Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Pittsburgh, Pennsylvania, May 10-14, 2011

Comparison of Cross Frame Strength and Stiffness for Steel Bridge Systems Using Angle and Tube-shaped Members

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Abstract

The stability of steel bridges is improved by cross frames, which provide restraint at discrete locations along the girder length. To provide adequate bracing, both strength and stiffness requirements must be satisfied. Although there are a variety of potential geometries, many cross frames are fabricated using steel angles to form an X-type brace with top and bottom struts and two diagonals. The cross frames are often sized based upon a tension-only design due to the low buckling strength of the diagonal angle members. This approach neglects the resistance supplied by the compression diagonal thereby increasing the amount of steel required for the tension diagonal.

Improved cross frame behavior may result by using tubular members, which have a relatively large buckling strength. The increased compression capacity of tubular members allows the use of single diagonal cross frames to provide effective bracing.

To verify the structural adequacy of using a single diagonal tubular cross frame, the Texas Department of Transportation sponsored a research investigation at the University of Texas at Austin focused on developing viable cross frames composed from tube shapes. This paper outlines a comparison of the use of tubular members versus angle members for cross frames used in bridge systems. The study consists of finite element analyses, and offers a method for sizing the tubular members for a single diagonal cross frame.

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. 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 the girders to translate or rotate as a unit.

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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.

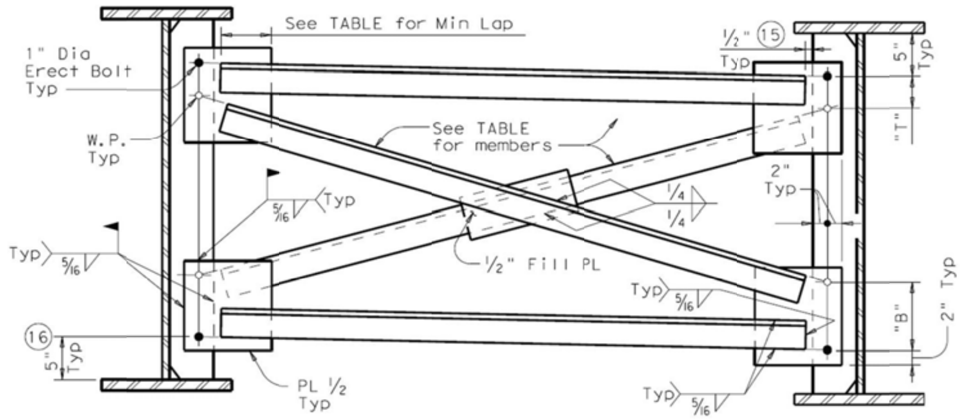

Figure 1: TxDOT Standard Detail for X-Type Cross Frame (TxDOT 2006)

Due to the relatively poor buckling resistance of 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 to construct the cross frame. Tubular members have significant buckling strength, which makes the tube efficient in both tension and compression. Thus, a single diagonal cross frame with tubular members can provide an effective brace for the steel bridge girders. The use of four steel angles often necessitates multiple rotations of the cross frame during fabrication to accommodate weld placement at numerous connections, including a spacer plate used to connect the two diagonals. By reducing the number of cross frame members, handling requirements in the fabrication shop should be reduced. Figure 2 shows an example of a single diagonal tubular cross frame.

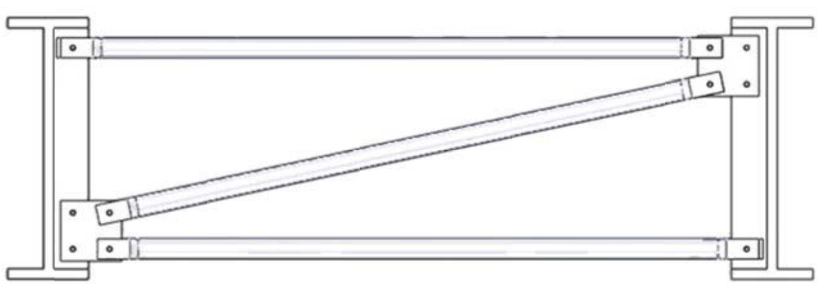

Figure 2: Single Diagonal Tubular Cross Frame

2. Cross Frame Stiffness

The concept of using a single diagonal cross frame stems from the tension-only system that is commonly used to model these braces in bridges. In all brace configurations, girder twist induces a torsional restraining moment from the cross frame, Fh_b. The torsional moment is represented by a force couple applied at the top and bottom of the brace (see Figure 3).

