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History and engineering analysis of the 1890 cable-stayed Bluff Dale bridge

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During the 1890s, Edwin E. Runyon and William Flinn constructed a group of innovative cable-stayed bridges in north central Texas. The Bluff Dale Bridge (Figures 1 and 2), the most complete example of the collaboration of these designers, was originally constructed in 1890 based on a bridge system patented by Runyon. Although renovated and relocated, Bluff Dale is the second oldest surviving cable-stayed bridge in Texas and possibly in the United States as well. Historians have recently identified a slightly earlier surviving Runyon cable-stayed bridge —the Barton Creek Bridge of 1890, completed several months prior to Bluff Dale (Figure 3). The towers, cables and floor beams at Barton Creek survive in their original form, thus providing important information on original construction details that no longer survive at Bluff Dale.

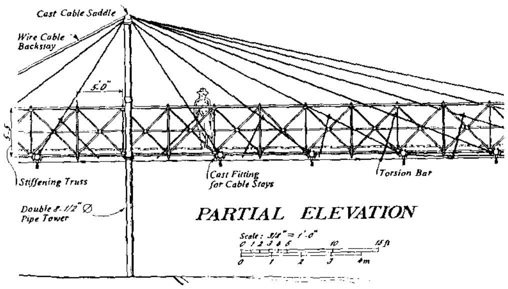


Figure 1
Bluff Dale Bridge with metal truss of 1899 (HAER TX–36, sheet 3; Erick McEvoy, delineator)

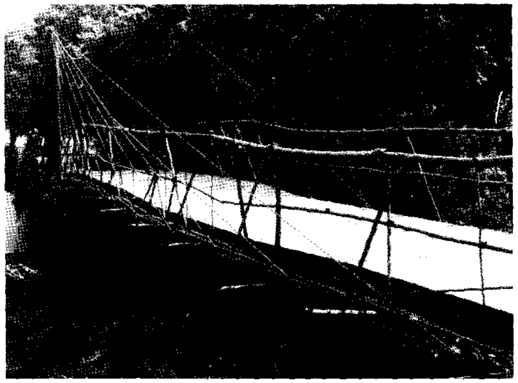


Figure 2
Bluff Dale Bridge in 1996 (HAER TX–36, photo 3; Joseph Elliott, photographer)

The Bluff Dale Bridge is a significant example of a local cable-supported bridge building tradition of the late 19th-century and demonstrates the inventiveness and proficiency of the designers. Runyon and Flinn responded to the engineering challenges of bridge design and construction with inventive solutions different from the designs of more prominent suspension bridges. This paper explores the significance of Runyon's bridges in the context of the development of 19th century cable-supported bridges, including historical precedents and engineering analysis of the unusual cable-stayed design.

In 1890 the commissioners of Erath County, Texas accepted a $4,200 bid by the Runyon Bridge

