Proceedings of the First International Congress on Construction History, Madrid, 20th-24th January 2003,
ed. S. Huerta, Madrid: I. Juan de Herrera, SEdHC, ETSAM, A. E. Benvenuto, COAM, F. Dragados, 2003.

Prestressing of 19th century wood and iron truss bridges in the U.S.

Dario A. Gasparini
Francesca da Porto

Many of the well-known American truss bridges built in the first half of the 19th century were prestressed. Specifically, the Long, Howe, Pratt and Rider/Moulton forms, built entirely of wood or iron or using a combination of wood and iron, were prestressed. The prestressing was achieved by driving wood or iron wedges or by tightening nuts on threaded iron rods. The level of prestressing was controlled only qualitatively, probably by observing if any elements became slack when a heavy live load traversed the span. The significant advantages of prestressing were that connections were simplified, some wood tensile connections were eliminated and, if all elements did not loosen, the stiffness of a bridge was increased.

This paper describes studies of the Eldean Bridge in Miami County, Ohio. The Eldean Bridge is a wooden Long truss, built in 1860 by James and William Hamilton. The experimental and analytical studies address the actual magnitudes of prestress forces achieved by driving wedges, the effects of prestress on the structural behavior, the loss of prestress from wood shrinkage and creep, and the need for periodic retightening. Also presented are studies of the Pine Bluff Bridge in Putnam County, Indiana. The Pine Bluff Bridge is a classic Howe truss, built in 1886 by Joseph Albert Britton. The studies quantify the actual magnitudes of prestress forces achieved by tightening nuts and examine the same issues as those for the Long truss.

After the Long and Howe trusses, two significant prestressed truss forms were patented in the U.S. They are the truss of Thomas and Caleb Pratt and the truss of Nathaniel Rider and Stephen Moulton. These designs are briefly discussed, to provide a more complete view of the early 19th century prestressed truss forms.

Stephen Harriman Long truss patents of 1830 and 1839

Gasparini and Provost (1989) and Gasparini and Simmons (1997) describe the

contributions of S. H. Long to the design of trusses. Long's understanding of truss behavior is perhaps best exemplified by his May 6, 1830 and November 7, 1839 (No. 1387) U.S. patents. Both patents show an ordinary St. Andrew's cross type of truss but one of Long's significant patent claims is for a system of wedges or «keys» for prestressing the trusses. Figs. 1 and 2 show details from his 1830 and 1839 patents, respectively.

Figure 1 shows a wedge driven at the end of a diagonal brace, thus prestressing both diagonals in compression and the verticals in tension. Writing in the Journal of the Franklin Institute, Long states that «the braces all act uniformly in the direction of their axes and exclusively by *thrust.* Their connection with the truss frames is such as to preclude any action by *tension*» (Long, 1830). Conversely, Fig. 2, from his

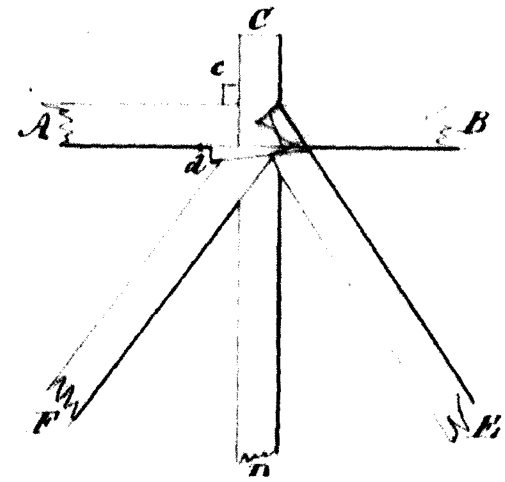

Figure 1
Wedge detail from S. H. Long's patent of March 6, 1830

1839 patent, shows wedges between the vertical post and the chord, thus precompressing the verticals and pretensioning the diagonals. In his 1839 patent description, Long states,

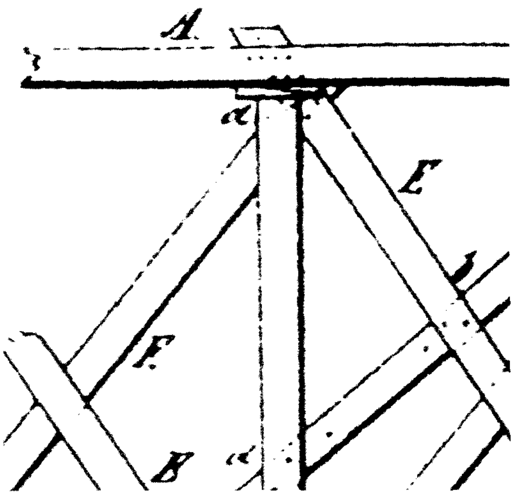

Figure 2
Wedge detail from S.H. Long's patent of November 7, 1839 (No. 1397)

