Simplified Analytical Model for a Queen-Post Covered Timber Bridge

By

F. Fanous
Professor
Iowa State University
Ames, Iowa, USA
fanous@iastate.edu

D. Rammer
Research Engineer
Forest Product Laboratory
Madison, WI, USA
drammer@fs.fed.us

T. Wipf
Professor and Chair
Iowa State University
Ames, Iowa, USA
tjwipf@iastate.edu

Summary

During the 19th century, the economic material to build bridges was timber due to its abundant availability, cost, and ease of construction. Many of the well-known timber bridge types are the Burr arch, Town lattice, Howe, Queen and King type of trusses. This paper summarizes an investigation that was sponsored by the Federal Highway Administration and the USDA Forest Products Laboratory to recommend simple but accurate analytical techniques for improving the analysis of historic covered timber bridges. Within this manuscript, field testing results of displacements and strains for covered Queen-Post-Truss timber bridges was utilized to validate the results of the developed finite element model.

A two dimensional model that included the properties of the truss individual members was utilized by the STAAD finite element program to carry out the analysis. Eccentricities that existed at the connectivity between timber members, i.e., details of the connection between the different members in the truss systems were included when calculating the stresses and the stains in each member. The moving load option that is available in the STAAD software was utilized to represent the moving load of the vehicle that was used in the field test.

The finite element results compared well with the field measured results. However, one needs to pay attention when modeling the applied load and the boundary conditions. In addition, care must be taken when calculating additional strains due to the eccentricity of the joints between the individual members.

Keywords: historical, timber, Queen Post, finite element, splice joints; joint eccentricities.

1. Introduction

During the 19th century, the economic material to build bridges was timber due to its abundant availability, cost, and ease of construction. Due to the availability of timber and the need for a safe way to cross the lands, thousands of these timber covered bridges were built during the 19th and early 20th centuries [3]. Many of the well-known timber bridge types are the Burr arch, Town lattice; Howe, Queen and king type of trusses. These types of bridges have many of the same characteristics, but each is uniquely different enough to cause concern when evaluating the structural behavior of each bridge. Also, these differences add some complexity to accurately analyze these types of bridges. For example, there are several eccentric connections, various load paths, connection uncertainty between the subassemblies (trusses and arches), and interaction between the trusses and their housing. When these are combined with material variability, it is easy to question the use of simplified truss analysis to design these types of bridges. This is recognized in the Federal Highway Administration's (FHWA) publication

FHWA-HRT-04-098, Covered Bridge Manual [6]. The manual states that there are inconsistencies with the assumptions of traditional simple static analysis of these covered bridges using simple analysis of trusses.

This manuscript summarizes the results of using a simple but more accurate analytical technique for the analysis of historic covered timber bridges. The STAAD [5] finite element program was utilized to accomplish this objective by analyzing the Moxely Bridge , and the results were validated using the results that are documented in a report of the field study that was conducted by Hosteng, et. al. [4].