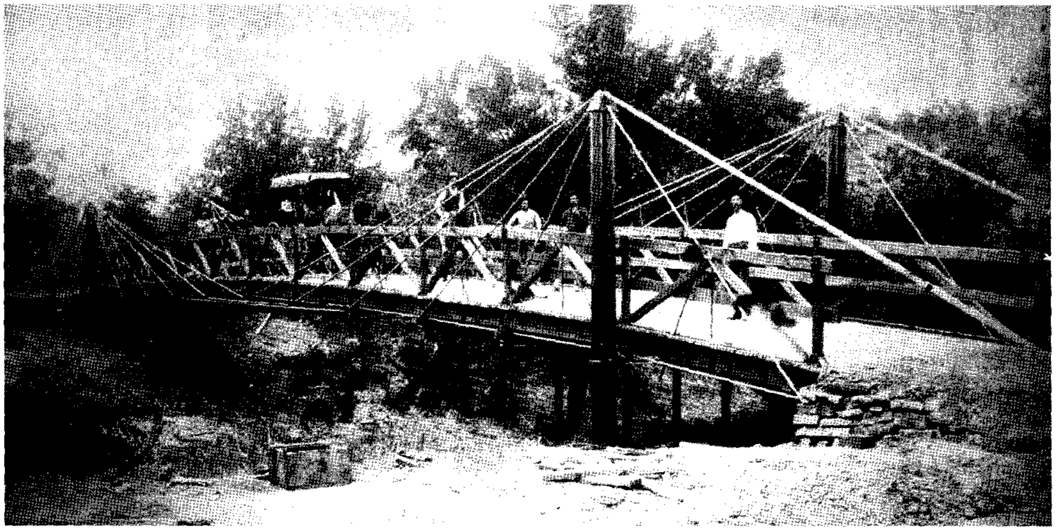


Figure 3
Barton Creek Bridge (HAER TX–36, photo 12)

Company for the construction of three bridges. The Runyon Bridge Company consisted of Runyon and Flinn, although there is no evidence of later collaborations between the two. Flinn built many other suspension bridges in Texas, and the Flinn-Moyer Company completed repairs to the Bluff Dale Bridge in 1899, replacing the original wooden truss with the surviving metal truss of pipe and rod sections. The Bluff Dale Bridge has a main span of 140′ (42.67 m) and side spans of approximately 30′ (9.14 m) each. The spans are supported by cable stays of two types—fixed and continuous, arranged in a fan pattern (Figure 4). In contrast, all stays of a typical modern cable-stayed bridge are fixed to the deck. The stay cables were composed of heavy gauge parallel wire strands. The stays of the Barton Creek Bridge contain about 30 strands of No. 9 gauge wire (0.148″, 3.75 mm diameter), and the builders of Bluff Dale probably used No. 9 wire, as it was the most common size for bridge construction (HAER NJ–132). The wires of the five continuous stays are bundled together to form the backstay. All of the stays of the Bluff Dale Bridge have been replaced by modern wire rope, probably at the time of its relocation in 1935. Additional description and drawings of the Bluff Dale Bridge can be found in HAER TX–36 and Brown (1998).

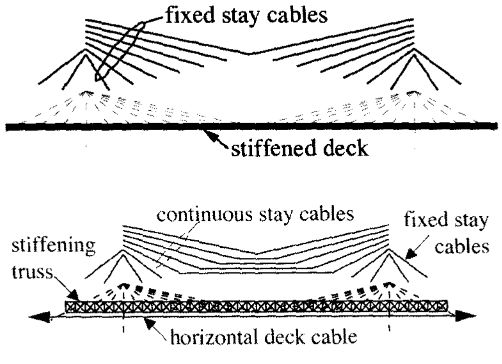


Figure 4
Exploded views of the cable systems of the Bluff Dale Bridge (above) and a modern cable stayed bridge (below)

Runyon's patents and the Bluff Dale Bridge

The Bluff Dale Bridge follows the concept of Runyon's 1888 patent (No. 394,940) for a cable-stayed bridge. The patent drawing (Figure 5) shows three panel points, but if extrapolated to include additional panel points, the resulting cable pattern could become either that of Bluff Dale or the «crossing fan» pattern used elsewhere by Runyon (Figure 6). The 1888 patent also includes horizontal «deck cables» that run longitudinally beneath the bridge deck. The center deck cable rests in saddles attached to the floor beams with no positive connection. The two outer cables sit in castings at the end of each floor beam, but U-bolts secure the cables to the floor beams. The patent description implies that the deck cables were the first elements to span the river during construction, providing an attachment point for the needle beams. The patent also states that the deck cables could replace longitudinal stringers, yet historical photographs show the more traditional wooden stringer and decking system on some Runyon bridges (Figures 3 and 6).

