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Cross Frame Stiffness Study by Using Full Size Laboratory Test and Computer Models

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Abstract

Cross frames are critical bracing elements for the stability of steel bridge systems. They help plate girders in resisting lateral torsional buckling and contribute to live load distribution. In curved bridges, cross frames serve as the primary structural members in resisting torsion generated by the eccentric loads. Therefore, accurately estimating the stiffness and strength of cross frames is important in bridge design. A Texas Department of Transportation (TxDOT) sponsored research project at the University of Texas at Austin is focused on improving the behavior of steel bridge cross frames. Previous studies have shown the effectiveness of a single diagonal tubular cross frame system in stabilizing plate girder structures. However, the stiffness and ultimate strength of this type of cross frame has not been thoroughly characterized. Also, connection details have not been considered. This paper documents the results of a study on the torsional stiffness of full size cross frame systems. Both conventional and newly proposed designs are being tested to establish the actual torsional stiffness of the cross frames. Furthermore, a comparison is made using different computer models to evaluate the stiffness.

1. Introduction

In a steel plate girder bridge system, cross frames are considered torsional braces because they stabilize the girders by restraining twist of adjacent girder lines. The most critical stage for girder stability is usually during the concrete deck placement, since the wet concrete poses significant dead load but provides no restraint to the girders.

The current AASHTO LRFD Bridge Design Specifications requires “rational analysis” for cross frame design (AASHTO 2010), and many states and jurisdictions use rules based on previous experience to set the size and spacing of cross frames. In addition, current bracing provisions in the AISC Standard Specification for Structural Steel Buildings (AISC 2010) provides general guideline for the design of stability bracing, which requires both stiffness and strength requirements to be satisfied in the design of torsional bracing. The torsional stiffness of a cross

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frame is defined according to Eq. 1. As presented in Figure 1, a moment (*M*) is applied to each side of the cross frame to cause a rotation (θ). The moment can also be represented as the resultant of a force couple (*F*).

$$\beta_b = \frac{M}{\theta} = \frac{Th_b}{\theta} \tag{1}$$

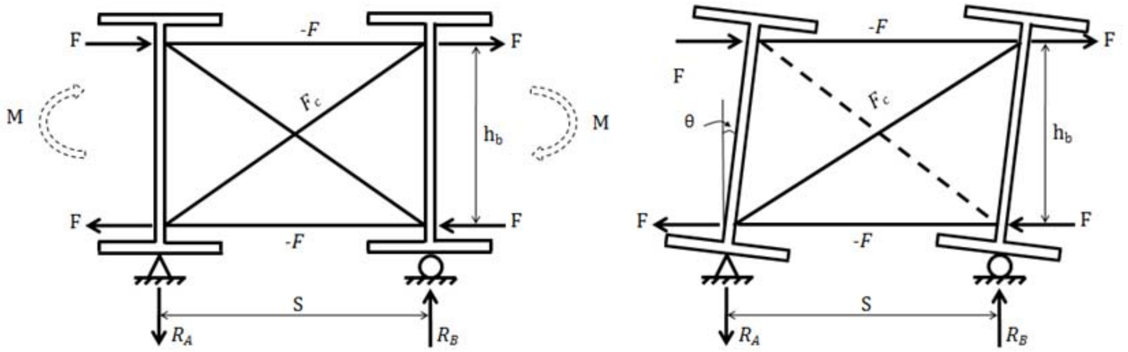


Figure 1: Loading Condition

Two of the most used cross frame models are the tension-only system and the tension-compression system as shown in the Figure 2 and Figure 3. The torsional stiffness provided by the cross frames can be estimated by using truss analogy (Yura, 2001). In the tension-only system, horizontal struts are required and the stiffness can be estimated by Equation 2. In the tension-compression system, the horizontal struts are not required and the stiffness can be estimated by Equation 3.