2. Field Test of Moxley Covered Bridge

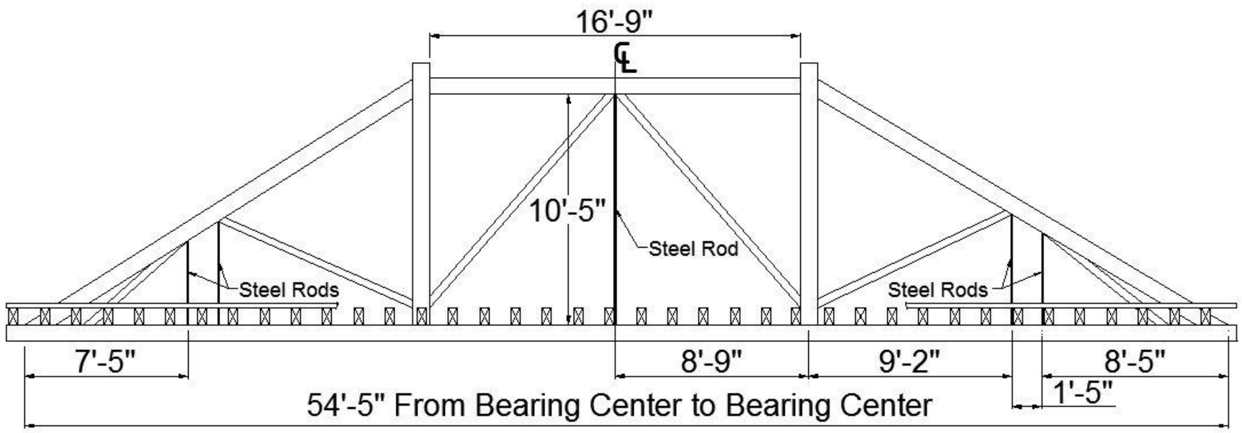
2.1 Bridge Descriptions

The Moxley covered bridge is located 2.5 miles south of junction then 0.1 mile in the town of Chelsea in Orange County of the State of Vermont. The bridge was constructed in 1883. Fig. 1 shows different photographic views of the bridge.

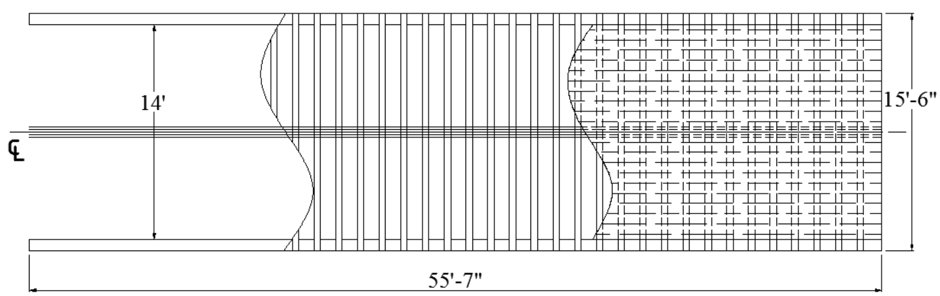
Fig. 1 Different views of the Moxley Bridge

The bridge span is approximately 54 ft. - 5 in. (see Fig. 2) and is 13 ft.-9 in. wide. The bridge deck is made of continuing 7 to 10 in. wide, 2 in. deep and 15 ft. long timber planks placed closely to each other. The bridge deck is seated on 5 in. by 9.5 in. floor beams which are about 1 ft. - 3 in. spacing from each other. All floor beams are supported on the two trusses bottom chord and a beam that is located at the middle of the bridge deck. The bottom chords of the two trusses of the bridge are 9 in. by 9 in., while the middle beam is formed by four 2 in. by 10 in. that are bundled together. However, the contribution of the middle beam to transfer any of the applied loads to the end supports was excluded in the following analysis. This was justified by the small flexural stiffness of such a long beam.

Figure 2 shows schematic elevation and plan views of the Moxley Bridge. Notice that Queen-Post truss system was provided by tension rods and were provided to act as additional supports to the trusses bottom chords. In addition, diagonal members were also provided as additional supports to the trusses top chords as shown in Fig. 2. The dimensions of structural members are listed in Table 1.



a. Elevation View



a. Plan View

Fig. 2 Schematic elevation and plan views of the Moxley covered Timber Bridge

Table 1 Measured member dimensions of the Moxley Bridge

Structural Member	Width (in.)	Height (in.)
Bottom & Top Chords	9	9
Floor Beam	5	9 ½
Verticals	9	9
Diagonals	4	9
Tension Rods	1 in. diameter	

Note: 1 inch = 25.4 mm, 1 feet = 762 mm.

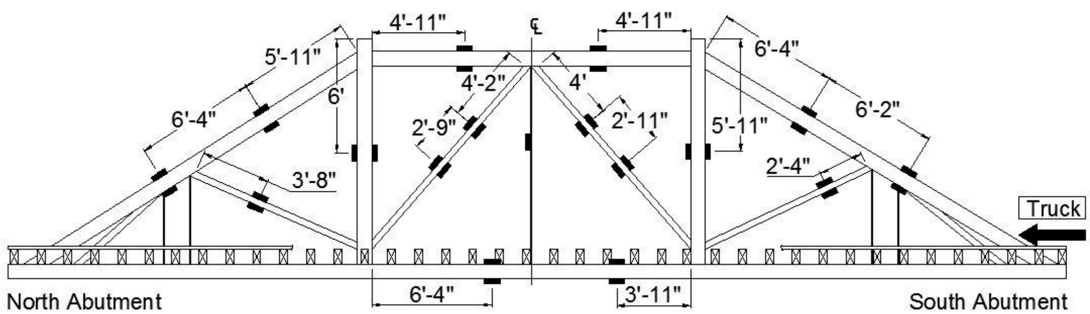
2.2 Vehicles Used in the Field Test of the Moxley Bridge

The vehicle that was utilized in the load testing of the Moxley Bridge is shown in Fig. 3. The front and back axles of the truck weigh 20.9 kN and 50.9 kN, respectively. The distance between the two axles was spaced at 4,470 mm.

