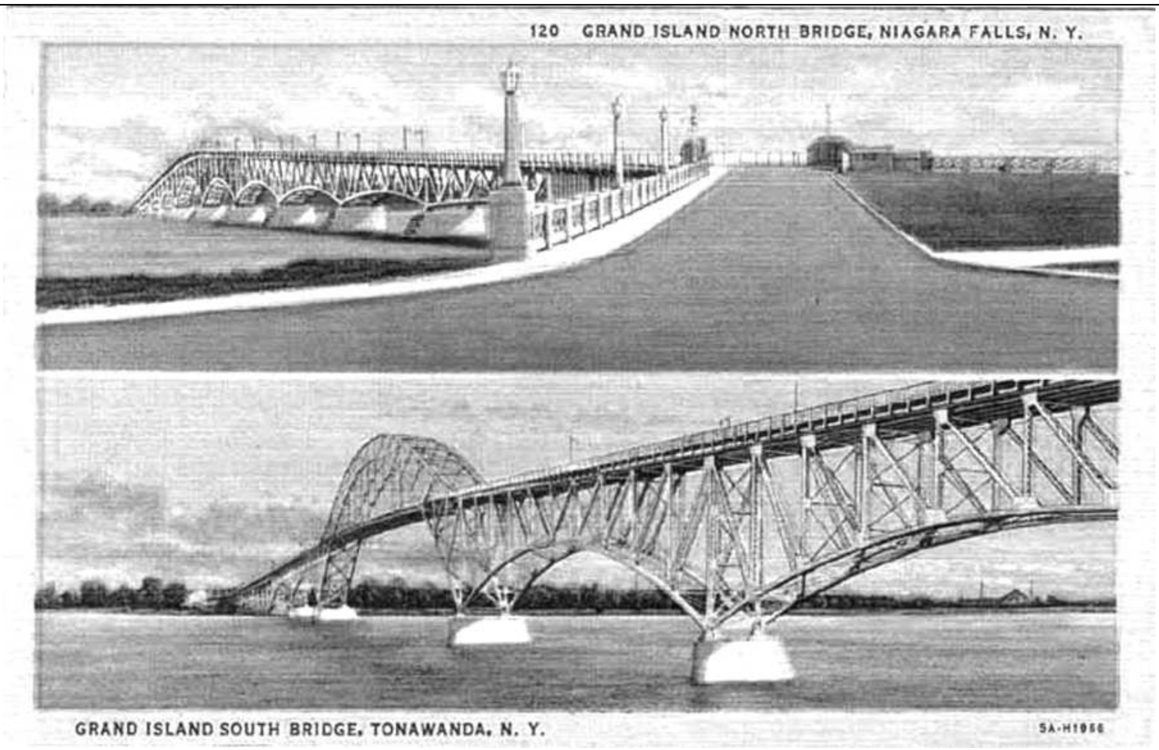

Figure 5: Grand Island, New York Bridges, 1935
no data

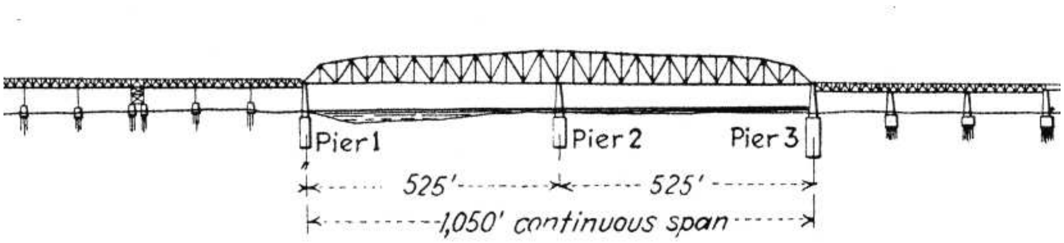

Figure 6: Missouri River Bridge, Omaha, Nebraska, 1935
main span 525', vert. clearance 49', continuous unit 1050', l.o.a. 4378'

