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Comparison of the Stiffness Properties for Various Cross Frame Members and Connections

A.D. Battistini[1], W.H. Wang[2], T.A Helwig[3], M.D. Engelhardt[4], K.H. Frank[5]

Abstract
Cross frames improve the stability of steel bridges by providing lateral and torsional restraint along the girder length. In order to be an effective brace, the cross frame must satisfy both strength and stiffness requirements. While cross frames are often constructed using steel angles to form an X-type brace, improved stiffness and fatigue behavior may result by using members with better compression strength, allowing the braces to be fabricated with a single diagonal.

A TxDOT sponsored research project at the University of Texas at Austin is investigating multiple details which would allow the use of a single diagonal cross frame. The T-stem connection is comprised of a tubular member welded to the flange of a WT section. The stem of the WT can then be welded to the gusset plate. A second detail being studied is a cast steel connection. The steel casting fits to the outside of a round tubular member and tapers to a flat section, helping to minimize stress concentrations. A third detail consists of a gusset plate, or knife plate, which is inserted into a precut slot in the HSS member. Finally, the use of a double angle member along the diagonal is under consideration.

This paper highlights results from axial tension experiments, with an emphasis on how the connections affect the individual stiffness of the tubular member as well as the overall cross frame stiffness.

1. Introduction
Cross frames are critical to the stability of straight and curved steel bridges. The cross frames provide lateral stability to the bridge system and increase the individual girder buckling capacity. In addition, cross frames act as the primary load-carrying members to resist the twist of the superstructure in curved bridges. In order to provide an effective brace, the cross frame must satisfy both strength and stiffness requirements (Winter 1958). Steel bridge cross frames are usually designed as torsional braces, which increase the overall strength of the system by forcing

[1] Graduate Research Assistant, University of Texas at Austin, <adb892@mail.utexas.edu>
[2] Graduate Research Assistant, University of Texas at Austin
[3] Associate Professor, University of Texas at Austin, <thelwig@mail.utexas.edu>
[4] Dewitt C. Greer Centennial Professor in Transportation Engineering, University of Texas at Austin
[5] Chief Engineer, Hirschfeld Industries, Austin, TX

the girders to translate or rotate as a unit. Therefore, an important aspect of providing an effective torsional brace is to use a strong diagonal member.

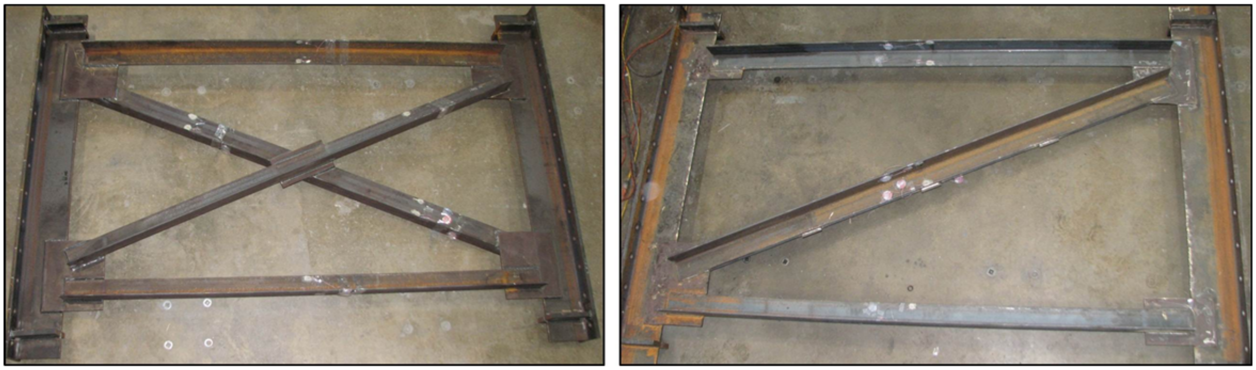

Figure 1: (a) Conventional X-Type Cross Frame and (b) Single Diagonal Z-Type Cross Frame

Conventional cross frames are often fabricated with steel angles using two diagonal members and two horizontal struts to create an X-type brace as shown in Figure 1 (a). Due to the relatively low buckling resistance of eccentrically loaded angle members, these cross frames are often designed as a "tension-only" system. In a tension-only system, the compression diagonal is conservatively neglected in strength and stiffness calculations, therefore requiring more steel for stability. In addition, the angles are connected to the end plates along only one leg of the member, resulting in an eccentric connection. The eccentricity causes bending of the members and decreases the fatigue performance (McDonald and Frank 2009).

Improved structural behavior may result by using tubular members or double angle members to construct a Z-Type brace as shown in Figure 1 (b). These members have significant buckling strength, which would make the diagonal efficient in both tension and compression, thus providing an effective brace for the steel bridge girders.

