The Roeblings and the Stayed Suspension Bridge: Its Development and Propagation in 19th Century United States

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INTRODUCTION

John A. Roebling was the preeminent suspension bridge designer in late 19th century United States, building suspension bridges for aqueducts, road and rail use. Over the course of his career John Roebling designed and constructed a series of suspension bridges of increasing length, beginning with the Pittsburgh Aqueduct in 1845 (seven spans of 162 ft each) and continuing through the Cincinnati Bridge in 1867 (main span of 1057 ft). His final design for the Brooklyn Bridge (main span of 1595 ft) was completed in 1883 under the direction of his son Washington A. Roebling. At the time of their completion both the Cincinnati and Brooklyn Bridges were the longest spans in the world, and the Brooklyn remained so until the opening of the Williamsburg Bridge in 1903.

John Roebling developed a hybrid structural system for his suspension bridges, consisting of three primary elements—parabolic suspension cables, inclined (or diagonal) cable stays and stiffening trusses. While Roebling was not the first bridge designer to use any one of these systems, his work is unique in that he successfully combined all three of these systems. It was precisely the combination of these three structural elements that allowed his bridges to be the longest spans in the world, and at the same time overcome many of the problems of flexibility associated with 19th century suspension bridges. The stayed suspension bridge is a highly indeterminate and non-linear structure, and accurate structural analysis of such a structure was not possible in the 19th century. Nevertheless, Roebling designed safe and serviceable stayed suspension bridges. The stayed suspension bridge became a “trademark” of Roebling design in the late 19th century, and other bridge designers in the United States adopted this structural form.

This paper studies the structural design methods developed by John Roebling for the unique structural system of the stayed suspension bridge, and explores the influence of the Roebling success on the work of other 19th century bridge designers in the United States. Much of this research is based on a collection of 59 proposed bridge designs archived in the Roebling Collection of Rensselaer Polytechnic Institute (RPI) (Stewart 1983).

Nineteenth Century Suspension Bridge Theory and Design

The development of suspension bridges in 19th century Europe was strongly influenced by the theoretical work of Navier and the bridges of Telford. The development of suspension bridge theory during this time has been reviewed in Buonopane and

Billington (1993). The analysis of an unstiffened suspension bridge, including the nonlinear deformation of the cable, was published by Navier in 1823, and in 1826 the 580 ft span of Telford's Menai Bridge was the longest in the world. However, several notable bridge failures due to wind-induced motions led British engineers to consider more effective methods for stiffening a suspension bridge against motion due to wind and otherwise. The development of stiffening methods for suspension bridges is discussed in Paxton (1999) and Gasparini et al. (1999). Of particular note are the incorporation of a substantial stiffening truss by J. Rendel during his 1840 reconstruction of the Montrose Bridge, and the consideration of inclined stays by J. Russell in his discussion of the wind-induced damage to the Menai Straits Bridge in 1839 (Rendel, 1841, Russell 1841). Although the importance of stiffening a suspension bridge was recognized, no suitable methods were available to analyze a stiffened suspension bridge until the publication of an approximate method by W. Rankine in 1858 (Pugsley 1968). The Rankine theory assumed the use of a stiff truss and thereby neglected the non-linear behavior of the suspension cable. Influenced by Roebling's Niagara Bridge, Clericetti (1880) published a method of analysis for a purely cable-stayed bridge, as well as an approximate method for the stayed suspension bridge form.

The stayed suspension bridge is a highly indeterminate structure, and therefore no simple methods were available in the 19th century to accurately determine the distribution of forces within the bridge. The internal forces depend on relative stiffness of the structural elements, non-linear deformation of the bridge, as well as construction sequence and pretensioning of the diagonal stays. To design stayed suspension bridges, John Roebling developed a strength method of analysis which was straightforward and easy to calculate in the context of 19th century analysis. Further, Roebling's design method resulted in safe and serviceable bridge designs, as evidenced by his built works.

ROEBLING DESIGN METHODS

The Roebling Collection at RPI includes preliminary design information related to 59 unbuilt suspension bridges between the years of 1847 and 1914. The earliest group of proposals, between 1847 and 1868, were completed by John Roebling himself, while those between completed during 1869 and 1869 have been judged to have been the combined work of John and Washington Roebling. After the elder Roebling's death in 1869, the remaining proposals are the work of Washington Roebling (Stewart 1983). Some of the archival information is related to major unbuilt bridge proposals, such as John Roebling's designs for the Wheeling Bridge and the Kentucky River Bridge. However, the large majority of information relates to medium length spans in the range of 100 ft to 600 ft. The proposed bridges include foot bridges, road bridges and rail bridges. The archival information on each bridge typically includes correspondence from the potential clients, and a cost estimate, calculations and sketches prepared by the Roeblings.

