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Staggered Bracing Layout in Skewed Steel Bridges

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Abstract

Cross frame braces are essential to the stability of steel girder bridge systems during construction. In straight bridges, the primary role of the cross frames is to stabilize the girders during construction and in the finished bridge the braces help to resist lateral loads from sources such as wind. In bridges with skewed supports, the cross frames may develop large forces from truck loads that can lead to fatigue concerns. The braces are often located along a continuous line across the width of the bridge. The continuous line of cross frames in skewed bridges often intensify the magnitudes of the live load induced forces due to differential displacements between the girders. This paper documents the results of an ongoing study on the impact of the geometrical layout of the braces. The behavior of skewed bridges with cross frames distributed along a continuous line and also staggered parallel to the skew angle were considered. The results demonstrated that staggering the cross frames can result in smaller live load induced forces in cross frame members while still maintaining stability of the girders.

1. Introduction

Cross frames serve as torsional braces since they stabilize the girders by restraining twist of adjacent girder lines. The critical stage for girder stability is generally during the concrete deck placement, since the wet concrete provides no restraint to the girders. Once cured, the concrete deck provides continuous lateral and torsional restraint to the girders. In the finished bridge, the cross frames help resist lateral loads from sources such as wind load.

In most straight girder applications, prescriptive sizes are used for the cross frames instead of designing the braces for a specific strength or stiffness requirement. The American Association of State Highways and Transportation Officials (AASHTO) design guidelines (2010) specify that the cross frame spacing should be based upon a rational analysis. Many states and jurisdictions use rules based on previous experience to set the size and spacing of intermediate cross frames. Effective stability bracing must satisfy both stiffness and strength criteria that are a function of several factors.

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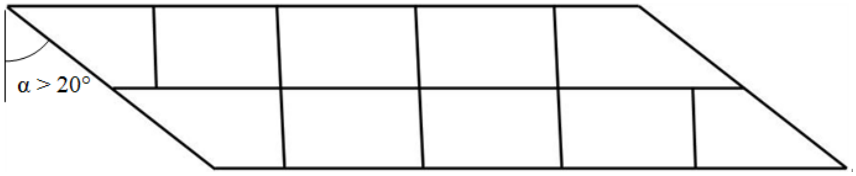
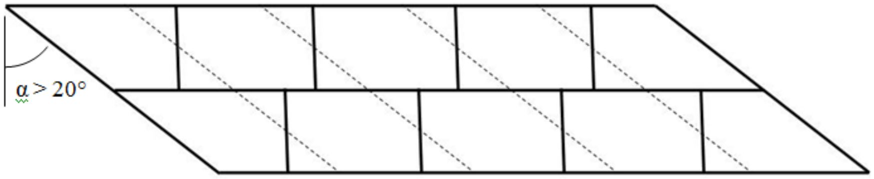
The design and detailing requirements for cross frames are further complicated in bridges with skewed supports where the geometry of the bridge can complicate both the layout and the behavior of the braces. Support skew refers to the angle of the line of supports relative to the longitudinal direction of the bridge. Normal supports intersect the longitudinal axis of the bridge at a 90 degree angle. Figure 1a shows the plan view of a girder system with the skew angle indicated as α. For skew angles less than 20 degrees the AASHTO LRFD Bridge Design Specifications (2010) allows the braces to be oriented parallel to the skew angle, while for support skews larger than 20 degrees the braces must be oriented perpendicular to the longitudinal axis. Most bridges make use of a continuous line of cross frames as shown in Figure 1 (a); however for larger skew angles, this bracing layout may result in relatively large live load forces in the braces since the cross frame line frames into the girders at significantly different longitudinal positions. Therefore, the ends of the cross frame lines go through substantially different vertical displacements, which can lead to large live load forces. In some instances, the staggered layout depicted in Figure 1 (b) has been used in an effort to minimize the forces induced from truck loads.



(a) Continuous Intermediate Cross Frame Layout



(b) Staggered Intermediate Cross Frame Layout

Figure 1: Skewed Bridge Cross Frame Layout Patterns

This paper outlines the results of an investigation on the behavior of cross frame systems in bridges with skewed supports. The study is sponsored by the Texas Department of Transportation (TxDOT) and was conducted at the Ferguson Structural Engineering Laboratory in the University of Texas at Austin. The study included both experimental testing and finite element analyses. The goals of investigation are to streamline the design and detailing of cross frames in current bridge practice. As part of the study, comparisons of the behavior of the continuous and staggered cross frame layouts were made to understand the impact on the effectiveness of the bracing and the behavior in the finished bridge.