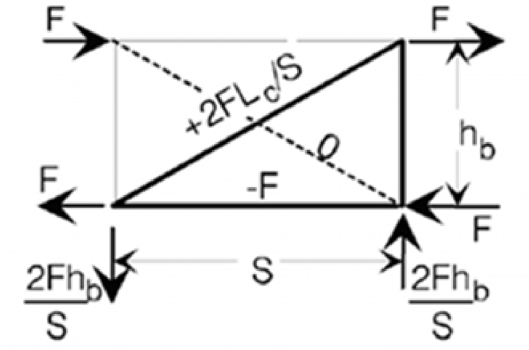


Figure 2: Tension-only System

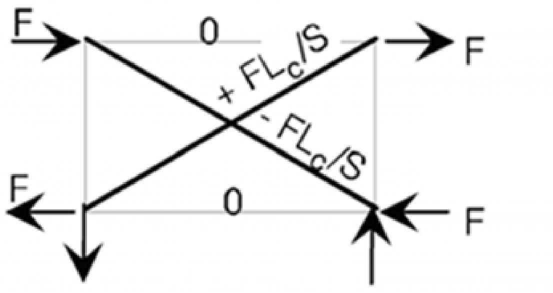


Figure 3: Tension-compression System

$$\beta_b = \frac{ES^2h_b^2}{\frac{2L_c^3}{A_c} + \frac{S^3}{A_h}} \tag{2}$$

$$\beta_b = \frac{A_cES^2h_b^2}{L_c^3} \tag{3}$$

Often, steel girder bridges employ the use of an X-type cross frame, which is comprised of single angle members and has two struts and two diagonals as shown in the Figure 4. Without more substantial experimental and computational data, it seems that either the tension-only system or the tension-compression system could be used to estimate the torsional stiffness of this type of cross frame. If the tension-only system is used, the contribution of the compression diagonal is conservatively ignored; if the tension-compression system is used, the contribution of the top and bottom struts is ignored, perhaps also resulting in a conservative approximation. In general engineering practice, the tension-only system is commonly used because it gives more conservative results than the compression system for a given cross frame geometry. To determine which model is most appropriate, an in-depth study of this type of cross frame is needed.

Figure 4: Single Angle X-Frame

Recent research, sponsored by the Texas Department of Transportation (TxDOT) and conducted at the Ferguson Structural Engineering Laboratory at the University of Texas at Austin has shown the possibility of using single diagonal cross frames (Z-frame) with tubular members (Battistini, 2011). Figure 5 shows a slotted square tube Z-frame in a testing frame. The advantages of a single diagonal cross frames include fewer structural members, concentric connections and potentially lower fabrication costs. In regards to the estimation of the strength and torsional stiffness of the single diagonal system, it is now easily assumed the tension-only system is a suitable model. Although geometrically similar to the tension-only model, this assumption still needs to be validated by test results and computer models analysis.