> The straining, or trussing, of the truss frames is effected by driving the counter wedges, above mentioned, which are situated as shown in the drawing, between the upper end of each post, and the upper string-piece, but which may, if preferred be situated between the lower ends of said posts, and the lower string pieces. This operation is calculated to elevate the upper string, at the points where the main braces are attached to it; and of course to increase the tension of the main braces in the adjacent panel. Every increment of tension thus produced is counteracted by a corresponding degree of antagonal tension in the counter braces. Hence the main and counter diagonal braces act by tension instead of thrust, and the posts by thrust instead of tension (Long, 1839).

Of course Long could not quantify the prestress forces that were achieved and could not predict whether shrinkage and creep in the wood would, in time, loosen the wedges. However, it was understood that the wedges could be periodically re-driven. The objectives of the studies of the Eldean Bridge, which is of the Long type, were in fact to quantify the forces produced by driving wedges and to determine the effects of creep and shrinkage on these forces.

Studies of the Eldean Bridge in Miami County, Ohio

The Eldean Bridge over the Great Miami River, in Miami County, Ohio was built by James and William Hamilton in 1860. The bridge has two spans of Long trusses. It is the second longest covered bridge in Ohio and the longest Long truss covered bridge in the U.S. Under a contract with the U.S. Federal Highway Administration (FHWA), the Historic American Engineering Record (HAER) documented the bridge during the Summer of 2002. Analytical and experimental studies of the bridge were performed as part of the documentation. The full study is contained in HAER report number OH-122, which is to be archived in the Library of Congress.

The bridge is constructed of white pine, shipped from Michigan. The floor is made of American elm. The length of each span is about 33.8m; the overall width is approximately 6.4 m with a 5.5 m wide roadway. The trusses have twelve panels, each approximately 2.7 m wide. The sizes of the main diagonals and of the posts increase from midspan to the ends. The main diagonals are made of two timbers that vary in dimension from 23 cm × 15.2 cm in the end panel to 15.2 cm × 15.2 cm in the central panel. The posts also are composed of two timbers that vary in dimension from 28 cm × 15.2 cm to 21.6 cm × 15.2 cm. All counterbraces have a cross-section of 12.7 cm × 17.8 cm. The cross-sectional areas of the upper and lower chords are 1290 cm^2 and 1420 cm^2, respectively. Chord splices are achieved by simple rectangular shear connectors, completely bolted through the chord. The prestressing wedges are located at the bottom of the counters. A wood plank is nailed horizontally to the posts in order to prevent the counterbraces from slipping inside the space between the two posts. This plank is located about 5cm above the lower chord, to allow driving the wedges in the slit. The bridge has had many repairs, which are described in HAER report number OH-122.

Analytical studies were performed using two linear elastic plane models, one with active (prestressed) counters and the other without them, as shown in Fig. 3.

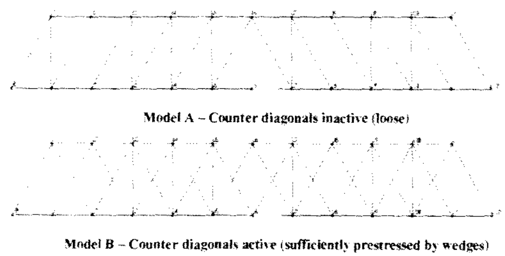

Figure 3
Linear elastic, plane models of the Eldean Bridge —Model A has inactive counters, Model B has active counters

The models were used to predict the effects of dead load, live load, prestressing, shrinkage and creep. Fig. 4 shows influence lines for three diagonal members for the model without active counters. A live load of 1 kN at panel point L5 produces an axial force in member L5U6 of 0.45 kN (tension). Dead load produces an axial force in the same diagonal equal to 11.4 kN (compression). Therefore by simple proportion, a live load of 25.3 kN applied at panel point L5; i.e., a total load of 50.6 kN applied to the entire bridge at L5, would cause diagonal L5U6 to