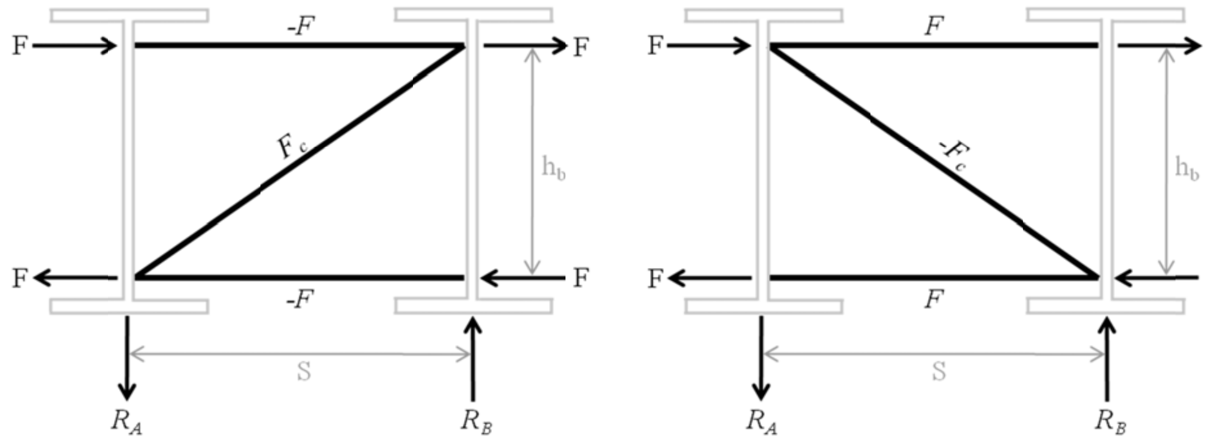

Figure 3: (a) Tension-Only System and (b) Compression System

Considering the cross frame as a truss member system, the forces that result on the cross frame as a result of girder twist are depicted in Figure 3 along with the corresponding internal forces. Static equilibrium on the cross frame system produce the following expressions for the resulting shears on the cross frame (R_A and R_B) and force in the diagonal, F_c:

$$R_A = R_B = \frac{2Fh_b}{S} \tag{1}$$

$$F_c = \frac{2FL_c}{S} \tag{2}$$

where h_b is the brace height, S is the girder spacing, and L_c is the length of the diagonal. Following the derivation provided by Quadrato (2010), a deflection analysis on the tension-only system can be performed to determine the rotation of the cross frame, and ultimately the brace stiffness is (in accordance with the formula given by Yura (2001)):

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

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, A_c is the area of the diagonal member, and A_h is the area of each strut. Eq. 3 assumes that the ends of the cross frame members are pinned. In the real cross frame system however, the members do not have the idealized pinned connections, but experience some bending due to connection restraint. As the girder cross section twists, the individual cross frame members bend in reverse curvature, provided the brace height extends above the mid-height of the girder (Quadrato 2010). To include this effect in the brace stiffness, the individual bending stiffness of the members is added to the axial stiffness of the members to provide the following expression for the cross frame torsional stiffness:

$$\beta_{br} = \frac{E h_b^2 S^2}{\frac{2L_c^3}{A_c} + \frac{S^3}{A_h}} + 2\frac{6EI_{strut}}{S} + \frac{6EI_{diagonal}}{L_c} \quad (4)$$

where I_{strut} is the moment of inertia of each strut and $I_{diagonal}$ is the moment of inertia of the diagonal.

