WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

Field Testing and Structural Analysis of Burr Arch Covered Bridges in Pennsylvania

Douglas Rammer[1], James Wacker[2], Travis Hosteng[3], Justin Dahlberg[4] and Yaohua Deng[5]

ABSTRACT: The Federal Highway Administration sponsored a comprehensive research program on Historic Covered Timber Bridges in the USA. This national program's main purpose is to develop improved methods to preserve, rehabilitate, and restore timber bridge trusses that were developed during the early 1800s and, in many cases, are still in service today. One of the many ongoing research studies is aimed at establishing a procedure for safely and reliably load-rating historic covered bridges though physical testing and improved structural modelling. This paper focuses on recent field work and analysis of four Burr Arch through-truss-type covered bridges located in Lancaster County, Pennsylvania. An overview of field evaluation methods, loading testing, and structural modelling procedures are included along with a comparison of field measurements and structural model prediction of bridge behaviour.

KEYWORDS: loading rating, structural analysis, covered bridges, historical landmark, burr arch

1 INTRODUCTION

The Federal Highway Administration (FHWA), in partnership with the USDA Forest Products Laboratory and the National Park Service (NPS), sponsored a comprehensive national research program on Historic Covered Timber Bridges in the USA. The main purpose is to develop improved methods to preserve, rehabilitate, and restore timber bridge trusses that were first developed during the early 1800s and, in many cases, are still in service today. The overall goal of the National Historic Covered Bridge Preservation Program (NHCBPP) is to preserve these iconic bridge structures for future generations [1,2]. Two areas of improvement to ensure the preservation of these covered bridges are focused on load rating and structural modelling.

Given their age and complex behavior, covered timber bridges are often assigned relatively low ratings. It is also widely known that when tested, most bridges are found to possess structural characteristics that supersede those assumed for the assigned ratings that were determined using prudent engineering judgment. In general, these behaviors result from additional, unaccounted for stiffness and unaccounted load distribution characteristics.

Although testing procedures have been established for conventional bridges, no such procedures have been established for historic covered bridges. Given the historic nature and unusual geometric features of these structures, a procedure needs to be established detailing how to safely and reliably determine load ratings for historic covered timber bridges through physical testing.

Similarly, the complex behavior and unique details of covered bridges make structural modeling a daunting task for the typical bridge engineer. Simple, static analysis of trusses is frequently used to analyze covered bridges, ignoring the fact that they behave more like frames than as trusses; both axial and bending forces are carried in their members and across joints. As such, over-simplified and inaccurate analyses are often performed; consequently, overly conservative safety factors are applied to account for known inaccuracies. This frequently leads to the conclusion that a historic covered bridge is inadequate to carry the required design load or to the use of inappropriate rehabilitation recommendations.

To improve load rating and structural modelling, four Burr Arch through-truss type bridges located in Lancaster County, Pennsylvania, were live load tested and subsequently structurally analyzed. The paper highlights this work and compares field results with structural model predictions. These results will provide the basis, along with several other types of covered bridge analyses, for

[1] Douglas Rammer, USDA Forest Products Laboratory, USA, drammer@fs.fed.us
[2] James Wacker, USDA Forest Products Laboratory, USA, jwacker@fs.fed.us, j.cascati@test.cl
[3] Travis Hosteng, Iowa State University, Bridge Engineering Center, USA, kickhos@iastate.edu
[4] Justin Dahlberg, Charles Saul Engineering, (formerly Iowa State University, Bridge Engineering Center) USA,
[3] Yaohua Deng, Iowa State University, Bridge Engineering Center, USA, jimdeng@iastate.edu

the development of a new load rating methodology for covered bridges utilizing physical testing.

2 BACKGROUND

2.1 Covered Bridges in the United States

The majority of U.S. covered bridges were constructed in the mid-1800s, but with the development of iron, steel, and concrete structural system, the number of new covered bridges in the United States decreased. Additionally, the development and use of wood preservative in the early 1900s reduced the need for covering the wooden superstructure to extend its service life, further reducing new covered bridge construction.