(a) Single Diagonal Cross Frame

(b) Slotted Tube

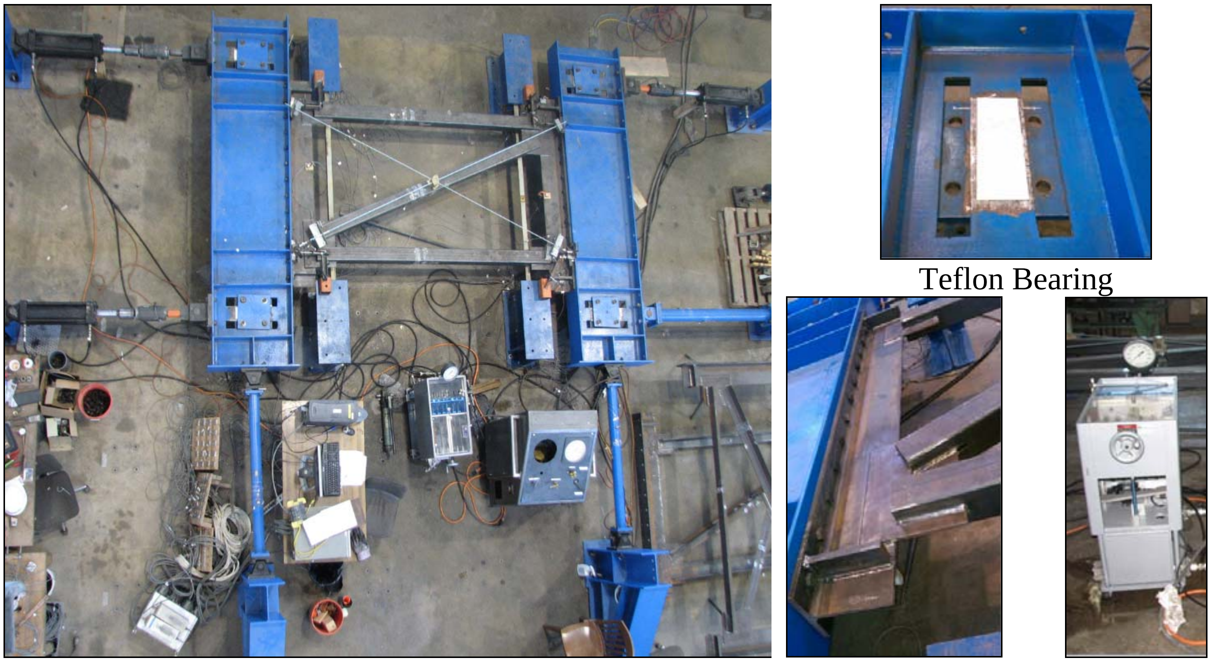
Figure 5: Slotted Tube Z-Frame

This paper presents the results of an investigation on the torsional stiffness of the two different types of cross frames: single angle X-frame and slotted tube Z-frame. The study included both experimental testing and computer modeling. The goals of the investigation were to measure the actual stiffness of the cross frame and compare the value to different methods of evaluating the torsional stiffness.

2. Full Scale Cross Frame Tests

2.1 Test Setup

The cross frame test setup shown in Figure 6 simulates the loading condition presented in Figure 1. The specimen in the picture is a slotted tube Z-frame. The cross frame was mounted to the two load beams using a WT member, and the load beams were elevated off the floor using W30x90 supports. Teflon bearings were placed between the supports and load beams to allow the load beams to move horizontally with minimized friction. Loads were provided by tension-compression actuators connected to the load beams. Actuators were used at three corners of the test frame and at the fourth corner; the load is exerted by a reaction strut. By equilibrium, if a force *F* is provided by the three actuators, the force in the reaction strut will be also *F*. In addition, two reaction struts (in the y-axis) were installed to simulate roller supports. To offer some redundancy in force measurement, axial forces in the three reaction struts were measured by strain gages at mid-length on opposite sides of the wall. Since the same *F* needs be applied at all four corners, a load maintainer is used to supply the hydraulic pressure proportionally and simultaneously to the multiple actuators.



Teflon Bearing

Overall Setup

WT connection

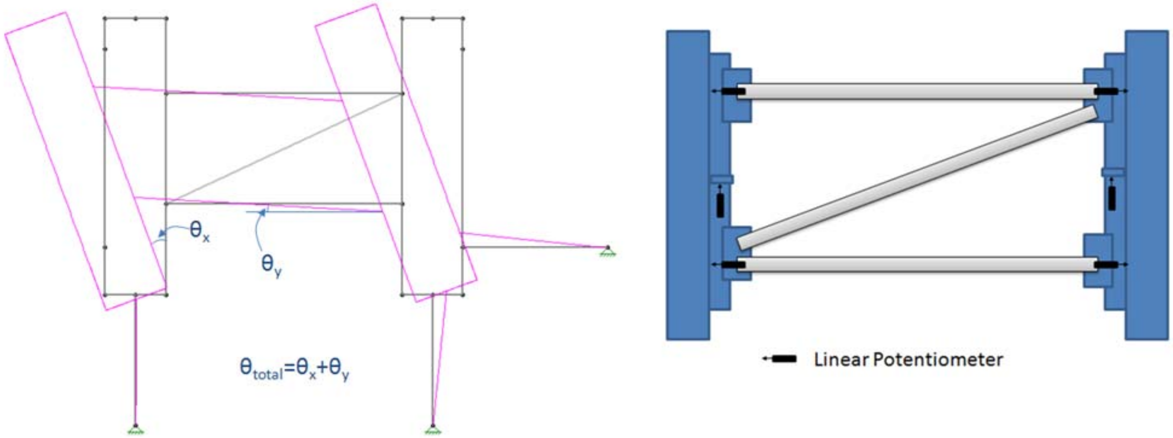
Load Maintainer

Figure 6: Test Setup

The measurement of rotation is done by measuring displacement at the four corners of the cross frame. The angle θ in Figure 1 needs to be modified slightly due to the test setup. Figure 7(a) shows a sketch of the test setup and how the test setup deforms under the applied loads. It appears that in addition to the rotation of the load beams, θ_x, an additional rotation θ_y will also cause structural forces in the cross frame. Therefore, the total rotation of the tested cross frame should be:

$$\theta_{total} = \theta_x + \theta_y \tag{4}$$

And both θ_x, and θ_y were computed from the displacements measured by linear potentiometers as shown in Figure 7(b).



