RAIL THROUGH-PLATE GIRDER 3-D ANALYSIS FOR FUNDAMENTAL EVALUATION OF KNEE BRACE BEHAVIOR

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BIOGRAPHY

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SUMMARY

Through-plate girders (TPGs) are a common structural choice for medium span railroad bridges, in particular where clearance below the structure needs to be maximized. Integral to TPG behavior is the knee brace connection from the girder web and top flange to the floorbeam or floor system. The Knee Brace acts as a multi-function structural element. It restrains the top compression flange from lateral displacement as a bracing device and it is a load transfer mechanism between the floorbeams and the TPG. Design manuals provide limited guidance on loads to proportion knee braces that have led to overly conservative designs and severely poor ratings that did not accurately reflect the behavior of the structures. In order to better understand the knee brace behavior and their effect on the structure, two full-scale 3-dimensional finite element models were developed to evaluate the actual behavior of TPGs subjected to Cooper E-80 design loads. Concurrently, instrumentation was applied to an existing TPG which corroborated the results of the finite element studies. The results have led to a more refined understanding of knee brace behavior.

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ABSTRACT

Through-plate girders (TPGs) are a common structural choice for medium span railroad bridges, in particular where clearance below the structure needs to be maximized. Integral to TPG behavior is the knee brace connection from the girder web and top flange to the floorbeam or floor system. The Knee Brace is defined by the American Railway Engineering and Maintenance-of-way Association (AREMA) (1) as a "stiffened diagonal plate connecting the top of a floorbeam to a girder or truss vertical" and it acts as a multi-function structural element. First, it restrains the top compression flange from lateral displacement as a bracing device. Second, it is a load transfer mechanism between the floorbeams and the TPG. The American Association of State Highway and Transportation Officials (AASHTO) (2) indicates that knee braces need to be designed in the same manner as gusset plates, but does not provide guidance on loads. AREMA provides limited guidance on loads to proportion knee braces, but leaves room for interpretation on their application. During a review of designs and ratings, AREMA Committee 15 for Steel Structures discovered that engineers were misinterpreting current recommendations for knee brace evaluation, likely as a result of the lack of available guidance. This led to overly conservative designs and severely poor ratings that did not accurately reflect the behavior of the structures. In order to better understand the knee brace behavior and their effect on the structure, two full-scale 3-dimensional finite element models were developed to evaluate the actual behavior of TPGs subjected to Cooper E-80 design loads. Concurrently, instrumentation was applied to an existing TPG which corroborated the results of the finite element studies. The results have led to a more refined understanding of knee brace behavior and are the subject of proposed ballot language for the AREMA Manual for Railway Engineering (2017 ed.). The results of the finite element study, the field instrumentation results, and the proposed change to the AREMA Manual are presented.

BACKGROUND

Specification Guidance

Through-plate girders (TPGs) are a common structural choice for medium span railroad bridges, in particular where clearance below the structure needs to be maximized. And although less common, TPGs can also be found on highway systems. Integral to TPG behavior is the knee brace connection from the girder web and top flange to the floorbeam or floor system. The American Railway Engineering and Maintenance-of-way Association Chapter 15 (AREMA) (1) defines a knee brace as a "stiffened diagonal plate connecting the top of a floorbeam to a girder or truss vertical." The knee braces primarily acts as a stiffening strut that restrains the top compression flange from lateral displacement.

For the design of knee braces, AREMA Chapter 15 has guidance in two sections. Article 15-1.11.1 states:

> *"The top flanges of through plate girders shall be braced at the panel points by brackets with web plates (knee braces). The brackets shall extend to the top flange of the main girder and be as wide as clearance will allow. They shall be attached securely to a stiffener on the girders and to the top flange of the floorbeam. On solid floor bridges the brackets shall not be more than 12 feet*

apart. The brackets shall be designed for the bracing force specified in Article 1.3.11."

Article 1.3.11 states:

"The lateral bracing of the compression chords or flanges of trusses, deck girders and through girders and between the posts of viaduct towers shall be proportioned for a transverse shear force in any panel equal to 2.5% of the total axial force in both members in that panel, in addition to the shear force from the specified lateral loads."

There is currently no associated commentary language for these articles. The implication by these two articles is that bracing of the TPG flange should be proportioned to carry a notional load that is 2.5% of the axial load in the compression flange. For example, if the compression flange stress is 19 ksi for a 3" x 24" flange, the required notional load would be:

$$2.5\%(19ksi \cdot 3in \cdot 24in) = 34.2kip$$

This notional load would then be applied at the compression flange elevation, perpendicular to the flange, to be resisted by the knee brace (Figure 1).