The design calculations for these bridge proposals are, in general, relatively simple and brief—typically contained on a few pages. Because the calculations are for medium length spans, they represent straightforward application of the design methods that the Roeblings would have developed and used on their built works. These bridge proposals can be used to understand the design methods used by the Roeblings for the complex problem of the stayed suspension bridge. The proposal calculations will be used to study several important structural design issues—the most important of which is the division of load between the suspension cable and inclined stays. The calculations also provide insight into the selection of cable and stay sizes, truss design, factors of safety and live loading. Some overall observations of the design method will be discussed based on the collection of proposals as a whole; a more detailed discussion of Washington Roebling's 1869 proposal for the Lowelville Bridge in Ohio will follow.

Load Distribution between Cables and Stays

The fundamental problem in a statically indeterminate structure is to determine the internal force distribution between the various structural elements. For the case of the stayed suspension bridge, the designer must estimate the distribution of forces between the parabolic suspension cables, the inclined stays and the stiffening truss. The internal distribution of forces in a statically indeterminate structure depends on the deformation of the structure, and requires calculations considerably more complicated than equilibrium alone. For suspension bridges (and cable structures in general) the deformations have a non-linear relationship to the applied forces, further complicating the solution. For the Roebling system of a parabolic cable, inclined stays and stiffening truss, an accurate solution is essentially impossible without a modern, non-linear structural analysis computer program. Instead John Roebling used an equilibrium strength approach, in which equilibrium is always satisfied but compatibility of deformations is not enforced. Provided that the structure possesses sufficient ductility, this is a valid design approach that has been used in the 19th century and continues to be used to this day (Ochsendorf 2005).

Roebling first computes the total self-weight (dead load) of the road deck, stiffening trusses and vertical suspenders. The magnitude of the live load used varies, depending on the potential use and clients' requests. For the 240 ft span of Bonner's Bridge (1860), the total live load is 30 000 lb, based on the weight of 2 four-horse teams or 30 head of cattle (RPI, box 11, folders 16-17). For the 550 ft span of the Rock Island Bridge (1868), Roebling used a live load of 50 psf to accommodate the potential for heavily loaded traffic as specified by the U.S. War Department (RPI, box 11, folders 23-24). For the East Rockport Bridge (1868), a 550 ft span footbridge, Roebling used a total live load of 150 persons of 150 lbs each (RPI, box 11, folders 33-34). For design of the cable systems, Roebling assumes that the live loads are uniformly distributed across the entire bridge deck. This distribution of live loading will produce the largest possible tension in the parabolic cables, but would not necessarily produce the maximum forces in the stays or truss.

The most important step in Roebling's design method is the distribution of total load between the parabolic suspension cable and the inclined stays. The calculations clearly show that the Roeblings intentionally divided the load between the cable and stays. Typically 1/4 to 1/3 of the total load was assigned to the stays and the remainder to the parabolic suspension cable. The justification for this load distribution remains unknown. Current research is ongoing to evaluate the accuracy of this assumption using modern structural analysis. Among the various proposals are some atypical load distributions: for the 300 ft span footbridge of the Jones Mill Bridge (1871) the stays are designed for only 16% of the total load (RPI, box 11, folder 65); and for the design of 750 ft span of the Union Bridge (1869), 45% of the load was assigned to the stays (RPI, box 11, folder 48).

Stiffening Truss

The typical bridge calculations begin with a detailed list of the components and weight of each element of the stiffening truss. The stiffening trusses were typically wooden Howe trusses with iron rods for verticals; some longer span bridges used iron truss members. No calculations are provided which show how the various wooden truss members were sized, and the method by which the truss members were selected remains undocumented.

In only one of the design proposals does Roebling assign some part of the total vertical load to the stiffening truss. In the calculations for the Rock Island Bridge Roebling writes "One half of this Wgt [weight] is to be born by the trusses, the other half by the Cables" (RPI, box 11, folders 23-24). It is possible that Roebling viewed the stiffening truss as distributing the effects of a concentrated live load, so as to produce a nearly uniform load on the vertical suspenders and thereby on the suspension cable. This view is consistent with the theory later developed by Rankine which assumes an 'ideal' stiffening truss—a truss which results in a uniform load on the vertical suspenders regardless of the distribution of live load on the truss. This assumption allowed Rankine to calculate the bending forces in the truss by superposition of the live load and the uniform suspender load (Pugsley 1968). From the calculations examined as part of this study, there is no evidence that the Roeblings directly used Rankine's method, although the 1876 edition of Rankine's *Manual of Applied Mechanics* appears in the list of contents of the Roebling library (Stewart 1983, p. 104). Two of the proposed bridges to be used for foot traffic only are actually designed with no stiffening truss at all: the East Rockport Bridge (1868, 550 ft span) and the Jones Mill Bridge (1871, 300 ft span) (RPI box 11, folders 33-34 and 65).

Selection of Cable and Stay Sizes

After distributing the total load the between the parabolic cable and inclined stays, Roebling applies a safety factor. The safety factors are generally in the range of 4 to 5, although in the case of the East Rockport Bridge a safety factor of 7 was used (RPI, box 11, folders 33-34). For the suspension cables, the maximum tension is computed based on the vertical load and the sag-to-span ratio (see Lowelville Bridge Design below). A suitable number and size of cables was then selected based on tabulated cable strengths.