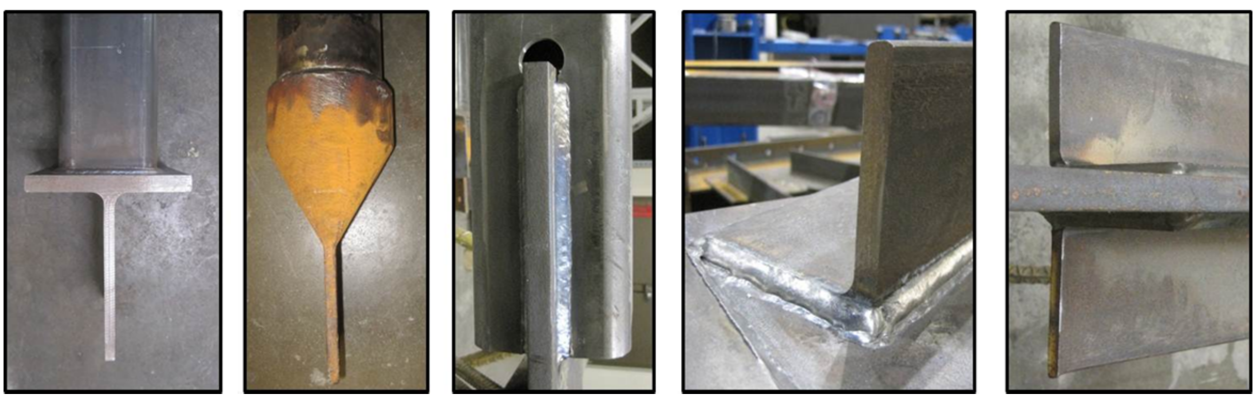

Figure 2: (a) T-Stem Connection, (b) Cast Steel Connection, (c) Knife-Plate Connection, (d) Single Angle Connection, and (e) Double Angle Connection

One of the difficulties of using tubular members for the cross frame is designing a connection that allows the tubular cross-section to connect to a flat gusset plate. Currently, experimental tests have been performed on three different HSS connections: a T-stem connection, a cast steel connection, and a knife-plate connection. The following sections will discuss the implications of the connection behavior on the stiffness of the cross frames using the results of axial tension tests with the three HSS connections, as well as single and double angle member connections. Examples of the connections tested are shown in Figure 2.

2. Cross Frame Stiffness

When calculating the torsional stiffness of the cross frame, an elastic truss analysis is often employed (Yura 2001). As previously stated, for a tension-only system, the contribution of the compression diagonal is ignored, and the single diagonal model shown in Figure 3 (a) is analyzed.

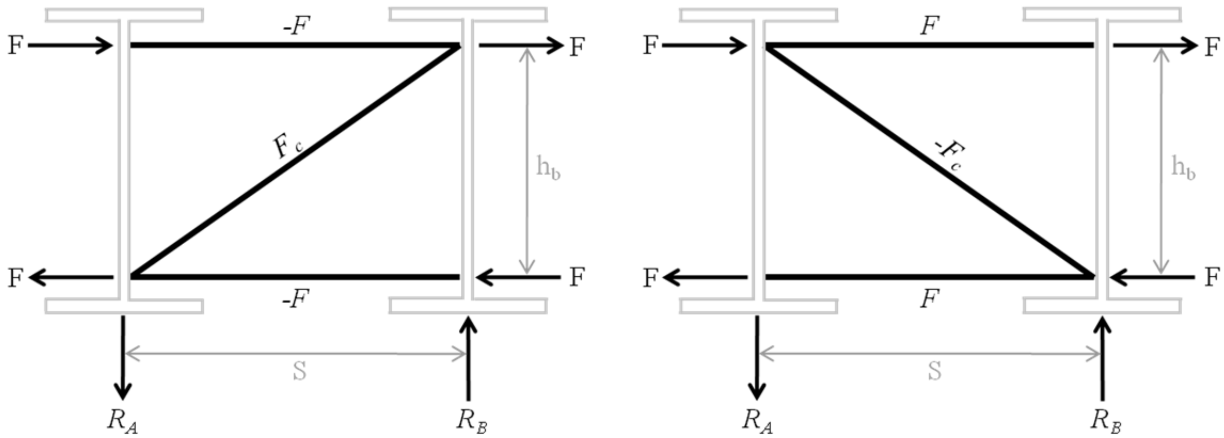

Figure 3: (a) Tension-Only System and (b) Compression System

Following the derivation provided by Quadrato (2010), a deflection analysis on the tension-only system is performed to determine the rotation of the cross frame, and ultimately the brace stiffness is (in accordance with the formula given by Yura (2001)):

$$\beta_{braxial} = \frac{E h_b^2 S^2}{\dfrac{2L_c^3}{A_c} + \dfrac{S^3}{A_h}} \tag{1}$$

where $\beta_{braxial}$ is the torsional stiffness of the cross frame considering only the axial stiffness of the cross frame members, E is the modulus of elasticity (29000 ksi), h_b is the height of the brace (centroid of top strut to centroid of bottom strut), S is the girder spacing, L_c is the length of the diagonal member, A_c is the area of the diagonal member, and A_h is the area of each strut. Eq. 1 assumes that the ends of the cross frame members are pinned.

Conversely, if the diagonal has significant buckling strength, the truss analysis could be performed on the geometry of Figure 3 (b), resulting in the same torsional stiffness as Eq. 1, with the diagonal member in compression instead of tension.