As covered bridges in the United States have been replaced with more conventional "uncovered" bridge types, the appreciation of the covered bridge has increased. Covered bridges have a rich history, and where these structures reside, proud communities invest both time and emotional effort to maintain and preserve them. In some instances, because of this heritage and love for covered bridges, some modern covered bridges are built. In 2009, the Smolen-Gulf Covered Bridge was built on CR 25 near Ashtabula, Ohio. This modified Pratt Truss spans 187 m with four 45.7-m sections across a river valley. But construction of these modern covered bridges is infrequent and the need to maintain the existing stock is great.

Covered bridges can be grouped into several truss-types (Figure 1), but typically each bridge is unique because of construction details, and this presents challenges to assessing their performance [3].

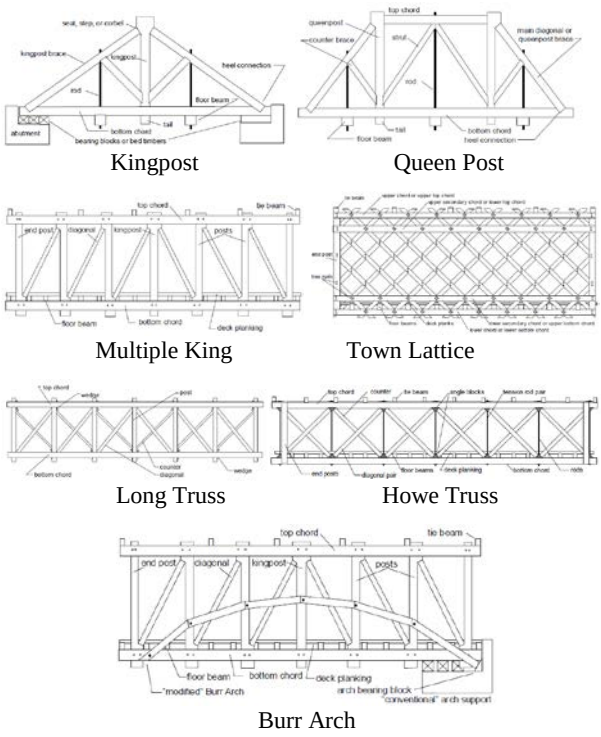

Figure 1: *General schematics of main types of surviving Covered Bridges (adapted from [3])*

As of 2005, the U.S. Department of Transportation Federal Highway Administration documented the types and numbers of covered bridges in the United States. Table 1 list the top five types of covered bridges and the number that existed of each type. Since 2005, news reports indicate that the United States has lost some of these iconic structures. This research efforts has been to maximize and document our understanding of the five types of covered bridge listed in Table 1. We hope that the loading rating and analysis techniques developed in this effort can be transferred to the additional types not listed in the table but also found within the United States.

Table 1: *Number of surviving bridges in the United States as of 2005 [3].*

Bridge Type	No. of Surviving
Burr Arch	224
Howe Truss	143
Town Lattice	135
Queen Post	101
Multiple King Post	95

2.2 COVERED BRIDGES FIELD TESTED IN THE UNITED STATES

Over the past several years, the USDA Forest Service Forest Products Laboratory and Iowa State Bridge Engineering Center have travelled to various regions of the United States to gather detail structural information and wood material properties and to conduct in-field load tests on Burr Arch, Queen Post, and Howe Truss covered bridge timber-truss types [4,5,6,7].

During October 2010, three covered timber bridges consisting of Burr Arch trusses were evaluated and tested in the state of Indiana (Table 2). These bridges were double-arch Burr Arch bridges, and are all located in Parke County, which maintains more than 30 historic covered bridges within their roadway network. These single-lane bridge structures are currently restricted to lower weight vehicle loads but still provide vital transportation links to rural communities in the western part of the state. Approximately 93 covered bridges exist within Indiana.

Table 2: *Burr-Arch bridges tested in the State of Indiana*

Name	Year Built	Length (m)
Portland Mills	1856	68.3
Cox Ford	1913	43.5
Zacke Cox	1908	41.1

During May 2011, four covered bridges consisting of Queen Post trusses were evaluated in the State of Vermont (Table 3). Two structures were evaluated in Washington and Orange Counties. Two of the bridges are located in town with the other two in rural settings. Approximately 100 covered bridges have survived in the relatively small

State of Vermont, which represents the highest concentration of historic covered bridges in the USA.