2. Laboratory Buckling Tests

Laboratory buckling tests were performed on a three-girder system with skewed supports. The girders consisted of W30x90 hot rolled beams. The supports had an end skew of 53-degrees. The end cross frames were fabricated with 2.5" square tubular sections and were connected to the girders by bent plates. Tests were also conducted using a circular pipe stiffener that allowed direct connection of the skewed end cross frames (Quadrato 2010). Tests were conducted with both continuous and staggered intermediate cross frames as shown in Figure 2. The loads were applied through gravity load simulators (GLS) to minimize lateral restraint at the load points. The loads were distributed to the test girders through a knife edge connected to load beams that were attached to the GLS. Two different loading conditions were used: fully loaded (Figure 2(a) and (b)) and partially loaded (Figure 2(c) and (d)). For the fully loaded condition, the two gravity load simulators were positioned so that 2/3 of the GLS load went to the outside and 1/3 went to the interior girder. Therefore the total load on each girder was 2/3 of the load applied by one of the GLS. For the partially loaded condition, only one load beam was set up for loading with 2/3 of the GLS load applied to one of the outside girders and 1/3 to the interior girder. The partially loaded girder test was conducted to obtain a measure of the load that gets transferred through the cross frame.

The test girders were instrumented to allow monitoring the twists and the lateral deflections of the girders as well as the axial forces induced in cross frame members. Since the maximum unbraced length of the girders in this setup was shorter that required for elastic buckling, the girders were not loaded up to the buckling load to keep the material within the elastic range. The data did provide a measure of the force distribution for the two different cross frame configurations.

Figure 3 presents the member axial forces in the East intermediate cross frame under both loading conditions. The East cross frame was the brace that connected to the unloaded girder in the case with the partial loading. It can be seen that the axial forces in the staggered cross frame members is approximately one-tenth of that in the continuous cross frames.

It can be concluded from the test results that staggering the intermediate cross frame can lower the induced cross frame forces for the specimen frame; however the tests were only conducted with a single cross frame at midspan. To obtain a better understanding of the behavior in typical bridge systems, computational investigations were conducted on systems with multiple intermediate bracing lines.

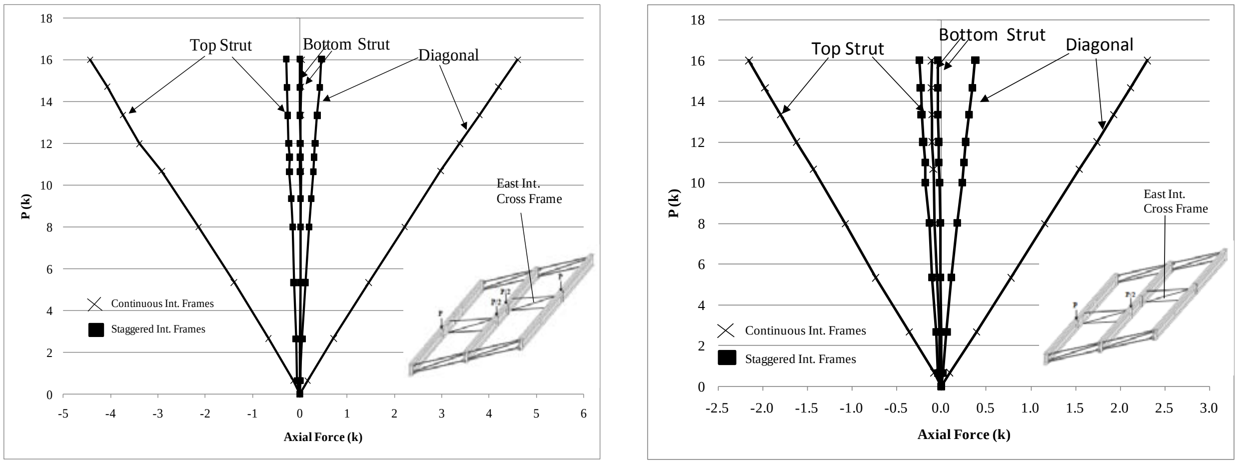
(a) Full load on continuous cross frames

(b) Full load on staggered cross frames

(c) Partial load on continuous cross frames

(d) Partial load on staggered cross frames

Figure 2: Large Scale Tests on Bracing Layout Study



(a) Fully Loaded (b) Partially Loaded

Figure 3: Axial Forces in Intermediate Cross Frames

3. Finite Element Modeling

A finite element model was created to simulate bridge girder systems so that several parameters could be studies such as: girder size, skew angle, and various bracing configurations. The detail modeling techniques and validation process are discussed by Quadrato (2010). The finite element model was modified to include the concrete slab to simulate the composite girder section. The following subsections provide an overview of the FEA model.