Eq. 1 offers a useful design calculation to determine the torsional stiffness of the cross frame, but it simplifies the typical cross frame geometry and it neglects the possible impact of the member connections. To better isolate the effects of the connection, it is useful to put Eq. 1 in terms of the stiffness of the strut and diagonal. Eq. 1 assumes the strut member stiffness to be defined as:

$$k_h = \frac{A_h E}{S} \quad (2)$$

and the diagonal member stiffness as:

$$k_c = \frac{A_c E}{L_c} \quad (3)$$

Revisiting the derivation of Eq. 1, but substituting Eqs. 2 and 3 where appropriate, the following formula for $\beta_{braxial}$ is obtained:

$$\beta_{braxial} = \frac{h_b^2}{\frac{2L_c^2}{k_c S^2} + \frac{1}{k_h}} \quad (4)$$

In order to determine the stiffness of the members, the equation for springs in series will be used:

$$\frac{1}{k_T} = \frac{1}{k_{member}} + \frac{2}{k_{connection}} \quad (5)$$

where k_T is the total stiffness, k_{member} is the analytic stiffness of the member (Eqs. 2 and 3), and $k_{connection}$ is the stiffness of each connection.

Using an MTS universal tension machine, test data for the total stiffness of the members and connections was obtained. From the experiments, $k_{connection}$ can be determined using Eq. 5. Once known, Eq. 5 can then be used in conjunction with the cross frame geometry to determine k_c and k_h (including the contribution of the member and connection). Substituting k_c and k_h in Eq. 4 will give the torsional stiffness of the cross frame including member connection flexibility.

While Eqs. 4 and 5 may better represent the actual condition, it is recognized the process may not be suited for design calculations. The goal is to use the equations to estimate the magnitude of the effect of the connections and determine if it is necessary to include in design.

3. Test Specimens

In order to determine the stiffness of the various connections, specimens were fabricated with each of the different connections identified for possible use with the single diagonal cross frame. The length of each of the members was selected to be 3 ft, which helps to reduce the boundary effects on the distribution of axial stress while still being able to fit into the MTS testing machine. The test specimens are shown in Figure 4, with a summary of the specimen geometry in Table 1.

3.1 T-Stem Connection

The T-stem connection specimens consisted of two sections of a WT member connected to square and round HSS tubes. The WT was sized to meet expected strength requirements based on the HSS tube strength, while also meeting the geometric constraint that the flange width had to exceed the tube width allowing enough space for the weld. The tube was centered on the flange of the WTs and welded to create the connection. Three types of T-stem connection specimens were created: (1) square HSS welded with the tube walls parallel to the edges of the WT flange, (2) square HSS welded with the tube walls at a 45 degree angle to the edges of the WT flange (diamond), and (3) round HSS. Examples of the HSS specimens and WT connections are shown in Figure 4 (a-c).

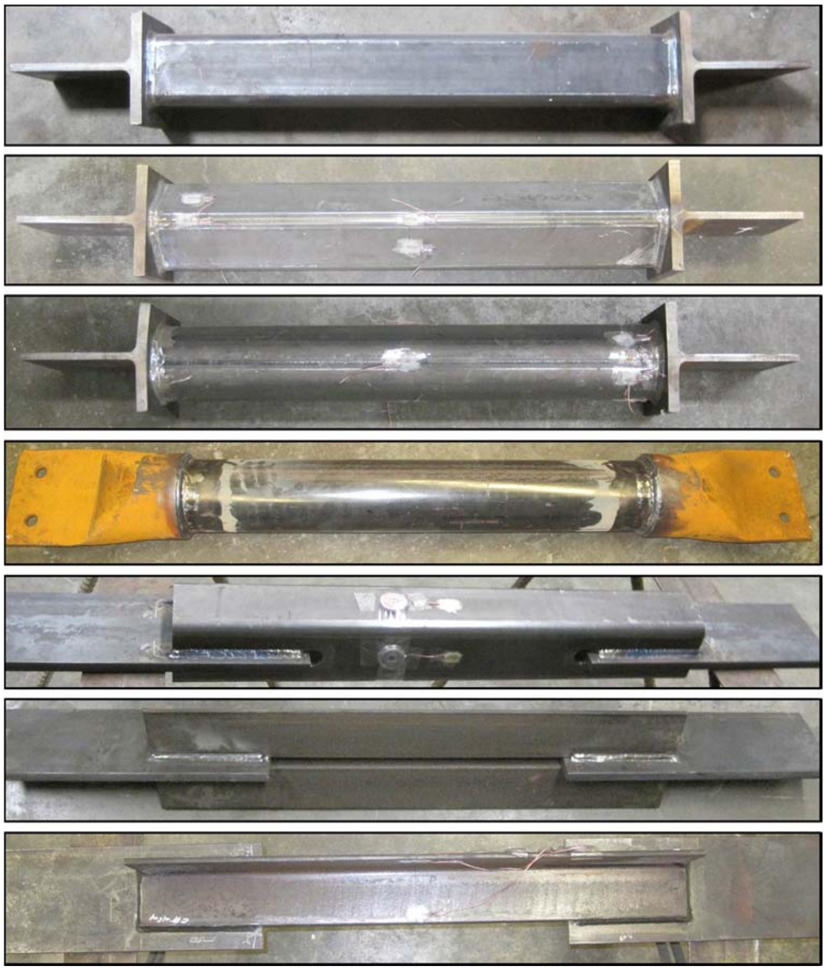

Figure 4: Test Specimens- (a) T-Stem and Square HSS, (b) T-Stem and Diamond HSS, (c) T-Stem and Round HSS, (d) Cast Connection, (e) Knife-Plate Connection, (f) Double Angle Connection, and (g) Single Angle Connection