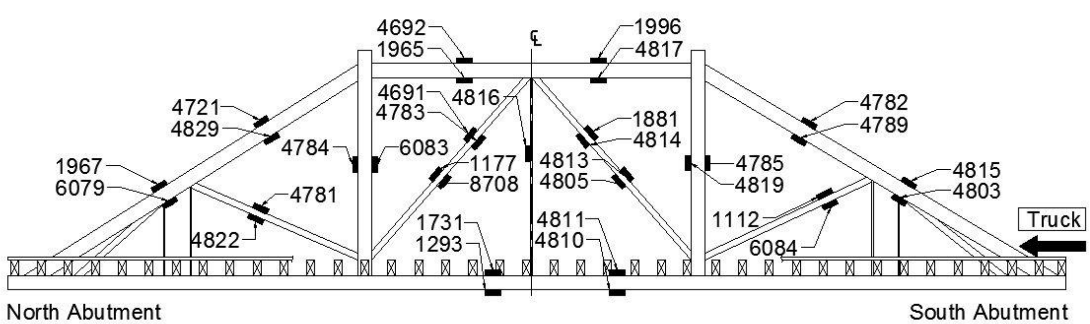
Fig. 3 Photo of the Truck used in testing of the Moxley Bridge

2.3 Bridge Instrumentation

Instrumentation used in testing the Moxely historical bridges consisted of BDI [1] strain sensors (referred to hereafter as strain sensors) with a resolution of 1 micro-strain ± 1 and the BDI testing software from Bridge Diagnostics Inc. Displacement data were obtained from Unimeasure PX string potentiometers having a resolution of 0.001 inches ± 0.001 connected to a Megadac logger. Both systems recorded data at 20 samples per second per sensor. Syncing of the data between the two systems was accomplished with a simultaneous data mark inserted into the files at the appropriate truck location positions. Several members of the Moxley Bridge were instrumented to measure the induced strain when a truck travels over the bridge. The locations and the identification number of these sensors are shown in Fig. 4. Sensors were also provided to measure the global displacements at the quarter and mid span of the Queen-Post truss.



i) Strain Sensor Locations



ii) *Strain sensor numbers*

Fig. 4 Strain sensor truss locations for the Moxley Bridge

3. Analysis of the Moxley Bridge

3.1 Finite Element Model

The STAAD computer software was selected to perform the analysis of the covered timber bridges studied in this work. This program was selected due to its simplicity in creating the required input file, to model the splice connections and to simulate a moving load. The Bridge was analyzed using two dimensional idealizations (see Fig.5). Beam elements were used to idealize the top and bottom chords of the Moxley Bridge. All diagonals were modeled as axial load members. Tension members only were utilized to represent the tie rods that were used in the construction of the Moxley Bridge. Figure 5 below illustrates the finite element model of the bridge as was utilized in the STAAD analysis. Internal hinges were inserted at specific locations to release the moments where elements were discontinued.

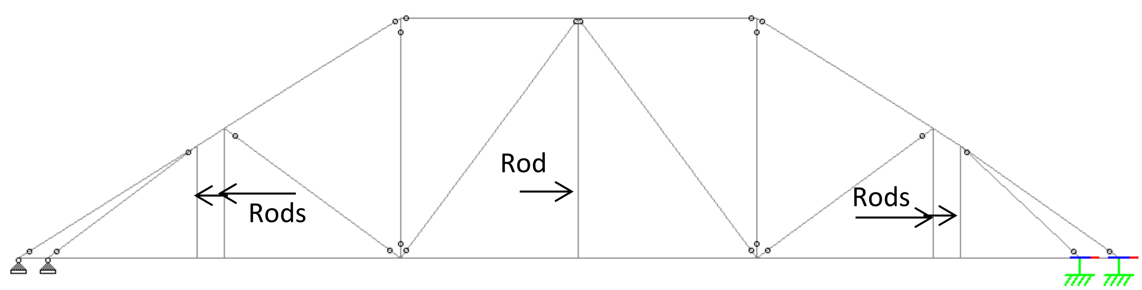


Fig. *5 STAAD two dimensional finite element model of the Moxley Bridge*

3.2 Boundary Conditions

Field inspection of the Moxley Bridge illustrated that each end of the truss structure was seated on a bearing surface that is approximately 1016 mm in length. This was characterized in the analysis by providing supports within the bearing length. All supports on one end were assumed pin type while roller supports were provided at the other abutment.