3.1 Girder Frame Model

The element used to model the steel girders was the 8-node shell element (ANSYS SHELL93). This element has been successfully used in previous girder buckling research to model the flat plates that make up most girders (Helwig, 1994) (Wang, 2002) (Whisenhunt, 2004).

Shell elements were also used to model end cross frames, connection plates and stiffeners. The intermediate cross frames were modeled using truss elements (ANSYS LINK8). This technique has been used successfully in previous research and has been found to be computationally efficient to accurately match analytical results (Yura, Helwig, Reagan, & Zhou, 2008), (Wang & Helwig, 2008).

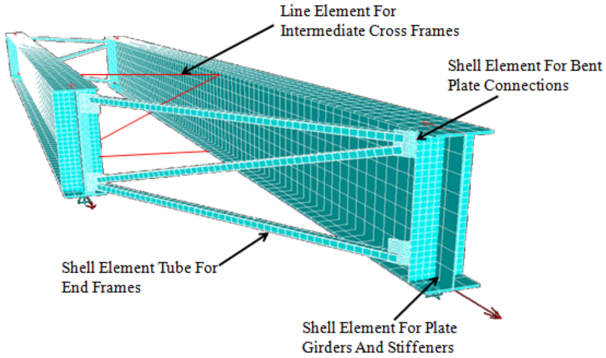


Figure 4: Girder Frame Model

4.2 Concrete Slab Model

A few different methods have been used in previous investigations to model the composite section consisting of the steel girders and concrete deck. The most accurate approach is to use brick elements to model the slab; however this method will lead to a very large number of degrees of freedom. Fan (1999) used a combination of 20-node brick elements and shell elements in modeling the concrete slab. The brick elements were located over the top flange of the steel girder. Shell elements connected to the brick elements at the centroid of bridge deck. Another method that has been employed is to utilize shell elements to represent the concrete slab with rigid link elements used to connect the slab elements to the girder elements. (Brockenbrough, 1987). This method, as illustrated in Figure 5, was employed in this study. Note that the mid-side nodes of Shell 93 element are not shown in the picture for clarity. For both element types, each node has six degrees of freedom. The slab shell element is positioned at mid-thickness of concrete slab and the thickness of the slab is an input of the shell element. This shell element slab model does not include representation of the steel reinforcement, concrete cracking or any plastic behavior. For the service level load considered in this study, this modeling approach adequately simulates the composite section stiffness. A validation example is included in the following section.

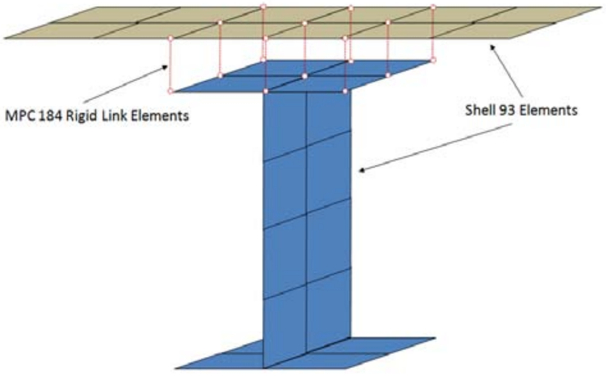


Figure 5: Girder and Concrete Slab Model

4.3 Validation Example

To evaluate the accuracy of the modeling approach used for the composite girder section, an analysis was conducted for a simply supported bridge that spans 120 feet. The superstructure is composed of two plate girders and an 8-in-thick concrete slab. The cross-section of the composite girder is shown in Figure 6. Each girder is subject to a 10 kip vertical point load at mid-span. The calculated moment of inertia of the transformed composite section is 107,049 in^4 and the theoretical mid-span deflection is 0.200 in. The bridge model by ANSYS is shown in Figure 7(a). Static analysis was performed on the model to get the vertical deflection of the bridge. Figure 7(b) shows the vertical (UY) deflection contour from the ANSYS model.