Table 1: Test Specimen Geometry

Specimen	**Member**	**Connection**	**Weld Length [in]**	**Weld Size [in]**
T-Stem Square	HSS 5 x 5 x 3/8	WT 9 x 35.5	20	5/16
T-Stem Diamond	HSS 5 x 5 x 3/8	WT 9 x 35.5	20	5/16
T-Stem Round	HSS 5.563 x 0.375	WT 9 x 35.5	17.5	5/16
Cast Connection	HSS 5.563 x 0.375	Steel Casting	17.5	5/16
Knife-Plate	HSS 5 x 5 x 3/8	PL 7 x 0.75	32	5/16
Double Angle	2L 4 x 4 x 3/8	PL 7 x 0.75	20	5/16
Single Angle	L 4 x 4 x 3/8	PL 7 x 0.75	24	5/16

3.2 Cast Steel Connection

The cast steel connection specimen comprised a round HSS member connected to two steel castings. The castings were designed to seal the tube, to minimize stress concentrations at the connection, and to allow for easy assembly. To achieve these effects, the casting fits to the outside diameter of the tube and tapers to a flat plate which can then connect to cross frame gusset plates or directly to girder stiffeners. The steel castings were produced at a foundry in Houston, Texas who worked with the researchers to design an efficient connection, both from structural strength and constructability standpoints. The completed casting is shown from the side in Figure 2 (b) and from the front in Figure 4 (d). The casting was made in accordance with the ASTM A709 50W Type C weathering steel grade, hence explaining the presence of the protective rust patina seen in both figures.

3.3 Knife-Plate Connection

The knife-plate connection was fabricated by first drilling a 1-5/16″ stress relief hole (1.75 times the thickness of the knife-plate), centered approximately 8.8″ from the either end of the HSS 5 x 5 x 3/8 member. A 3/4″ slot was then saw cut to allow insertion of the gusset plate. The tube was then welded longitudinally to the knife-plates to create the connection. The stress relief hole was selected to reduce the stress field in the vicinity of the weld toe on the HSS section at the forward edge of the connection, which was seen to significantly decrease fatigue life (Liu et al 2006).

3.4 Double Angle and Single Angle Connections

The double angle connection was fabricated using 2 L 4 x 4 x 3/8 members, which is a typical size used in steel bridges (TxDOT 2006). The members overlapped the gusset plate by 8″, and were welded around all sides of the angles. Although designers will sometimes detail the welds for a balanced condition, i.e. the center of gravity of the weldment will align with the center of gravity of the angle, it was found the fully welded condition usually results in decreased fatigue behavior (McDonald and Frank 2009). Since both stiffness and fatigue criteria are important in these connection tests, the fully welded condition was selected.

Similar to the double angle specimen, the single angle specimen was constructed from an L 4 x 4 x 3/8 member, overlapping the gusset plate by 8″, and utilizing the fully welded condition. Additionally, a second transverse weld was situated on the back side of the angle, consistent with standard practice for TxDOT bridges (TxDOT 2006). The double and single angles specimens can be seen in Figure 4 (f) and (g) respectively.

4. Test Results

Each of the specimens was placed in a uniaxial tension test machine and loaded to determine the stiffness of the assembly. The displacements were measured using two dial gages which rested on angle sections clamped to the flat plate portion of the connection. The clamping bolts were 3/4″ diameter, centered 3.25″ below the end of the connection. The dial gages were suspended on a threaded rod from the same location at the top connection. The exception was for the cast connection specimen, where the gages were attached to smaller angle sections that were epoxied at the point where the flat plate of the casting began, thereby including the tapered portion of the connection. The two test setups can be seen in Figure 5.

The stiffness of each specimen was determined by plotting the load versus deflection curve based on the measured force from the load cell in the MTS machine and the deflection read from the dial gages. Using a best-fit line through the data, the slope represents the stiffness of the specimen. Since the displacement readings include some region of the connection, which varied in width and thickness amongst the tests, the stiffness results from all the connection types are not directly comparable.