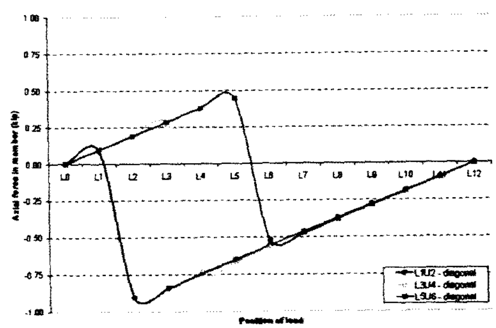

Figure 4
Influence lines for three diagonals for the model with inactive counters

become loose, since it is not positively connected at its ends. Again using the influence lines, it is further determined that a uniformly distributed load of 1.82 kPa over half of the span would also loosen member L5U6. With such a concentrated or uniformly distributed load, the structure would develop a kinematic mechanism if the connections were perfect pins. In reality, the joints of the actual bridge are not perfect pins, since the lower and upper chords are continuous. Because of this continuity, the bridge does not develop a mechanism, but it is clear that such loads produce a «limit state» condition for the structural behavior of the bridge. Prestressing the diagonals in compression increases the live loads that produce such a limit state.

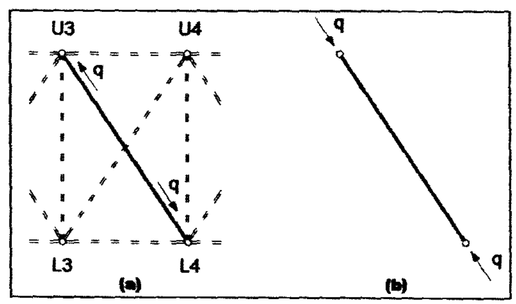

Figure 5
Effective nodal loads and fixed end forces from driving a wedge at the base of a counterbrace

The prestressing action of driving wedges is modeled by loads at the nodes in the direction of the diagonal elements. For example, if counter L4U3 is being «lengthened» by driving a wedge, the affective nodal loads are as shown in Fig. 5. To determine the actual force in a counter, the fixed end force shown in (b) must be superposed with the force in the counter from the nodal displacements caused by the effective nodal loads.

Figure 6 shows axial forces in a portion of the model centered on panel L3U3–L4U4 due to unit effective nodal loads from driving a wedge at the end of counter L4U3. In this example, counter L4U3 has an axial force of 0.43kN due to the effective nodal loads. Adding its fixed end compressive force of –1kN, its total axial compressive forces is –0.57kN. Conversely, both the posts and the chords are in tension. The forces in the vertical elements are comparable in absolute value to the forces in the diagonals. The chord forces are about half those in the diagonals. The relative values of the forces in the elements obtained by prestressing depend on the panel geometry. The effects of driving one wedge rapidly decrease to zero in other panels. In the two adjacent panels the magnitudes of the axial forces are ten times smaller that in the panel in which the wedge is driven. Therefore the prestressing action of driving a wedge is effective only in one panel, so to prestress an entire truss, all the wedges have to be driven. If this is done, the prestress forces are very uniform all along the span. In general, the combined actions of prestressing and live load lead to the following critical elements: the midspan lower chord element, where prestressing increases the tensile force, the most compressed main diagonal near the ends, and the counter with the largest tensile force from a live load, which thus has the greatest probability of having a null axial force. But in order to determine the live load that could cause loose counter diagonals, it is necessary to estimate the actual prestress force achieved by driving wedges.

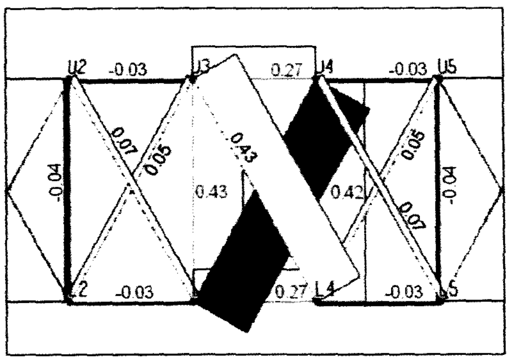

Figure 6
Member forces from unit effective prestressing loads

The shrinkage action is also modeled analytically by effective nodal loads given by $\varepsilon_s EA$, in which ε_s is a shrinkage strain, E is the modulus of elasticity and A is a cross-sectional area of an element. For the all-wood Eldean Bridge, if all elements are assumed to have equal shrinkage strains, the shrinkage action does not cause significant axial forces, not only in the model without the counters but also in the model with active counters. This observation is not true for creep since creep strains are approximately proportional to the initial elastic axial stresses, which are not equal for all members. Therefore creep produces changes in element forces in the model with active (prestressed) counters. To determine if and when creep causes looseness; i.e., complete loss of prestress, the initial prestressing forces from driving wedges must be known and analyses must be performed using viscous constitutive models for wood.

Experiments were performed on the Eldean bridge with the objectives of estimating the forces produced by driving wedges and comparing the behavior of the bridge in non-prestressed and prestressed conditions. Details of the tests are given in HAER report number OH-122. To measure forces produced by driving a wedge, fourteen strain transducers, as shown in Fig. 7, were attached on members of one panel. Four displacement transducers, one for each truss plane, were mounted at the midspans to measure overall bridge response to the passage of a truck.