Finally, to determine the total torsional brace stiffness, the following equation is offered by Yura (2001), modified to include connection stiffness (Battistini 2009):

$$\frac{1}{\beta_T} = \frac{1}{\beta_{br}} + \frac{1}{\beta_{\sec}} + \frac{1}{\beta_{girder}} + \frac{1}{\beta_{connection}} \quad (5)$$

where, β_T is the total torsional brace stiffness, β_{br} is the stiffness of the cross frame, β_{sec} is the stiffness of the web cross-section including any stiffeners, β_{girder} is the in-plane stiffness of the attached girder, and $\beta_{connection}$ is the stiffness of the plates connecting the brace to the girder. Expressions for β_{sec} and β_{girder} are provided in Yura (2001), while Quadrato (2010) provided expressions for $\beta_{connection}$.

3. Cross Frame Design

For straight girder systems, the current Texas Department of Transportation (TxDOT) design procedure for cross frames makes use of typical sizes that are often conservative compared to the braces that are required. Based upon the girder spacing and depth, the engineer selects an appropriate size member for the cross frame layout. Once the geometry has been finalized, computer models are used to verify the cross frame layout and the cross frame members are adequate.

The TxDOT standard plans provide three typical angle sizes for cross frames (TxDOT 2006). The angle properties are given in Table 1 along with the capacity calculated assuming A36 Grade steel and including a 0.9 safety factor (ϕ_t) for a tension member (AISC Steel Construction Manual 2005).

Table 1: Standard Angle Sizes and Properties

Angle Size	Area	Tension Capacity
L4 x 4 x 3/8	2.86 in^2	92.7 k
L5 x 5 x 1/2	4.75 in^2	154 k
L6 x 6 x 9/16	6.45 in^2	209 k

The angle sizes listed in Table 1 are to be used for X-type cross frames for web depths of 52 in to 96 in with varying spacing (TxDOT 2006). Since the angle cross frames are designed as tension-only systems, a single diagonal tube replaces two angle diagonals in the proposed single diagonal cross frame. The strength of the tube will be controlled by the buckling strength, which is generally less than the tensile yield strength, unless the connection strength controls the capacity.

In order to develop a preliminary design for a single tubular diagonal, the column strength tables from the AISC Manual (2005) were used. Since these tables include a 0.9 safety factor (ϕ_c) for compression, the values obtained are directly comparable to those in Table 1. To size the tubular member, an effective length factor (K) of 1.0 was used. Therefore, the unbraced length was set equal to the diagonal length (L_c). If a 10 ft girder spacing is used, the calculated diagonal length ranges from 10.9 ft to 12.8 ft, corresponding to a web depth of 52 in to 96 in. In actuality, these diagonal lengths will be less than those calculated since the diagonal does not connect at the web-to-flange interface (see Figure 1 for typical offsets). Table 2 presents square and round tubular members with compression capacities that are comparable to the tension capacities of the TxDOT standard angle sizes for the 96 in web depth condition. These tube sizes were used in finite element analyses, the results of which are presented in the remainder of this paper.

Table 2: Angle Tensile Strength vs. Tube Buckling Strength

Angle Size	Angle Capacity (36 ksi)	Tube Size	Tube Capacity[1,2]
L4 x 4 x 3/8	92.7 k	HSS 5 x 5 x 3/16	88.6 k
		HSS 5.563 x 0.258	99.6 k
L5 x 5 x 1/2	154 k	HSS 5 x 5 x 3/8	160 k
		HSS 5.563 x 0.375	139 k
L6 x 6 x 9/16	209 k	HSS 5 x 5 x 1/2	199 k
		HSS 6.000 x 0.500	207 k

1. Tube capacity was calculated using a length of 13 ft
2. Yield stress (F_y) is assumed to be 46 ksi for square tubes and 42 ksi for round tubes (AISC 2005)

4. **Finite Element Analysis for Cross Frame Stiffness**

4.1 Line Element Cross Frame Model

Commercial programs often simplify the analysis of cross frames by using line elements to represent the cross frame geometry. When modeling a tension-only cross frame, a single diagonal is typically used since the two-node line elements are equally stiff in compression or tension.