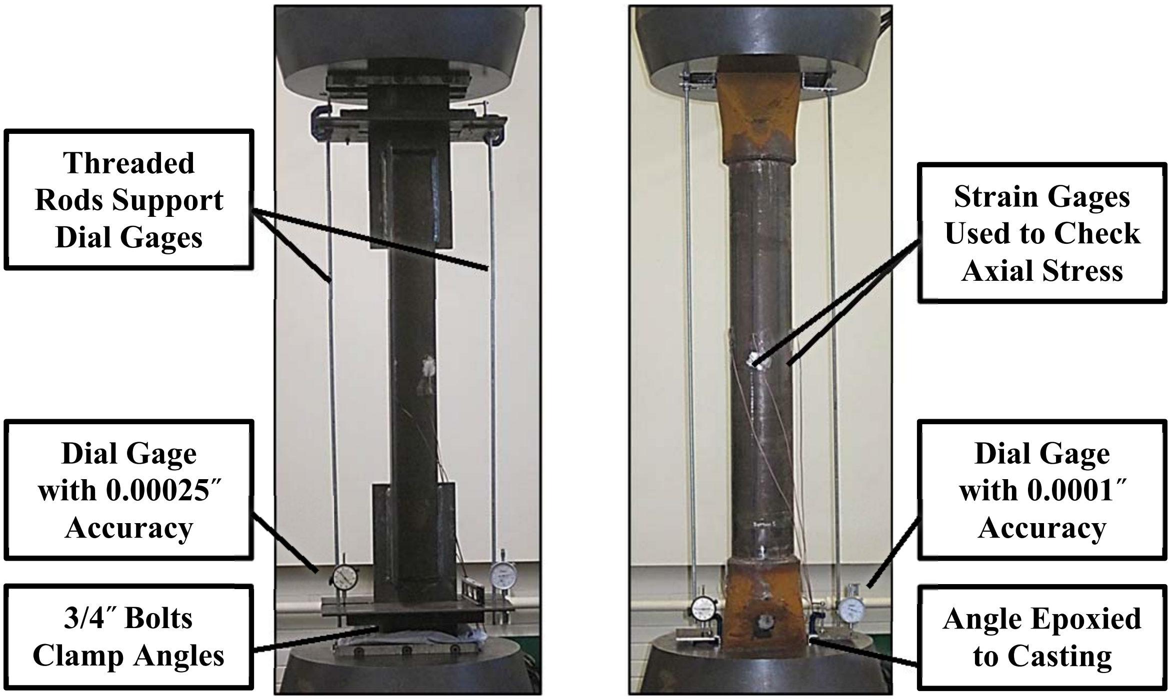

Figure 5: Test Specimen and Instrumentation for (a) Fabricated Connections and (b) Cast Connections

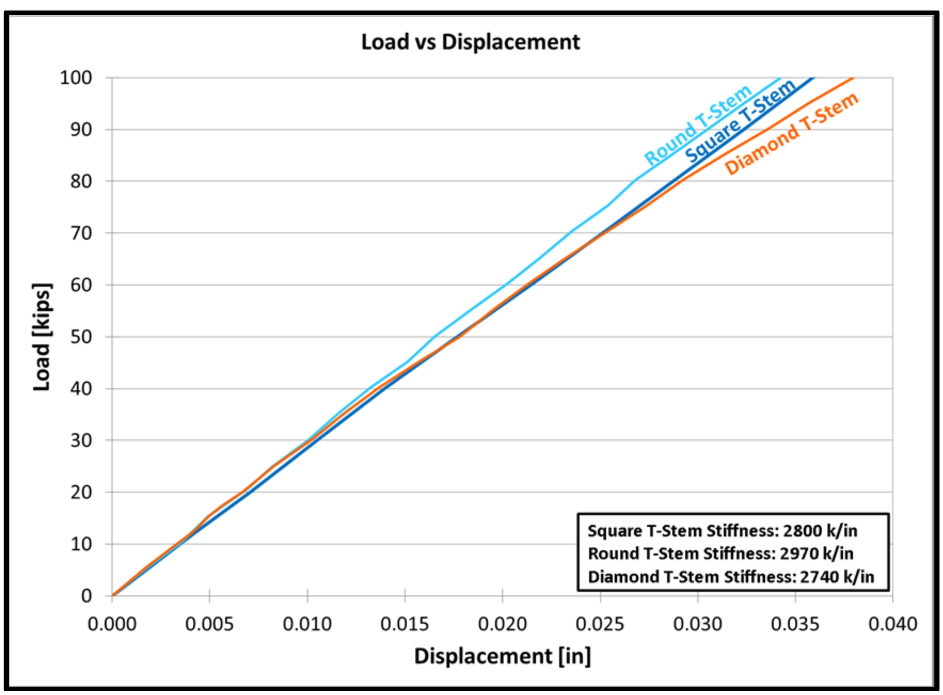

Figure 6: Summary of Stiffness Test Results- T-Stem Connections

4.1 T-Stem Connection Test Specimens

As was previously discussed, three different T-stem connection specimens were tested. Since all the T-stem tests used the same WT connection, the stiffness results can be compared to one another. Although the finite element analysis revealed the diamond tube to have a lower stress concentration, it is seen the stiffness of the specimen (2740 kip/in) was similar to the stiffness of the square tube specimen (2800 kip/in). The result makes sense since both specimens utilize the same size tube and connection. The round tube and T-stem combination had the best performance of the group, offering a modestly higher stiffness of 2970 kip/in. Associated finite element analyses indicated the round tube had a more uniform distribution of stress near the connection, perhaps improving its overall stiffness characteristics in relation to the square tubes, which also had a larger area. The test results are shown in Figure 6.

4.2 Cast Connection Test Specimen

The results for the cast connection specimen are shown in Figure 7. The stiffness of 3310 kip/in is higher than the T-stem connections. While the results cannot be directly compared, the measurements on the casting were over a longer distance and the stiffness was higher, so it is concluded the cast connection is more axially rigid than any of the T-stems. The increase is likely the result of supplying a more uniform stress pattern through the connection, eliminating the increased deflections that may occur at stress concentrations.