Figure 8 shows forces (in pounds) in the diagonal and vertical elements produced by driving a wedge. The test was repeated twice, and the average force in the counterbrace was 26.8kN, compression. Since unit live load at node L10 produces a tensile force of 0.4 in counter L10U11, the live load at L10 that would loosen counterbrace L10U11 is approximately 67 kN, or 134 kN on the bridge. The live load required to loosen the diagonals near midspan is significantly larger than for the truss without active counters. However, the prestress forces produced by

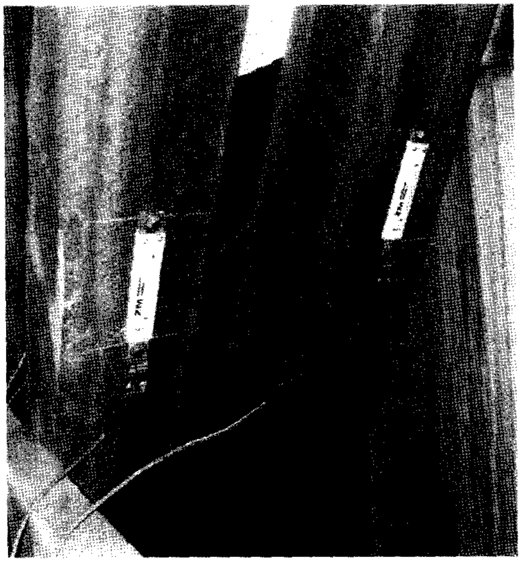

Figure 7
Strain transducers attached to main diagonals

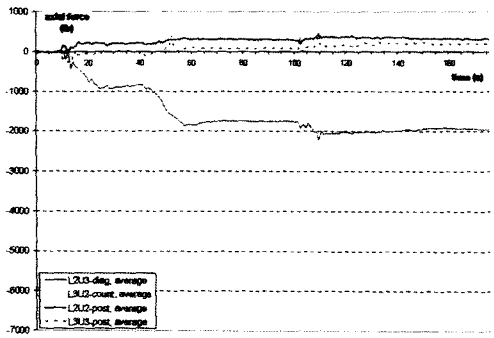

Figure 8
Member forces (in pounds) from driving a wedge

driving wedges are very likely not sufficient to preclude looseness under the action of creep, especially if it is assumed that creep strains are of the same order as the initial elastic strains. To determine the time at which looseness is likely to occur, analyses using viscous constitutive models for wood must be performed.

Figs. 9 shows time histories of midspan displacements from the passage of a truck weighing 35.2 kN, with no prestressing in either span. Fig.10 shows time histories of displacements with the eastern span prestressed. The constant displacement portions reflect the fact that the truck stopped at certain panel points. The spikes in displacement correspond to the truck accelerating from a stopped position. All tests show that when the truck is moving from the midspan position, L6, higher displacements are measured for load positions L8, L10 than for the corresponding ones on the first half of the bridge span (L4, L2). Also, when the truck leaves the span, a residual displacement, which slowly decreases to zero

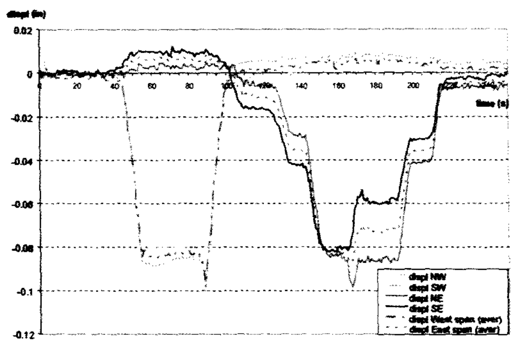

Figure 9
Time histories of midspan displacements (in Inches) from a moving truck load —counters inactive

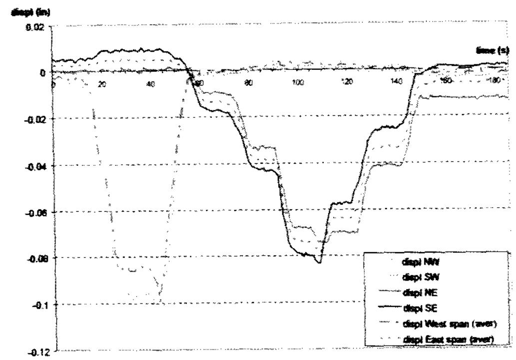

Figure 10
Time histories of midspan displacements (in inches) from a moving truck load —eastern span prestressed

with time, is observed. These observations strongly show that the stress-strain behavior of wood is time-dependent or viscous. After driving the wedges on the counterbraces of the eastern span, the measured displacements decreased by 12%. The wedges on the western span were not re-driven, so that the average displacement remained practically the same.

