



## **Brace Stiffness and Forces of X-Type, K-Type, and Z-Type Cross Frames in Steel I-Girder Bridge Systems**

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### **Abstract**

The stability of steel bridges is improved by using cross frames, which provide lateral and torsional restraint along the girder length. In order to be considered an effective brace, the cross frame must satisfy both strength and stiffness requirements. Cross frames can utilize a variety of layouts: the X-Type and K-Type cross frames are commonly used in current practice for steel I-girder bridges, while the single diagonal Z-Type cross frame is being researched at the University of Texas at Austin as part of a TxDOT sponsored research project.

Cross frame members are often designed following slenderness limits for tension and compression members given in the AASHTO Bridge Design Specification. Depending on the complexity of the steel bridge design, basic computer software may also be used to determine the member forces. While sizing cross frame members using these methods may result in a conservative design, slenderness limits may not be a good indication of the forces.

In order to further examine the forces in the cross frame members, as well as provide insight into the stiffness of the brace, results from two different experimental setups will be provided. The first setup investigates the stiffness of each cross frame type subjected to applied equal and opposite moments, representing the forces induced when the girders begin to buckle. The second setup looks at forces in the cross frame caused by the application of a live point load, such as when a heavy truck passes the brace location.

### **1. Introduction**

Cross frames are critical to the stability of straight and curved steel bridges. First and foremost, cross frames provide lateral stability to the bridge, especially during construction when the weight of the concrete deck and other construction loads are acting on the non-composite steel girder section. In addition, cross frames help strengthen the completed bridge structure by transferring applied loads to adjacent girders. These loads can be the result of lateral wind or

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earthquake forces, live loads from traffic, or as in the case for curved bridges, the cross frames resist the twist of the superstructure under dead load. In all cases, in order to provide an effective brace, the cross frame must satisfy both strength and stiffness requirements (Winter 1958).

Steel bridge cross frames come in a variety of layouts. For plate girder applications, the two main arrangements are the X-Type and K-Type cross frames comprised of single angle members (TxDOT 2006). Research conducted as part of this project has also verified the potential of using a single diagonal member cross frame, or Z-Type, provided the diagonal has sufficient compression capacity (Battistini et al 2011, Battistini et al 2012, Wang et al 2012). The different layouts, referred to hereafter as X frames, K frames, and Z frames, can be seen in Figure 1.

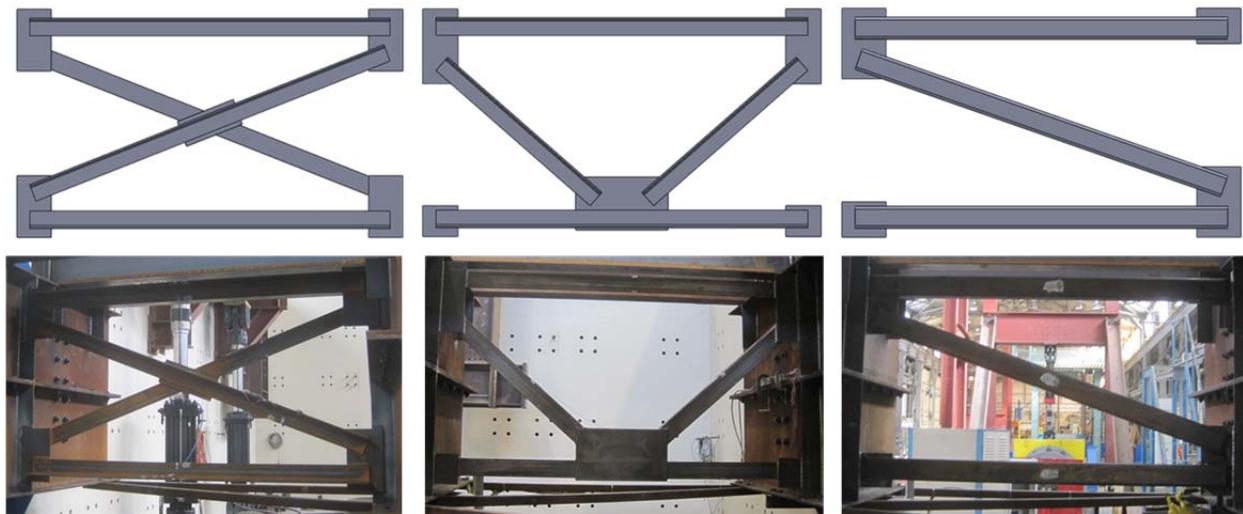


Figure 1: (a) X-Type Cross Frame, (b) K-Type Cross Frame, and (c) Z-Type Tube Cross Frame

In previous versions of the AASHTO LRFD Bridge Design Specification, cross frame spacing was restricted to a maximum of 25 ft. However, the current version of the AASHTO Specification allows a “rational analysis” to be performed to determine the cross frame spacing, permitting longer distances between braces (AASHTO 2012). A major advantage of this clause is the potential cost savings obtained from reducing the number of cross frame lines in the completed bridge. But as analysis techniques become more advanced, and bridges become more slender and efficient, it is imperative to fully understand the behavior of the cross frame systems used and to verify the braces are providing the restraint necessary to provide safe structures.

The stiffness of the different cross frame layouts was investigated under two loading conditions: (i) equal and opposite moments, achieved by applying a force couple to both sides of the brace and (ii) a point load, achieved by applying a vertical load to one side of the frame and holding the other side essentially rigid. Forces, rotations, and displacements were measured to quantify the stiffness of the systems.

Additionally, the project has been determining the fatigue behavior of the various layouts as cross frame members are frequently initiation sites for cracking. As the cracks continue to grow, the stiffness of the brace is reduced. Results on the degradation of stiffness due to fatigue cracking are presented at the end.