For Bessemer steel cables, the unit strength was typically taken as 15 tons per lb per ft. (e.g. Hancock Bridge 1869; RPI, box 11, folders 37-38). This tensile strength is actually a normalized strength based on the self-weight per foot length of cable, and thus applies to cables of any diameter. The self-weight per foot length is directly proportional to the cross-sectional area of the cable, and this allowable strength is equivalent to a modern allowable stress. Since Roebling's calculations are done entirely in terms of force, this normalization is simpler than allowable stress. In addition this normalized strength may have been easier to measure in the lab, as it does not require any measurement of the true cross-sectional area of the wire rope. This 15 ton strength is equivalent to about 97 000 psi (670 MPa) ultimate stress. Withey and Aston (1926, p. 669) report an ultimate strength of 90 000 psi for Bessemer steel wire.

The total load assigned to the inclined stays (including a factor of safety) is divided equally among all of the stays, such that the vertical component of force in each of the stays is equal. This method clearly satisfies equilibrium, but does not attempt to consider deformation of the deck and tower. Since the stays are inclined at different angles, the total axial forces will vary, even if the vertical components are considered equal. The stays nearest the tower will have the smallest total tension, while those furthest into the span will have the largest tension. The Roebling designs do use stays of varying rope size with the largest diameters furthest into the span, although none of the designs examined showed specific calculation of the total cable tensions. The variation of stay sizes is considered in more detail for the design of the Lowelville Bridge.

DESIGN OF THE LOWELVILLE BRIDGE

The Lowelville Bridge was designed by W.A. Roebling at the request of Robert Lowry on behalf of the county commissioners of Canfield, Ohio. The proposed bridge had a 475 ft span with a 16 ft wide roadway and two sidewalks. The deck was to be supported by two parabolic cables of 7 wires each and a total of 40 inclined stays. The deck was stiffened by two Howe trusses with a chord-to-chord depth of 59.5 inches. The bridge contract was ultimately awarded to a Cleveland company for construction of a tubular wrought-iron bowstring arch bridge (Simmons 1999).

The calculations for the Lowelville Bridge provide a clear and relatively complete set of engineering design calculations. The calculations run approximately 3 legal size pages; the cost estimate, 4 pages; and sketches, 4 pages (RPI, box 11, folders 40-41). The primary calculations are reproduced in **figs. 1 and 2** and summarized in **table 1**.

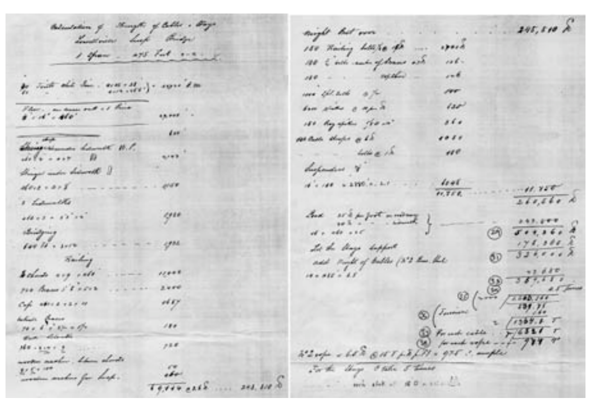

Figure 1. Lowelville Bridge design calculations (RPI, box 11, folders 40-41)

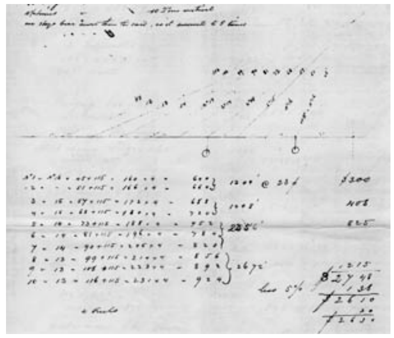

Figure 2. Lowelville Bridge stay calculations (RPI, box 11, folders 40-41)

Table 1. Summary of Lowelville Bridge design (RPI, box 11, folders 40-41)

Line	Description	Value and Units	Formula
1	Self-weight of suspended structure: trusses, roadway, suspenders	260 560 lbs	
2	Live load of 25 psf on roadway & 20 psf on sidewalk	243 800 lbs	
3	Total Load	504 360 lbs	Line 1 + Line 2
4	Load supported by inclined stays	178 360 lbs (35%)	
5	Load supported by suspension cables	326 000 lbs (65%)	
6	Self-weight of suspension cables	43 680 lbs	
7	Total load on cables	369 680 lbs	Line 5 + Line 6
8	Total load on cables including a safety factor of 4.5	831.78 tons	4.5 × Line 7
9	Maximum tension in suspension cables	1364.1 tons	1.64 × Line 8
10	Tension in each suspension cable	682.1 tons	Line 9 ÷ 2 cables
11	Tension in each rope of cable	97.4 tons	Line 10 ÷ 7 ropes
12	Strength of one No. 2 rope	97.5 tons	
13	Total vertical load per stay group	22.25 tons	Line 4 ÷ 4 groups
14	Vertical load per stay including a safety factor of 4.5	10 tons	Line 13 ÷ 10 stays × 4.5