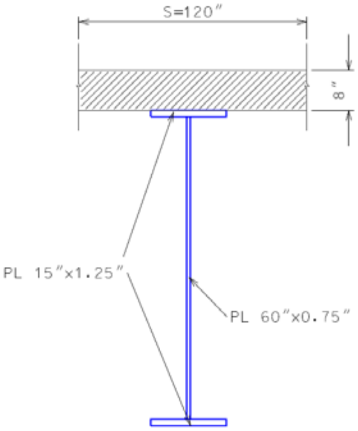
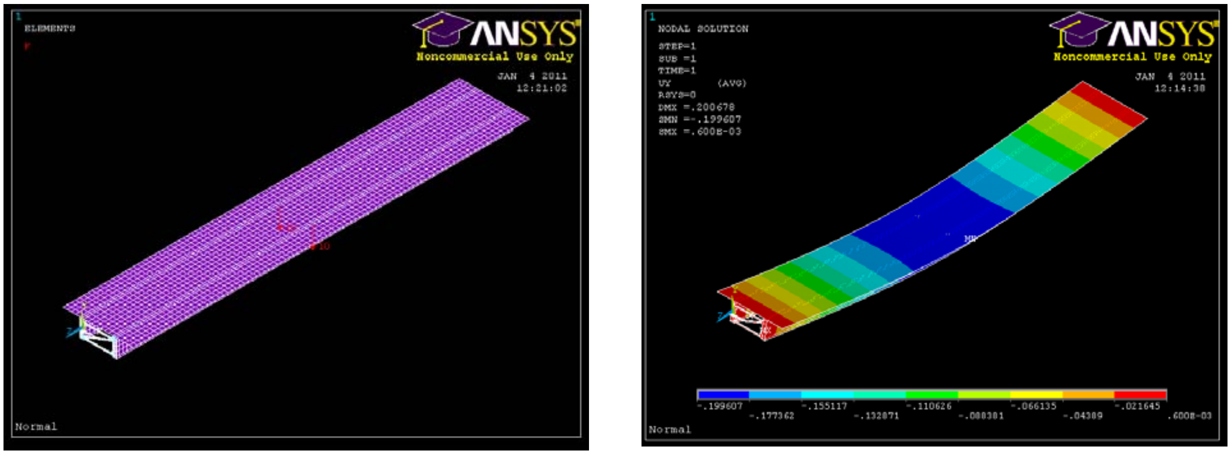


Figure 6: Cross Section of Composite Girder



```
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UY        (AVG)
RSYS=0
DMX =.200678
SMN =-.199607
SMX =.600E-03
```

(a) Bridge Model (b) UY Deflection Contour

Figure 7: Bridge Validation Model

The ANSYS model predicted a midspan deflection of 0.200-inches, which is in agreement with the theoretical result. This simple comparison indicates that the modeling approach used in ANSYS provides an accurate representation of the bending stiffness of a fully composite girder.

4. Stability of Girders During Construction

The effect of various cross frame layouts on the stability of girders during construction was examined through a series of finite element analyses. An example bridge was investigated by using the previously validated FEA girder frame model. The plan of this bridge is presented in Figure 8. Supports of the one span bridge are skewed at a 56.3° angle. The superstructure is composed of four plate girders at a 10 feet spacing and with an 8-in-thick concrete slab. The same cross section dimensions as in Figure 6 was used in this skewed bridge model. The construction load has been taken as 0.2kips/in on each girder, and includes the self-weight of the steel girder and the concrete slab and other construction loads.