## 2. Cross Frame Behavior

There are a multiple models available to determine the torsional stiffness of the X, K, and Z cross frames. Often, the cross frame members are modeled as truss elements, and some simplifying assumptions on the forces in the members are made to make the systems determinate. As the girder begins to buckle, a uniform moment is applied to the cross frame, which is then simplified into a force couple acting on the nodes of the truss. The resulting forces and displacements are calculated, leading to a determination of the rotation of the brace. By dividing the moment by the rotation, the torsional stiffness of the brace is obtained. Yura (2001) summarizes the different cross frame models available and the results from the displacement analyses as follows:

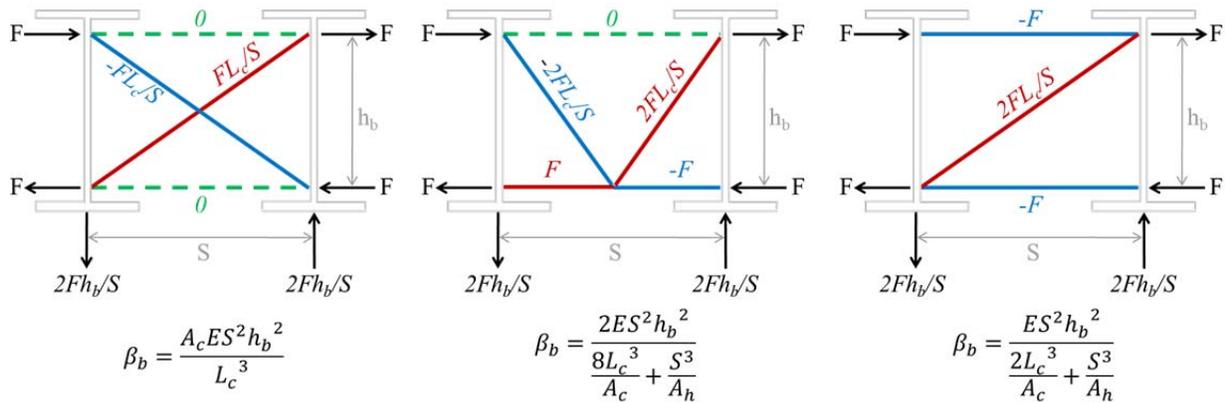


Figure 2: Torsional brace stiffness for (a) X Frame, (b) K Frame, and (c) Z Frame

where,  $F$  is the applied force,  $\beta_b$  is the torsional brace stiffness,  $A_c$  is the cross sectional area of the diagonal member,  $E$  is the modulus of elasticity,  $S$  is the girder spacing,  $h_b$  is the brace height,  $L_c$  is the length of the diagonal, and  $A_h$  is the cross sectional area of the horizontal strut.

Similarly, we could analyze the forces in the cross frame when only a vertical load is applied to the right girder, as seen in Figure 3, while keeping the left girder fixed. This loading condition might represent a heavy truck load passing the brace location. The load is shown acting in the upward direction as this was convenient for the test setup described in Section 4.

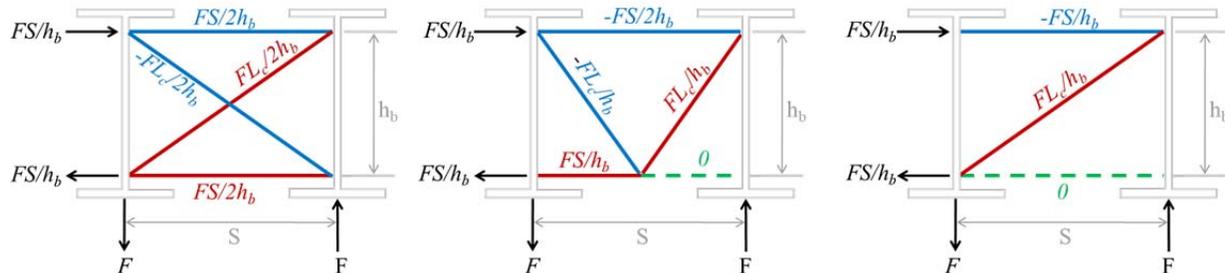


Figure 3: Forces and reactions from an applied point load (on right girder) for (a) X Frame, (b) K Frame, and (c) Z Frame

It is important to note that conventional X and K cross frames are typically fabricated using steel angle sections. The angles are connected to the gusset plates along one leg only, resulting in an eccentric connection. Due to the eccentricity of the force relative to the centroid of the angle member, a significant amount of out-of-plane bending occurs at the gusset plate and stiffener, even under tensile loading (See Figure 4). From a stability standpoint, the eccentricity reduces the stiffness of the member, meaning the truss analogy equations for torsional stiffness listed in Figure 2 may over-predict the provided stiffness. Additionally, the increased bending at the connection decreases the fatigue performance (McDonald and Frank 2009).



Figure 4: (a) Single angle member yielded in tension and (b) Out-of-plane movement of cracked gusset plate with stiffener shown

### 3. Cross Frame Stiffness Test

In order to replicate the forces induced in the cross frame at the onset of girder buckling as depicted in Figure 2, an experimental test setup was fabricated at Ferguson Structural Engineering Laboratory at The University of Texas at Austin. The setup, shown in Figure 5, used three hydraulic tension-compression actuators and three reaction struts to apply equal and opposite moments to the cross frame. Load cells were connected to each actuator and strain gages were applied to the reaction struts and the cross frame members to monitor the forces during the test. The forces in the angles were calculated using a numerical regression technique that has been successful in previous research (Helwig and Fan 2000) and was verified in this project using a universal test machine. The rotation of the cross frame was measured with linear potentiometers located at the corners and mid-height of the cross frame. In order to supply equal loads to each hydraulic actuator, a load maintainer was used. For more details on the test setup, measurement techniques, and specimen geometry see Wang et al (2012).