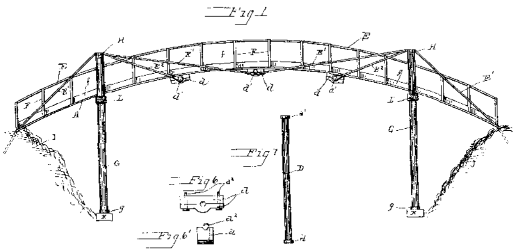


Figure 5
Elevation of cable stayed bridge from Runyon's patent (No. 394,940)

Figure 6
Unidentified Runyon bridge with «crossing fan» cable pattern (HAER TX–36, photo 14)

The transverse floor beams, or «needle beams,» are based on an 1889 patent (No. 400,874). They are composed of a horizontal pipe section and a lower chord of about 25 strands of No. 9 wire, separated by three vertical castings. The bowstring action of the beams provides substantial rigidity and bending resistance. The ends of the needle beams are fitted with a complex set of castings, which include attachment points for the bowstring cable, the deck cables, lateral X-bracing and the main stay cables (Figure 7). The needle beams of Bluff Dale survive in original condition including the parallel wire lower chords.

All of the cable elements of the Bluff Dale and Barton Creek Bridge were tensioned using a twisting device patented by Runyon in 1889 (No. 404,394) (Figure 8). The wires of the cable were separated into two bundles by a small casting (Figure 9). A circular device, clamped to the casting and rotated about the axis of the cable, twisted the two bundles and tensioned the cable. The builders then inserted a metal «torsion rod» into a hole in the casting and braced it against the bridge to prevent unwinding. The twisting device could then be removed and reused elsewhere on the bridge. Pretensioning the cables of a stayed system to remove slackness can provide substantial vertical stiffness to the bridge. This construction technique is instrumental to the success of a stayed bridge and Runyon's use of it

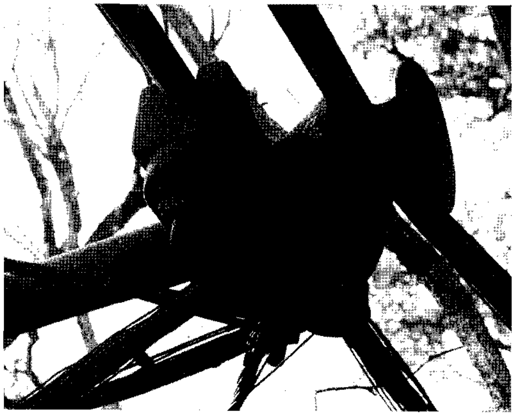


Figure 7
Castings and cables at end of needle beam from Barton Creek Bridge (HAER TX–87, photo 7; Bruce Harms, photographer)

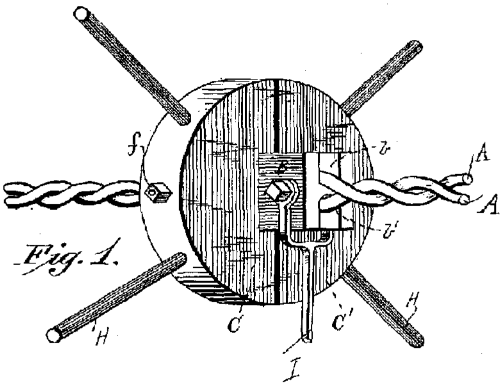


Figure 8
Patent drawing of Runyon's cable twisting device (No. 404,934)

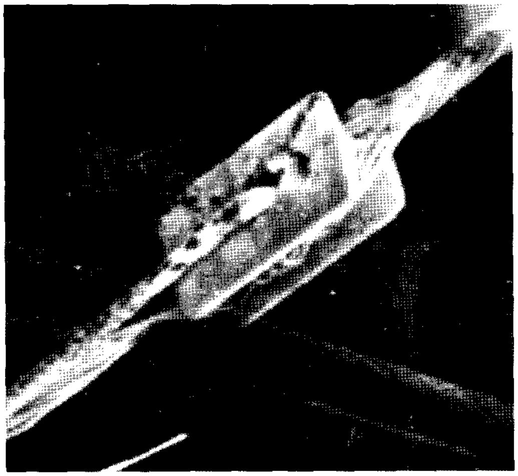


Figure 9
Twisting block on bowstring cable of needle beam of Bluff Dale Bridge (HAER TX-36, photo 6; Joseph Elliott, photographer)

demonstrates his sophistication as an engineering designer.