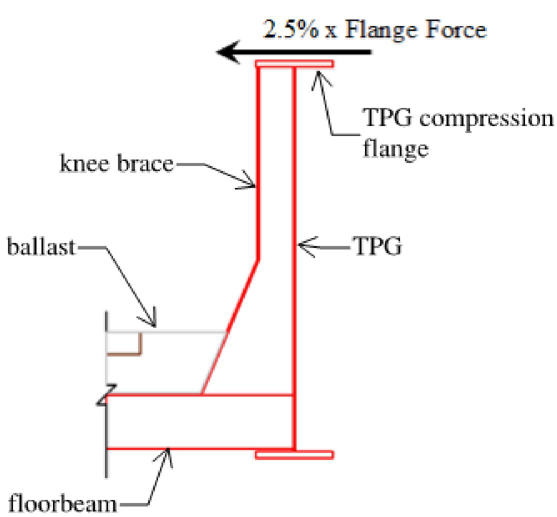


Figure 1. TPG section showing knee brace notional load

The American Association of State Highway and Transportation Officials (AASHTO) (2) does not provide nearly as specific guidance on knee braces, indicating that knee braces need to be designed in the same manner as gusset plates, but does not provide guidance on loads. Article 6.14.1 states:

"6.14.1—Through-Girder Spans

Where beams or girders comprise the main members of through-spans, such members shall be stiffened against lateral deformation by means of gusset plates or knee braces with solid webs connected to the stiffeners on the main members and the floorbeams."

This information is not particularly useful to the designer, other than the acknowledgement that the knee brace must be designed for the appropriate loads.

Additional References

Chapter 12 of the Guide to Stability Design Criteria for Metal Structures by Galambos (3) is on bracing systems for compression members, and contains additional guidance for designers. The chapter states that the bracing force (F_{br}) for strength design is related to the applied moment (M), the depth (h) of the girder and a factor relative to single curvature or reverse curvature of the girder (C_d):

$$F_{br} = \frac{0.01 \cdot M \cdot C_d}{h}$$

Eq. 1

It can be seen that this guidance is similar to that of AREMA, with the flange force (M/h) multiplied by a factor ($0.01 \cdot C_d$). The chapter also recommends for discrete bracing of columns, that a bracing force of 0.01P should be used, which is equivalent to the flange force at a point using Eq. 1. It should be noted that this chapter references load and resistance factored design (LRFD) methodology, while AREMA is based on allowable stress design (ASD).

AREMA Bracing Notional Load

Further understanding of the AREMA notional load comes from Nattere et al (4). The paper presents a more direct derivation of bracing based on an initial out of straightness and adjacent point of support (Figure 2).

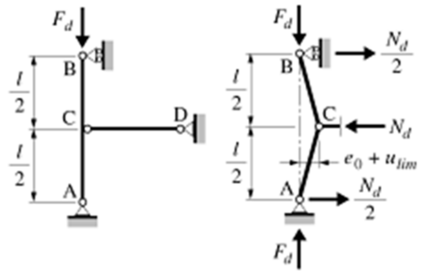


Figure 2. Nattere et al., discrete point column bracing (reproduced)

To determine N_d, we set the tolerance limit (u_{lim}) to zero, and take the moment about point C. Thus we have:

$$\frac{N_d}{2} \cdot \frac{L}{2} = F_d \cdot e_0$$

Eq. 2

Setting the initial assumed eccentricity at L/160, the equation becomes $N_d = 0.025 \cdot F_d$. However, the assignment of the initial eccentricity appears to be relatively arbitrary. By comparison the Eq. 1 from Galambos states an initial out of straightness of 0.002·L (L/500), and indicates that Eq. 1 should be modified if out of straightness is larger.

PROBLEM STATEMENT

General

During a review of designs and ratings, AREMA Committee 15 for Steel Structures discovered that engineers were misinterpreting current recommendations for knee brace evaluation, likely as a result of the lack of available guidance. This led to overly conservative designs and severely poor ratings that did not accurately reflect the behavior of the structures. Ratings were so severe in one case that it would indicate that any train crossing the bridge would have caused failure of the floorbeam system, whereas simple field observation and the history of the structure shows that it is in good condition.

It was determined that the main source of confusion was the concept of the notional load applied to the knee brace. It is readily apparent that the bracing members themselves (knee braces) should be proportioned for this load. The debate, however, is the resolution of this notional load, i.e. how and where is the 2.5% of the total axial force (hereafter referred to as the notional load) in the flange resolved?

At issue may be the difference between guidance using a notional load and advanced analysis. Rules of thumb or established parameters continue to be an asset for design. For example, the AASHTO lane equivalent distribution widths for Live Loads (LL) allows designers to use general equations or tables as an alternate to a complete evaluation of LL distribution for each bridge design. Additionally, evolution of design demonstrated that certain details are acceptable based on a history of performance or a thorough evaluation of parameters. These allow designers confidence to specify a detail without a complete analysis. For example, portions of compact sections do not need to be checked for local buckling because analysis of the section has already been evaluated and is accepted by the engineering community.

Modern analysis procedures, however, have the ability to evaluate every component of a structure for strain and displacement. Thus, there is a tendency to think about the entire system and how the components interact. There is an inherent potential for confusion when both the advanced analysis techniques and recommended practices interact.

Knee Braces Forces

The knee brace is designed to the notional load from the out of plane force of the compression flange. And if this is not interpreted as simply a force used to size a shape, but rather as an actual load for analysis, it needs to be resisted at the opposite end of the knee braces at the floorbeam. Following this through, the floorbeam needs to resist the forces from the knee brace. Thus for the floorbeam design condition, the engineer must consider the direct live load (LL) with the additional force from the knee brace. There is no guidance, however, on how to apply these two loads to the floorbeam, if they should be concurrent, or if the notional load needs to be applied at all.