Each cross frame type was loaded in both directions, meaning the forces were applied in the direction shown in Figure 5 and then reversed to verify the stiffness of the cross frame was not dependent upon direction in the elastic range. The applied moment and measured rotation were plotted at various load levels and the test was repeated multiple times. Using Excel to place a

“best-fit” line through the data, the slope of the line represents the torsional stiffness of the brace, in units of kip-in/rad. A sample plot of the results for the K frame is shown in Figure 6.

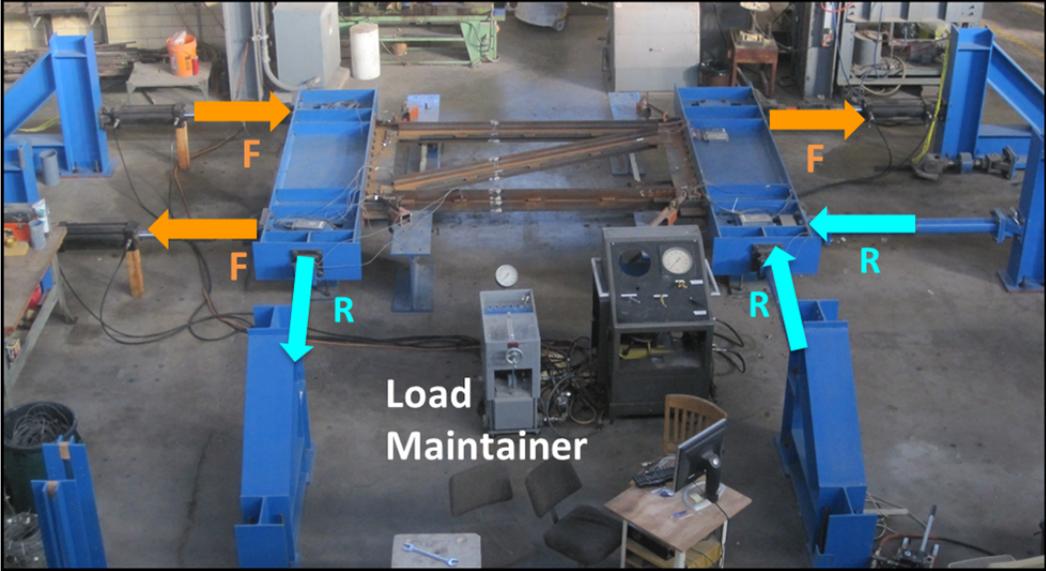


Figure 5: Cross frame stiffness test setup with Z frame

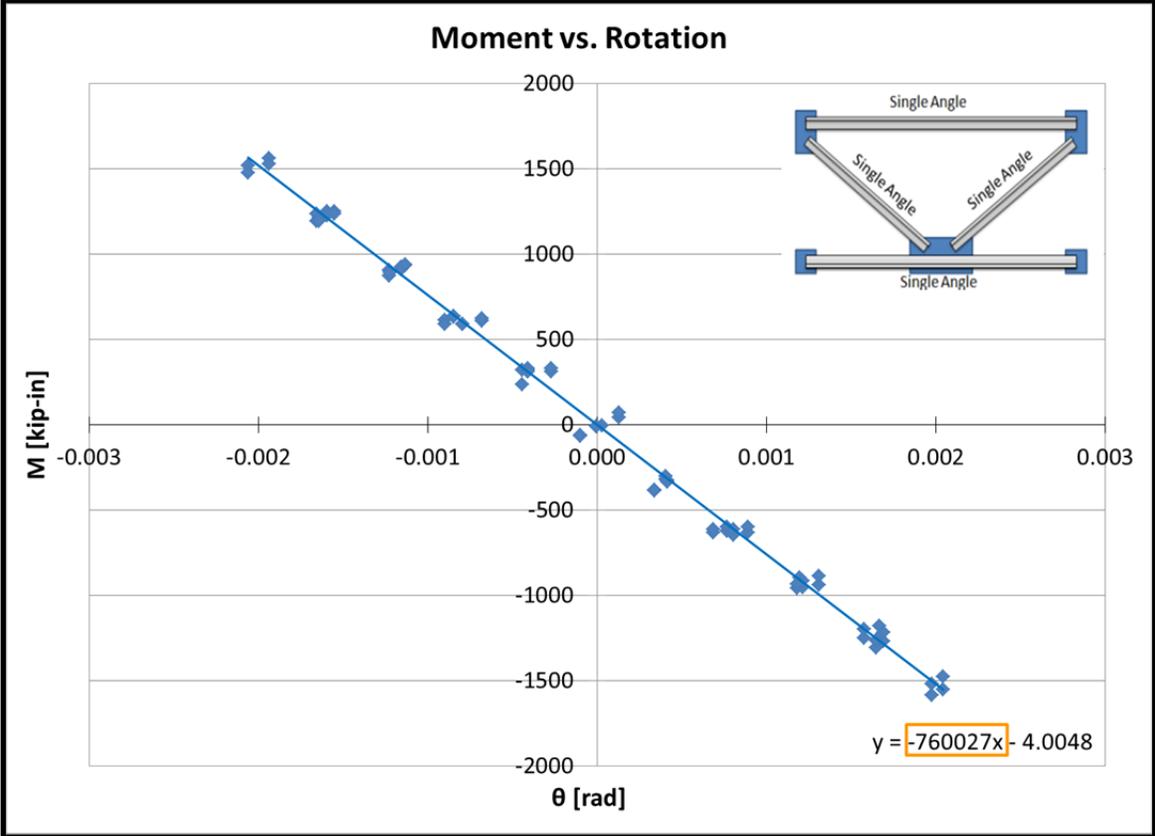
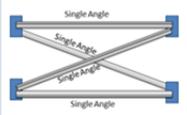
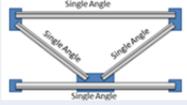
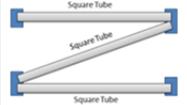