DEVELOPMENT OF CABLE-SUPPORTED BRIDGE FORMS

Both trained engineers and empirical builders have shaped the history and development of cable-supported bridges, as they independently translated the principles underlying these structures into a wide variety of bridge forms, from ancient examples in Asia and South America to the more well-documented European examples. In the early 19th century, a wide variety of cable-supported bridge forms were constructed, including stayed, parabolic and hybrid forms, and these bridges used various materials for the stays, including wire cables, wrought-iron chains and solid rods. A group of twelve unusual stayed bridges built in Scotland and England by local builders between 1816 and 1834 demonstrates such variety (Ruddock 1999). In 1823 Navier's *Rapport . . . et memoire sur les ponts suspendus*, the first theoretical analysis of cable-supported bridges, concluded that parabolic suspension bridges were preferable to cable-stayed since their flexibility allowed them to change shape in response to loads. Navier's work widely influenced bridge designers in Europe and the United States, and his conclusions may have contributed to the decline of cable-stayed bridges during the second half of the 19th century. Not until the end of the 19th century did the cable-stayed form re-emerge in France with the bridges of Gisclard, Arnodin and Leinekugel le Coq. The development of the modern cable-stayed bridge, characterized by high strength steel wires and large pretension forces, is generally attributed to Dischinger's work in the 1930s and the construction of the Strömsund Bridge in Sweden in 1955 (Troitsky 1988, Walther et al. 1999).

James Finley is supposed to have built the first chain suspension bridges in the United States about 1800, and Kranakis (1997) details his career and empirical design methods. Josiah White and Erskine Hazard introduced the use of wire cables in 1816 for a pedestrian bridge over the Schuylkill River in Philadelphia (Peterson 1986). The development of the suspension bridge in the United States was played out through the careers of Charles Ellet, Jr. and John Roebling. Ellet favored European design methods with shallow cables and a very lightly stiffened deck, exemplified in his Wheeling Bridge of 1849 (Kemp 1999). Roebling's career and that of his son Washington are well documented elsewhere. Of interest here is the manner in which Roebling's last two bridges —Cincinnati (1866) and Brooklyn (1883)— influenced other bridge builders and captured the imagination of the general public. The

«Roebling system» of parabolic cables, stiffening truss, and inclined stays became an engineering and visual trademark adopted by bridge builders nationwide and favored by public agencies awarding new bridge contracts. In the Ohio Valley, not far from the Cincinnati Bridge, John Shipman built several suspension bridges with inclined stays with spans from 300′ to 560′ (90 m–170 m) between 1852 and 1876. The Roebling Company wrote the specifications for some of these bridges and often supplied the wire that was used (Simmons 1999). An 1877 advertisement for Shipman's New York Bridge Co. includes an image of «the celebrated "Roebling" Steel Wire Suspension Bridge» (Darnell 1984).

CABLE-SUPPORTED BRIDGE TRADITION IN TEXAS

The cable-supported bridge tradition in Texas begins with Thomas Griffith's construction of the Waco Bridge in 1870 over the Brazos River (HAER TX–13, TX–98). The relationship of Griffith to the Roebling Company is unclear, but he may have worked on the construction of Roebling's Niagara Bridge in the 1850s. He later independently built two suspension bridges in Minneapolis in 1855 and 1875. The Waco Bridge clearly bears the mark of Roebling influence —parabolic cables, inclined stays and a deep stiffening truss— and we know that the builders consulted with and purchased materials from the Roebling Company. Ease of transport of materials and on-site construction are among the technical reasons that may have favored the selection of a suspension bridge at Waco, instead of a fabricated metal truss (Brown 1998). Indeed, transport of materials and fabrication still concerned Griffith in 1883 when he patented a suspension bridge system (No. 285,257) «composed entirely of pieces of moderate length and weight which can easily be carried by men or pack-mules, and which when once delivered at the site of the proposed structure can be easily and cheaply put together». The Waco Bridge shaped Texans' concept of «bridge» —two different Texas bridge companies used its image in their advertising (HAER TX–36).