EVALUATION OF KNEE BRACE AND FLOORBEAMS IN TPG SYSTEMS

General Concept

The live load is eccentric to both of the supporting TPGs and creates a rotation of the TPG-floorbeam frame structure. The loads create an inward rotation (torsion force) with the system deforming to the shape (exaggerated) show in Figure 3.

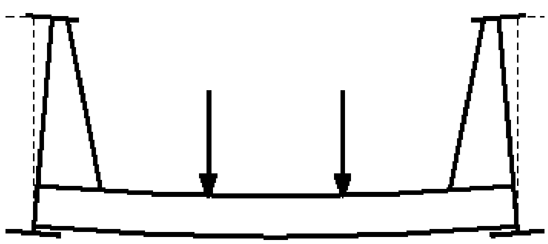


Figure 3. TPG Frame-action rotation

The rotation is resisted by both the out of plane stiffness of the flange plate and the frame structure. The knee braces contribute to the stiffness and resistance of the frame. The inward rotation can create a compression force between the compression flange and the floorbeam as it resist the inward rotation. Conversely, as the floorbeam is loaded by the axles, this can induce tension between the floorbeam and the compression flange. The key to evaluating how the system works is to evaluate how the whole TPG system acts in three-dimensional (3D) space. Or in other words, how are knee braces and floorbeams loaded relative to the position of the LL along the span.

In order to better understand the knee brace behavior and their effect on the structure, two full-scale 3-dimensional finite element models were developed to evaluate the actual behavior of TPGs subjected to Cooper E-80 design loads. Both are modeled as open deck systems (no ballast), the first using a floorbeam-stringer configuration, the second using a floorbeam only configuration. Concurrently, instrumentation was applied to an existing TPG which corroborated the results of the finite element studies.

Modeling – Floorbeam system

Structural analytical modeling for the floorbeam-stringer configuration was done using LARSA FEA software. Standard static simulations were performed with Cooper E80 moving loads applied along the bridge. The bridge is a simply supported span, 72 feet 6 inches long with two main girders and a floorbeam system.

The girders are spaced transversely at 20 feet from center to center and the floorbeams are spaced at two feet center to center in the longitudinal direction. Knee braces are placed on every other floorbeam with a spacing of 4 feet (Figure 4).

The main TPGs are welded girders built up from 1" x 120" web plates and 2" x 24" flange plates. Floorbeams are W16x89 steel beams. Knee braces are built up with a 3/4" web and a 3/4" x 10" vertical flange plate that extend from the floorbeam to the top flange at a constant angle.

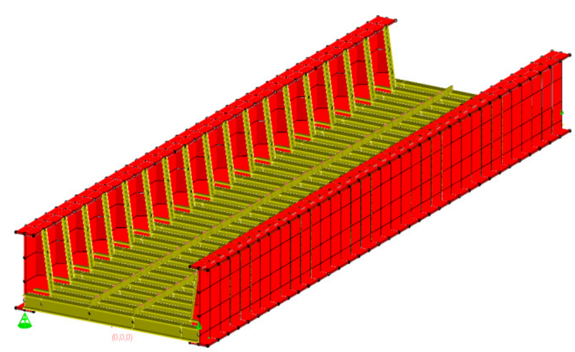


Figure 4. LARSA TPG Model for floorbeam only system

For modeling, the TPG was created from simple LARSA standard 4-node shell elements for both the web and the flange. Floorbeams were modeled with 2D beam elements. Knee braces were modeled with plate elements for the web and beam elements for the flange. Connections are simplified using common nodes between plate and beam elements and do not include the connecting elements. The model did not include timber ties, but the rail is modeled with a beam element having equivalent properties to standard rail for load distribution effects.

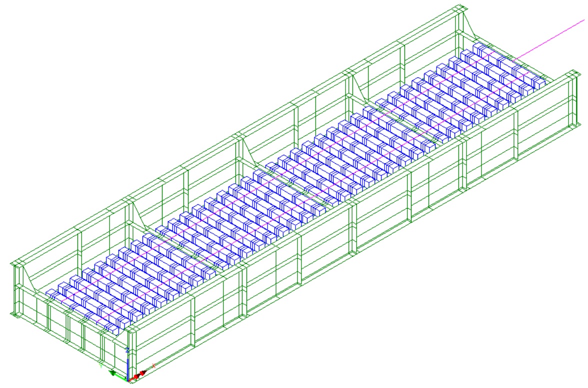
Model – Floorbeam-stringer system

Structural analytical modeling for the floorbeam-stringer configuration was done using LUSAS FEA software. Standard static simulations were performed with Cooper E80 moving loads applied along the bridge. The bridge is a simply supported span, 64 feet long with two main girders and system of floorbeams and stringers.