Figure 6: Determination of torsional brace stiffness for K frame

Following the outlined procedure, the torsional brace stiffness was obtained for the X frame, K frame, and Z frame tube specimens. The measured stiffness was compared to the analytical formulations derived in Figure 2, as well as a line element solution obtained using Risa 2D and a 8-noded shell element model using ANSYS finite element analysis software. In addition to the cross frame, the loading beams and reaction struts were included in both the line and shell element models, with the analysis restraining the out-of-plane displacements of the load beams. The results are summarized in Table 1.

Table 1: Torsional Cross Frame Stiffness Comparison

Type of Cross Frame	Test Results [k-in/rad]	Solution [k-in/rad]		Error [%]
Single Angle X Frame 	872,000	Analytical	1,579,000	82%
		Line Element	1,572,000	81%
		Shell Element	867,000	-1%
Single Angle K Frame 	760,000	Analytical	1,189,000	56%
		Line Element	1,180,000	55%
		Shell Element	781,000	3%
Square Tube Z Frame 	658,000	Analytical	649,000	-1%
		Line Element	647,000	-2%
		Shell Element	657,000	0%

From the results, it is evident there is a large amount of error when using the analytical formula or line element solution for the X frame and the K frame. As was previously discussed, the error is mainly due to the eccentric single angle connection. The analytical calculations and the line element solutions show good agreement because both use a truss element model approach in which only axial shortening/elongation are considered. In contrast, the shell element FEA model can accurately predict the measured stiffness of the cross frames because it allows the single angle members to bend due to the applied forces. When examining the Z frame with tubes, all the solution types seem to agree with the results from the laboratory tests. Since the tubes are connected using a knife-plate connection, the forces from the gusset plates are transmitted through the centroid of the tube, minimizing the out-of-plane bending of the cross frame members. Therefore, a truss-type model is representative of the actual behavior of the brace and will provide an accurate solution.

In addition to measuring the torsional brace stiffness, forces in the cross frame members were monitored during the tests. For the X frame, the critical members are the two diagonals, which take almost all of the applied force as shown in Figure 2 and verified by Wang et al (2012). For the K frame, the diagonals are also the members that carry the most force, one in tension and the other in compression. In the Z frame, the diagonal again is the primary load carrying member,

with the critical direction being when the diagonal is in compression. Figure 7 shows the forces in these members at different cross frame rotations for the three different layouts.

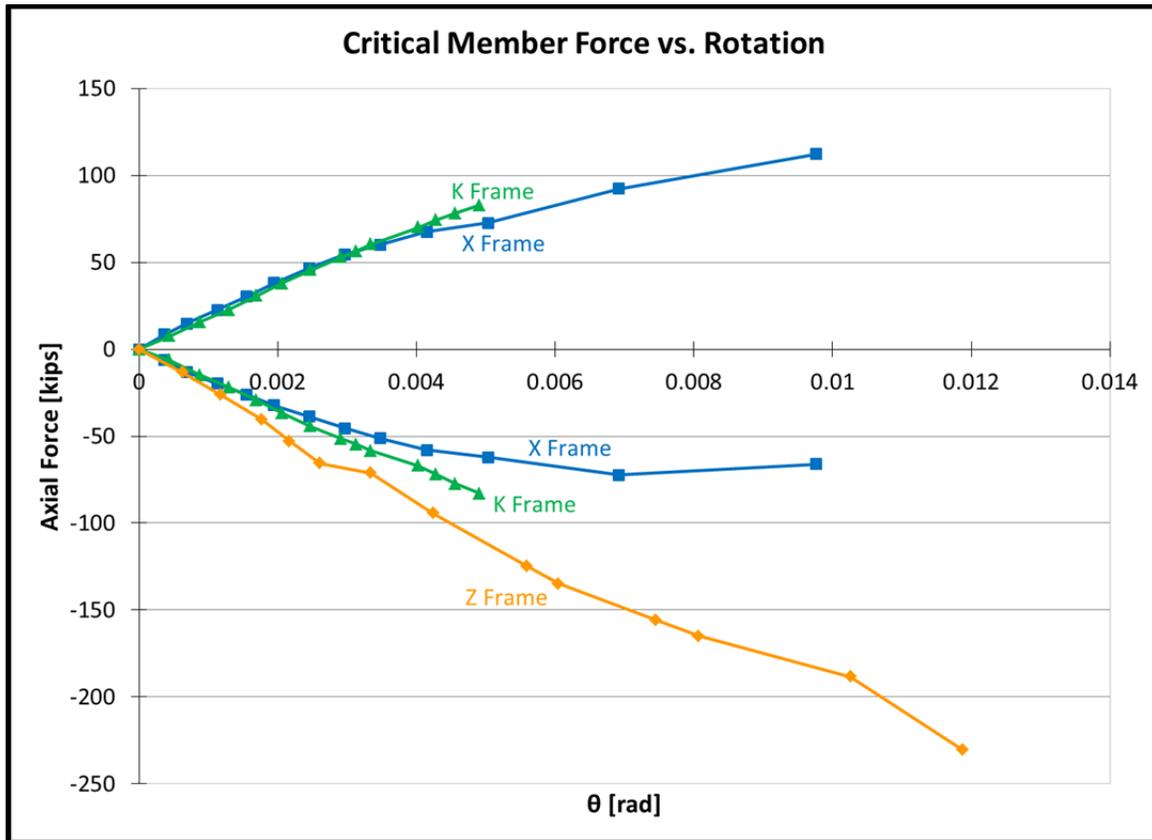


Figure 7: Comparison of forces measured in X, K, and Z frames at different brace rotations

Since the different cross frames were similarly sized for the same girder spacing and height of brace, one can directly compare the forces in the critical members at different cross frame rotations. As seen in Figure 7, the Z frame diagonal is subjected to the most force per unit rotation of the brace, which correlates with it providing the lowest torsional stiffness of the different layouts (see Table 1).