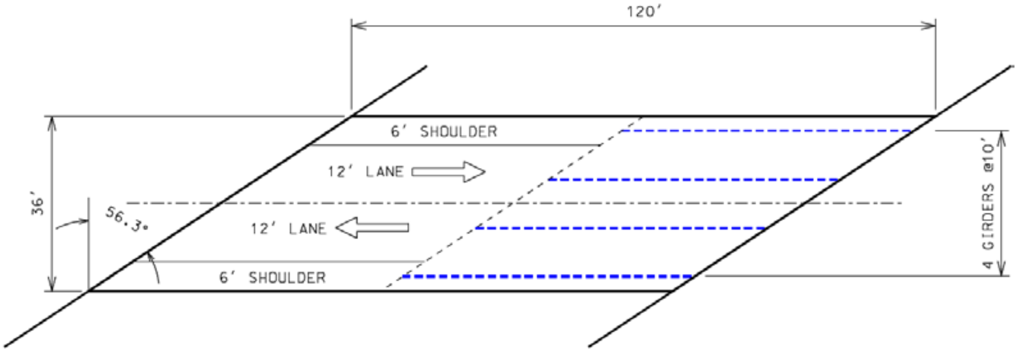
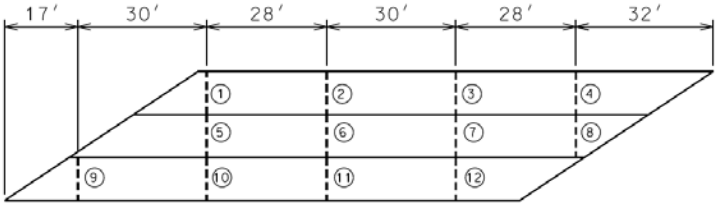
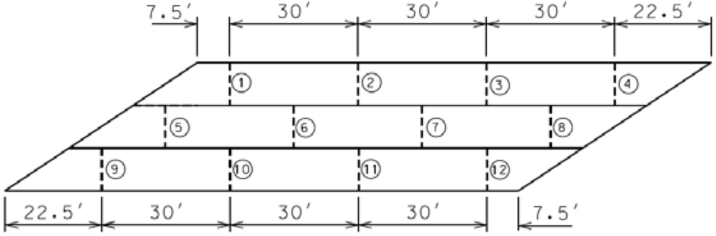


Figure 8: Skewed Bridge Plan

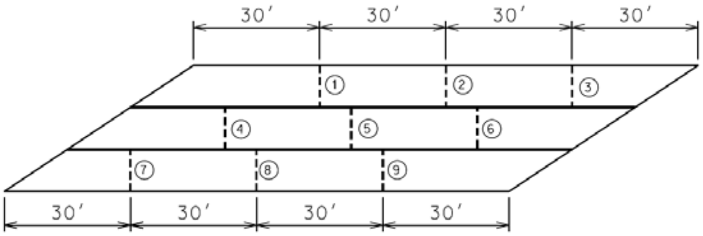
Three cross frame layouts considered in this study are shown in Figure 9. A maximum 30-foot unbraced length was used for all three layouts such that the non-composite girders will be stable under the construction load. For the continuous layout, the cross frames near the supports were offset 2 feet to help reduce brace forces resulting from differential girder displacement. The staggered layout 1 has the same number of cross frames as the continuous layout while staggered layout 2 has one less cross frame per bay to provide the 30 feet unbraced length.



(a) Continuous Cross Frame Layout



(b) Staggered Cross Frame Layout 1



(c) Staggered Cross Frame Layout 2
Figure 9: Skewed Bridge Plan

According to the AISC Specification (2005), the required stiffness of stability bracing is twice the ideal stiffness to keep the stability induced brace forces low. The ideal stiffness of the bracing is the minimum stiffness that will allow the girder to buckle between the bracing points. However, there are two challenges in obtaining the ideal stiffness of cross frames for skewed bridges and for staggered cross frames:

(1) When the bridge is skewed, the cross frames near the support areas work as a combination of a lateral brace and a torsional brace.
(2) If the bracing layout is staggered, it is difficult to differentiate whether the girder buckles between bracing points or if it buckles over the bracing points.

To address these difficulties, a non-skewed bridge with similar geometry was first analyzed to find the ideal stiffness of the cross frames. The resulting ideal stiffness was then used to examine the impact of the skew condition and the bracing layouts. The layout of the non-skewed bridge is shown in Figure 10.

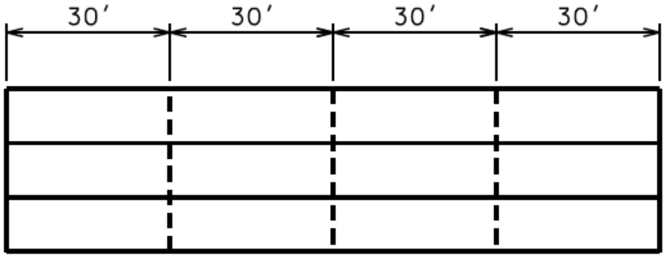


Figure 10: Non-skewed Bridge Plan

Eigenvalue analyses were performed on the non-skewed girder frame model with various cross frame member sizes. Many cross frames make use of angle sections for the diagonals and struts. The distribution of the forces on the cross frames usually result in one diagonal subjected to tension and the other to compression. Because angle sections often have relatively low buckling strength, many cross frames are conservatively designed as tension-only systems so that a single diagonal in tension is designed to possess adequate stiffness and strength to stabilize the girders (Figure 11). For this study, the cross frame was modeled as a tension only system for which the torsional stiffness is given by Equation (1) (Yura et al 1992).