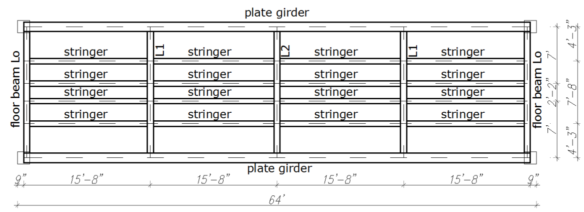
The girders are spaced transversely at 16 feet 1 inch from center to center, the floorbeams are spaced at 15 feet 8 inches in the longitudinal direction and the stringers are spaced transversely with 2 feet 9 inches from exterior stringers to the interior stringer and 2 feet 2 inches between internal stringers (Figure 5).

The main girders are built up from 3/8” x 73” web plates total depth, 3/8” x 14” upper and lower cover plates, with 6” x 6” x 3/8” angles. Vertical web stiffeners are spaced at approximately 7 ft. intervals. The floor-beams are also built up sections with 3/8”x42-1/4” web plates and 6” 6” angles: external floor-beams have 6” x 6” x 9/16” double angles, while internal floorbeams L1 and L2 have 6” x 6” x 3/4” double angles. At the connection with the plate girder, knee bracing is extended to the web plates up to the top of the girders. The knee brace plates are 3/8” x 32” long x 30” tall. The stringers are historic rolled S20x75 beams. All connections between members within the structure are made using rivets with a nominal diameter of 7/8”. The stringer-to-floorbeam connection is made using double angles riveted to stringer and floor-beam webs. All parts of main girders were created as thin shell elements. Regular quadrilateral shape (QSI4) of elements was used to mesh all parts.

Timber ties and the rail were modeled for load distribution effects. Rail is modeled by a beam element with equivalent properties to standard rail. Timber ties are modeled as 10” x 10” x 9’-0”, spaced 16 in. from center to center. Volume elements were used to create ties in LUSAS. Regular hexahedral shape (HX8M) of elements was used to mesh all parts.



(a)



(b)

Figure 5. LUSAS TPG Model for floorbeam-stringer system (a) overall model, and (b) framing plan layout

The overall system mesh is shown in Figure 6.

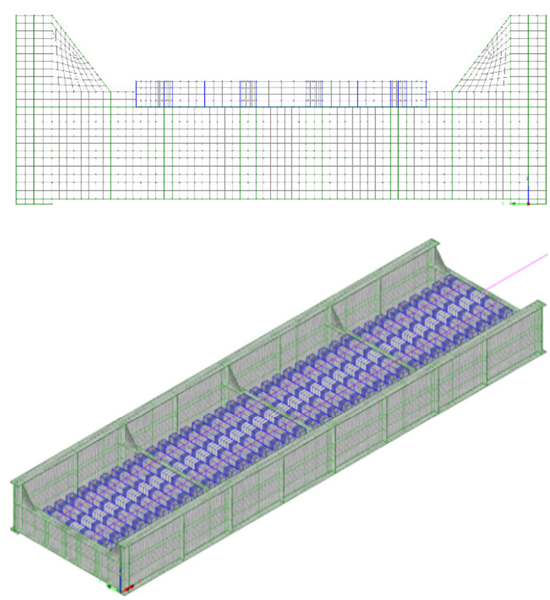
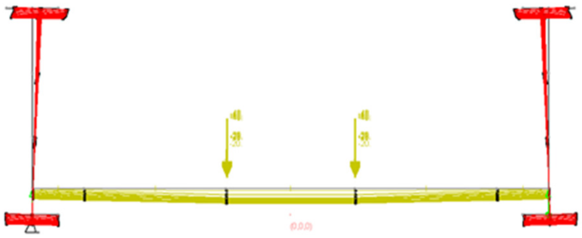


Figure 6. Finite element mesh for TPG floorbeam-stringer system

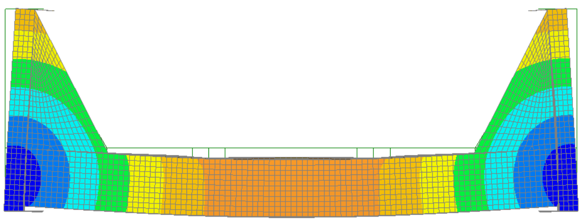
Modeling Results

Deflected Shape

For both models, the deflected shape is as expected. Notably, the TPG deflects as a pinned supported girder and the girder rotates inward towards the eccentric LL (Figure 7).



(a) (knee braces not shown)



(b)

Figure 7. TPG deflected shapes and torsional rotation for (a) LARSA Model and (b) LUSAS Model

Flange Loads at Knee Braces

Similar to Figure 7, the maximum flange compressive stresses are shown in Figure 8.

<u>LARSA Model</u>: This model has a Nominal Flange stress of 6.2 ksi (and a peak stress of 8.4 ksi that includes out of plane bending effects that are ignored by AREMA ASD methodology). Therefore at the point of peak compression, the AREMA specified 2.5% of the axial compression load in the flange would be

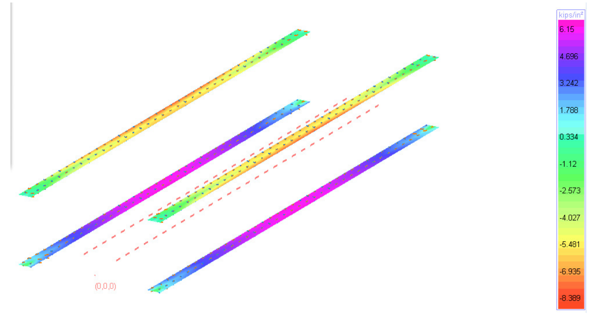
$$0.025 \cdot (2\text{in} \cdot 24\text{in}) \cdot 6.2\text{ksi} = 7.4 \text{ kip}$$

Thus, the knee brace should be proportioned for a transverse shear force in any panel equal to 7.4 kips in both members in that panel.