3.3 Loading

As previously mentioned, the Moxley Bridge was tested using a two axle truck. The load was driven at a slow speed across the bridge structure. This was simulated in the analysis using the moving load option that is available in the STAAD program. The truck's two axle loads were directly applied on the bottom chord of the truss system since the floor beams in this bridge were spaced approximately 50.8 mm on center.

3.4 Material Properties

The listed values for the timber members were estimated by the researchers of the Forest Product Laboratory after conducting moisture content, stress wave and resistor graph field tests. The tests resulted in young modulus for the bottom chord members of 15.3 GPa and 12.76 GPa for all other timber members. A young's modulus of 200 GPa was used for the steel rods.

4. ANALYSIS RESULTS and DISCUSSION

4.1 Displacement at Mid-span

Figure 6 shows the variation in the displacement at the midpoint of the truss bottom chord as the truck was driven across the bridge. The figure shows that there is a lag between the field measured displacements in the east and west trusses, but they are similar in magnitude. This lag is caused by the skew angle for the bridge structure. Also, the figure illustrates that there is a slight difference between the analytical and the measured displacements near the locations of the tension rods. These differences could have resulted from the behavior of the idealized connection between the tension rods and the truss top and bottom chords at these locations. In the analytical model, the two chords of the truss and the rods were assumed to be connected to these rods at common nodes. However, this idealization does not allow for local deformation that occurs in top and bottom chord members in the vicinity of the nuts at the end of these rods. These deformations result from the application of the tie rod forces which act perpendicular to the wood grain of the top and bottom chord members. Such deformation can be significant since the timber of the elastic modulus in the direction perpendicular to the wood grain is approximately one-tenth of the longitudinal elastic modulus in the direction parallel to the wood grain. The differences in the material moduli were not considered in the analytical model.

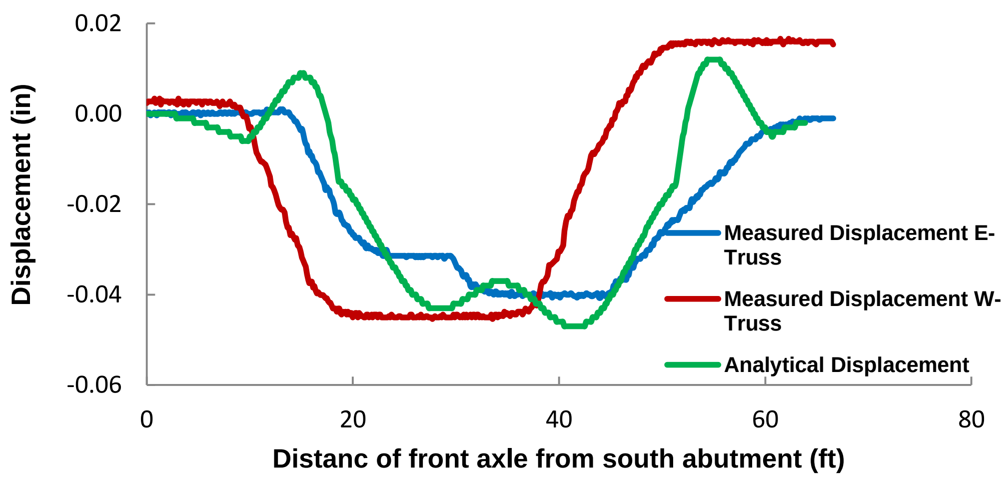


Fig. 6 Variation in the mid-span displacement as the truck travels along the Moxley Bridge

4.2 Comparison of Analytical and Field Strains

Figures 7 to 11 document the agreement between the measured and analytical strains in all members except in the bottom chord. For example, Fig. 7 depicts the variation in the strains in a diagonal member just to the right of the middle rod as truck travels along the center of the bridge deck. One may notice that there are differences of the locations of the peaks of the analytical and the recorded strains. This was due to the inability to match the exact truck locations when the field data was recorded to the analytical locations where the truck was positioned on the bridge in the STAAD analysis. Similar behavior was also noticed when examining the strains in the timber post to the right of the middle rod (see Fig. 8).