The prominence of the Waco Bridge, and the popularity of suspension bridges in general, contributed to the emergence of this bridge form in north central Texas. Economic considerations, such as cost of materials, ease of transport and construction, also were significant factors in making bids for cable-supported bridges competitive with, and often cheaper than, truss alternatives. Further, the ability to span rivers without a mid-stream pier provided an additional technical advantage for cable-supported bridges; Texas river-courses are notorious for flash floods and poor soil conditions unfavorable for foundations. This is the context in which Runyon proposed the cable-stayed form, intentionally departing from the parabolic form, even while such bridges were successfully being built at nearby sites in Texas.

Joseph Mitchell

Although there are few obvious precedents for Runyon's bridges, the work of Joseph Mitchell bears striking similarities to that of Runyon. Little is known of Mitchell's work in Texas, other than records from four different Texas counties indicating bridge contracts between 1886 and 1888, including one for repair of bridges he had previously built (HAER TX–98). In 1887 Mitchell received a patent (No. 368, 483) for a bridge with a primary structural system best described as a wooden truss, but featuring deck cables similar to those later used by Runyon. Mitchell used five galvanized wire cables to replace the longitudinal stringer beams, allowing the transverse floor boards to rest directly on the cables. The deck cables were tensioned by twisting with rods which were then braced against an adjacent cable to prevent unwinding. Mitchell describes his patent as providing «a bridge which is cheap in construction . . . and also to do away with the floor-beams and substitute therefor cables which are so constructed that they may be tightened without the necessity of removing the floor-boards . . . » In 1890 Mitchell received a patent (No. 440,490) for bridge construction that includes a bowstring beam with a lower chord of twisted wires. Mitchell also describes a «lozenge shaped block» used to twist the wires, very similar to that later used by Runyon.

The last known reference to Mitchell's work in Texas occurs on 10 September 1888 in Cooke County, the same day on which Runyon was awarded a commission. Shortly thereafter on 27 October 1888, Mitchell was awarded a bridge contract in Fulton

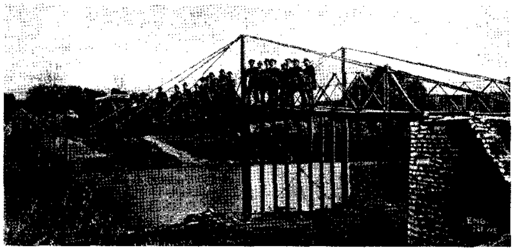


Figure 10
Whitewater River bridge by J. Mitchell at Richmond, Indiana (Bridges over . . . 1899)

County, Indiana, for «Three Cable Bridges of his Patent of August 16, 1887.» One of these bridges, completed in 1889, spanned the Whitewater River in Richmond, Indiana (Figure 10). An advertisement for Mitchell's bridges, illustrated with a photograph of the Whitewater River bridge, stated: «It cost $2,150 for sub and superstructure complete, or about one-fourth of the cost of other iron bridges, and equal to them in strength and superior durability, as there is no wood except the floor, and it rests on galvanized steel cables, so anchored that it cannot be washed away.» The bridge at Richmond had a main span of 150' (45.7 m) with six equal panels, pipe tower bents, a stiffening truss fabricated from strap-iron and round sections, and presumably the Mitchell-patented deck cables. Based on the only known photograph of the Whitewater Bridge, its stiffening truss was discontinuous at the towers and the main span exhibited a noticeable sag. Reportedly a person exciting the bridge at its quarter-point could produce vertical undulations of 12» to 18» (30–45 cm) (Bridges over . . . 1899). These observations suggest that the stay cables were not effectively tensioned and the deck not sufficiently stiffened by the truss. Perhaps similar behavior on Mitchell's earlier bridges in Montague County, Texas led county commissioners in 1888 to order him «to repair all Bridges built by him in this County» (HAER TX–98). The Whitewater River bridge was destroyed in a flood in 1897.