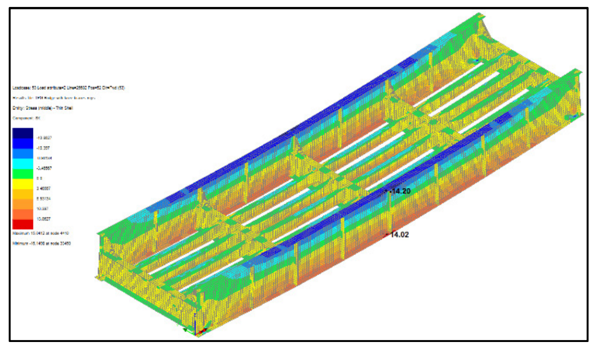
<u>LUSAS Model</u>: This model has a Nominal Flange Stress of 14.2 ksi (and a peak stresses of 16.2 ksi that include out of plane bending effects). Therefore at the point of peak compression, the AREMA specified 2.5% of the axial compression load in the flange would be

$$0.025 \cdot [(3/8\text{in} \cdot 12\text{in}) + (1/2\text{in} \cdot 14\text{in})] \cdot 14.2 \text{ ksi} = 4.1 \text{ kip}$$

Thus, the knee brace should be proportioned for a transverse shear force in any panel equal to 4.1 kips in both members in that panel.



(a) only flanges shown



(b)

Figure 8. TPG stress profile showing (a) 6.2kip of in compression flange for the LARSA Model and (b) 14.2kip of compression flange for the LUSAS Model.

In each case, however, the concern is how and when to apply this load to the knee brace and the TPG system. As such, the following section will concentrate less on the load value and more on the system behavior.

Knee Brace Forces

As consideration of both arguments would indicate, the axial forces in the knee brace flange are both in tension and compression. The envelope function in LARSA shows that the knee braces are loaded both in tension (purple/pink) and compression (orange) in Figure 9.

Similarly for the LUSAS model in Figure 10, the stresses in the knee brace web are presented.

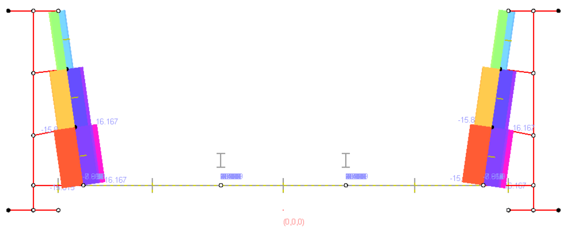


Figure 9. LARSA Knee Brace flange force showing both tension and compression

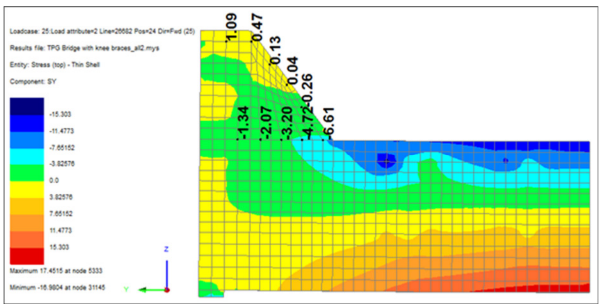


Figure 10. LUSAS Knee Brace plate stresses showing both tension and compression

The knee braces are distributing forces that are clearly being resisted by the floorbeam, otherwise, this would be a zero force member. It is therefore how those loads affect the floorbeam that is investigated. That is, does the load being resolved impart an increase (or decrease) in moment on the floorbeam, or does it act as a separate system away from the loaded floorbeam? Also, of note is that the largest knee-brace axial force shown is representative of the resolved forces for a transverse load of approximately 1.75% of the applied axial compression flange force as predicted by the model (within the LARSA model).

Interestingly, the force distribution in the LUSAS TPG for the maximized load condition shows that the knee brace web plate transitions from compression to tension through the depth of the section indicating that a notional force at the top of the knee brace is not the controlling function for the stress.

The difference in the models is most likely the large difference in knee brace stiffness relative to the floorbeam and TPG system.

TPG System (3D) response to load

To look at how the TPG system is reacting, the controlling load case was selected that (1) maximized the load on the TPGs and (2) the floorbeams, and (3) also placed one knee brace in near-maximum tension force and one in near-maximum compression force. For reference, the selected case places the second grouping of 80 kip axles for the Cooper E80 load near the center of the span. The resulting knee brace forces are shown in Figure 11. It can be seen in the figure that the force in the knee brace varies with the position of the load. In various locations adjacent knee-braces have one loaded in compression (orange) and the other in tension (purple/pink).

To further evaluate the system behavior, the maximum compression condition (Figure 12) and maximum tension (Figure 13) conditions are isolated with their respective floorbeam bending.