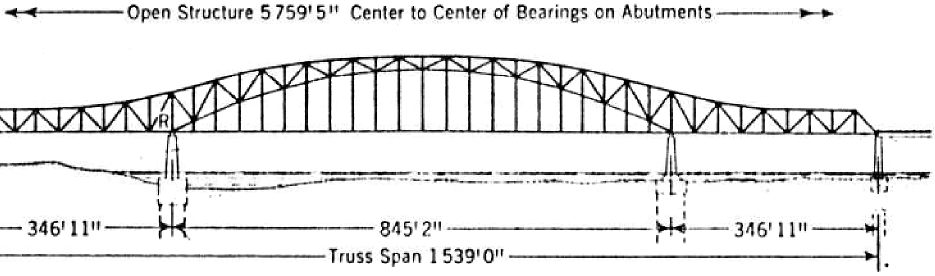

Figure 7: Mississippi River bridge at Dubuque Iowa, 1949
main span 845', vert. clearance 64', continuous unit 1539', l.o.a. 5760'

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[11] Gustav Lindenthal, "The Continuous Truss Bridge Over the Ohio River at Sciotoville, Ohio, of the Chesapeake and Ohio Northern Railway," *Transactions of the American Society of Civil Engineers* 35 (1922): 910-975.

[12] C.A.P. Turner, "Discussion on Sciotoville Bridge over the Ohio River," *Transactions of the American Society of Civil Engineers* 35 (1922): 954, 961.

[13] Lindenthal, "The Continuous Truss Bridge Over the Ohio River at Sciotoville, Ohio, of the Chesapeake and Ohio Northern Railway," pp. 971-975.

[14] Daniel B. Steinman, "Discussion on Sciotoville Bridge over the Ohio River," *Transactions of the American Society of Civil Engineers* 35 (1922): 964.

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[15] Cecil Vivian von Abo, "Secondary Stresses in Bridges," *Transactions of the American Society of Civil Engineers* 89 (1926): 1-193.

[16] Gustav Lindenthal, "Bridges With Continuous Girders," *Civil Engineering* (July 1932): 424.

[17] Lindenthal, "Bridges With Continuous Girders," p. 423. Note: It could not be conclusively determined from a review of the literature who built the first continuous truss highway bridge in the U.S., but it appears to have been Lindenthal. In 1932 Lindenthal wrote an article entitled "Bridges with Continuous Girders" in which he reviewed the American practice over the previous fifty years. Lindenthal studied various designs for continuous truss bridges in 1883 and in that year built a variation of the type using the "funicular principle" with counterweights at the piers to balance the stresses in the trusses. The Herr's Island Bridge carried a highway over the Allegheny River near Pittsburgh with three thru-spans of 200'-300'-200'. In 1890 he built another bridge on the same principle to carry highway and streetcar traffic over the Monongahela River at McKeesport. Lindenthal abandoned the funicular principle and it was not until the late 1930s that the principle was incorporated into the patented Wichert Truss system to combine the advantages of continuity with a statically determinate design.

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[31] I.L. Pesses, "Silicon Steel Used Liberally in 1257-ft Continuous Truss Bridge," *Engineering News-Record* (October 9, 1930): 572-575.

[32] "Awards made for Most Beautiful Bridges of 1930," *Engineering News-Record* (July 2,1931): 30.

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[34] Lindenthal, "Bridges With Continuous Girders," pp. 421-424.

[35] Ibid., p. 423.

[36] Charles M. Spofford, "Little Bay and Bellamy River Bridges," *Journal of the Boston Society of Civil Engineers* (January 1935): 3-4.

[37] "High-Level Bridge Link in the Dover-Portsmouth Road," *Engineering News-Record,* (September 27,1934): 387.

[38] Spofford, "Little Bay and Bellamy River Bridges," p. 6.

[39] Spofford, "Lake Champlain Bridge," p. 647.

[40] Spofford, "Little Bay and Bellamy River Bridges," p. 6-7; "High-Level Bridge Link in the Dover-Portsmouth Road," pp. 388-389.

[41] Spofford, "Little Bay and Bellamy River Bridges," 12, 14.

[42] C. M. Spofford and C. H. Gibbons, "Weighing Bridge Reactions With Proving Rings," *Engineering News-Record* (March 28, 1935): 446-449.

[43] Ibid, p. 446.

[44] Ibid.

[45] Spofford, "Little Bay and Bellamy River Bridges," p. 14.

[46] Spofford and Gibbons, "Weighing Bridge Reactions With Proving Rings," p. 447.

[47] "Three New Bridges for Cape Cod Canal," *Engineering News-Record,* (January 25,1934): 107-109; "First of Cape Cod Bridges Erected," *Engineering News-Record* (November 8, 1934): 607; "Institute Awards Prizes to 2 Bridges," *New York Times* (June 7, 1935):11.

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