William Howe truss patents of July and August, 1840

Long's patents, booklet, and bridges, which were built throughout New England, were certainly known by and inspired another New England bridge builder, William Howe. Howe received two patents for prestressed bridges in 1840, one in July and another in August. His July 1840 patent was for an all-wood design, using wedges for prestressing, much like Long, although Howe used the wedges in a different arrangement. On August 3, 1840, Howe received a patent for the truss form shown in Fig.11. Howe replaced the vertical wooden posts with wrought iron threaded rods, and prestressed the bridge by tightening the nuts, a much simpler and effective process than driving wedges.

Perhaps unknown to Howe was the fact that Marc Seguin had used this form in 1824 for the stiffening truss of his Tournon-Tain suspension bridge (Seguin, 1826; Cotte, 1998). Howe's original patent shows diagonals that extend over two panels and an auxiliary tensile chord, located at the lower intersection of the diagonals. The detail used to transfer the rod tensile force to the diagonals is critical. If the transfer of force is by bearing perpendicular to the grain of the chord, crushing of the chord may occur. Moreover, shrinkage in the radial and tangential directions of wood is much greater than in the along-grain direction. Both crushing of the grain and shrinkage would cause a loss of prestress. Two critical improvements that allowed the Howe truss to become dominant in the U.S. in the period from 1840 to about 1870 were the use of diagonals that extended over only one panel and the introduction of iron node castings with webs that extended through the chord in order to transfer the rod axial force directly to the diagonals, eliminating bearing stresses perpendicular to the grain of the chords. It is uncertain who devised these improvements, perhaps Howe, perhaps his contractor brother-in-law, Amasa Stone, who built some of the earliest Howe trusses in New England. Beginning in 1845, all-iron Howe trusses began to be built by Richard B. Osborn, Frederick Harbach and Amasa Stone (Gasparini and Simmons, 1997).

Studies of the Pine Bluff Bridge in Putnam County, Indiana

The Pine Bluff Bridge over Big Walnut Creek in Putnam County, Indiana

was built by Joseph Albert Britton in 1886. The bridge is a classic Howe form, with threaded vertical wrought iron rods and cast iron nodes. The bridge consists of two simply-supported spans. Each truss is divided into ten panels, approximately 3m in length. The wood species used for the Pine Bluff Bridge was not determined, but the majority of the covered bridges in Putnam county are made of Michigan pine,

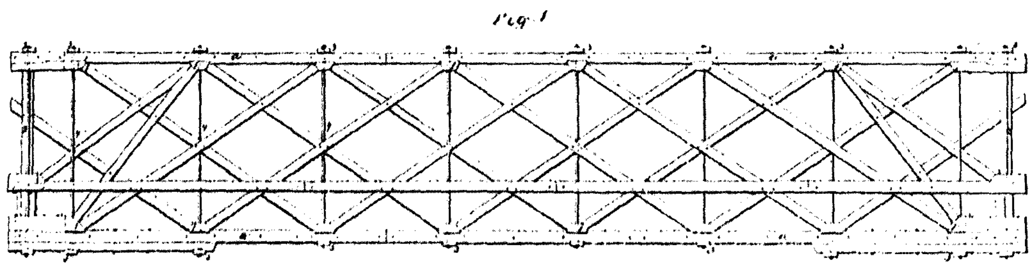

Figure 11
Howe truss drawing for his August 3, 1940 U.S. patent

which is a type of white pine. In its present condition, practically all the counterbraces are loose and, since the vertical members consist of pairs of wrought iron rods, the individual rods are clearly not equally loaded and, in fact, some are almost slack. The bridge truss therefore essentially behaves as a statically determinate truss with single (compressive) diagonals which are not positively connected to the chords. It is only the action of the dead load that prevents the single diagonals near midspan from becoming slack when a heavy live load traverses the span. The present condition of the bridge indicates that current maintenance practices do not recognize the original technology of the classic Howe truss.

The Pine Bluff Bridge was also recorded by HAER during the summer of 2002. As part of the documentation, analytical and experimental studies similar to those performed for the Eldean bridge were carried out. HAER report number IN-103 describes the studies. The analytical models used for the Pine Bluff Bridge are analogous to those shown in Fig. 3, except the Pine Bluff models have ten panels rather than twelve. Of course the geometry and member properties are different.