In the elastic range, the forces in the tension diagonal and compression diagonal were similar in magnitude for both the X frame and K frame tests, which makes sense when considering the symmetry of the cross frames. The critical compression force in the K frame was slightly higher than in the X frame, suggesting the X frame may provide the best option to minimize the forces in the individual members while offering the highest system stiffness. However, it must be stressed that the analytical formula and the line element solution for the X frame torsional brace stiffness provide a gross overestimate of the stiffness that is actually provided (greater than 80% error). As the research for this project is completed, design recommendations to address this unconservatism will be made.

#### 4. Cross Frame Live Load Test

When the concrete deck hardens, the deck acts as a large diaphragm attached at the top flange of the steel girders and subsequently provides a fair amount of bracing for the girders. At this point, the loading on the cross frames is no longer dominated by girder buckling (as shown in Figure 2) but rather the loads resulting from live load traffic, such as heavy trucks. To represent this scenario, a vertical point load can be applied to one side of the brace, while the other side remains at a fixed displacement (see Figure 3). While this extreme boundary condition may not hold true for all situations, as both sides of the cross frame will frequently deflect under passing traffic, it is representative for skewed bridges, where braces on adjacent girders may be located at different lengths from the supports and will therefore undergo a differential deflection (Quadrato 2010).

To examine the cross frame behavior under a live load force, a second test setup was fabricated. The primary focus of the new setup was to have the ability to run cyclic loads so the fatigue behavior of the various cross frame layouts could be examined, however stiffness and force measurements were also obtained. Figure 8 and Figure 9 show an overview and some of the details of the setup.

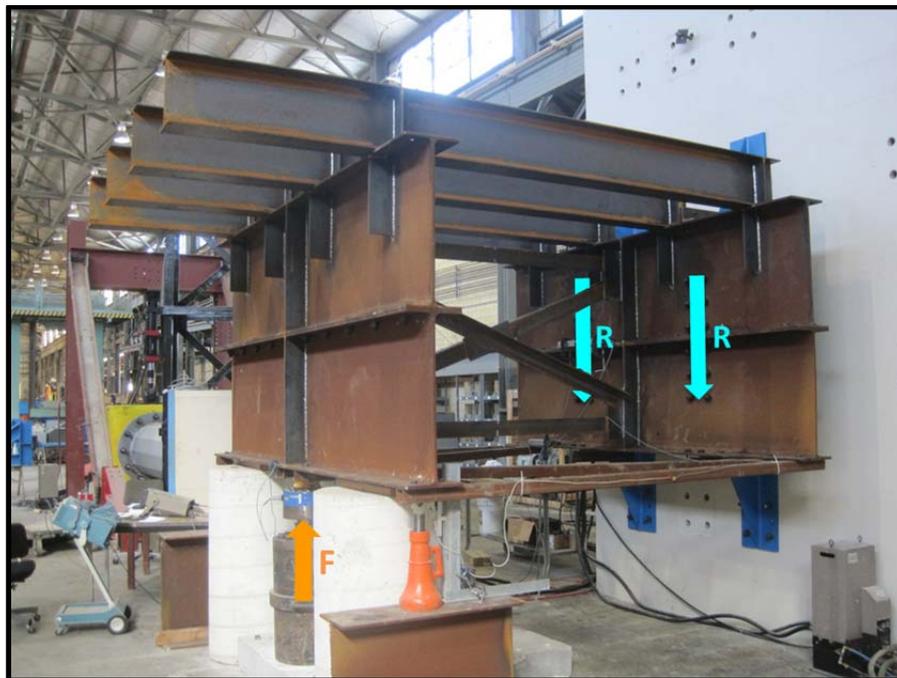


Figure 8: Cross frame live load test setup with X frame

The test setup utilizes two 10ft lengths of W30X90 rolled beams stacked on top of one another to create a pseudo plate girder by bolting the two sections together along the length of the flange. The resulting section is 59 inches deep with a web slenderness ratio of 125.5. The test girders were spaced 8 ft apart. The cross frames were designed in accordance with typical details used by the Texas Department of Transportation (2006).