Table 3: *Queen Post bridges tested in the State of Vermont*

Name	Year Built	Length (m)
Warren	1879	17.7
Flint	1845	27.1
Moxley	1883	18.6
Slaughterhouse	1872	20.1

Finally, in the spring of 2012 a set of Howe truss bridges, were investigated (Table 4).

Table 4: *Howe Truss bridges tested in the State of Indiana*

Name	Year Built	Length (m)
James	1887	42.7
Dick Huffman	1880	81.4
Scipio	1886	47.5
Rob Roy	1860	36.6

2.3 Analysis of Covered Bridges

According to the *Covered Bridge Manual* [3], there are inconsistencies with the assumptions of traditional simple, static analysis of trusses that are frequently used to analyze covered bridges. Recent efforts to structurally analyse covered bridges with finite-element-based approaches have had mixed success.

Lamar and Schafer [7] developed two dimensional beam models to evaluate the structural system behaviour of the Pine Grove Burr Arch. They investigated the influence of connection behaviour and the interaction of the arch and truss for various loading scenarios. Sangree [8] analysed multiple covered bridge types that had load testing data. She concluded that details within the truss system were strongly influencing the differences between field testing and modelling.

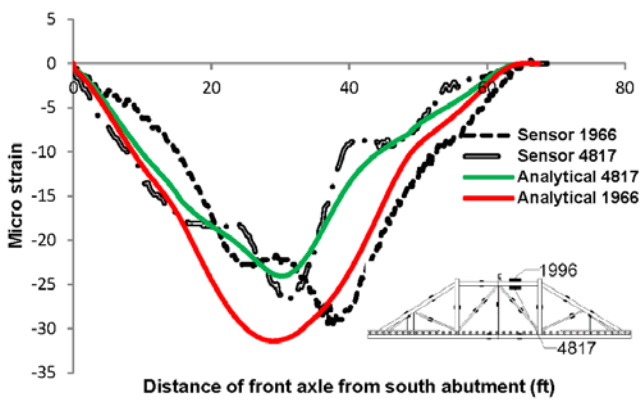

Figure 2: *Field and model strain for top chord of Moxley Queen Post Bridge.*

In conjunction with the cooperative load rating studies being conducted by ISU and FPL, Fanous and others [6,7] developed structural models to predict strain and deformation of the in-field load tests. They developed models for the Queen Post and Burr Arch type bridges, but due to site conditions, the modelling success of the Burr Arch bridges is limited. Only the Zacke Cox Bridge was modelled successfully. A simplified modelling approach for Queen Post bridges was developed. To successfully model Queen Post type bridges, one must take into account the effect of the inherent eccentricity within the joints at both ends of members of the bridge structure. Figure 2 compares the field and model strains for the top chord of the Moxley Bridge that has taken the eccentricity into account. The strong agreement between model and field strains can be seen. If joint eccentricity is not considered, stiffer model behaviour will result (Figure 2). Because the success of modelling Burr Arch bridge was limited and the greatest number of remaining covered bridges are of this type, a second set of Burr Arch bridges were field tested in Pennsylvania.

3 BURR ARCH COVERED BRIDGES—PENNSYLVANIA

Burr Arch bridges are a combination of arches and multiple king post trusses. The arches are not monolithic but segmental, and the trusses are pinned to the arch at the vertical members or by vertical steel rod that connect the bottom truss chords to the top of the arch. Four representative single span Burr Arch covered bridges ranging in length from 27 m to 55 m were selected from the 32 total covered bridges located in Lancaster, Pennsylvania (Table 1) for investigation. A brief description of the load rated bridges will be presented.