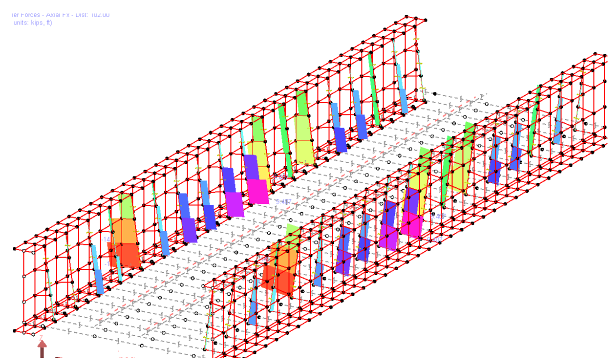
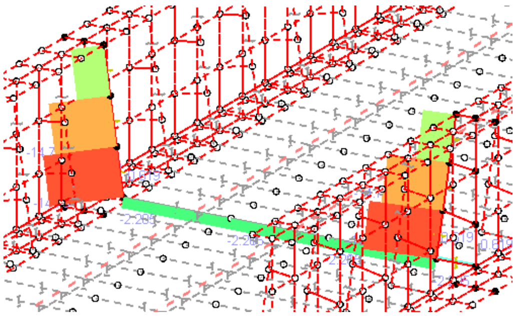


Figure 11. Knee Brace flange forces for E80 Cooper loading

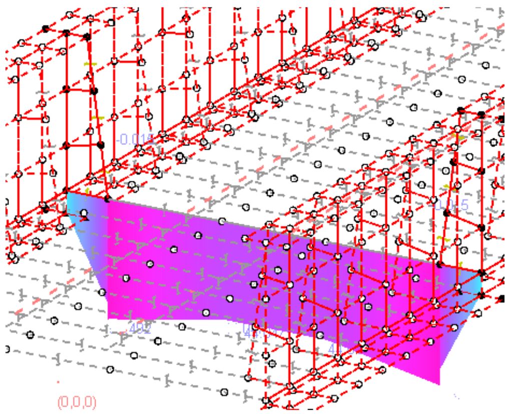
In Figure 12, the moment in floorbeam induced by the compression knee braces; that is, the live load is not directly loading the floorbeam.

In Figure 13, the moment is slightly reduced at the knee braces. For this case the 80 kip axle from the Cooper E-80 loading is directly over the floorbeam and the moment is created directly by live load from the rail.

For scale, the floorbeam bending moments shown in the previous images are superimposed in Figure 14. The live load induced moments (purple/pink) are more than double the knee brace-induced moments (blue/grey).

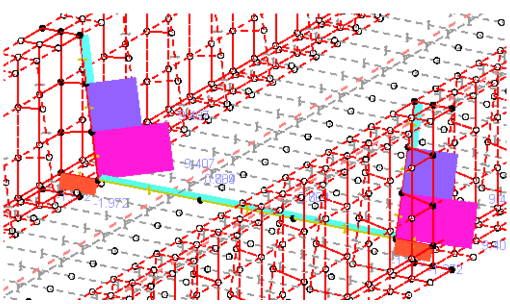


(a) knee brace

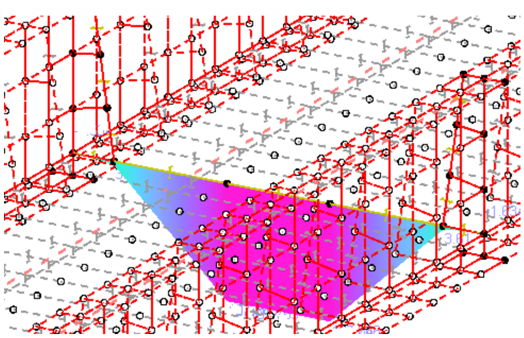


(b) floorbeam

Figure 12. Compression in the (a) knee braces and associated (b) floorbeam bending



(a) knee brace



(b) floorbeam

Figure 13. Tension in the (a) knee braces and associated (b) floorbeam bending

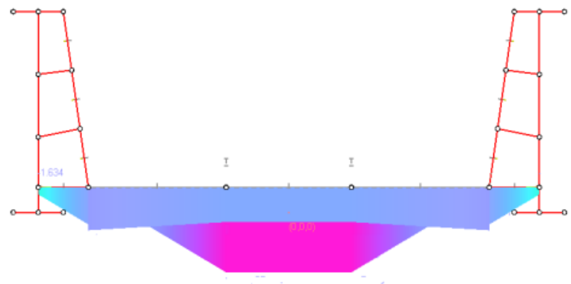


Figure 14. Moment in floorbeam for associated knee braces in compression (grey) and tension (purple/pink) demonstrating qualitative controlling moment condition

Moreover, the preceding images show that the moment induced by the compression force in the knee braces is not concurrent with the moment directly induced by the live load moment. To further demonstrate this, Figure 15 shows the locations of the load relative to the knee brace forces.