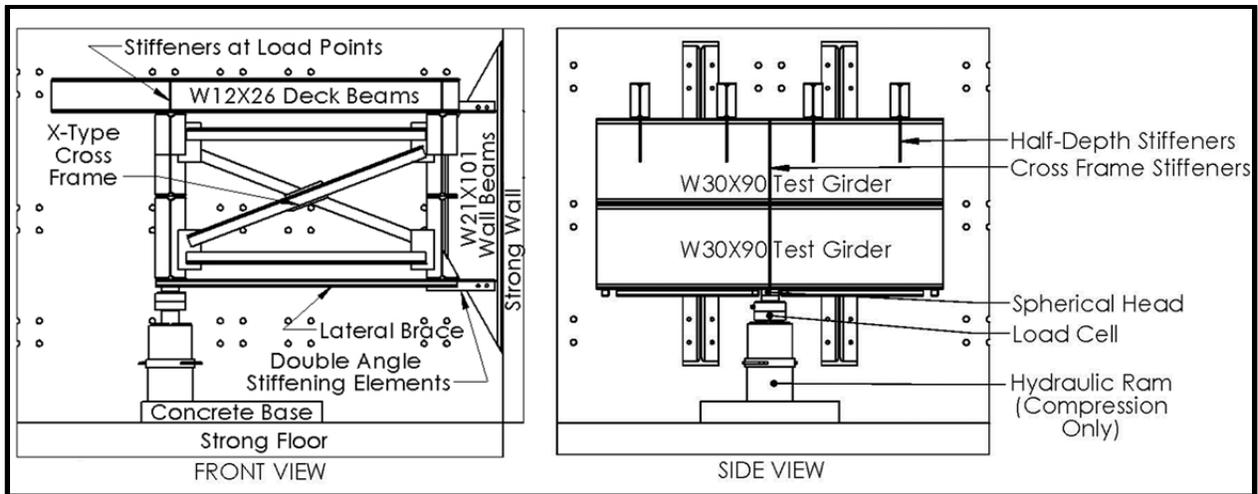


Figure 9: Cross frame live load test setup details

In order to restrict the displacement of one side of the cross frame as described in Figure 3, the web of one of the test girders is bolted to W21X101 sections that are anchored to the strong wall. Additionally, double angles are attached to the top and bottom flanges of the test girders and the wall beams to prevent the flanges from excessive rotation. The role of the lateral brace shown is to prevent the entire frame from twisting about the load point when viewing the setup from the side.

To simulate the presence of the concrete deck acting as a diaphragm, four W12X26 beams are bolted to the top of the test girders. The size of the deck beams was selected by equating the rotational stiffness of a typical 8 in concrete slab to that of multiple steel beams (specifically, the stiffness  $EI/L$  was equated where  $E$  is the modulus of elasticity,  $I$  is the moment of inertia, and  $L$  is the length of the deck/beams). In addition to representing a concrete deck, the beams help to stabilize the system under cyclic loading.

During the tests, the applied force from the ram is measured using a load cell, the deflection of the outside test girder is measured at both ends using linear potentiometers, and the cross frame member forces are monitored using strain gages. The vertical displacement at the cross frame is obtained by averaging the two readings from the potentiometers.

Similar to the previous torsional brace stiffness tests, it is useful to compare performance of the different brace layouts by measuring the displacement of the cross frame at different applied forces. The result in this case is a linear stiffness, in units of kip/in. As was done in Figure 2, an analytical formulation for the vertical stiffness of the cross frame could be calculated; however, due to the numerous complexities of the cross frame system, it would be difficult to show agreement with the measured values when considering variables like the stiffness of the deck, the flexibility of the stiffeners and gusset plates, the interaction of the lateral braces, and the weight of the testing frame. Therefore, only the measured data from the tests is presented in Figure 10, with the values shown as a change in force and change in displacement. The resulting slopes of the lines represent the stiffnesses and are shown in the figure.

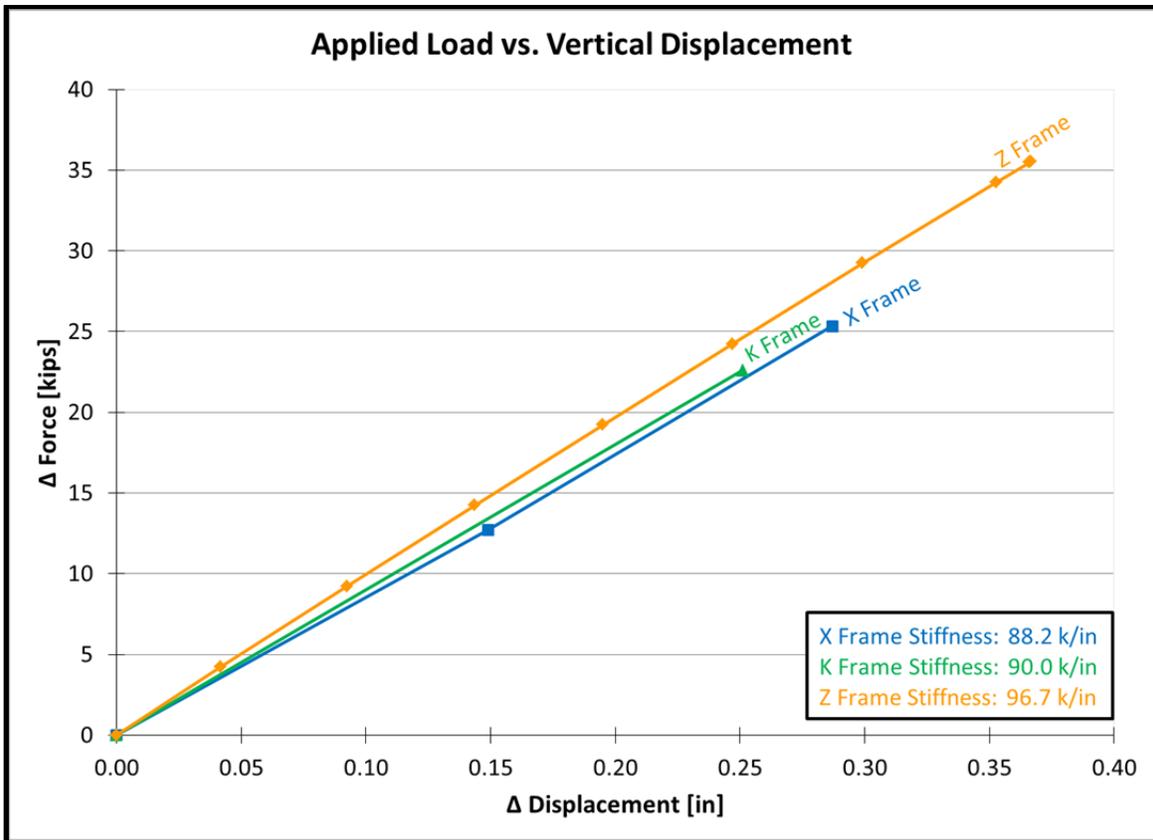


Figure 10: Comparison of stiffness of different cross frame layouts subjected to a vertical point load