However, as finite element models of steel bridges become more readily used, it is prudent to determine if the line element model accurately portrays the torsional stiffness provided by the braces. Models consisting of only the cross frame were constructed with both line elements and shell elements using the three-dimensional finite element program ANSYS® (Academic Research, Release 11.0, 2010). The line element model used three-dimensional linear finite strain beam elements (BEAM188), based on Timoshenko beam theory and including shear deformations, with six degrees of freedom at each node (ANSYS 2010). The elements allow the cross-section geometry to be input by the user for calculation of the member properties. Figure 4a shows the cross frame model with only the lines shown while Figure 4b displays the member cross-section.

In performing the analysis of the line element cross frame, the deflection of the node where the diagonal and bottom strut meet was restrained against vertical and horizontal deflection. The deflections of the other nodes were restrained against vertical movement, which assumes the cross frame will experience small rotations only. All nodes were restricted from out-of-plane deflection, which is consistent with the planar interpretation of this problem. These boundary conditions are the same as those used in the derivation of the axial stiffness of the brace given by Eq. 3 and allow direct comparisons between the finite element brace stiffness and the analytical solution.

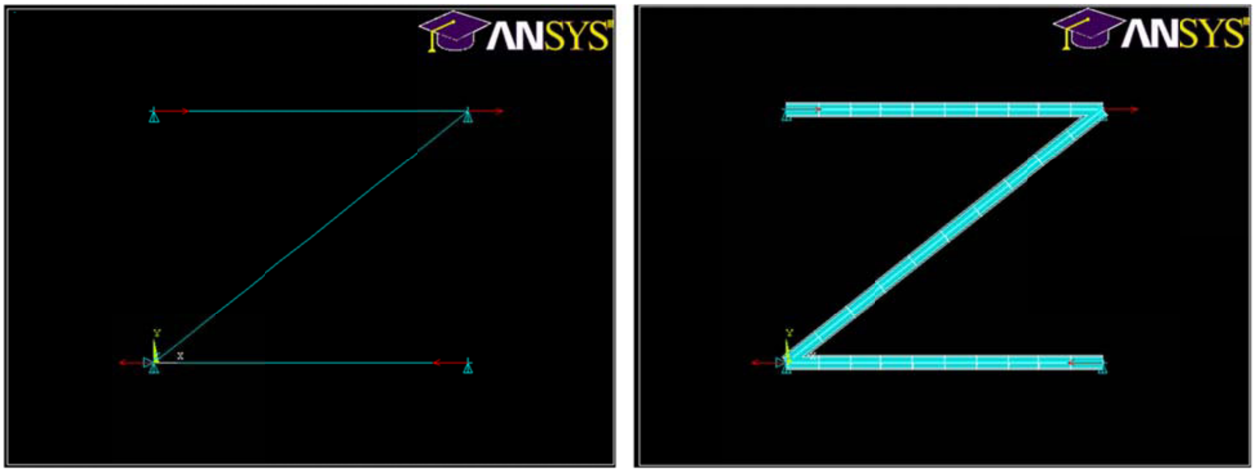

Figure 4: Line Element Cross Frame Model (a) without and (b) with Member Cross-Section Displayed

Several linear elastic static analyses were conducted with the line element model using the properties of the angle members, square tubes, and round tubes listed in Table 2. The results of these analyses are tabulated in Table 3.