Table 5: *Burr Arch Bridges Evaluated*

Bridge	Year Built	Span (m)
Hunsecker	1843	55
Zooks Mill	1849	27
Eshleman	1845	34
Jackson Sawmill	1878	44

3.1 Hunsecker Bridge

The Hunsecker Bridge is located on Hunsecker Road and allows residential vehicular traffic to cross the Conestoga River (Figures 3, 4, and 5). The original bridge was built in 1843 but was swept away by Hurricane Agnes. In 1973, a replicate design to the original bridge was rebuilt at the same location.

The bridge is a single-lane, single span, simply supported Burr Arch. The total height from the bottom of the bottom chord to the top of the top chord for the truss was measured as 5.22 m and center to center spacing of the truss was 4.61 m. Unlike all the other arches studied, the arch consist of “twin” stacked arches on either of the built up post. At every other post the arches were butt spliced using metal and wood side plates with bolts while at the middle post the arch also bolted. The truss consisted of rectangular parallel chord members connected top and

bottom with a single diagonal and built up spaced post, except the middle panel section consisted of cross diagonal members. In total, 17 truss panels exist. The top and bottom chords consist of two parallel rectangular beams member connected with a wood block side plate and bolts. Most connection between members used conventional bolts. The total length of the structure is 54.9 m and is currently posted for a load limit 2.72 t (3 ton).

Figure 3: *Profile view of Hunsecker Bridge*

Figure 4: *Interior view of Hunsecker Bridge*

Figure 5: *Floor System of Hunsecker Bridge*

3.2 Zooks Mill Bridge

The Zooks Mill Bridge is located near the intersection of Log Cabin and Rose Hill Roads and allows vehicular traffic to cross Cocalico Creek (Figures 6, 7, and 8). The original bridge was built in 1848, and unlike other bridges in the area, it survived the effect of Hurricane Agnes despite being awash in water.

The bridge has a single span, wooden, double Burr arch bridge with six additional steel rod hangers that connected the truss to the arch in the 2nd, 4th, and 6th panels. The total height from the bottom of the bottom chord to the top of the top chord for the truss was measured as 4.92 m, and center to center spacing of the truss was 4.61 m. The truss consisted of rectangular parallel chord members connected top and bottom with a single diagonal and chord, except middle panel section consisted of cross diagonal members. The top chord consisted of a single member connected at three locations using single lap joints. The bottom chords consisted of two parallel rectangular beams. When a lap joint was used on one of the single members, the bolts went through the entire chord width. Butt jointed connection that bolted through the vertical and sister arch were used to fabricate the double arch. The total length of the structure is 25.5 m, and it is currently posted for a 2.72 t load limit.

Figure 6: *Profile view of Zooks Mill Bridge*

Figure 7: *Interior view of Zooks Mill Bridge*

Figure 8: *Floor System of Zooks Mill Bridge*

3.3 Eshleman Bridge

The Eshleman's Bridge, also known as Leaman's Place, is located on Belmont Road, north of U.S. Route 30, and allows significant vehicular traffic to cross Pequea Creek as (Figures 9, 10, and 11). The original bridge was built in 1845 and rebuilt in 1983.

The bridge has a single span, wooden, double Burr arch trusses design with additional steel hanger rods that connect arch to the bottom chord and the top chord to the bottom chord in all 11 truss panels. The total height from the bottom of the bottom chord to the top of the top chord for the truss was measured as 4.94 m and center to center spacing of the truss was 5.11 m. The truss consisted of rectangular parallel chord members connected top and bottom with a single diagonal and post, except middle panel section consisted of cross diagonal members. The top chord consisted of single member connected at five locations using single lap joints. The bottom chords consisted of two parallel rectangular beams attached to the post with a double notch. A third rectangular beam sistered to the other beams with through bolts. When a chord was spliced, an oblique tabled scarf joint with key was used and the bolts went through the entire chord width. Arch sections were butt together at on one side of the post, while the arch on the other side was bolted to the post. The total length of the structure is 37.5 m and is currently posted for a 2.72-t load limit.