(a) (b)

Figure 7: Measurement of Rotation

Measuring axial force in the single angle members is important in order to determine the force distribution in the single angle X-frames. Forces were monitored by using stain gages. A method using four strain gages was used to calculate the axial stress at the center of gravity of the cross-section assuming a linear distribution of stress (Helwig and Fan 2000). A view of the angle cross-section and strain gage layout can be seen in Figure 8.

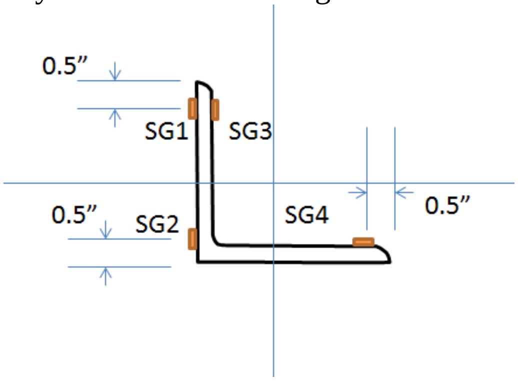


Figure 8: Measurement of Rotation

2.2 Test of Single Angle X-Frame

A single angle X-frame, as shown in Figure 9, was fabricated in our lab and mounted to the test setup. The design of this cross frame is in accordance with TxDOT Standard Drawing (TxDOT 2006). The cross frame was loaded up to 20 kips and all members are still in its elastic range. After unloading, the cross frame was loaded in the reserved direction so forces in cross frame members were reversed. Data sets were taken at intervals of 4 kips of the applied load. The plot of moment versus rotation is presented in Figure 10. A best fit trend line was added to the plot, where the slope of the line indicates the stiffness of the cross frame to be 862,000 k-in/rad.