Analyses of the non-prestressed model were performed for the action of the actual dead load and for a unit live load traversing the span. On the basis of these analyses, it is found that a live load of 29kN applied at node L4; i.e., a total load of 58kN on the bridge, makes member L4U5 loose. As for the Eldean Bridge, such a load would produce a kinematic mechanism in the bridge if all joints were perfectly pinned. Because of the continuity of the chords, a mechanism is not formed, but nonetheless such a load represents an important limit state at which a change in the behavior of the bridge occurs.

Effects of the action of tightening the nut on one vertical are shown in Fig.12 for unit effective nodal loads from prestressing. The total force on element U3L3 is found by adding the fixed end force, which is assumed to be 1kN. The prestressing action affect only the two adjacent panels. The actual distribution of axial forces is, of course, a function of the aspect ratio of the panels. If all the vertical rods are tightened equally, practically uniform initial force conditions are achieved along the entire span. To determine how the effects of prestressing combine with the effects of dead load and live load, the actual forces achieved by tightening the nuts must be determined.

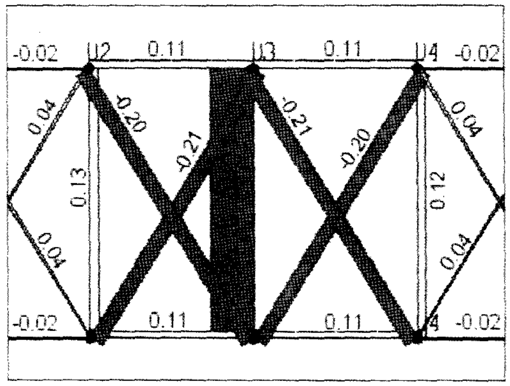

Figure 12
Member forces from unit effective prestressing loads

The effects of wood shrinkage on a Howe truss are very different from the effects of shrinkage on a Long truss. This is so because the iron rods do not shrink. Shrinkage of wood members in a Howe truss in fact reduces prestressing forces significantly and may cause the counters to become loose. Additional shrinkage after the counters become loose causes additional displacements but no further changes in forces because the truss has become a statically determinate form. Although the magnitudes of the changes in forces may differ, the effects of creep of wood on initial prestress forces are similar.

As for the Eldean Bridge, experimental studies were performed to determine the actual prestress forces that could be achieved by *manually* tightening the nuts. Strain gauges were bonded to the iron rods and strain transducers were attached to the wood members as shown in Fig. 7. An «inside» rod that was practically slack was selected for retightening. Figs. 13 and 14 show time histories of forces induced on the inside and outside rod and on the wooden diagonals as the nut was tightened. The actual maximum force induced in the rod by *manually* tightening the nut was approximately 29.4kN. At present, the actual size of wrench and method used by the original builders to tighten the nuts is unknown. Fig. 13 shows that the force in the *outside* vertical bar actually decreases as the *inside* rod is tightened. Fig. 14 shows that tightening the inside rod affects primarily the corresponding inside timber of the main diagonal. Therefore any pair of vertical rods should be tightened in stages in order to achieve equal

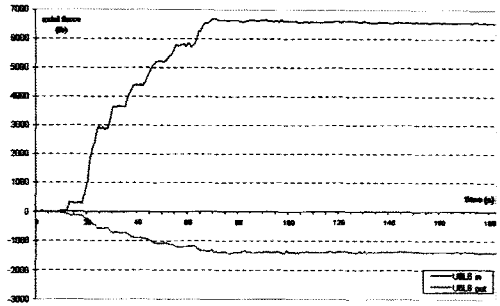

Figure 13
Forces (in pounds) on the inside and outside rods produced by tightening the nut on the inside rod

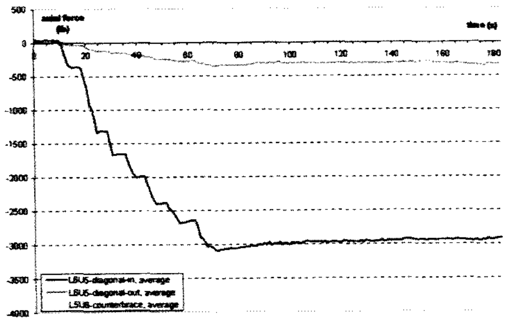

Figure 14
Forces (in pounds) on the diagonal members produced by tightening the nut on the inside rod

forces in members. It was not possible to «slacken» and properly pretension all the vertical rods on the Pine Bluff Bridge. Therefore the condition of the bridge remained such that most counter diagonals were loose and some vertical rods were slack. Therefore, in actuality, the bridge in its current condition is not a truly symmetric structure. Nonetheless, to determine the actual stiffness of the Howe truss, two displacement transducers were mounted at midspan, one for each truss, and a truck weighing approximately 53.4 kN was driven across the span. Fig. 15 shows the time history of midspan displacement. Constant displacement lines again reflect that the truck was stopped at certain nodes. These displacements were correlated with analytical predictions using the non-prestressed model. Details of the comparison are given in HAER report number IN-103.