This figure clearly indicates that the knee brace acts as both a compression member and tension member (with a nearly full reversal of load, the compression load is greater) depending on the location of the live load axles. The important distinction is the lack of superposition of forces in the 3D TPG system for when the knee braces are in compression. In other words, the live load:

- Flows through the directly loaded floorbeam to the TPG, placing the knee brace in tension and rotating the floorbeam-knee brace-TPG frame inward
- This rotation is then countered by the unloaded frames.
- The knee braces that are not attached to floorbeams being loaded restrain the TPG from rotating inward.
- This then creates a compression force that is transferred to the floorbeam not directly loaded by the live load.

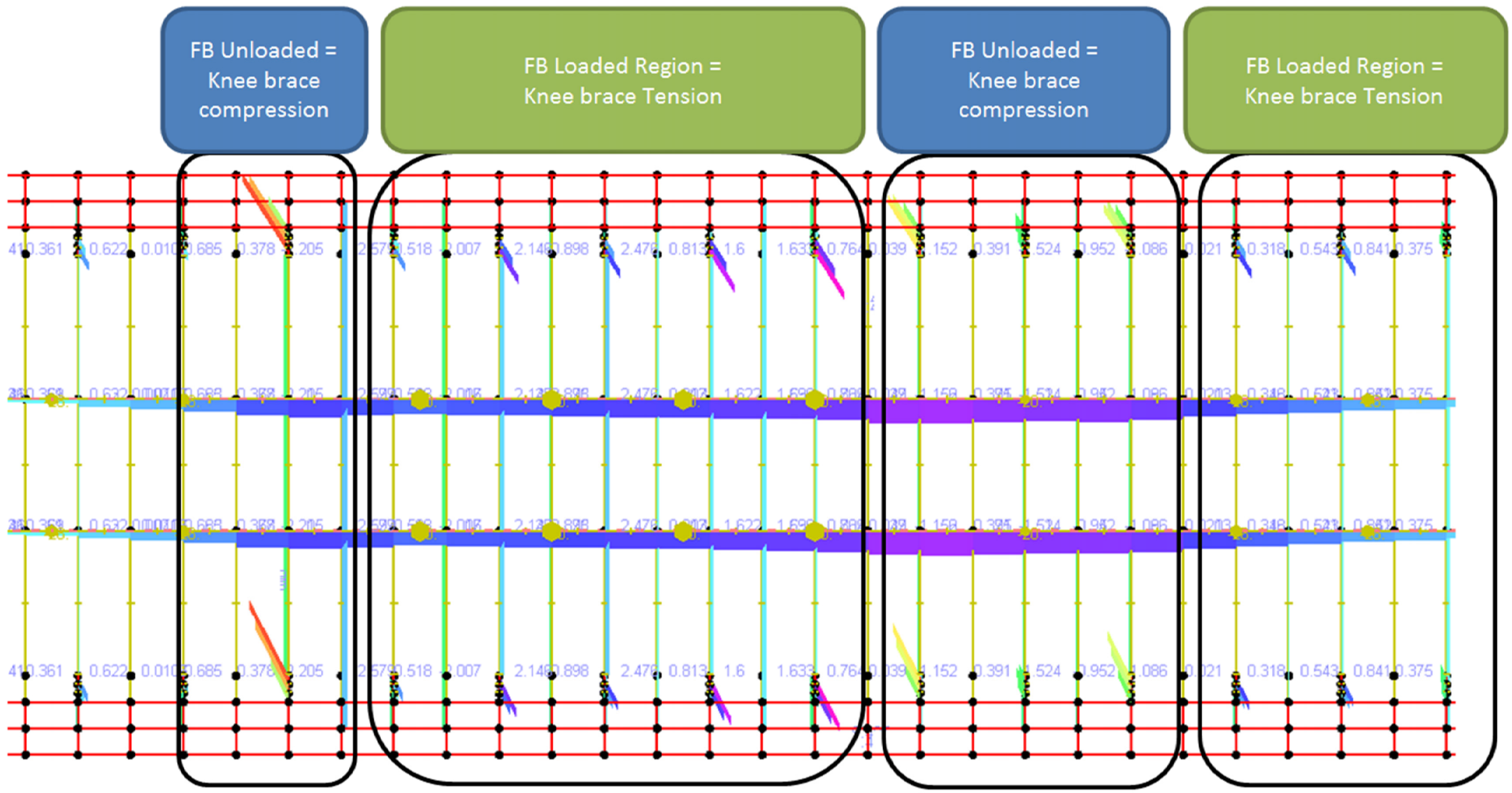


Figure 15. Through plate girder knee brace forces displayed relative to position of the Live Loads. Knee braces show tension (purple/pink) where the floorbeams are directly loaded and compression (orange/red) when in compression.
(*Note that the purple shown at the center of the span is the rail dummy member for load distribution*)

BRIDGE MONITORING

In December of 2013, a rating of a TPG in California showed exceptionally load ratings for the floorbeam system. The bridge was built in 1928 with rolled floorbeams spaced at approximately 2 feet. As such, an array of nearly 56 sensors was applied to the top and bottom flanges of the TPGs and floorbeams, and applied to the knee braces to record live load response of the structure (Figure 16).