Table 3: Line Element Cross Frame Stiffness- Comparison to Analytical Solution

Type	Member Size	Web Depth = 52″			Web Depth = 96″		
		ANSYS (10^6 k-in/rad)	Analytical[1] (10^6 k-in/rad)	Error (%)	ANSYS (10^6 k-in/rad)	Analytical[1] (10^6 k-in/rad)	Error (%)
Angle	L 4 x 4 x 3/8	0.520	0.521	0.00	1.225	1.225	0.01
	L 5 x 5 x 1/2	0.865	0.865	0.01	2.035	2.034	0.02
	L 6 x 6 x 9/16	1.171	1.171	0.01	2.756	2.755	0.02
Square Tube	HSS 5 x 5 x 3/16	0.657	0.657	0.01	1.546	1.546	0.04
	HSS 5 x 5 x 3/8	1.263	1.263	0.01	2.972	2.971	0.04
	HSS 5 x 5 x 1/2	1.639	1.639	0.01	3.856	3.854	0.03
Round Tube	HSS 5.563 x 0.258	0.782	0.783	-0.07	1.841	1.842	-0.04
	HSS 5.563 x 0.375	1.112	1.113	-0.07	2.616	2.618	-0.04
	HSS 6.000 x 0.500	1.572	1.573	-0.07	3.699	3.700	-0.04

1. The analytical cross frame stiffness was calculated using the nominal areas, not the areas provided in the AISC Manual, which include decreases due to fabrication methods and tolerances.

Reviewing the results, the finite element model with line elements accurately matches the analytical solution. Furthermore, when the line element cross frame model is switched to a compression diagonal system, the finite element program confirmed the supposition that under linear elastic behavior, the cross frame stiffness is the same as the tension diagonal system.

While line elements accurately match the analytical formulation, it is important to consider the behavior of the various cross-sections in the real structure. For instance, the member forces that result from force couple (F) acting on the cross frame are often eccentric to the center of gravity (C.G.) of the cross frame members as depicted in Figure 5. This eccentricity leads to bending in the member out-of-the-plane of the cross frame and may result in a decrease of the overall stiffness of the brace. Additionally, real cross frame dimensions will lead to a decrease in the angle the diagonal makes to the strut, potentially reducing its effectiveness. Shear lag effects in the connection may also prove detrimental.

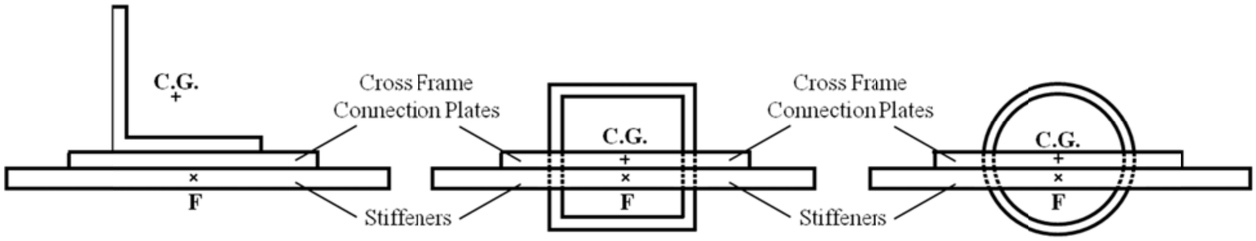

Figure 5: Cross Frame Eccentricity for (a) Angle Members, (b) Square Tube Members, (c) Round Tube Members

4.2 Shell Element Cross Frame Model

To better understand the cross frame behavior a shell element model was created. The steel plates and cross frame members were modeled using 8-node shell elements (SHELL93) with six degrees of freedom at each node (ANSYS 2010). Shell elements have been used in previous research to model the flat steel plates that constitute most girders and cross frame assemblies (Helwig 1994, Wang 2002, Whisenhunt 2004, and Quadrato 2010). In addition to flat plates, the mid-side nodes of the shell element make it well suited to model curved plates (ANSYS 2010).

Rigid beam multipoint constraint elements (MPC184) with six degrees of freedom at each node were used to model the welds connecting the members of the cross frame to the connection plates, as well as the welds between the connection plates and the stiffeners. These constraint elements have nonlinear geometry capabilities and have been used successfully in previous research to model welds between overlapping plates of varying mesh densities (Quadrato 2010).