Figure 9: *Profile view of Eshleman Bridge*

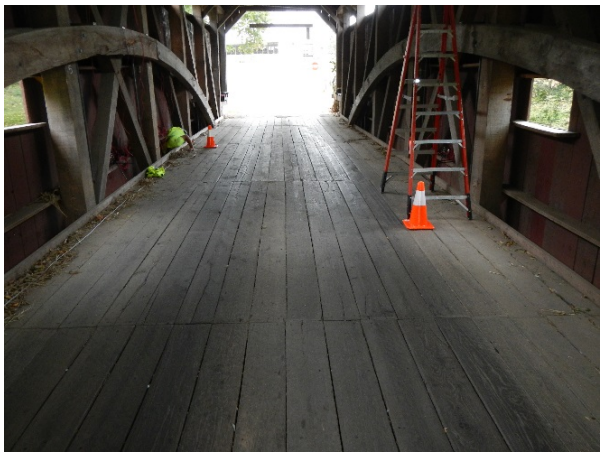

Figure 10: *Interior view of Eshleman Bridge*

Figure 11: *Floor System of Eshleman Bridge*

3.4 Jackson Sawmill Bridge

The Jackson Sawmill Bridge is at the intersection of Mount Pleasant and Hollow Roads and allows vehicular traffic to cross West Branch of the Octoraro Creek (Figures 12, 13, and 14). The original bridge was built in 1878, but in 1985 it was destroyed by flooding and subsequently rebuilt and removed from the National Register of Historical Places. The most recent rehabilitation occurred in 2005.

The bridge has a single span, wooden, double Burr arch design with the addition of steel hanger rods connecting the arch to the bottom chord in the middle of 10 panels and near the post in the remaining 6 panels. The total height from the bottom of the bottom chord to the top of the top chord for the truss was measured as 4.75 m and center to center spacing of the truss was 4.76 m. The truss consists of rectangular parallel chord members connected top and bottom with a single diagonal and post. The top chord consists of single member connected at five locations using scarf lap joints with two bolts. The bottom chords consist of two parallel rectangular beams attached to the post with a double notch and spliced with wood fish plate. On the either side of these chords, additional rectangular beams were sistered with through bolts. These sistered beams were spliced with an oblique tabled scarf joint. Arch sections were butted together with a

metal plate at every other post and attached middle post with a single through bolt. The total length of the structure is 43.6 m and is currently posted for a 3.63-t load limit.

Figure 12: *Profile view of Jackson Sawmill Bridge*

Figure 13: *Interior view of Jackson Sawmill Bridge*

Figure 14: *Floor System of Jackson Sawmill Bridge*

4 RESEARCH PROCEDURES

Research procedures consisted of field evaluations, in-field loading testing, and structural modelling.

4.1 Field Evaluation

Field evaluation consisted of collecting detail measurements and calibrated photographs for development of as-built drawings. Using the calibrated photographs, three dimensional renderings of the covered bridges could be generated to facilitate structural modelling work.

Material evaluation consisted of coring, species identification, ultrasound measurements, resistograph drilling, and moisture content determination. From the coring and ultrasound measurements, the longitudinal elastic modulus (E) of the structural members was determined for use in structural modelling. Resistograph drilling and ultrasound also assessed the integrity of wood members.

4.2 In-Field Loading Testing

Field testing of the covered bridges involved installing displacement and strain transducers on the structures at various cross sections and loading the structure with a vehicle of known weight. Global displacements of the structure, specifically the trusses, were measured at different locations along the bridge length relative to the bottom chords of truss. These displacements were recorded with ratiometric displacement transducers mounted on tripods connected to the bridge via aircraft grade steel cable extensions or aluminium step ladders and recorded with an Optim Megadac data acquisition system (DAS) along with a Dell laptop computer running software. Figure 15 shows the setup for the measurement of global deflection of the Hunsecker Bridge. For this bridge, deformations were measured at midspan and quarter points. Member strains were recorded at various locations on one truss using Bridge Diagnostics, Inc. (BDI) DAS and BDI strain transducers [10]. The strain transducers were attached to the timber members with hex-head screws and washers. Due to the limited number of gages available, time constraints, and symmetry, a majority of the gages were also placed on mostly on one side of the bridges. Unlike previous studies, a limited number of gages were placed on the opposite side of the bridge to assess the distribution of load to each bridge side, and some gages were placed on the transverse stringers to investigate how the plank deck distributed the load. In Figure 16, the outside strain transducers are attached to the top of the double arches and the middle strain transducer is attached to the diagonal member of the truss.