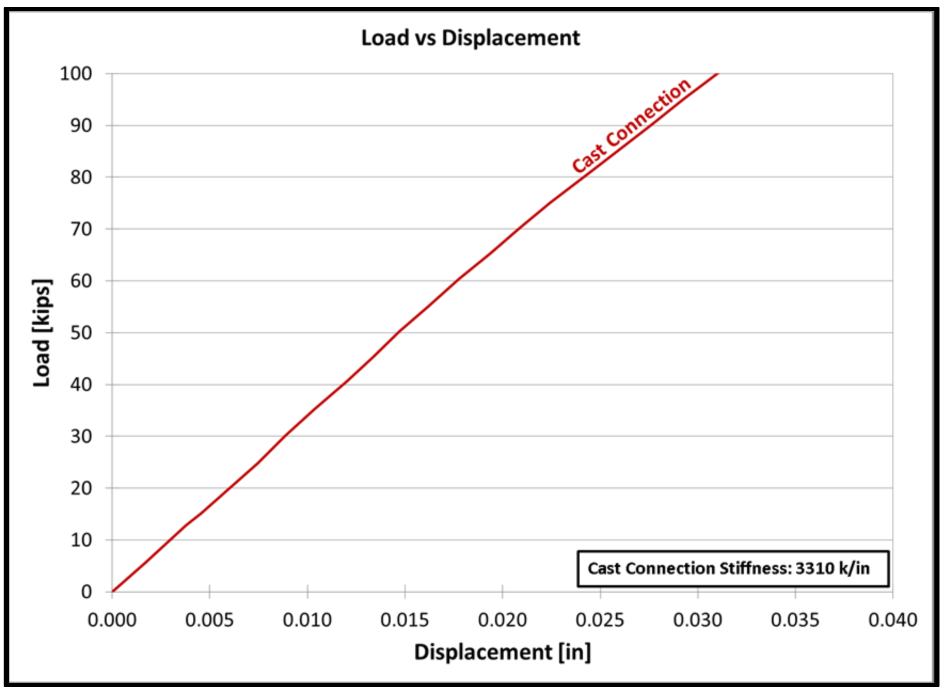

Figure 7: Summary of Stiffness Test Results- Cast Connection

4.3 Knife-Plate Connection Test Specimen

The knife-plate connection, double angle connection, and single angle connection utilized the same plate material to make the connections (PL 7 x 0.75), thereby allowing comparisons to be made between the tests. The total stiffness of the knife-plate specimen was measured to be 3750 kip/in, about 7% less than the stiffness of the double angle specimen despite having a 5% larger area. The lower stiffness may indicate the connection has a greater shear lag than the double angle specimen. Results for the knife-plate specimen, as well as the angle specimens are plotted in Figure 8.

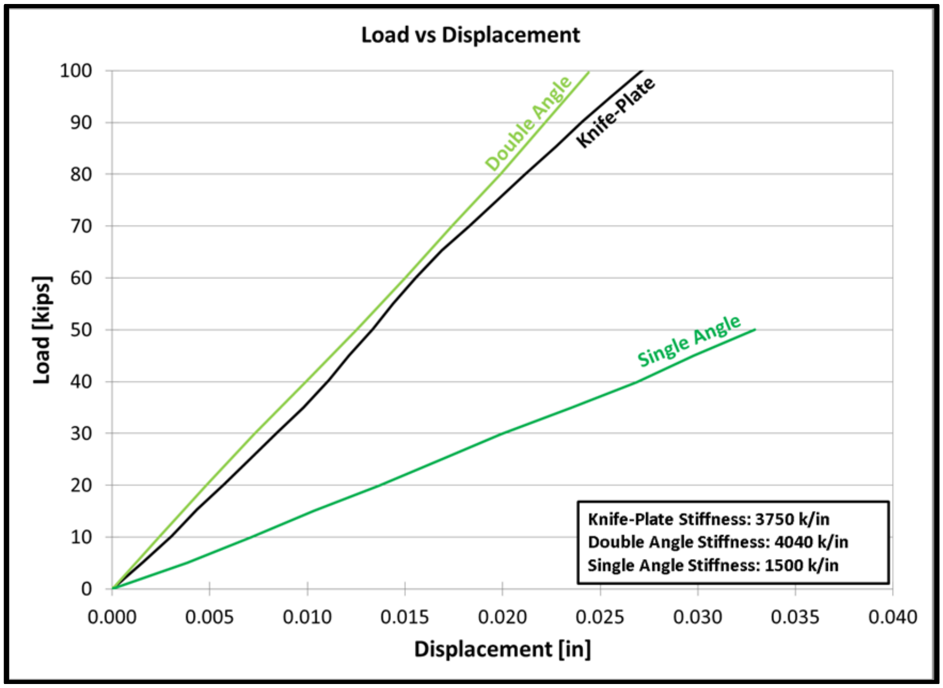

Figure 8: Summary of Stiffness Test Results- Knife-Plate, Double Angle, and Single Angle

4.4 Double Angle and Single Angle Test Specimens

The double angle specimen performed the best of these three connections, with a total stiffness of 4040 kip/in. On the contrary, the single angle specimen, representing the vast majority of cross frame members currently used, had a low stiffness of 1500 kip/in. While it would be expected the stiffness would reduce by half due to the cross-sectional area, the single angle stiffness is only 37% of the stiffness of the double angle. The most likely explanation is the eccentricity of load relative to the member. All of the other connections are concentric, reducing the amount of bending that occurs under direct tensile load. However, the single angle member is loaded through one leg only, causing substantial bending of the member and therefore decreasing the stiffness available.

4.5 Relative Behavior of the Connections

In order to better understand the behavior of the connections relative to one another, an average stress versus average strain plot was created as shown in Figure 9. The stress was calculated using the measured force from the MTS machine and the measured area, which was calculated based upon the length of the member and the member weight. The strain utilizes the measured displacement divided by the sum of the length of the member and the distance from the end of the connections to the gage location/attachment point. The displacement was calculated by taking the average of the dial gages. By normalizing the force by the area of each member, and the strain by the length, Figure 9 shows the approximate performance offered by each connection.