Unlike the torsional stiffness test results, the X frame was seen to be the most flexible when subjected to a vertical force acting at the cross frame location. The Z frame was the stiffest system at a measured stiffness of 96.7 k/in, nearly 10% higher than the X frame and 7% higher than the K frame. In addition, the effect of the eccentrically loaded single angle was quite noticeable during the tests on the X and K frames. The researchers witnessed significant bending at the angle-gusset connections and the gusset-stiffener connections. The Z frame, which has concentric knife plate connections, had no noticeable out-of-plane movement.

As was done in the previous section, a comparison between member forces for the different brace layouts can be made since the braces are similarly sized. The forces plotted in Figure 11 are for the critical force members of each brace, namely the diagonals (compression and tension for X frame and K frame, and tension only for Z frame). The X frame, which was the most flexible brace, seems to take the least force from the applied load. The K frame takes slightly more load, especially in the compression diagonal. Both the X and K frames exhibited some symmetry in forces between the tension and compression diagonals, however as the displacements increased, the disparity between the opposing values grew.

The Z frame diagonal picks up the most force when a load is applied. This makes sense because it is the primary member resisting the applied force. In contrast, the X frame is able to split the load between the two diagonals. The K frame is also more effective because the tension diagonal is situated at a smaller angle away from the vertical, and therefore can better resist the point load.

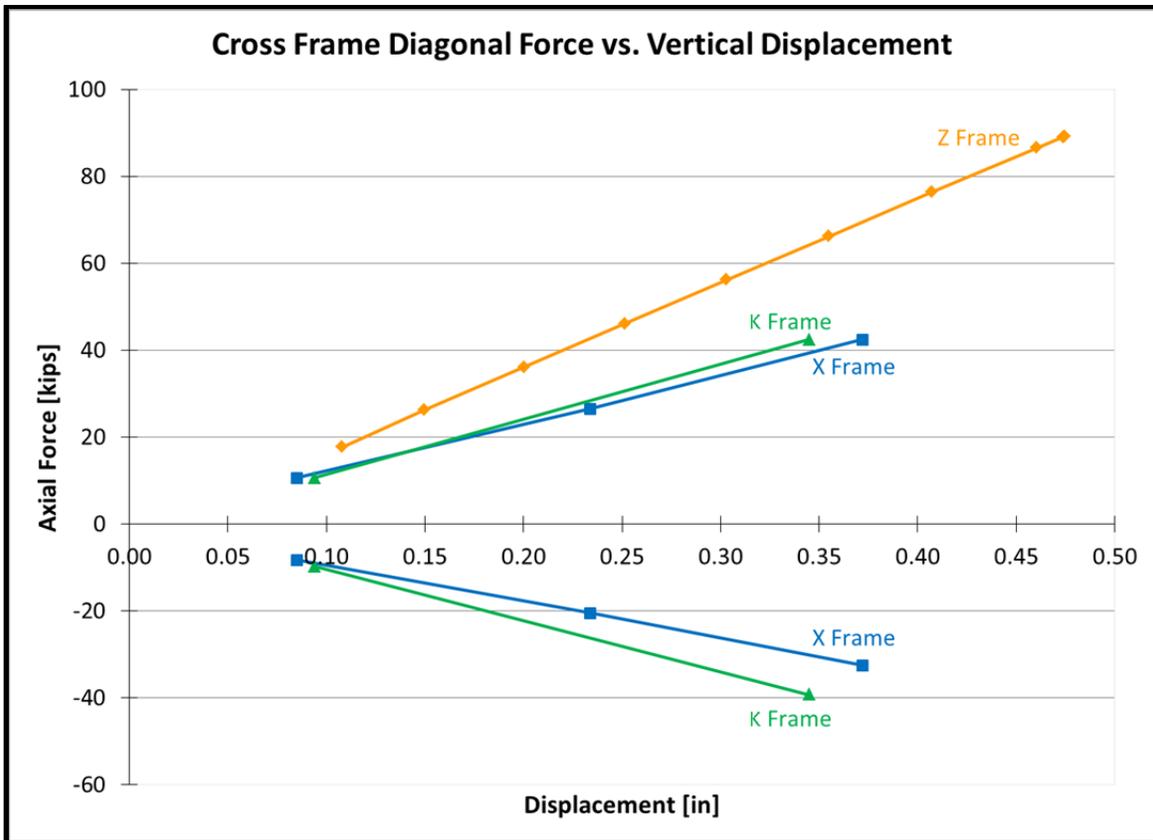


Figure 11: Comparison of forces measured in X, K, and Z frames at different brace displacements

As aforementioned, the live load test setup was primarily constructed to determine the fatigue behavior of the cross frame connections. One concern from a stability standpoint is the degradation of brace stiffness as cracking occurs in the cross frame. To quantify the change, stiffness tests were conducted as the fatigue cracks in the members and gusset plate connections became very large. Figure 12 shows examples of the fatigue cracks, Figure 13 shows graphically the loss in stiffness for each cross frame layout, and Table 2 summarizes the results.