The load vehicle was driven slowly across the bridge in the middle of the roadway and with a wheel line as close to the arch and truss with the greatest density of instrumentation (Figure 17). Data were recorded continuously as the vehicle crossed the bridge. The location of the load vehicle is recorded into the data acquisition systems every 3.05 m along the bridge deck beginning from the abutment the vehicle first crosses.

Figure 15: *Global displacement measurements with transducers supported by aluminium ladders for Hunsecker Covered Bridge.*

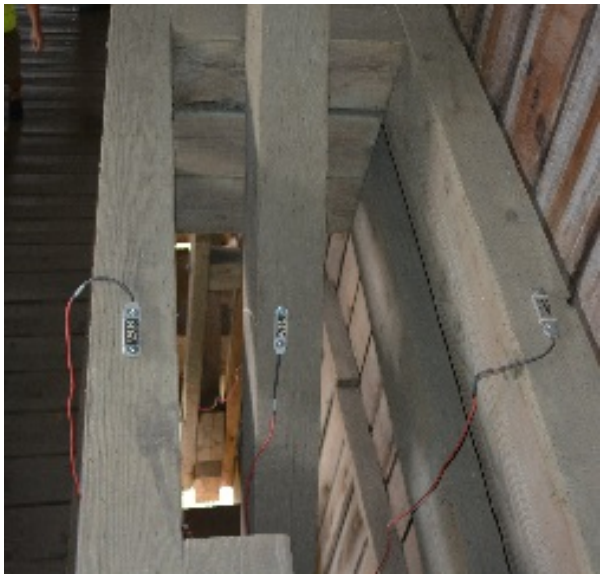

Figure 16: *Local strain measurements for Hunsecker Covered Bridge.*

Figure 17: *Pennsylvannia Dept. of Transportation light truck loading of Hunsecker Bridge*

5 ESHLEMAN BRIDGE

Although four Burr Arch Covered Bridges were field tested in the fall of 2015, results will only be presented for the Eshleman Bridge.

5.1 In-Field Testing

Due to the load posting, a standard Chevy Suburban was utilized as the load vehicle. The load vehicle was driven several times across the bridge while local traffic was restricted from crossing. Two crossing were made with the vehicle centered on the bridge deck and two crossing were made with the vehicle located 406 mm from inside edge of the east curb.

Due to the limit load rating and bridge span, only the mid span deformation was recorded on each side of the bridge. Thirty-eight strain transducer channels were used on this bridge, with 9 strain measurement used for the west side of the bridge, 2 strain transducers used on the transverse stringers each side of mid span, and 27 strain transduces were used on the south half of the east side of the bridge.

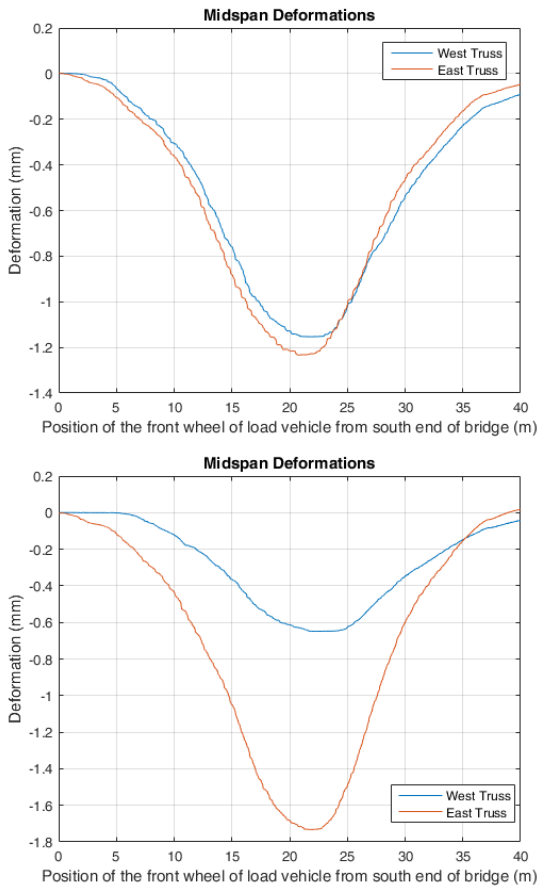

Figure 18: *Mid span deformation of each side of Eshleman bridge for loading with the load truck transversely centered (top) and 406-mm from east curb (bottom).*