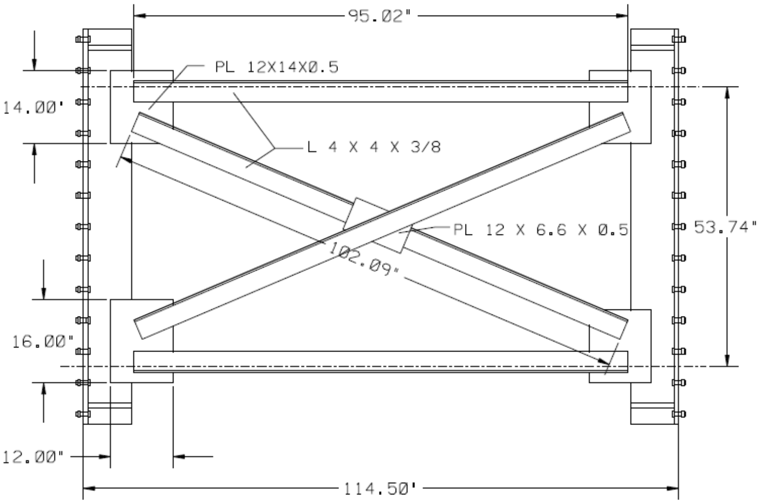


Figure 9: Single Angle X-frame

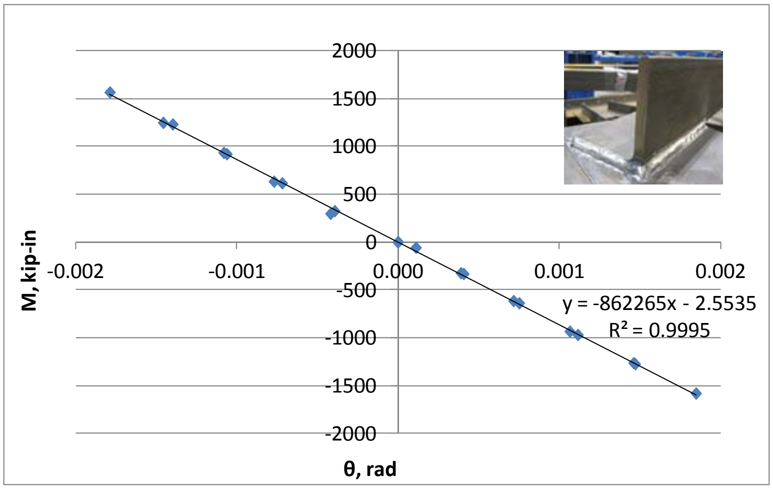


Figure 10: Moment vs. Rotation - Single Angle X-Frame

The force monitored in the test can give an in-depth understanding of how the cross frame works. As Figure 11 shows, the top and bottom struts are taking very low load, and the diagonals are doing the major portion of resisting the applied torque. It is also noticed the contributions of the compression and tension diagonals are the same magnitude but opposite sign. It can be concluded that, based on the test results, the cross frame is working in a tension-compression mode rather than in a tension-only mode at the given load level.

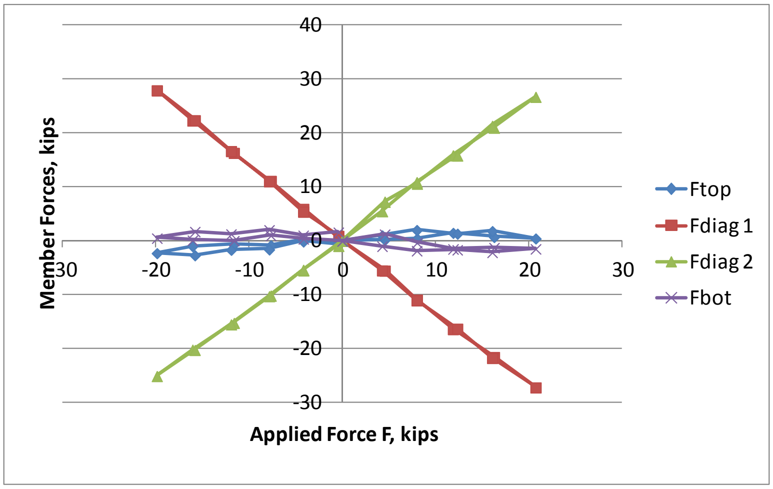


Figure 11: Member Forces - Single Angle X-Frame

2.2 Test of Slotted Tube Z-Frame

The second cross frame type tested was the slotted tube Z-frame. Figure 12 shows the dimensions of this brace. In a similar procedure to the single angle Z-frame test, the cross frame was subjected to applied forces to determine the moment versus rotation plot shown in Figure 13. The plot indicates the stiffness is approximately 658,000 k-in/rad.