Roebling begins with a detailed estimate of the weight of the suspended, including all pieces of wood, connection hardware and vertical suspenders. The estimate of the weight of the vertical suspenders appears to be based on an "average" length of 16 ft and a unit weight of 2.1 lb/ft, giving 6048 lbs. Some of the bridge proposals (e.g. Hancock Bridge 1869, RPI, box 11, folders 37-38) include a detailed sheet which computes the length of each suspender. Uniformly distributed live loads of 25 psf on the roadway and 20 psf on the sidewalks are used. The total load of 504 360 lbs is divided between the stays and cables. In this case, 35% is assumed to be supported by the stays. The remaining load on the suspension cables (369 680 lbs) is then increased by a safety factor of 4.5 times to result in 831.78 tons.

From the uniformly distributed vertical suspender load, the maximum tension in the parabolic cable at the tower can be determined based on the following formulas

$$H = W\left(\frac{L}{8f}\right) \tag{1}$$

$$V = H\left(\frac{4f}{L}\right) \tag{2}$$

$$T = \sqrt{H^2 + V^2} = W\left(\frac{L}{8f}\right)\sqrt{1 + \left(\frac{4f}{L}\right)^2} \tag{3}$$

where W is the total vertical load, L is the cable span, f is the cable sag, H is the horizontal cable tension, V is the vertical cable tension at the tower, and T is the axial cable tension at the tower. As shown by the above equations, the relationship between vertical load (W) and maximum cable tension (T) depends *only* on the sag-to-span ratio (f/L). These relations were known as early as 1794 (Pugsley 1968) and would have been known by the Roeblings. Presumably the Roeblings would have had a table of factors for various sag-to-span ratios. For the Lowelville Bridge, the sag-to-span ratio is 1/12.5 and Eq. 3 reduces to $T = 1.64W$.

Roebling calculates the maximum tension on each of two cables, and then on each of the seven ropes comprising the cable. The resulting required rope strength is 97.4 tons (including the safety factor of 4.5). Roebling then calculates the strength of a No. 2 rope by multiplying the unit weight of 6.5 lb per ft length by the strength of 15 tons per ft per ft, giving an actual strength of 97.5 tons.

The total vertical load on the stays of 178 360 lbs is divided equally among 40 stays and a safety factor of 4.5 times is applied, resulting in 10 tons vertical per stay. Since the stays are inclined at various angles the axial tension will vary according to the angle—the stays which extend the furthest out into the span will have the largest horizontal component and therefore the largest total axial tension (**table 2**). Roebling varies the stays sizes, increasing the size from No. 16 nearest the tower to No. 13 toward the center of the span.

The force ratio in the rightmost column of **table 2** is the ratio of axial force to self-weight per foot length. The values of the ratio fall in a relatively narrow range, indicating that Roebling was varying the stay sizes with the assumed total axial force. Further the force ratio for the stays is somewhat less than the ultimate normalized strength of 15 tons/lb/ft for Bessemer steel, indicating that their actual factor of safety is larger than the value of 4.5 actually used in the design calculations. In contract, the size selected for the main suspension cables maintains the assumed factor of safety of 4.5 almost exactly.

Table 2. Inclined stay sizes and forces for Lowelville Bridge (RPI, box 11, folders 40-41)

Stay location	Rope size	Approx. diameter	Approx. self-weight	Horizontal force	Axial force	Force ratio
	(No.)	(in)	(lb / ft)	(tons)	(tons)	(tons / lb / ft)
1	16	7/8	1.35	4.9	11.1	8.2
2	16	7/8	1.35	7.3	12.4	9.2
3	15	1	1.67	9.8	14.0	8.4
4	15	1	1.67	12.2	15.8	9.4
5	14	1-1/8	2.11	14.6	17.7	8.4
6	14	1-1/8	2.11	17.1	19.8	9.4
7	14	1-1/8	2.11	19.5	21.9	10.4
8	13	1-1/4	2.64	22.0	24.1	9.1
9	13	1-1/4	2.64	24.4	26.4	10.0
10	13	1-1/4	2.64	26.8	28.6	10.8

INFLUENCE OF THE ROEBLING SYSTEM

The stayed suspension bridge system developed by John A. Roebling and continued by Washington was highly successful and had a widespread influence on suspension bridge design in the late 19th century United States. The work of the Roeblings was widely published in American periodicals. Publications covering Roebling's design for the Niagara Railroad Bridge appear in *Scientific American* in 1852 (Jakkula 1941). The Niagara Railroad Bridge was also favorite subject of 19th century stereo photographers; and therefore would have been known to the general public. The planning and design of the Brooklyn Bridge was widely published in engineering journals and the popular press of the day. John A. Roebling's initial report to the New York Bridge Co. was published in 1867 and subsequently excerpts appeared in engineering journals. Construction progress was followed closely by such publications as the *Journal of the Franklin Institute*, *Engineering* (London) and *Scientific American*, as well as local newspapers and periodicals (Jakkula 1941).