When measuring the arch, diagonals, and post behavior, the strain transducers were placed on opposite side of the member to determine flexural behavior. Bottom chord strain measurement used only one strain transducer,

located on the top surface of the member at each location. Prior studies [4, 5] indicated that these member have little flexural behavior

Figure 18 illustrates the displacements measured at the mid span of both truss bottom chords for the load truck transversely centered and 406 mm from east curb. For the centered loading, it is noted that both sides of the bridge have similar displacement behavior and magnitude. This indicates approximately equal load distribution transversely across the bridge deck to the trusses. As expected, when the load vehicle is positioned near the east curb, the nearer truss carries has more deformation than the west truss. These two difference responses are valuable to analytical model developed and understanding of the bridge deck behavior.

Figure 19 shows the strains developed in the diagonal member's one truss panel south of the mid span and highlights the complexities of the bridge systems. While one would believe little or no tensile strain should be transferred through this member due to the end connections being simple angled bearing joint (Figure 20), significant tensile strain is developed. With the model, both compression and tensile behaviour will need to be addressed.

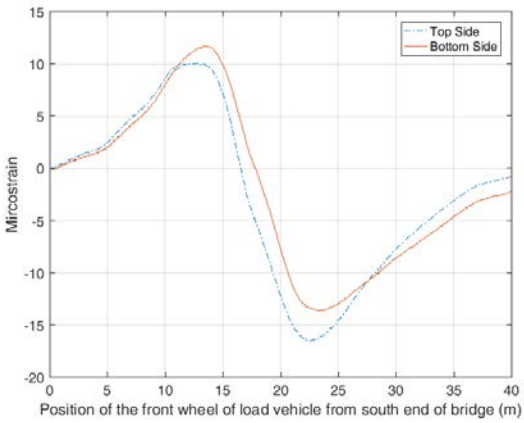

Figure 19: *Strains in diagonal member located near the mid span of the east side of the Eshleman Bridge*

Figure 20: *Simple angled bearing joints connection the diagonals t the vertical post for Eshlemann Bridge.*

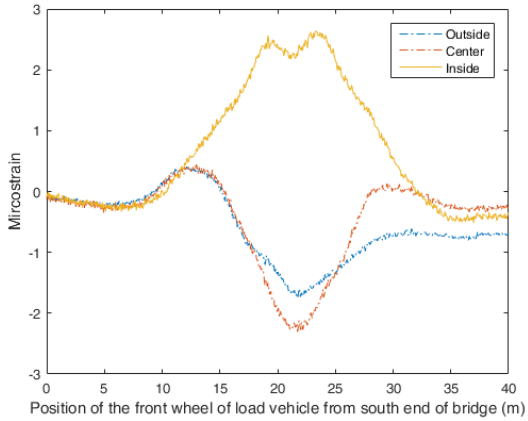

Figure 21: *Strains in east side bottom chord members at mid span for eccentric loading of the Eshleman Bridge.*

Additional complexities are observed in the bottom chord member strains (Figure 21). For all bottom chord measurement locations, the bottom inside chord strains were inconsistent with the center and outside chord strains. In general, the behaviour was a mirrored response with respect to the center and outside chords with tensile strain being generated. It is speculated that this behaviour is attributed to the bearing plate and steel vertical rod used to connect the bottom chord to the double arch. Modeling of this detail will need to be incorporated in future work.