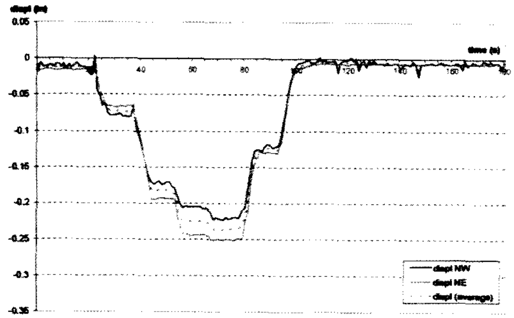

Figure 15
Midspan displacements (in inches) from a truck traversing the span

«Suspension» trusses

Long's 1830 patent truss and Howe's truss are prestressed to place the diagonals in compression and the verticals in tension. Prestressed truss forms that cause tension diagonals and compressive verticals were also conceived. Such forms, which were sometimes called «suspension» trusses, are described by Gasparini and Simmons (1997). Two basic techniques were used to achieve the desired behavior. Long (in his 1839 patent shown in Fig.2), Nathaniel Rider and Stephen Moulton used wedges on the vertical members while Thomas and Caleb Pratt prestressed by tightening nuts on threaded iron diagonals. The Pratt's introduction of threaded iron diagonals, as shown in Fig.16, was analogous to the simplification introduced by Howe to Long's 1830 patent. The Pratt truss required no positive connection between the chords and the verticals, which were prestressed in compression. Their patent description, which prescribes a method of erection, emphasizes that fact. The Pratt form is more efficient than the Howe form because the longer members (the diagonals) are in tension. Nonetheless, the design was not immediately successful, becoming dominant only in the 1870's in its nonprestressed, single-diagonal form. Its slow acceptance was probably due to its less-than-satisfactory performance when wood was used for the

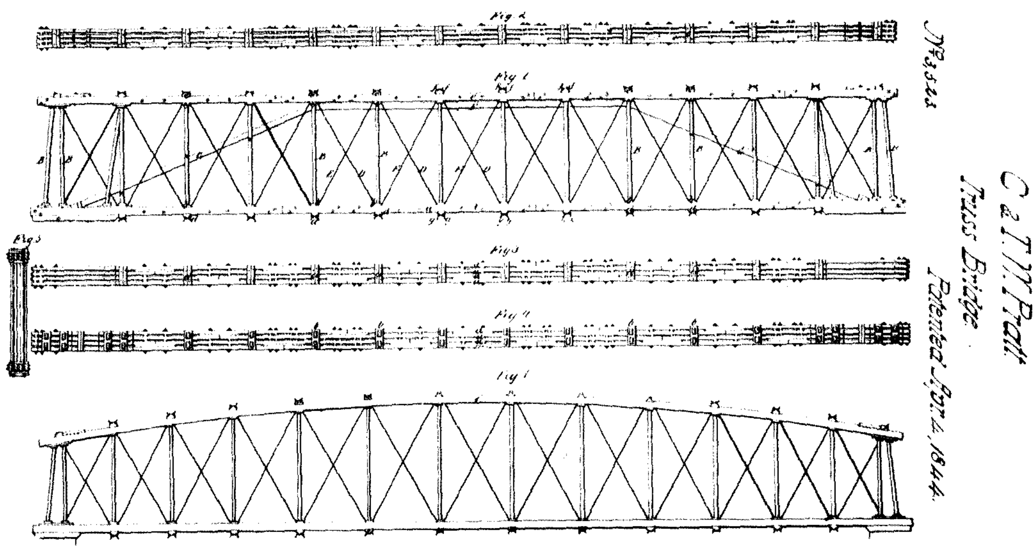

Figure 16
Truss patented by Thomas and Caleb Pratt on April 4, 1844 (No. 3523)

chords and for the vertical elements. In comparison with the Howe truss, twice as many rods had to be tightened; moreover, the nuts were in an awkward inclined position and were more difficult to tighten. Additionally, the prestress forces probably caused some local crushing of the wood chords, which led to a loss of prestress and decreased vertical stiffness. Further, from a stress viewpoint, the prestressing increased the compressive forces in the top chord, which, in turn, increased the risk of buckling.