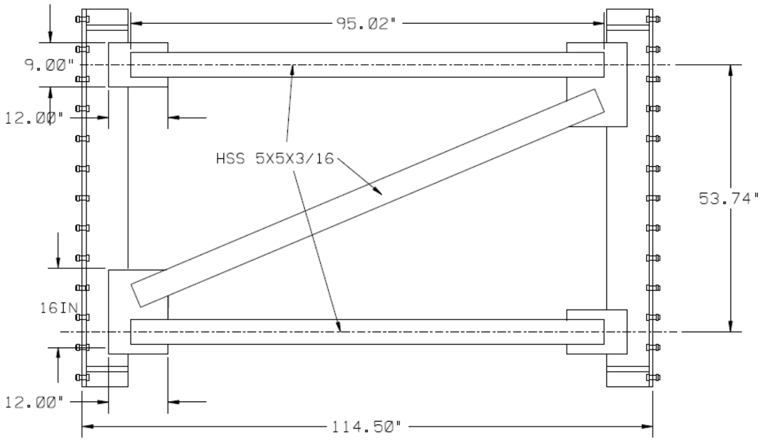


Figure 12: Member Forces - Single Angle Z-Frame

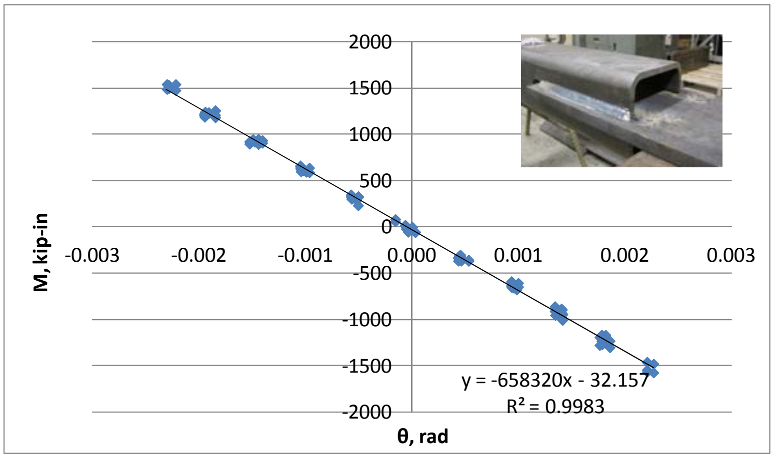


Figure 13: Moment vs. Rotation –Slotted Tube Z-Frame

3. Computer Modeling

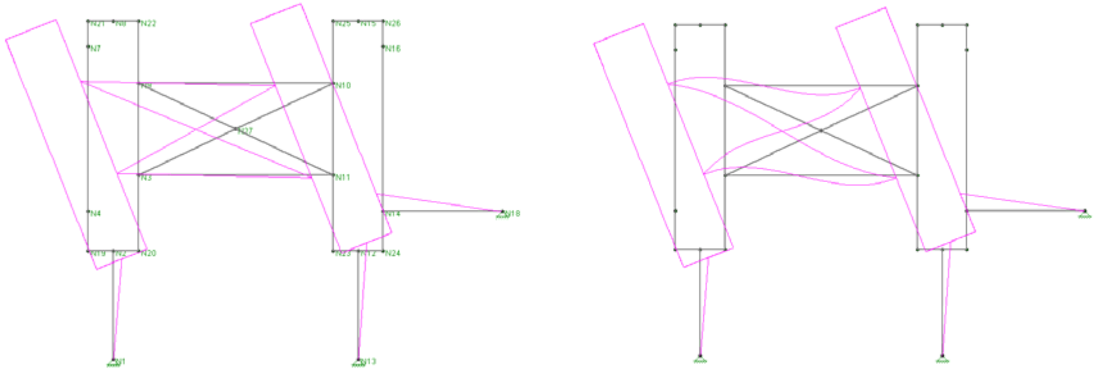
Three different types of computer models were created to evaluate the torsional stiffness of the cross frames (see Figure 14). The cross frame and the whole test setup was included in models. The line element models were created by using the Risa 2D version. The shell element model was constructed in ANSYS. In this model, 8-noded Shell 93 elements were used for the load beams and all the cross frame members, and the analysis restrained the out-of-plane displacements of the load beams.

4.1 Single Angle X-Frame

Table 1 shows the summary of results from the computer model analyses along with analytical solutions and laboratory results. It can be seen that among all methods, only the shell element model can nearly predict the torsional stiffness of this type of cross frame.

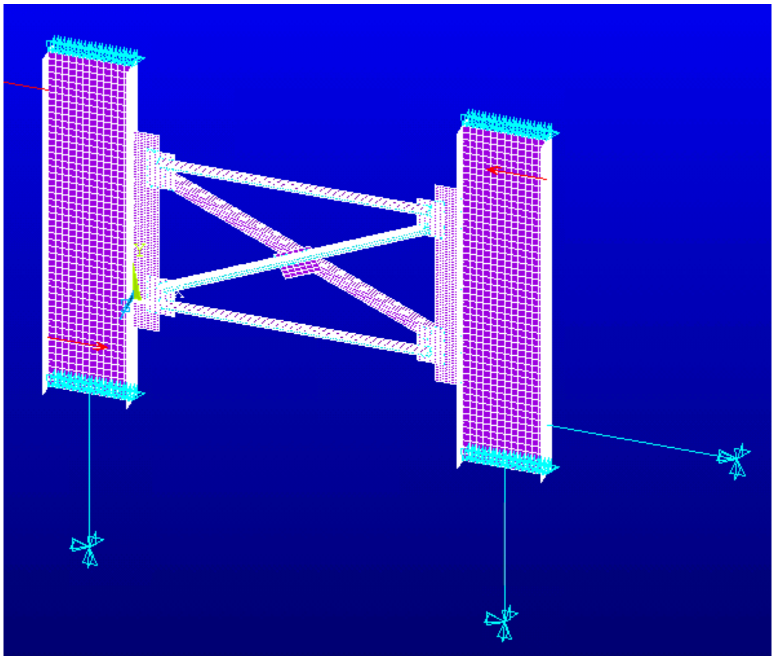
If analytical solutions are used, the tension-compression system will significantly overestimate the cross frame stiffness, even though the force distribution in the cross frame confirmed the accuracy of this assumption. The reason of this high reduction in stiffness should lie in the bending of the single angle member due to its eccentric connection (Battistini, 2012). On the other hand, the tension-only system will significantly underestimate the torsional stiffness of the cross frame due to its defected assumption – "tension-only". However, until this topic has been thoroughly researched, this assumption should result in a lower bound value for general practice.