Edwin E. Runyon

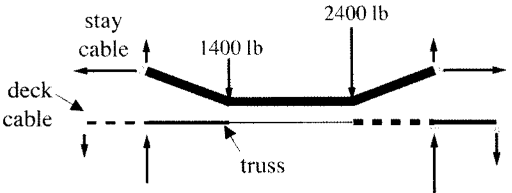
The similarities between the Mitchell and Runyon bridges and their presence in north central Texas circa 1888 certainly suggests that their work influenced one another. Unfortunately the historical record does not indicate whether they were collaborators or competitors. Very little is known about the life and career of Runyon. The primary sources are county records, patents, photographs and a business card. In 1879 Runyon lived in Cooke County and worked as a schoolteacher and shopkeeper. It is unlikely that he received any formal advanced engineering training. Based on the patents issued to him between 1888 and 1893, Runyon lived in several towns in north central Texas and appears to have been a somewhat itinerant inventor. Runyon received six patents related to bridge construction, as well as patents for a cotton cultivator and a lawn mower (HAER TX–36).

ENGINEERING ANALYSIS

Modern engineering analysis of the Bluff Dale Bridge can address several issues of historical importance, regarding the overall behavior of the bridge, its unique stayed form and unusual design features. In the 19th century, the Bluff Dale Bridge would have been designed using approximate analyses and empirical rules. But modern structural analysis can accurately determine forces and stresses in the statically indeterminate bridge form. Geometrically non-linear effects are also included to properly account for the large deformations associated with cable structures. An analytical model was developed that captured the fundamental behavior of the stayed bridge system, and a set of important non-dimensional parameters were identified from the model. The detailed behavior of the bridge was also examined with finite element (FE) models based on the surviving 1899 metal truss. Since the construction sequence and cable pretensioning of the bridge are not known, dead and live loads were applied simultaneously to the complete FE model, providing an upper-bound estimate of forces and stresses in the bridge truss. The complete engineering analysis of the Bluff Dale Bridge is contained in HAER TX–104.

Cable systems

The structural system of the Bluff Dale Bridge can be best described as cable-stayed, although it possesses two unique features that differentiate it from modern cable-stayed forms —horizontal deck cables and continuous inclined stays (Figure 4). The simplified analytical model with a single continuous stay, deck cable and truss showed that the stay cable carries 42% of the applied vertical load; the truss, 58%; and the horizontal deck cable virtually none of the load (Figure 11) for both symmetric and asymmetric load conditions. In combination with the stiff truss, the deck cables do not contribute to the gravity load capacity of the bridge. Non-dimensional analysis confirmed that the deck cables will not carry gravity load, even with large levels of pretension force.



Thickness of line proportional to axial force in cables and shear in truss.

Figure 11
Force distribution in simple model of a stayed bridge composed of a continuous stay, deck cable and truss.