5.2 Structural Modelling

Based on the previous work by Fanous and others [6] STAAD computer software [11] will be used. The Burr Arch bridges will be analysed using three dimensional idealizations (Figure 21) of a single truss. Internal hinges will be included in these bridge models to represent the connectivity between the different members. The splice joints will be modelled in the three dimensional model by releasing the moment in the bottom chord members at the corresponding location of the splices. In all cases, the joint eccentricities will be incorporated into the models. One end of the truss was assumed to be pinned, while roller support was imposed at the other end. The two ends of the arch were assumed to be pinned.

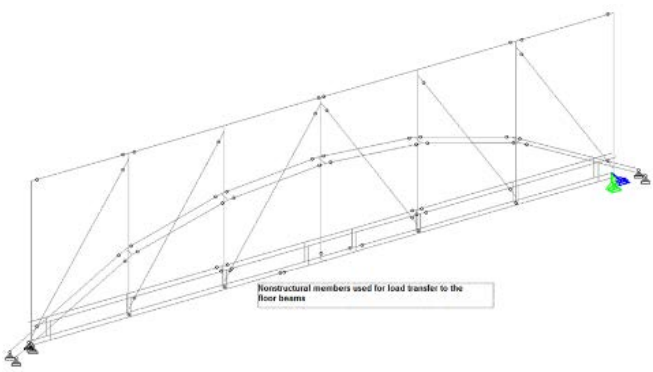

Figure 22: *Three dimensional rendering of covered model of Burr Arch type bridge.*

The bridge model will be loaded using the moving load option available in the STAAD program. To transfer the moving load to the truss bottom chord at the locations of the floor beam, it was necessary to add at the deck level, two longitudinal beams that were not part of the bridge structure. These members will be added to facilitate the application of the moving loads. Each of these beams will be connected using rigid links to the truss bottom chord at the locations of the floor beams. Additional models will be developed that considered the effect of the roadway structure to distribute the vehicle loads to the truss chords.

6 LOAD RATING

The final step in the process is performing a load rating for the subject bridges using the calibrated finite element (FE) model developed for that structure from live load testing results. The basic procedure for performing the load rating via the calibrated FE model is as follows: 1) based on the findings and recommendations from the previous section, create a FE model of the structure; 2) run rating vehicles and/or different trucks across the 2-D model to obtain member forces (noting that things such as vehicle height and width in addition to weight may control if the vehicle can safely enter and cross the covered bridge); 3) calculate the capacity of each key member to be evaluated taking into consideration any deterioration or decay found during inspection; 4) calculate the ratio of the member capacity to the member forces output from the FE model to determine the load rating factor. A load rating factor greater than or equal to 1 is desired.

7 CONCLUSIONS

Efforts are underway in the United States to develop improved methods to preserve, rehabilitate, and restore timber bridge trusses that were developed during the early 1800s and in many cases are still in service today. As part of this on-going effort, four Burr Arch Covered Bridges in Pennsylvania were field tested and are being structurally modelled. Preliminary review of the data indicates additional complexities that are attributed to the presence of steel vertical rods between the arch and bottom chord not observed in the previously analysed Burr Arch covered bridges in the State of Indiana.

8 FUTURE COVERED BRIDGE WORK

Field testing is planned on a group of King Post and Town Lattice covered timber bridges in the New England states for later in 2016. Additional structural analysis of previously collected field test data for the Howe Truss and Burr Arch will continue with an emphasis on the behaviour of the key members: top and bottom chords, diagonals, verticals. Structural models will consider the eccentricities of the connection locations and use hinges to account for member splices.

The final product will be recommendations and guidelines for instrumenting covered bridges, load testing covered bridges, generating a simple but accurate bridge model of covered bridges, and load rating covered bridges such that load limits that are both safe and reflective of the actual performance of the structure may be assigned to the bridge.

Once final FE models and load ratings for the subject bridge have been completed, recommendations and guidelines for instrumenting covered bridges, load testing covered bridges, generating a simple but accurate bridge model of covered bridges, and load rating covered bridges such that load limits that are both safe and reflective of the actual performance of the structure may be assigned to the bridge. These documents will be published in a format similar to load rating guides for other bridge types made using steel and concrete materials.

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