As the prominence of the Roebling system became more widespread in the United States, other bridge designers began to use the stayed parabolic system for moderate spans. The Roebling bridge system became a signature bridge type and both clients and engineers sought to associate their bridges with the Roebling name in some way. Given the complicated nature of the Roebling system—with its suspension cables, inclined stays and stiffening truss—did these other designers use some valid engineering analysis? Or did they simply include stays in imitation of the Roebling bridges? The involvement of John A. Roebling's Sons Company with may of these moderate span bridges is somewhat obscured by the fact that the Roebling Company functioned both as a producer wire and as an engineering design firm. The two most significant purveyors of the Roebling-type suspension bridges were Thomas Griffith and James Shipman.

The Bridges of Thomas Griffith

Thomas Griffith's suspension bridges at Waco, Texas (1870) and Minneapolis, Minnesota (1877) exhibit the basic characteristics of the Roebling system, in particular inclined stays and a substantial stiffening truss. Prior to being appointed as the engineer of the Waco Bridge, Griffith had worked as an assistant to Capt. Edward Serrell on the 1043 ft span of the Lewiston-Queenston Suspension Bridge (1850). The association between Griffith and Serrell is confirmed by an archival document in John A. Roebling's hand in which Roebling performs a structural evaluation of the bridge's design (RPI, box 11, folder 4).

The 1870 Waco Bridge has a main span of 475 ft and is supported by two main parabolic cables and a series of 3 inclined stays from each tower (**fig. 3**). Conger (1963) writes that the Col. John Flint, president of the Waco Bridge Co., first advocated the use of Roebling-style suspension bridge. Flint himself traveled to New York and Trenton in August of 1868 and decided on a suspension bridge as the best type. He informed his business associates in Waco of his conclusions by letter, writing

> Shall employ Griffith to put it up. His bid was for not quite strong enough cable in my judgment, and I desire to add guys, etc., for more sure protection against storms, Therefore with his and John A. Roebling's advice will prepare the order for the bridge carefully.
>
> (Conger 1963, p. 187)

In the case of the Waco Bridge, the bridge company clearly wanted to build a Roebling bridge, even though Griffith's original proposal apparently did not include guys (stays). Further, Flint visited the Roebling Company not only to place an order for the wire rope and cable, but more importantly to receive advice about the bridge. This is an example of John A. Roebling's Sons Co. acting both as a material supplier and engineering consultant for bridges that would use their product. Given the difficult engineering design of a stayed suspension bridge, it is likely that the Roebling's Company provided substantial design input as to the sizes of the cables and stays required. Renovations of the Waco Bridge in 1913-14 have since removed the stays and replaced the original truss

(Walker 1999). The image of the Waco Bridge became a symbol of state-of-the-art bridge construction in Texas and was used by at least two bridge companies for local advertising, although neither company had a direct involvement in its original design and construction (**fig. 4**).

Figure 3. Waco Bridge (David Denenberg collection)

In 1877 Griffith returned to Minneapolis, Minnesota to build a second suspension bridge of span 675.1 ft, at the site of the earlier suspension bridge he had built. Griffith's first suspension bridge at Minneapolis (1855, 620 ft span) did not include inclined stays (**fig. 5**), but the new bridge included four inclined stays radiating from each tower (**fig. 6**)**.** In describing the second bridge Griffith wrote

> The platform is—the weight of suspended material, the span and deflection considered—very free from the usual vibratory motions of this kind of structure. And any additional strain which they involve, is more than compensated for by the sixteen floor stays which have not entered into the estimate of the strength of the bridge.
>
> (Griffith 1878)

This statement suggests that Griffith designed his suspension bridge as if it had no stays and then included the stays as an additional measure of safety against vibrations of the bridge. This approach is in contrast to the Roebling method in which the strength of the stays was considered an integral part of the bridge design. This suggests that the design methods used by the Roeblings were not available to other bridge designers of the day.

Figure 4. Bridge company advertisements featuring image of the Waco Bridge (Polk 1892, pp. 256, 276)

Figure 5. First Minneapolis Suspension Bridge (Minnesota Historical Society, neg. no. 586)

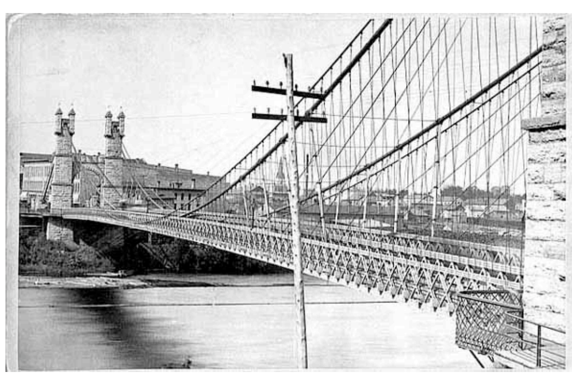

Figure 6. Second Minneapolis Suspension Bridge (Minnesota Historical Society, neg. no. 17198)

The Bridges of the Ohio Valley

Simmons (1999) has traced the development of suspension bridges in the Ohio River Valley in the second half of the 19th century, which was heavily influenced by Ellet's Wheeling Bridge (1849) and Roebling's Cincinnati Bridge (1867). A number of bridges built, or proposed, during this period included Roebling features such as inclined stays, a substantial stiffening truss, single wrapped suspension cables and eyebar anchorages. The strong reputation of the Roebling's was apparent even to potential clients in the Ohio Valley. In 1868 a private land owner in East Rockport, Ohio wrote to John Roebling to request a bid for a 550 ft span footbridge: "Having heard your name mentioned in connection with suspension bridges in this country" (RPI, box 11, folders 33-34).