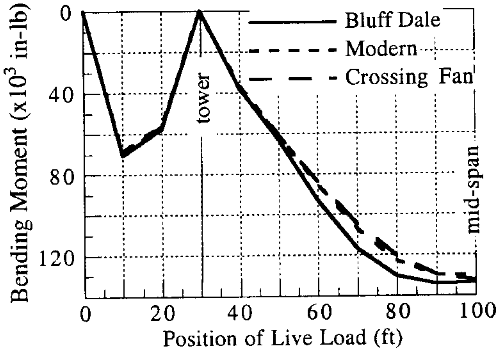


Figure 12
Axial force in truss due to dead load for three cable stay systems

The structural behavior of the continuous stay system of the Bluff Dale Bridge was compared to that of two other possible cable patterns —the crossing fan pattern (Figure 6) and the modern fan pattern (Figure 4). The Bluff Dale stay system uses approximately the same total weight of wire as the crossing fan pattern, but nearly 20% more than the modern fan pattern. The bending moments and deflections of the truss due to a uniform dead load of 140 lb/ft (2.0 kN/m) were found to be remarkably similar. The only significant behavioral difference between the cable patterns appears in the axial force distribution in the truss (Figure 12). The continuous stay cables of the Bluff Dale Bridge result in constant axial tension of about 1130 lb (5.0 kN) in the center of the bridge, while the modern cable pattern results in a maximum tension of 9940 lb (44.2 kN). In a modern cable-stayed bridge, the axial force in the deck is controlled through construction methods and cable tensioning, typically resulting in compression throughout the deck. Such modern construction techniques were not available to the builders of the Bluff Dale Bridge. Large axial tensions in the original wooden truss or the surviving pipe truss could have contributed to loosening of the connections and would have been considered undesirable. The designers of the Bluff Dale cable system may have been aware of this reduction in tension through experience. The live load influence lines of both truss bending moment and vertical deflection were also remarkably similar for the three cable patterns, with no clear behavioral advantage for any of the three systems (Figure 13).

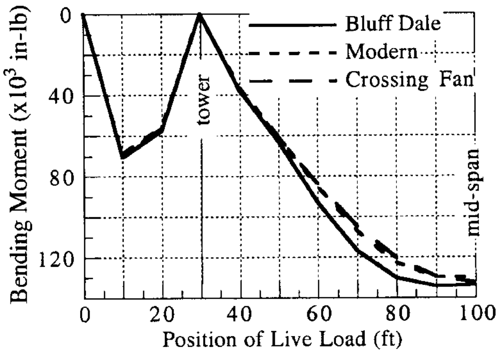


Figure 13
Live load influence lines of truss moment for three cable stay systems

Comparison to parabolic cable suspension bridge

The Beveridge Bridge is a parabolic cable suspension bridge built in 1896 with a main span of 140′ (42.67 m) by the Flinn-Moyer Co. over the San Saba River in San Saba County, Texas (HAER TX-46). The main span length is identical to that of Bluff Dale and its stiffening truss nearly the same as the 1899 truss installed by Flinn-Moyer at Bluff Dale. Therefore, the Beveridge Bridge provides an ideal example to compare the behavior of the unique stayed form of Bluff Dale to that of a typical 19th century truss-stiffened suspension bridge. The live load influence lines show the Bluff Dale Bridge to have slightly smaller vertical deflections (Figure 14). However, the cable system of the Beveridge Bridge is estimated to use about 15% less material than that of the Bluff Dale Bridge, and thus could be considered a more efficient design.