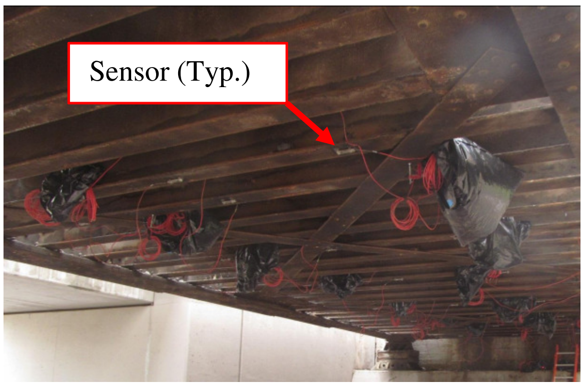


Figure 16. Strain gages applied to TPG (showing underside of bridge)

Four different train configurations were applied to the bridge with known axel loads, both at a slow load (non-impact) and at track speed (40mph, to include impact effects) velocities. The overriding conclusion of the instrumentation was that the floorbeams with knee braces followed a load response similar to the model. Additional compression in the knee braces were not experience simultaneous with the loading and did not impart a secondary additional moment on the floorbeams. Moreover, one major finding was that the floorbeams with knee braces actually experienced a decreased bending stress as compared to floorbeams without knee braces.

The key conclusion of the report (unpublished) is that:

> *"There was no observed moment or stress amplification in floorbeams with knee braces compared to those without knee braces, as assumed by the AREMA code. It was found that the end-moment applied through the knee braces was not cumulative with moments applied by direct loading of the train. In general the two load mechanisms tended to counteract each other because mid-span moments of braced floorbeams were typically less than measured from unbraced floorbeams."*

A similar conclusion was found in a previous study by Unsworth et.al. (5). They concluded that that the loaded floorbeam transferred the load through the stiff knee brace to the TPG and acted as a stiffness transfer mechanism from the floorbeam to the TPG, rather than as a loading mechanism.

CONCLUSIONS

The concluding statements are made acknowledging that only two TPGs have been evaluated in a finite element model and collaborated by two field tests. For this reason, the qualitative results demonstrating the system behavior is presented and not quantitative conclusions. Also, it was not the goal to verify the value of 2.5% times the compression axial load, only the appropriate assessment of the knee brace loading condition.

The following conclusions are presented based on the TPG analyses.

- The system is not a true braced condition, it more like a system of connected frames. The top flanges of the TPGs are relatively free to rotate with no true means to restrain the out of plane distortion (e.g. struts, cross bracing).
- AREMA guidance indicates that floorbeams should be designed as pinned supported members even where the knee braces are connected. The analysis confirms this and demonstrates that the knee brace does not affect the floorbeam design.
- The floorbeam bending induced by the compressive knee brace and the bending from direct live loading could be treated concurrently for

conservatism. In this case however, it would be recommended to treat them as a combination of longitudinal and lateral forces (as indicated in 1.3.14.3) with an increase in allowable of 25%. This would still be considered conservative since the estimated knee brace induced moment on the floorbeam is on the order of one half of the direct live load bending moment.

- The resolution of the transverse force is not such that a moment of (M = 2.5% Axial x Depth of TPG) is created. The force is resolved through the knee brace frame action and imposed on the floorbeam as a point load at the connection away from the main point of load.
- The model was also checked for a continuously distributed E80 force of 8k per linear foot. In this load condition, there were relatively small tensile loads in the knee brace along the member, and relatively small compression force at bearings. The floorbeam moments are not affected by the knee brace loads, consistent with the Cooper E-80 load conditions. This would seem to indicate that when evenly loaded, the floorbeam-knee brace-TPG frame rotates inward evenly along the length of the structure.
- It may be more appropriate to think of the knee brace as a stiffness transfer mechanism as noted in Galambos and to avoid the confusion of the resolution of the 2.5% notional load.

RECOMMENDATIONS

Based on the evidence from the model, the transverse force of 2.5% times the axial load in the braced compression member is appropriate, but not be incorporated into the floorbeam design. This force should, however, be used to proportion the knee bracing.

Stated similarly, do not use the bracing force as an induced moment, rather an axial force resolved through the knee brace flange (stiffened free edge). Conservatively, a 2.5% axial load that represents the triangular distribution of the 2.5% lateral load can be placed as an additional axial force on the floorbeam.

Don't superimpose a knee brace moment of (M = lateral load x depth of TPG) for the floorbeam design with the bending moment induced by direct live load.

It has been recommended to AREMA Committee 15 for Steel Structures that the following commentary language be incorporated:

> *"The 2.5% proportioning force for the brace is derived from a fixed point restraint of the compression member with an assumed initial out-of-straightness. The intent of the article is to establish the proper restraining force imparted on the bracing members that restrain against out-of-plane displacement. For through plate girders (TPG), the proportioning force is not intended as an additional design load to be imparted on the structure, it is only a value used to ensure that the floorbeam-knee brace-TPG system acts as a frame."*

FURTHER STUDY

During the investigation, it was noted that the peak stresses in the knee brace are more concentrated toward the outstanding portion of the brace. This location is also the most prevalent location of broken welds and popped rivet heads as noted by field inspections. It is recommended that further investigation could improve this detail for increased TPG service life.

Additionally, this project was limited to tangent bridges without skew. The effects of curved track and skew should also be investigated.

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