Prior to constructing the Tiffin Bridge (1853, 210 ft span) a representative of the bridge company traveled to Pittsburgh to study the suspension bridges there. In 1853 Roebling's Pittsburgh Aqueduct and Smithfield Street Bridge would have still been in use. John Gray of Pittsburgh was hired to build the Tiffin Bridge which had some Roebling features, although no diagonal stays. All of John Gray's later bridges in Ohio included inclined stays: Licking River Bridge (1853, 550 ft span), Hamilton Bridge (1867, 400 ft span), Whitewater River bridge (1868, 460 ft span) and Branch Hill Bridge (1871, 305 ft span). In the case of the Branch Hill Bridge, Gray's firm contacted Washington A. Roebling directly to seek advice on the size and material (iron or steel) of the cables (Simmons 1999). Interestingly, these bridges were built between the time when the Wheeling Bridge suffered major damage in a windstorm (1854) and the 1871 design by Washington Roebling to retrofit the Wheeling Bridge with inclined stays (Kemp 1999). The Wheeling Bridge failure may well have contributed to the increased use of the Roebling-style stays in Ohio Valley.

The Bridges of James W. Shipman

For construction of the Harrison Bridge over the Whitewater River between Ohio and Indiana, the county commissioners hired John A. Roebling's Sons Company to write the specifications for a 425 ft span suspension bridge. The specifications included the required cable and truss sizes and materials. This bridge is another example of the Roebling Company functioning as an engineering design consultant. Washington Roebling actually submitted a bid in partnership with a local engineer, but the contract was awarded to James W. Shipman & Co. of Cincinnati. The completed bridge included a stiffening truss and inclined stays (Simmons 1999). Roebling's design calculations and cost estimate survive, although it is not clear which parts of the calculations were completed in order to write the specifications and which parts were completed as part of the bid (RPI, box 11, folder 73). In Ohio, Shipman's company went on to build the Franklin Bridge (1873, 365 ft span) and the Linwood Bridge (1876, 353 ft span) and both bridges employed the Roebling-style inclined stays (Simmons 1999).

By 1877 Shipman was practicing under the name of the New York Bridge Co. and the Roebling-style suspension bridge figured prominently in their advertising and letterhead (**figs. 7 and 8**) (Darnell 1984). Clearly the Roebling name and bridge type had become a desirable marketing image. In 1878 Shipman's New York Bridge Co. (also known as

Hutchinson & Shipman) won the contract for a suspension bridge of 550 ft over the Connecticut River at Turners Falls in Massachusetts, later to become known as the 'Old Red Bridge' (**fig. 9**). Copies of the original bridge specifications and contract survive in the Holly Collection. The construction contract states

> The parties of the first part [Hutchinson & Shipman] agree to furnish a certificate from John A. Roebling's Sons that the materials used in the cables and stays in the above bridge is of ample strength to sustain a rolling load of forty pounds per square foot in addition to its own weight with a factor of 4. Also that the elastic limit of each 2 1/4" steel wire rope is not less than 6-9 tons and the breaking strength is no less than 15-6 tons.
>
> (Holly Collection, Old Red Bridge)

The final sentence of the above quotation refers to a material strength requirement, which would have been a common expectation of a material supplier. The first sentence, however, relates the cable strength to the dead and live loads of the bridge. This statement implies that the Roebling Company is certifying the actual design of the bridge—the relationship between applied loads and strength of the bridge elements. Thus, the Old Red Bridge stands as further evidence that the Roebling Company was closely involved with the structural design of bridges for which they supplied wire and cable.

Shipman also constructed the Windsor Locks Bridge in Connecticut (1884, one span of 500 ft and two spans of 300 ft) using inclined stays (**fig. 10**) (Jakkula 1941; RPI, box 11, folder 78).

Other records indicate additional Roebling influence in bridges of Western Massachusetts. In 1871 Harris & Wright requested plans for suspension bridges of spans of 381, 220, 156, 110 ft, stating "We frequently have inquiries for suspension bridges and would like to be able to give prices when called for." (RPI, box 11, folder 66). In 1870 D. Harris requested a bid for a 350 ft span at Deerfield near the Connecticut River Railroad (RPI, box 11, folders 57-58). Other bridges using the Roebling system of inclined stays include the Lower (White) Bridge at Turners Falls (1872) and the Stillwater Bridge over the Deerfield River (ca. 1868) (Lutenegger 2005).