It is observed the cast connection and the double angle connection perform the best, while the T-stem connections connected to the HSS 5 x 5 x 3/8 tubes are the most flexible. The current standard using single angle connections is not as effective as the casting, double angle, or knife-plate connections.

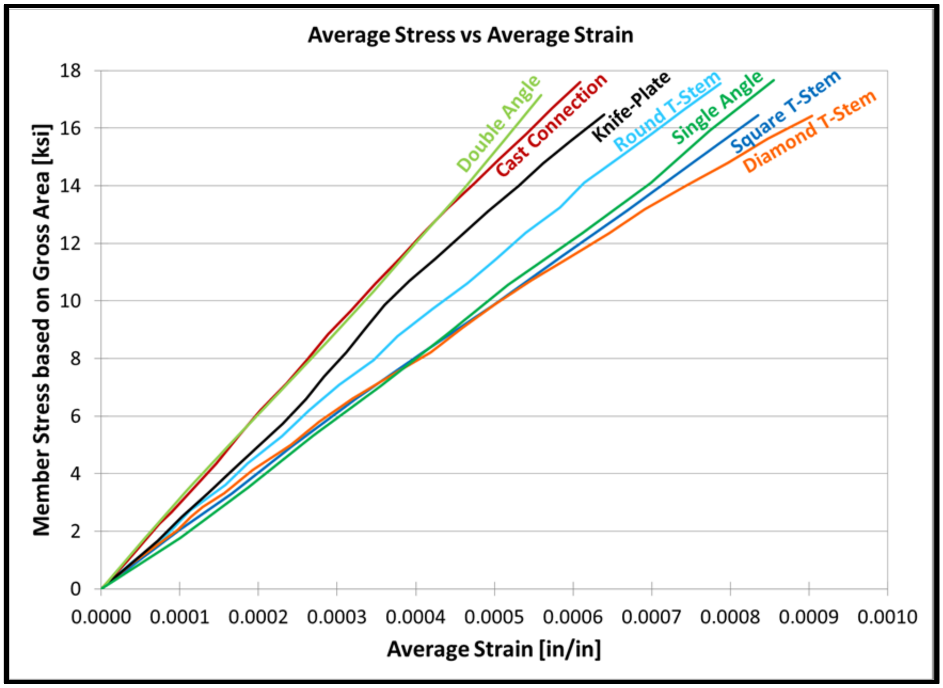

Figure 9: Relative Performance of Different Connections

5. Connection Stiffness

As outlined in Section 2, the connection stiffness can be calculated from the test data using Eq. 5. The results of these calculations are displayed in Table 2 and are grouped into the connections that could be compared to one another. In order to completely characterize the stiffness of the various connections, a parametric finite element analysis study will be performed to determine the effects of changing the connection geometry and thickness of the connection plates. However, the focus of this paper is on the test data, which will be used to provide a preliminary understanding of the effect of including connection stiffness in the calculation of the torsional cross frame stiffness.

The T-stem connection combined with square tubular members produced similar values of stiffness for the connection, about 13,000 kip/in. However, use of the round tube with the T-stem offered better performance at 16,900 kip/in.

The cast connection stiffness was determined to be 23,900 kip/in. The stiffness value of the cast connection is very useful in understanding the behavior since the casting was designed to fit a specific diameter of tubes, but multiple tube thicknesses. Therefore, the stiffness will not fluctuate due to connection plate thickness changes, weld length variations, or tube thickness changes.

The knife-plate connection had a test stiffness of 31,700 kip/in. The double angle connection was more rigid with a stiffness of 59,100 kip/in and performed better than the knife-plate while having a smaller overall area. Finally, the single angle connection was the most flexible, supplying only 8800 kip/in. It is interesting to see the detrimental effect of the eccentric loading on the single angle connection, by comparing it to the double angle comprised of the same cross-section.

Table 2: Calculation of Connection Stiffness based upon Laboratory Tests

Specimen	**Member Area [in^2]**	**Member Length [in]**	**Total Stiffness k_T [kip/in]**	**Member Stiffness k_{member} [kip/in]**	**Approximate Connection Stiffness $k_{connection}$ [kip/in]**
T-Stem Square	6.09	36	2800	4910	13000
T-Stem Diamond	6.09	36	2740	4910	12400
T-Stem Round	5.69	36	2970	4580	16900
Cast Connection	5.69	36	3310	4580	23900
Knife-Plate	6.10	36	3750	4910	31700
Double Angle	5.81	36	4040	4680	59100
Single Angle	2.83	36	1500	2280	8800

Note: The connection stiffness includes the stiffness of the connecting plate, which varied between tests. Therefore, the connection stiffnesses shown are not comparable to one another.

6. Cross Frame Stiffness

Now that the stiffness of each connection has been determined, the values can be combined with the cross frame member lengths to determine the effect of including connection behavior in the calculation of the torsional brace stiffness. Two extreme cases for plate girder depth, 54″ and 96″, will be considered to identify the effect of connection stiffness on different cross frame sizes.

Using Eq. 5, total member stiffnesses for the struts and diagonal were found including the effect of the connection. These calculations utilized the dimensions shown in Figure 3, along with the standard areas given in the AISC Steel Construction Manual (2010). Once solved for, the stiffnesses from Table 2 were substituted into Eq. 4 to determine the total torsional brace stiffness. The value was compared to Eq. 1 which does not include connection behavior. The results are summarized in Table 3.