$$\beta_{braxial} = \frac{E h_b^2 S^2}{\frac{2L_C^3}{A_c} + \frac{S^3}{A_h}} \qquad (1)$$

where:

A_h=area of horizontal members
A_c=area of diagonal members
E=modulus of elasticity
L_c=Length of diagonal members
S=spacing of girders
h_b=height of the cross frame

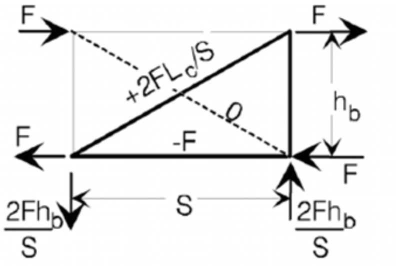
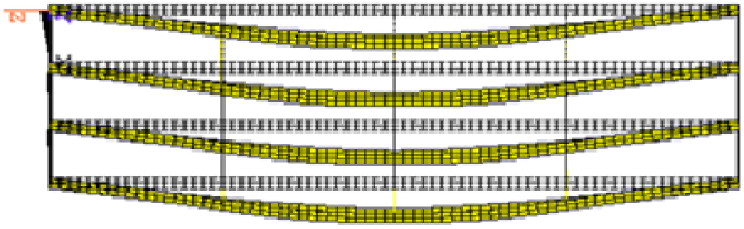
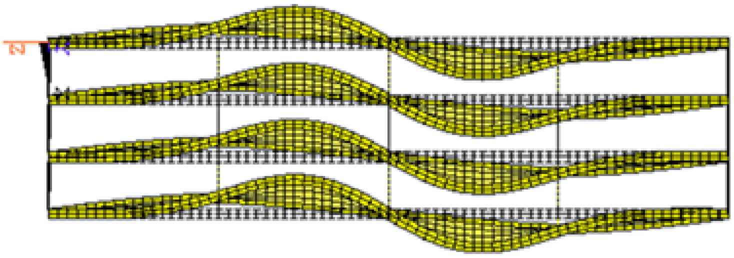


Figure 11: Tension-only cross frame

Error! Reference source not found. Two different modes of buckling occurred in the analysis, and the minimum stiffness (around 100,000 k-in/rad) of the cross frames that resulted in the buckling shape as shown in Figure 12 (b) was taken as the ideal stiffness.



(a) Girders Buckle Over the Bracing Points



(b) Girders Buckle Between Bracing Points

Figure 12: Buckled Shapes of Girders with Various Cross Frame Torsional Stiffness

The same ideal stiffness determined for the non-skewed bridge then was used to for the skewed bridge. The same analysis was performed for the three layout patterns. The resulting buckling capacities with the corresponding bracing stiffness are plotted in Figure 13. The brace stiffness at the change in buckling modes is largely independent of the layout of the cross frames.

Also it can be seen that at a brace stiffness of $2\beta_i$ (200,000 k-in/rad), the buckling capacity of the continuous and staggered layout 1 (0.25 kip/in) is slightly higher than that of the staggered layout 2 and the non-skewed case (0.23 kip/in). The reasons for this could be the additional lateral stiffness provided by the cross frames near the supports and also the additional restraint the shorter girder sections to the longer sections in the continuous or staggered 1 layouts.