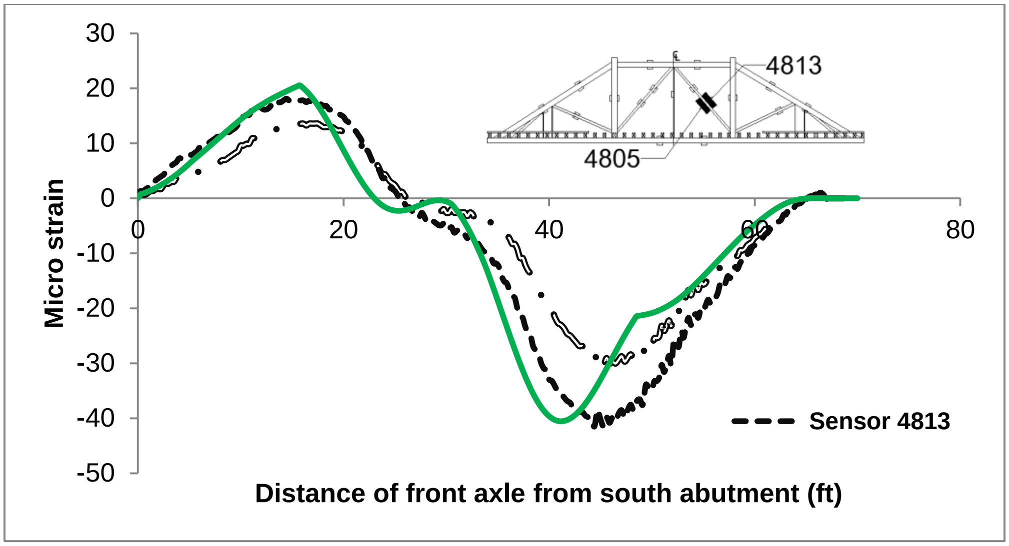


Fig. 7 Analytical and field strains in the diagonal member just to the right of the middle rod