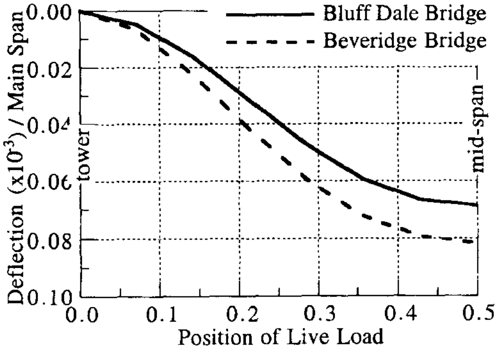


Figure 14
Live load influence lines for Bluff Dale and Beveridge Bridges

Evaluation of the Bluff Dale Bridge design

The FE analyses provide forces and stresses in all bridge members for dead and live load conditions. Based on the dead load truss moments, plus moments due to a live load at midspan, the maximum bending stress in the truss is about 6100 psi (42 MPa). The yield point of wrought iron typically ranges from 25 to 35 ksi (170–240 MPa) and typical design practice at the turn of the century would have allowed a working stress of about one-fourth of the elastic limit (Withey and Aston 1926). If the truss of the Bluff Dale Bridge were to be used with no cable support, the bending stresses would be as large as 20 ksi (140 MPa), certainly well above a typical design level for the late 19th century. Although the designers of the Bluff Dale Bridge were not able to perform the detailed calculations necessary for a complete analysis of the cable-supported truss, they may have been capable of calculating the stresses for the unsuspended three-span truss. The Bluff Dale Bridge was designed, and its truss members proportioned, with the intent that a significant portion of the load would be carried by the cable stay system. Additional non-dimensional analysis of the relative stiffness of the truss and cable stay system indicated that the truss of the Bluff Dale Bridge is significantly stiffer than necessary to maintain vertical deflections within serviceable limits, further confirming that the bridge was originally designed by an approximate or empirical method.

The designers' method of distributing load between the truss and cables is not known. One possible approximate design method for deck-stiffened, cable-supported structures is to design the cable system to carry all of the dead load and to design the truss as an unsuspended span for the live loads only. This method satisfies equilibrium, since all gravity loads are accounted for, and is attractive due to its simplicity. Typically the method results in conservative estimates of truss stresses, and somewhat unconservative estimates of cable stresses, although the strength of drawn wire cables typically was sufficient to accommodate the true stress levels. Conceptually, this method is similar to that used by John Roebling to design his parabolic cable suspension aqueducts:

> The original idea upon which this plan has been perfected, was to form a *wooden trunk*, strong enough to support its own weight, and stiff enough for an aqueduct or bridge, and to combine this structure with wire cables of a sufficient strength to bear safely the great weight of water. (The wire suspension aqueduct . . . 1845)

The construction sequence of the aqueducts would have resulted in an actual load distribution different from that assumed in the design.

CONCLUSIONS

The Bluff Dale Bridge is a rare example of 19th century cable-stayed bridge design and a striking part of a larger tradition of cable-supported bridge construction in Texas. Cable-supported bridges provide advantages for construction in remote areas, including ease of ground transport of materials, ease of construction and economic use of materials. The prominence of the long-span suspension bridges of Ellet and Roebling contributed to the adoption of the suspension bridge form for many moderate spans. Runyon's work shows many similarities to that of Joseph Mitchell, but their relationship remains unclear. While all of these influences shaped Runyon's work, his remarkable 1888 patent illustrates a purely cable-stayed form, rather than the more common parabolic form. This and other patents show Runyon's basic understanding of engineering principles, more likely gained through experience than formal education. Runyon and bridge-builder Flinn were able to design and construct several successful bridges on this innovative scheme. Especially crucial to the performance of Runyon's bridges was the twisting of cable elements to remove slack and perhaps provide some pretension.

In light of the modern cable-stayed form, two design features of Bluff Dale are especially intriguing —the horizontal deck cables and continuous stays. The deck cables, used in parallel with a stiff truss and stays, do not carry vertical loads, but they could have supported the transverse flooring and were probably useful during construction. The continuous stay cables prevent the transfer of axial tension to the stiffening truss, which could have been detrimental to the integrity of the stiffening truss. The designers of the Bluff Dale Bridge clearly accounted for some distribution of applied load between the cable and truss systems, although the nature of their approximate design method remains unknown.

Combined historical and engineering study of vernacular bridge design can reveal innovative solutions, and suggests that the history of cable-supported bridges is much deeper and richer than the canon of famous and monumental examples. Historical and engineering study may also inform and improve the design of modern structures. A recent innovative design for the Maumee River Bridge in Toldeo, Ohio, by Figg Bridge Engineering employs cable stays which are continuous through the towers with their ends anchored at the bridge deck. By not requiring cable anchorages in the towers, this method allows for lighter and more aesthetically pleasing tower designs (Cradle system . . . 2002). This cable system bears great resemblance to the fixed stays used by Runyon on the Bluff Dale and Barton Creek Bridges more than a century ago for the very same reasons.

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