4.2.1 Cross Frame Model Validation

To validate the shell element cross frame model, analyses were first conducted with the same geometry used in the line element cross frame model described in the previous section. The force and displacement boundary conditions also remained constant, with the exception of the member end constraints. To eliminate shear lag in the members, the nodes at the very end cross-section of each member were constrained to each other using the multipoint constraint elements. The ensuing analyses showed the shell element cross frame model produced comparable results to the analytical solution, with the model being within 5% of the calculated stiffness.

4.2.2 Comparison of Cross Frame Stiffness

With the simplified shell element cross frame model successfully validated, it is desirable to construct a more accurate geometric model that includes the effects of shear lag in the connections and of out-of-plane displacements introduced by the force eccentricity. The brace stiffnesses recovered from the finite element analyses will be compared to the stiffness calculated using the analytical solution of Eq.3 (which are the same stiffnesses found using the line element cross frame model). However, since the shell element model connects the cross frame members through a moment resisting connection using the multipoint constraint elements, the resulting cross frame deformation will bend the horizontal struts and diagonal in reverse curvature. Therefore, the resulting model stiffnesses will be compared to the analytical solution of Eq.4, which includes the bending stiffnesses of the members.

Moreover, because the shell element cross frame model included the stiffeners and connection plates, the total brace stiffness recovered from ANSYS reflected these additions, as given in Eq. 5. However, the stiffness of the web-section (β_{sec}) and of the connection ($\beta_{connection}$) was taken as near infinity by applying a large modulus of elasticity to the stiffeners and the cross frame connection plates. Thus, the stiffness recovered from the finite element program can be compared to the analytical solution.

In terms of cross frame geometry, the shell element cross frame model uses dimensions consistent with the values given on the TxDOT standard detail shown in Figure 1 (TxDOT 2006). The force couple induced by the girder twist was applied close to the centroid of the top and bottom struts. Vertical and horizontal deformation constraints were the same as those applied in the line element cross frame model. For comparison with the analytical solution, all out-of-plane deformations were restrained. Results from the analyses are given in Table 4.

Table 4: Shell Element Cross Frame Stiffness- Comparison to Analytical Solution

Type	Member Size	Web Depth = 52″ (h_b = 37.25″)			Web Depth = 96″ (h_b = 82.19″)		
		ANSYS (10^6 k-in/rad)	Analytical[1,2] (10^6 k-in/rad)	Difference (%)	ANSYS (10^6 k-in/rad)	Analytical[1,2] (10^6 k-in/rad)	Difference (%)
Angle	L 4 x 4 x 3/8	0.299	0.395	-24.4	1.284	1.297	-1.02
	L 5 x 5 x 1/2	0.461	0.656	-29.8	2.064	2.208	-6.55
	L 6 x 6 x 9/16	0.570	0.891	-36.1	2.736	3.063	-10.7
Square Tube	HSS 5 x 5 x 3/16	0.378	0.518	-27.4	1.534	1.697	-9.59
	HSS 5 x 5 x 3/8	0.716	0.991	-27.7	2.997	3.257	-7.98
	HSS 5 x 5 x 1/2	0.930	1.281	-27.4	3.870	4.219	-8.28
Round Tube	HSS 5.563 x 0.258	0.400	0.602	-33.6	1.755	2.034	-13.7
	HSS 5.563 x 0.375	0.560	0.857	-34.6	2.504	2.891	-13.4
	HSS 6.000 x 0.500	0.780	1.217	-35.9	3.494	4.135	-15.5

1. The analytical cross frame stiffness was calculated using the nominal areas, not the areas provided in the AISC Manual, which include decreases due to fabrication methods and tolerances.
2. The analytical cross frame stiffness also uses the actual height of the brace (h_b), and the length of the strut is used in place of the girder spacing.