From Table 3 it is observed the inclusion of connection behavior can reduce the cross frame stiffness by up to 19%. The square and diamond T-stem connections cause the biggest error, ranging from 16-17% at the larger 96″ girder depth, and from 18-19% at the shallower 54″ depth.

The castings performed fairly well only reducing the stiffness by 9-10% at both girder depths considered.

In reference to the double angle cross frame, it is anticipated that single angles would be used for the top and bottom struts, with a double angle along the diagonal. The inclusion of the single angles contributed to brace stiffness errors around 7-9%. Meanwhile, using all single angle sections in the tension-only calculation caused errors of 12-13%. The knife-plate cross frame was comparable to the double angle with errors of 7-9%.

Referencing Table 3, it is also concluded the reduction in axial brace stiffness due to connection effects is not highly sensitive to the girder depth. Comparing each connection at the two extreme depths considered, the percent decrease does not vary significantly between the two cases.

Table 3: Calculation of Cross Frame Stiffness Including the Effect of Member Connections

Girder Web Depth = 96 in, Girder Spacing = 10 ft							
Cross Frame Member Type	**Member**	**Connection**	**k_h [kip/in]**	**k_c [kip/in]**	**$\beta_{braxial}$ (Eq. 1) [10^6 kip-in/rad]**	**$\beta_{braxial}$ (Eq. 4) [10^6 kip-in/rad]**	**Percent Decrease**
T-Stem Square	HSS 5 x 5 x 3/8	WT 9 x 35.5	1210	1040	2.172	1.810	16.7%
T-Stem Diamond	HSS 5 x 5 x 3/8	WT 9 x 35.5	1200	1030	2.172	1.793	17.4%
T-Stem Round	HSS 5.563 x 0.375	WT 9 x 35.5	1190	1010	1.992	1.744	12.4%
Cast Connection	HSS 5.563 x 0.375	Steel Casting	1240	1050	1.992	1.814	8.9%
Knife-Plate	HSS 5 x 5 x 3/8	PL 7 x 0.75	1360	1150	2.172	2.008	7.6%
Double Angle	2L 4 x 4 x 3/8	PL 7 x 0.75	600	1090	1.721	1.596	7.3%
Single Angle	L 4 x 4 x 3/8	PL 7 x 0.75	600	500	1.048	0.921	12.1%

Girder Web Depth = 54 in, Girder Spacing = 10 ft							
Cross Frame Member Type	**Member**	**Connection**	**k_h [kip/in]**	**k_c [kip/in]**	**$\beta_{braxial}$ (Eq. 1) [10^6 kip-in/rad]**	**$\beta_{braxial}$ (Eq. 4) [10^6 kip-in/rad]**	**Percent Decrease**
T-Stem Square	HSS 5 x 5 x 3/8	WT 9 x 35.5	1210	1170	0.683	0.560	18.0%
T-Stem Diamond	HSS 5 x 5 x 3/8	WT 9 x 35.5	1200	1160	0.683	0.555	18.7%
T-Stem Round	HSS 5.563 x 0.375	WT 9 x 35.5	1190	1140	0.616	0.532	13.6%
Cast Connection	HSS 5.563 x 0.375	Steel Casting	1240	1190	0.616	0.556	9.7%
Knife-Plate	HSS 5 x 5 x 3/8	PL 7 x 0.75	1360	1300	0.683	0.624	8.6%
Double Angle	2L 4 x 4 x 3/8	PL 7 x 0.75	600	1250	0.550	0.503	8.5%
Single Angle	L 4 x 4 x 3/8	PL 7 x 0.75	600	570	0.357	0.311	12.9%

Note: The calculations for the double angle cross frame assume single angle struts and a double angle diagonal

7. Conclusions

Often in design, simplified formulas are used to determine the axial brace stiffness of the cross frame. These formulas typically do not consider the effect the type of member connection may have on the stiffness of the brace. As part of using a singular diagonal cross frame, experimental tests were conducted to characterize the stiffness of five different connections: (1) the T-stem connection, (2) the cast steel connection, (3) the knife-plate connection, (4) the double angle connection, and (5) the single diagonal connection. While further finite element parametric studies are needed to completely examine the connection behavior, the tests showed that the round HSS tube with T-stem connections offers higher stiffness than using square HSS members, despite having a lower cross-sectional area. Subsequent analysis showed the WT 9 x 35.5 T-stems to have a major impact on the torsional stiffness of the cross frame, reducing the value calculated by the current analytical formula by 12-20%.

The cast connection performed fairly well, only resulting in a 9-10% decrease of stiffness relative to the current analytical formula.

The knife-plate connection reduced the brace stiffness by 7-9%, assuming the connection plates are similarly sized to the specimen. The eccentric loading of the single angle connection caused the reduction in brace stiffness to be larger (12-13%), but when combined with a double angle along the diagonal, the loss was limited to 7-9%. Again, these expected reductions are based on similarly sized connection plates and weld lengths.

Lastly, comparing brace stiffness reductions at a larger and smaller girder depth, the effect of including the connections led to roughly the same percent decrease between the two cases.

These stiffness calculations were determined based on specific connection sizes and details. Future parametric studies will be used to isolate the effect of the connection to apply to a broader range of connection geometries. While including the connection behavior in determining the torsional stiffness of the brace may be more accurate, it is not practical for design. For now, it seems the expected loss in stiffness is less than 10% for the connections commonly used, which can be accounted for by using appropriate safety factors.

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