An all-iron «suspension» truss was patented in the U.S. by Nathaniel Rider in 1845 and then by Stephen Moulton in England in 1847. It was a truss prestressed by wedges, as shown in Fig.17, precisely as Long had done for his 1839 patent truss. Because prestressing by wedges was awkward, the Rider/Moulton trusses were built only for a relatively short time. Still they represent an alternate way of achieving prestressed tensile diagonals.

Conclusions

The 19th century truss forms patented in the U.S. by S. H. Long, W. Howe, T. Pratt, N. Rider/S. Moulton were all intended to be prestressed. This is evident from their patent descriptions, from their use of «non-positive» connections and from executed designs. Of course, the prestress forces were not quantified. Nonetheless, prestressing simplified connection details, facilitated erection and added stiffness to bridges.

Studies of the Eldean Bridge, a Long truss, indicate that driving wedges can induce forces in the counters of approximately 26.8kN. Driving a wedge induces forces in only one panel. Equal longitudinal shrinkage of all the wooden members does not cause significant changes in member forces for a simply-supported truss. Conversely, creep, which is a function of initial elastic stresses, does cause a decrease or even a complete loss of prestress. Therefore periodic retightening of the wedges is very likely required.

Studies of the Pine Bluff Bridge, a Howe truss, indicate that *manual* tightening of a nut can induce forces in the vertical rods of approximately 29.4kN. Analyses show that tightening a vertical rod causes forces only in adjacent panels. Because the iron rods do not shrink, both longitudinal wood shrinkage and creep cause decreases or even a complete loss of prestress.

The current conditions of the two bridges that were studied indicate that indeed effects of shrinkage and

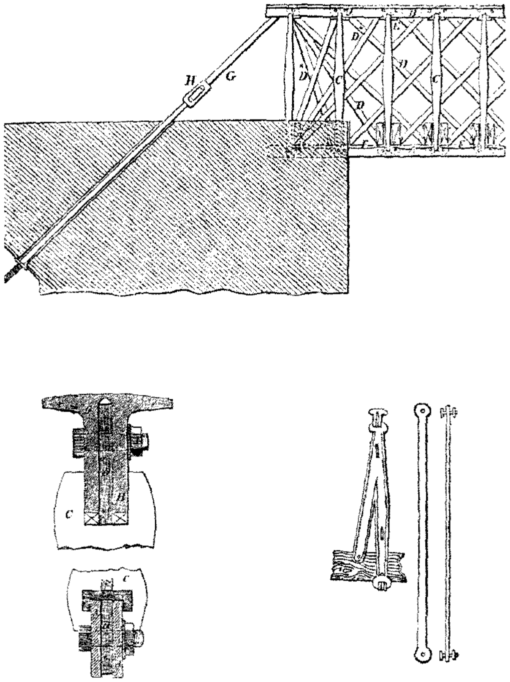

Figure 17
Truss patented by Nathaniel Rider in 1845 (No. 4287)

creep can reduce prestressing forces to zero. They also indicate that periodic retightening, which probably was the norm when the bridges were new, has not been part of current maintenance. It seems that this prestressing and retightening technology developed in the 19th century has been forgotten. It is both a historic and structural necessity to re-establish this prestressing technology, for both maintenance and new designs, using modern means for controlling prestress forces. Understanding of the effects of shrinkage and creep needs to be improved by analyses using viscous models for wood behavior. Such analyses can be used to establish rates at which prestress forces decrease and thus provide guidelines for the frequency of periodic retightening maintenance operations.

ACKNOWLEDGEMENTS

This work was performed under contract with the U.S. Federal Highway Administration by the Historic American Engineering Record, Eric De Lony, Chief.

REFERENCE LIST

Cotte, M. 1998. Innovation et transfert de technologies, le cas des enterprises de Marc Seguin. *P.U. du Septentrion,* Lille.

Gasparini, D.; Provost, C. 1989. Early Nineteenth Century Developments in Truss Design in Britain, France and the United States. *Construction History: Journal of the Construction History Society*, Vol. 5, 21–33.

Gasparini, D.; Simmons, D. 1997. American Truss Bridge Connections in the 19th Century. *ASCE Journal of the Performance of Constructed Facilities,* Vol. 11, No3, August 119–129.

Seguin, A. 1826. *Des Ponts en Fil de Fer* 2nd Edition.

Historic American Engineering Record, 2002. The Eldean Bridge, Report number HAER OH-122, Library of Congress, Prints and Photographs Division.

Historic American Engineering Record, 2002. The Pine Bluff Bridge, report number HAER IN-103, Library of Congress, Prints and Photographs Division.

Long, S. H. 1830. Remarks on Wooden, or Frame Bridges. *Journal of the Franklin Institute*, Vol. X, 252–255.