Figure 12: Fatigue cracks at failure for (a) X frame, (b) K frame, and (c) Z frame

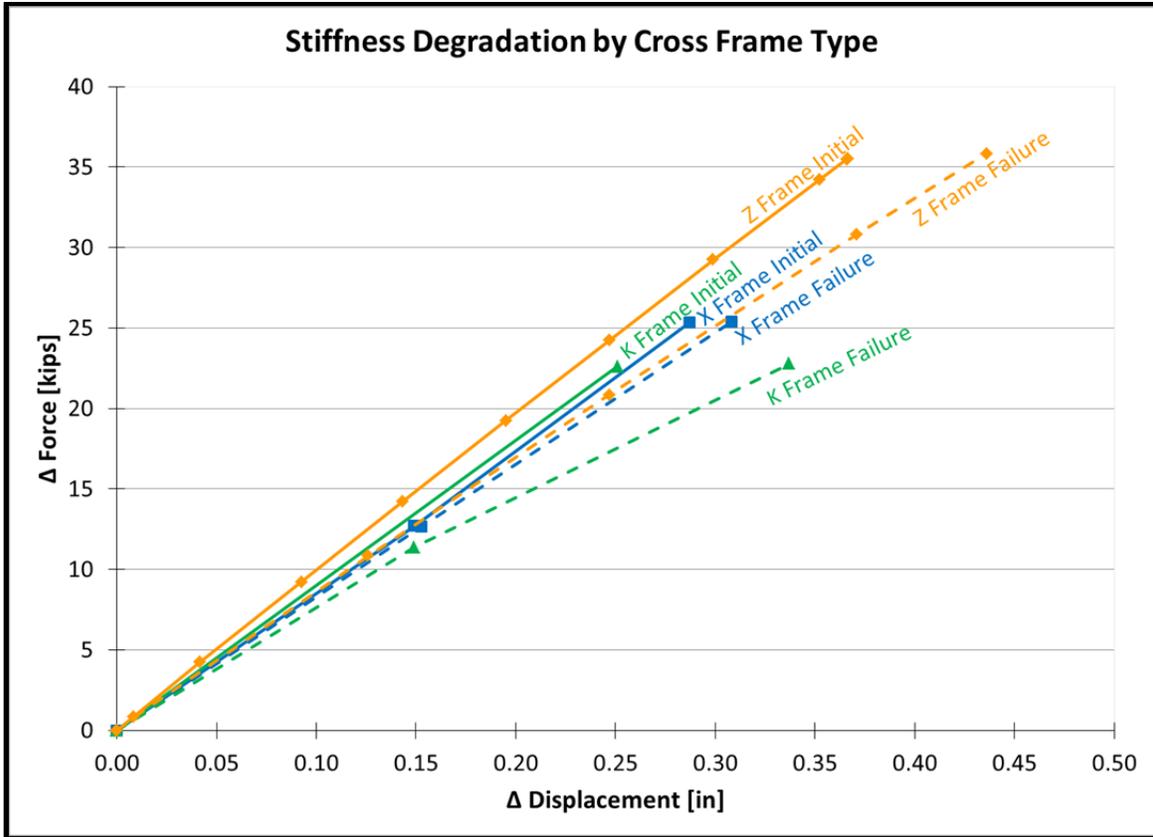


Figure 13: Degradation of vertical cross frame stiffness due to fatigue cracking in X, K, and Z frames

Table 2: Loss of Cross Frame Stiffness Due to Fatigue Cracking

Cross Frame Specimen	Initial Stiffness [k/in]	Final Stiffness [k/in]	Percent Loss [%]
X Frame 1	84.61	79.34	-6.2%
X Frame 2	88.25	82.37	-6.7%
X Frame 3	87.65	84.59	-3.5%
X Frame 4	88.75	79.21	-10.7% <sup>1</sup>
K Frame 1	90.04	67.30	-25.3%
Z Frame 1	96.65	82.35	-14.8%

1- Due to reusing the test frame, the stiffeners had developed cracks after multiple tests. The cracks were first noticed when testing X Frame 4 and grew large enough that the stiffeners were replaced after the specimen failed. However, this could lead to an apparent larger loss of system stiffness.

Referencing Figure 13 and Table 2, it is apparent the K frame undergoes the most significant change in stiffness with an approximately 25% loss from the initial elastic value. On the other hand, the X frame seems to only lose about 4-6% of the stiffness making it a more robust system.

The most probable reason for this behavior is that as the tension diagonal or associated gusset plate connections begin to crack, load can be redistributed through the compression diagonal.

## 5. Conclusions

In the course of this research, the torsional brace stiffness and the vertical brace stiffness for the X frame, K frame, and Z frame cross frame layouts was examined. In addition, the cross frame member forces at given rotations and displacements were compared. The following observations were made:

- The single angle X frame provided the highest torsional brace stiffness of the layouts investigated, while simultaneously incurring the lowest forces per unit rotation.
- The analytical and line element solutions for the X frame and K frame greatly over-predicted the torsional stiffness of the brace because they do not consider the eccentric nature of the single angle connection. The behavior can be accurately captured using a shell element finite element model.
- The concentric knife plate tube connection minimizes out-of-plane bending at the gusset plate and stiffener, therefore making the analytical and line element solutions accurate predictions of the torsional brace stiffness.
- When subjected to a vertical point load, the X frame is the least stiff system, while the Z frame is the stiffest. Consequently, the X frame diagonals pick up lower forces from the applied load than the Z frame diagonal.
- Due to the redundancy of two diagonals, the X frame does the best in redistributing load as fatigue cracking occurs.

As the research is completed, recommendations on how to accurately calculate the torsional brace stiffness for each layout will be developed. In addition, the researchers are investigating the use of double angle members for use in the Z frame orientation.

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