If computer modeling is used in estimating this cross frame's stiffness, simplified line element models tend to show unconservative results. Only the shell element model can predict the stiffness closely because it can capture the eccentric bending effect of the single angle connections. It should be also noted that in evaluating torsional stiffness by using the simplified line element model, there is almost no difference between a pinned end model and a fixed end model.



(a) Line Element Model with Pinned Ends

(b) Line Element Model with Fixed Ends



(c) Shell Element Model

Figure 14: Computer Modeling

Table 1: Torsional Stiffness of Single Angle X-Frame

Method	Stiffness(k-in/rad)[1]	Errors from Lab Results
Lab Test Results	862,000	0
Analytical - Tension-only System	576,000	-33%
Analytical - Tension-Compression System	1,579,000	83%
Model - Line Element with Pinned Ends	1,602,000	86%
Model - Line Element with Fixed Ends	1,602,000	86%
Model - Shell Element Model	912,000	6%

4.2 Slotted Tube Z-Frame

Table 2 shows the summary of results of computer model analyses along with the analytical solution and laboratory results. It is apparent that all methods show good agreement, except the line element model with fixed ends gives a slightly higher stiffness.

Since the single diagonal cross frame is a statically determinant system, it is reasonable that the tension-only system and line element model with pinned ends gave close results. The line element model with fixed ends may be more realistic on one hand since the welds from the slotted tube to gusset plate form a rigid connection, but on the other hand, the flexibility of the gusset plate and slotted ends of the tube might offset the gain of stiffness in the fixity of connection itself. Therefore, to fully understand the end condition of the connections, more FEA parametric studies are needed.

Table 2: Torsional Stiffness of Slotted Tube Z-Frame

Method	Stiffness(k-in/rad)[1]	Errors from Lab Results
Lab Test Results	658,000	0
Analytical - Tension-only System	649,000	-1%
Model - Line Element with Pinned Ends	653,000	1%
Model - Line Element with Fixed Ends	702,000	7%
Model - Shell Element Model	657,000	0%

4. Conclusions

A test setup was built to investigate the torsional stiffness of two types of cross frames, the conventional X-type cross frame using single angles, and a Z-type cross frame using slotted HSS tubes. In addition, computer models were created to estimate the torsional stiffness of the cross frames and comparisons were made using the results from laboratory tests, analytical methods and computer analyses. The major findings of this research to date are summarized as the following:

1. A single angle X-frame behaves more like a tension-compression system because the horizontal struts show very low force. But using the tension-compression system analytical solution tends to highly overestimate the cross frame torsional stiffness because bending related to eccentric connection of single angle member could reduce the stiffness of the angle member greatly. The same issue was also observed if line-element models are used in the evaluation. While the shell element model can predict the stiffness rather accurately, it is not practical for use in everyday design. For now, a more practical analytical method assuming a tension-only system gives safe results, but is overly conservative. In order to achieve a practical method that is also accurate, parametric studies by FEA and more research in regard to connection stiffness are needed.
2. The prediction of the torsional stiffness of a slotted tube Z-frame is more straightforward than the single angle cross frame. Since the tension-only model reflects the reality of this type of cross frame and the connection stiffness is relatively high compared with the single angle, results from most analytical and computational methods had good

agreement. However, the connection stiffness is still unknown, and may need to be included to more accurately understand the cross frame behavior.

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