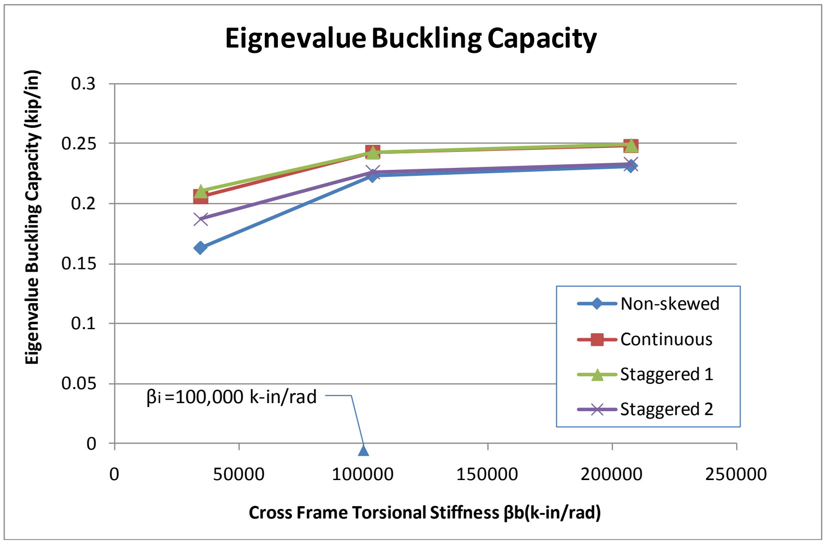


Figure 13: Eigenvalue Buckling Capacity

Overall this study indicates that using a staggered layout of cross frames instead of continuous cross frames does not significantly affect girder stability. This study also showed that even though one less brace line was used in staggered layout 2, the lateral torsional buckling capacity of the girders did not decrease substantially. This allows the possibility of using a smaller number of cross frames when the staggered layout is considered.

5. Live Load Induced Cross Frame Forces

Live load induced forces in cross frames can be significant in skewed bridges, and can result in fatigue problems. Using a staggered layout may help reduce these forces. The FEA bridge model that includes the composite concrete deck was used to investigate the live load induced force in cross frame members for different cross frame layouts. Elastic analyses were performed on the bridge model under truck loading. The truck load consisted of an HS20-44 truck live load as shown in Figure 14. The spacing of two back axles was conservatively taken as 14 feet. Multiple analyses were performed with various truck locations along the traffic lane. The forces in the cross frame members were extracted after the analysis. Due to the high stiffness of the concrete slab, forces in the top struts of the cross frames were generally small. However, large forces were observed in the bottom struts and in the diagonal members.

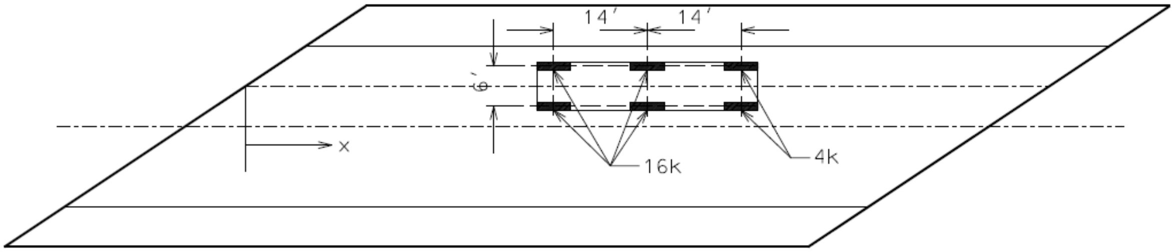


Figure 14: HS20-44 Truck Load

Since the cross frame members are usually in the same size, the member with the highest force will also be the member with the highest stress, and therefore the member with the highest potential for fatigue problems. Member forces were therefore used to compare the different cross frame layouts. The highest live load induced forces and the loading condition with respect to various brace layouts are summarized in Table 1.

Table 1 Highest Induced Force

Layouts	Member Where The Highest Force Occurs	Location of The Truck, x (in)	Induced Axial Force (kips)
Continuous	Bottom Strut of #6	46.5	4.2
Staggered 1	Bottom Strut of #7	46.5	1.5
Staggered 2	Diagonal of #1	46.5	2.0

To better understand cross frame response due to the moving truck, examples of the changes in cross frame member force with respect to the truck location are shown in Figure 15. The cross frame members at similar locations from different layouts were grouped in the plots to show the comparison. The analysis results clearly show that the live load induced forces are significantly smaller for the staggered layout in comparison with continuous cross frames.