In general, the shell element cross frame model predicts lower stiffness than the analytical solution. For shallow cross frames, this stiffness is as much as 36% less than calculated, while deeper cross frames were found to be a maximum 16% lower. One reason the values of the stiffness of the shell element models are less than the analytical solutions is likely due to shear lag in the connections, which is modeled by welding the nodes of the cross frame members which are in contact with the connection plate (as would be represented by a welded connection). By not engaging the entire cross-section at the end of the members, the overall stiffness of the system is reduced. Additionally, the decrease in the angle of inclination of the diagonal is more pronounced in the shorter cross frames, perhaps minimizing the effectiveness of the diagonal.

4.2.3 Tension-Only Cross Frame Behavior: Angle Members

Using the same shell element cross frame model, the effect of out-of-plane deformations on the cross frame system, caused by the eccentricity of the connections (shown in Figure 5), was explored. In accordance with the TxDOT standard details, a connection plate thickness and stiffener thickness of 0.5 in was used with E = 29000 ksi (TxDOT 2006). Results for a web-depth of 96″ are presented.

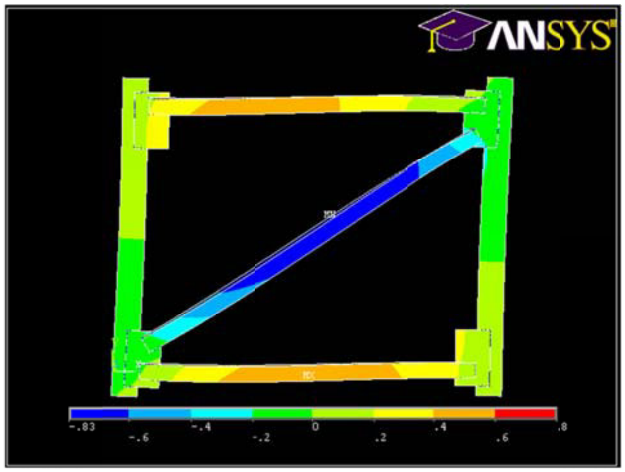

Figure 6: Deflected Shape of Tension-Only Angle Cross Frame with Out-of-Plane Displacements Allowed (Max = 0.83″)

Figure 6 shows the deflected shape for a tension-only cross frame system with L 5 x 5 x 1/2 angle members. It is evident that the angle diagonal, even under a tensile load, experiences significant out-of-plane displacements due to the force eccentricity. In fact, under an applied load creating a calculated force in the diagonal (see Eq.2) near its yield capacity (154 k), the out-of-plane displacement perpendicular to the plane of the cross frame near mid-length of the diagonal was almost 0.83 in (out-of-plane displacement is plotted in Figure 6).

Not only does the cross frame experience large deflections, the stiffness is drastically reduced. The finite element stiffness for the L 5 x 5 x 1/2 member given in Table 4 is 2.064 x 10^6 k-in/rad. By including out-of-plane effects and using the TxDOT standard plate thicknesses, the brace stiffness is reduced to only 0.756 x 10^6 k-in/rad, which is only 36.6% of the original ANSYS predicted stiffness (63.4% reduction), and 34.2% of the analytical stiffness (65.8% reduction). The flexibility of these angle members are of particular concern when considering the fatigue category of this detail, which is also one of the motivations behind exploring the use of tubular members.

4.2.4 Tension and Compression Cross Frame Behavior: Angle Members

While the tension-only cross frame with angle members experiences significant decreases in stiffness due to the inclusion of out-of-plane effects, the tension-only model of cross frame behavior may be overly-conservative. In reality, since the two angles are typically joined at mid-length, the tension diagonal provides significant restraint to the compression diagonal. Using the finite element model, a compression diagonal was included to determine the stiffness of the combined system shown in Figure 7. Also depicted in Figure 7 is the magnitude of the out-of-plane displacement at the force level when the tension diagonal reaches the yield strength (compare to Figure 6b).

From the analysis, the combined model has a stiffness of 1.765 x 10^6 k-in/rad, which is approximately 80% of the analytical solution of 2.208 x 10^6 k-in/rad. Compared to the tension-only model with planar behavior and stiffness of 2.064 x 10^6 k-in/rad, the combined system is

86% of the ANSYS predicted stiffness. While only the results for the L 5 x 5 x 1/2 angle member are discussed, the other TxDOT standard angle sizes showed similar results.