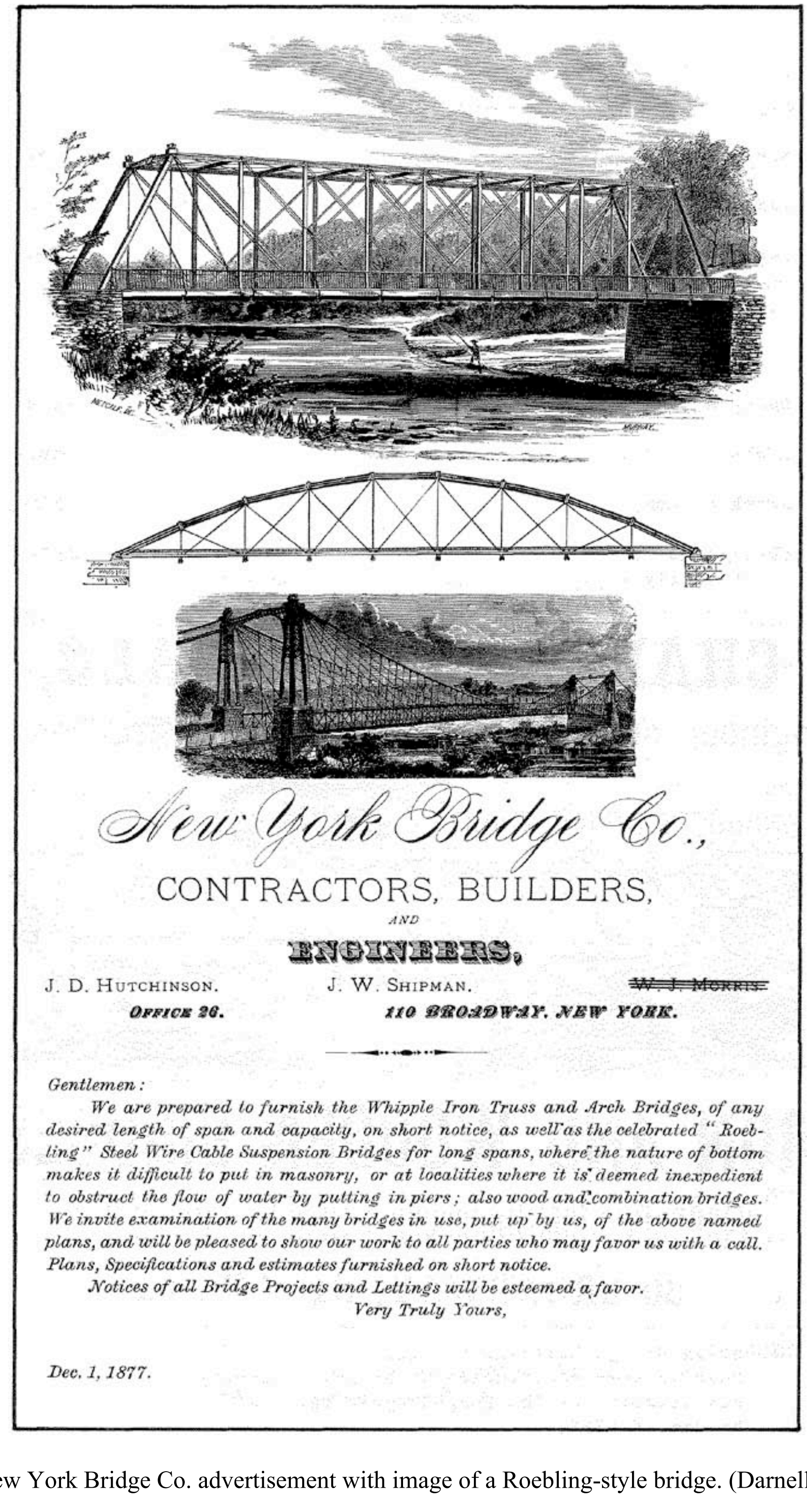

Figure 7. New York Bridge Co. advertisement with image of a Roebling-style bridge. (Darnell 1984, p. 42)