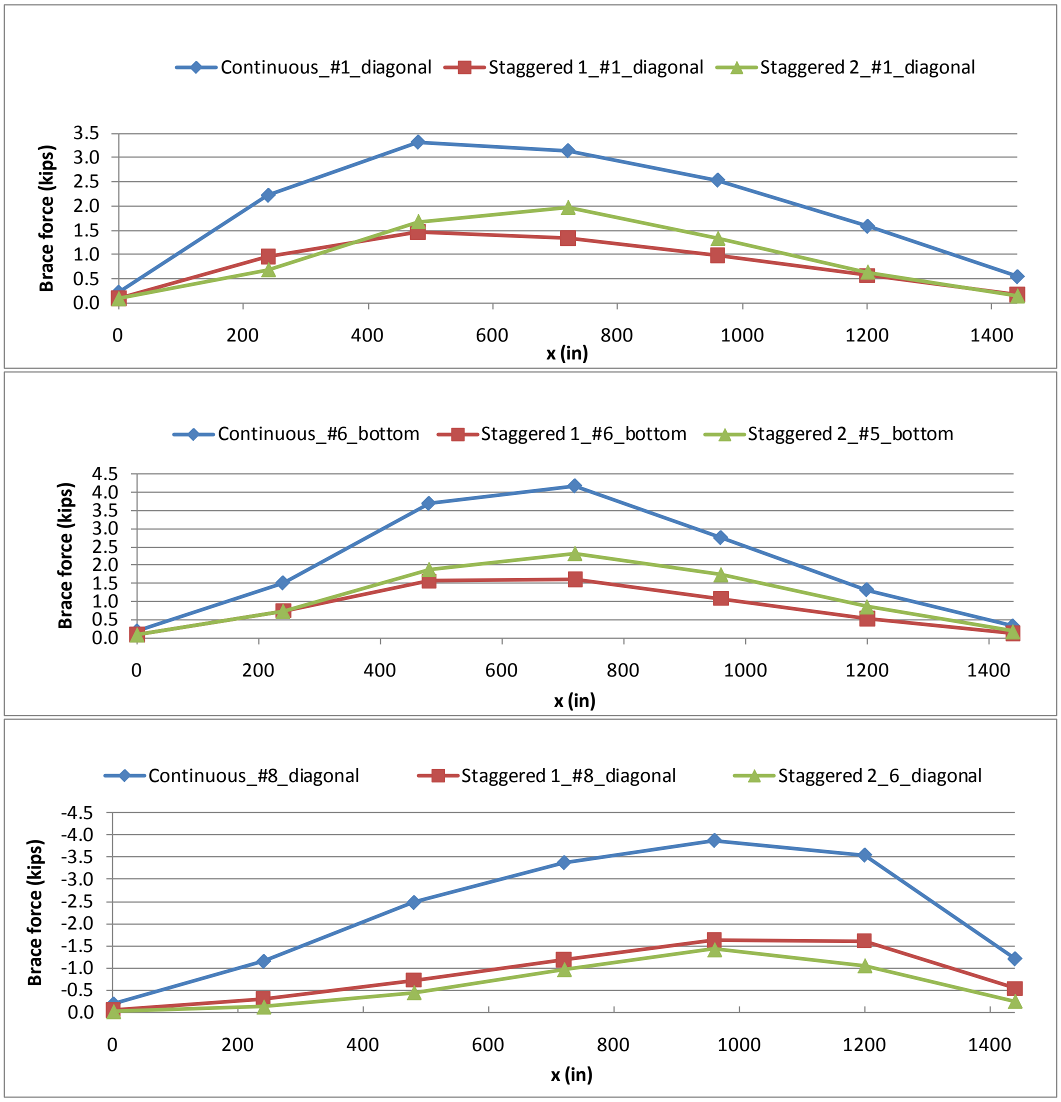


Figure 15: Member Forces VS. Truck Locations

6. Conclusions

Overall, the results from the laboratory tests and the finite element analyses have shown that the use of a staggered layout of cross frames instead of a continuous layout can offer advantages in skewed bridges. Using the staggered layout significantly reduces the live load induced forces in the cross-frame members, which can be advantageous in reducing the risk of fatigue problems. The use of a staggered pattern may also allow a reduction in the total number of cross frames, with consequent cost savings. At the same time, the research showed that essentially the same girder buckling capacities can be achieved with a staggered cross frame layout as with a continuous cross frame layout.

The use of a staggered cross frame layout may offer significant structural performance advantages for skewed bridges. However, discussions with a bridge fabricator suggest that staggered cross frames may introduce some difficulties in fabrication and erection. The writers are continuing research of the use of staggered cross frames in skewed bridges, including evaluation of fabrication and erection concerns.

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