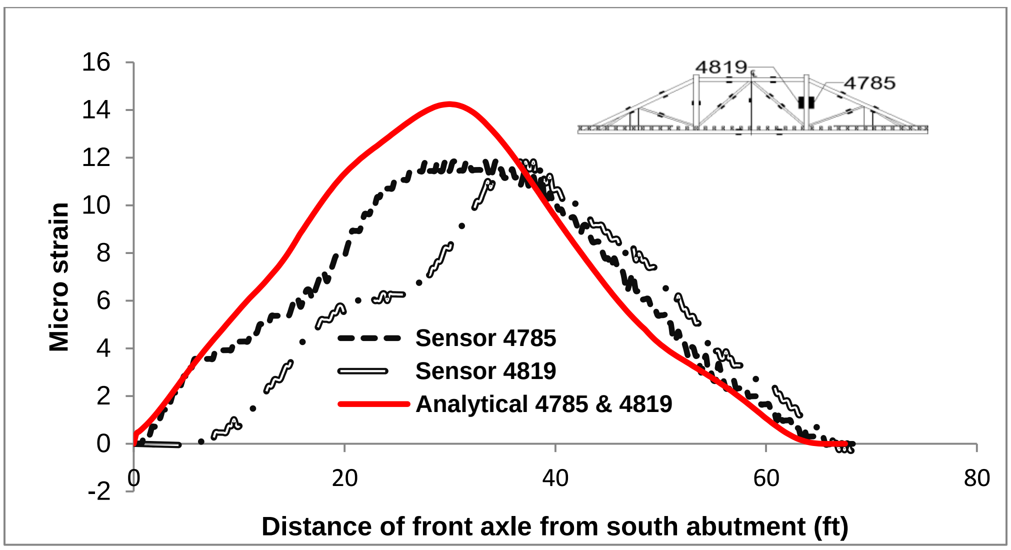


Fig.8 Analytical and field strains in the left timber post

Figure 9 illustrates that there is a slight difference in the analytical and recorded field strains in the first top chord member (see Fig. 9). These differences can easily result from not using the actual material modulus of the members in the analytical model. On the contrary, large differences between the field measured and the analytical strains were observed when investigating the performance of the middle rod (see Fig. 10). This could have resulted from the method used to mount the strain sensor on the element. In the field test two clamps were used to mount the flat sensor on the round bar. Another disagreement between the field measured and the analytical strains was noticed when examining the behavior of the truss bottom chord member just to the right of the middle rod (see Fig. 11). Both analytical and field measurements showed that the bottom chord is subjected to direct axial and bending strains (see Fig. 12). However, the effect of the bending strain was very noticeable in the analytical results. Examining the photo from the field of the location in the vicinity of these strain sensors showed that there was a noticeable check and irregularity in the chord cross section in the vicinity of the sensors that were located on the bottom chord of the Moxley truss (see Fig. 12). This could be one of the reasons for the large differences between the measured and the calculated strains. Additional comparison between measured and calculated strains in other members is summarized in [2].