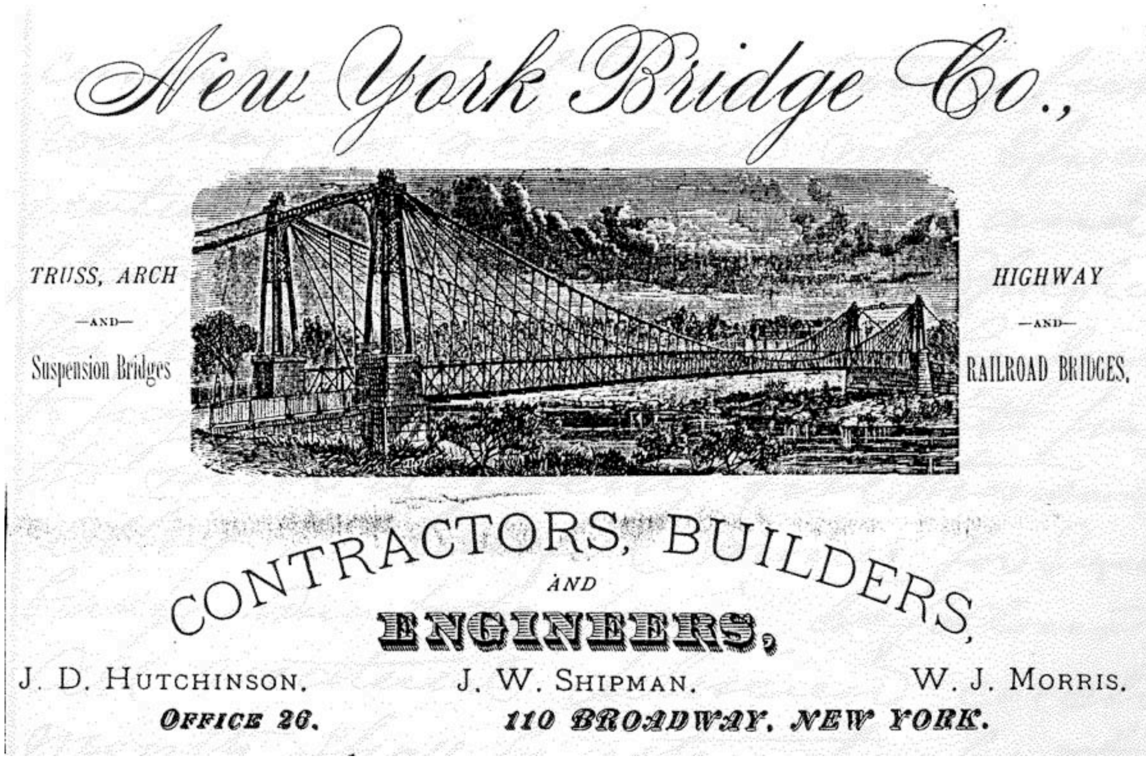

Figure 8. New York Bridge Co. letterhead with image of a Roebling-style bridge. (Holly Collection)

Figure 9. Old Red Bridge at Turners Falls. (Alan Lutenegger collection)

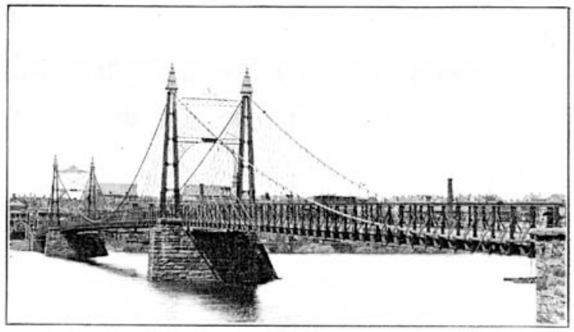

Figure 10. Windsor Locks Bridge. (Roebling Collection, RPI)

CONCLUSIONS

This paper has studied the methods developed by John A. Roebling, and continued by Washington A. Roebling, for the design of stayed suspension bridges. Because the Roebling system of parabolic cable, inclined stays and stiffening truss is both indeterminate and non-linear, Roebling used a simple strength approach to satisfy equilibrium and ensure the safe design of his bridges. Roebling's design methods are revealed in a collection of bridge design proposals at the Roebling Collection of RPI.

The Roebling bridges were widely known in the engineering community, and the stayed suspension bridge became a signature bridge form for late 19th century suspension bridges in the United States. The reputation of the Roeblings spread to potential clients, who frequently wrote unsolicited to the Roeblings requesting a bid for suspension bridge. A total of 59 bridge design proposals from 1847 to 1914 are found in the Roebling Collection. Additional financial records indicate that between the years 1868 and 1878, Washington Roebling worked on design proposals for approximately 50 bridges, during which time he was also serving as the chief engineer of the Brooklyn Bridge (RPI, box 12, folder 11). Washington Roebling reports having lost a total of $1260 on these unbuilt design proposals.

Bridge builders and clients relied on John A. Roebling's Sons Company not only to provide wire and cable, but also to provide engineering design services. In some cases such as the Waco Bridge, the bridge company sought the 'advice' of the Roebling Company; while in other cases, such as the Harrison Bridge, the Roebling Company was hired to write the bridge design specifications. John and Washington Roebling had a strong influence on suspension bridge design and construction in late 19th century United States, which extended well beyond the bridges directly attributed to them.

Although the hybrid stayed suspension bridge system developed and built by the Roeblings was highly successful, the system was not used after the Brooklyn Bridge. By the turn of the century analytical methods for deck stiffened suspension bridges (without stays) had progressed to the point where they could provide safe and efficient designs. Further the inclined stays proved difficult to properly pretension during construction and maintain during the lifetime of a bridge. Even Washington Roebling would eventually recommend against the use of inclined stays. In an 1896 letter to James McKee regarding a design for a suspension bridge across the Mississippi River at St. Louis, he wrote

> I would further dispense with the stays and rely entirely on the trusses for stiffness. With stays you would have to cut the truss at the middle or at the end of the stays so as to have the two systems act in unison.
>
> (RPI, box 11, folder 79)

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