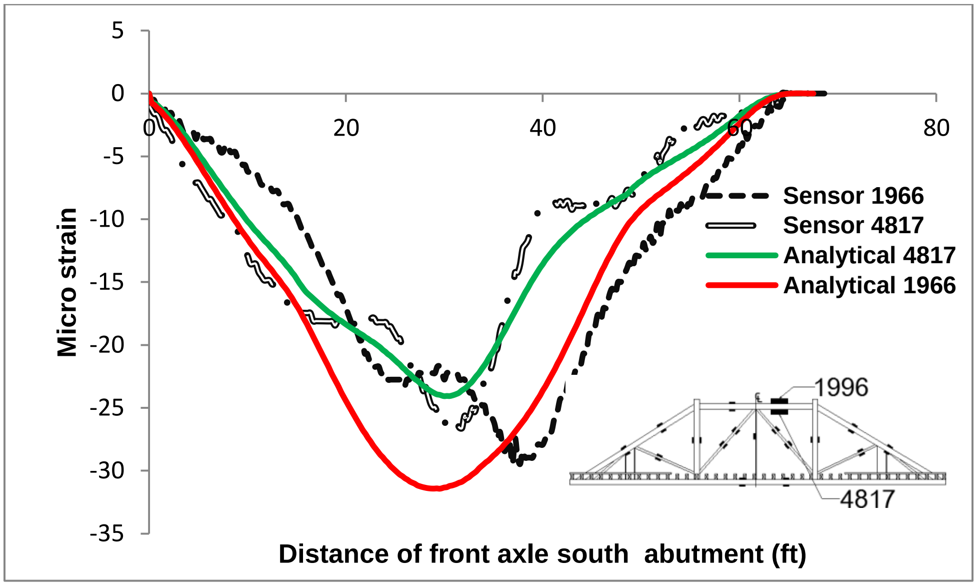


Fig.9 Analytical and field strains the left diagonal member

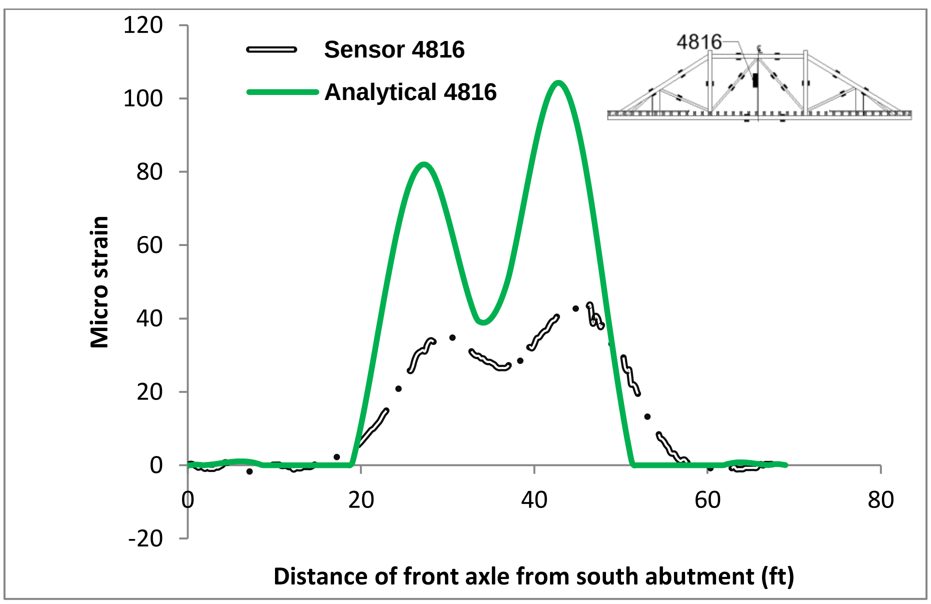


Fig. 10 Analytical and field strains in the middle rod

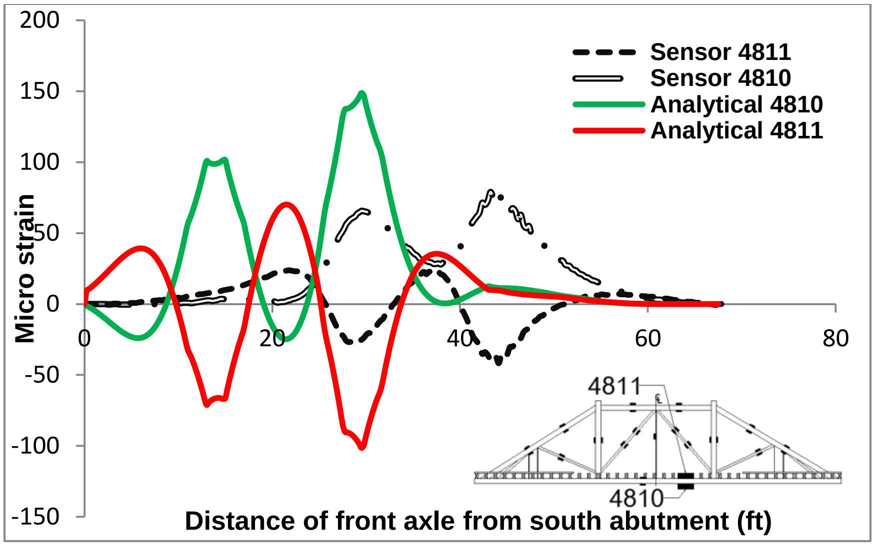


Figure 11 Analytical and field strains in the bottom chord member to the right of the middle rod

Fig. 12 Photo showing the condition bottom chord member of the Moxely- south truss

5. Summary and Conclusions

This paper summarizes an investigation that was sponsored by the Federal Highway Administration and the USDA Forest Products Laboratory to develop a simple but accurate analytical model to analyze a Queen-Post Truss bridge. A three dimensional model that included the splice joints that were used in the construction of the bridge was utilized in the analysis. The results of the analytical model were validated with the data obtained from the field testing of the same bridge structure.

The finite element results showed that idealizing the truss-arch structure excluding the eccentric in the connection between the vertical and diagonals, top chord and bottom chord members may yield a more stiff structure. In addition, the analytical model showed that the arch contributed to the load carrying capacity of the bridge. The strains obtained using the analytical model yielded very reasonable strain results; however, one must take into account the effect of the inherent eccentricity within the joints at both ends of members of the bridge structure.

6. Acknowledgement

The study presented in this paper was supported by the FHWA and the USDA Forest Products Laboratory (FPL) under the National Historic Covered Bridge Preservation Program. The authors wish to thank Mike Ritter, Assistant Director, USDA FPL, for his cooperation and assistance during the course of the work. Special thanks to Allison Lunde (Machtemes) for her assistance in performing some of the finite element analysis presented in this manuscript. Special thanks are extended to Douglas Wood, ISU Structural Engineering Laboratory Manager, for his assistance with data interpretation and conduct of the testing.

7. Bibliography

[1] Bridge Diagnostics, Inc., BDI. 1989. Bridge Testing, Load Testing & Structural Monitoring Solutions, Boulder, CO.

[2] Fanous, F., et. al., Improved Analytical Techniques for Historical Covered Bridges, Report submitted to Forest Product Laboratory, January 2013.

[3] "History of Covered Bridges." 2010. Welcome to the GDOT. Georgia Department of Transportation.<http://www.dot.state.ga.us/travelingingeorgia/bridges/coveredbridges/Pages/HistoryofCoveredBridges.aspx>.

[4] Hosteng, T., et. al., Covered Bridge Rating through Load Testing, Report submitted to Forest Product Laboratory, January 2013.

[5] STAAD.Pro, 2011. Structural Analysis and Design, Revision 8.0: Bentley Systems, Exton, PA. USA.

[6] US Department of Transportation Federal Highway Administration. 2005. Covered Bridge Manual. Rep. no. FHWA-HRT-04-098. McLean, VA: Federal Highway Administration, Print.