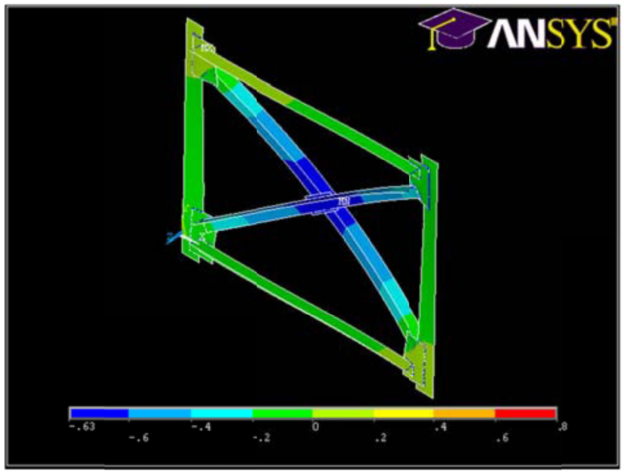

Figure 7: Out-of-Plane Deflection of Angle Cross Frame with Two Diagonals (Max = 0.63″)

4.2.5 Tension-Only Cross Frame Behavior: Tubular Members

Using the validated shell element cross frame model, out-of-plane effects were also considered on the single-diagonal system utilizing tubular members that have significant strength in both tension and compression. Again, in accordance with the TxDOT standard details, a connection plate thickness and stiffener thickness of 0.5 in was used (TxDOT 2006).

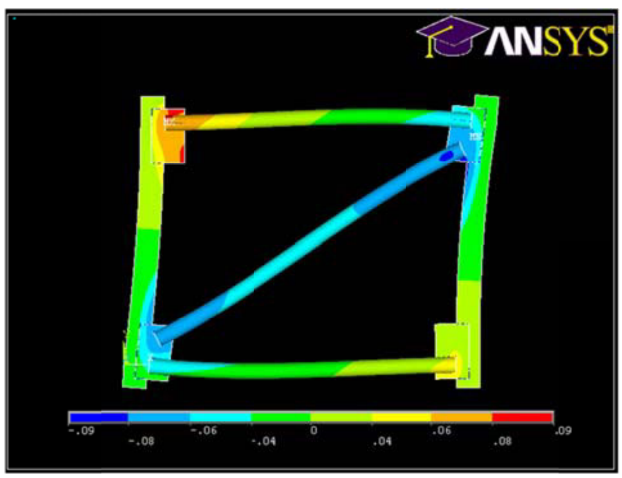

Figure 8: Deflected Shape of Tension-Only Round Tube Cross Frame with Out-of-Plane Displacements Restricted

The reduced eccentricity of the tubular members compared to similar angle systems results in a reduction in the out-of-plane displacement of the cross frame. Figure 8 shows the relative behavior of the tubular cross frame for unrestricted out-of-plane deformation subjected to the same force described in Section 4.2.3 and represented in Figure 6 and Figure 7. The maximum displacement in the tubular brace was approximately 0.09 in, which is essentially an order of magnitude less than observed for the single-diagonal and double-diagonal angle cross frames.

4.2.6 Compression Cross Frame Behavior: Tubular Members

There is concern that as the force in the compression diagonal nears the buckling capacity of the member, the member deformations will increase dramatically thereby decreasing the cross frame stiffness. The use of tubular members to provide effective cross frames necessitates the compression resistance of the tube diagonal exceeds the force required to resist the brace moment induced in the cross frame. To verify the structural integrity of the brace, a nonlinear, large displacement finite element analysis was conducted on the compression diagonal, tubular cross frame geometry. Initial imperfections of 1/500 of the member length were applied in the analysis and rigid stiffeners and connections were assumed. By plotting the finite element brace stiffness versus the calculated force in the compression diagonal (Eq.2), the behavior of the compression diagonal system can be assessed (see Figure 9).

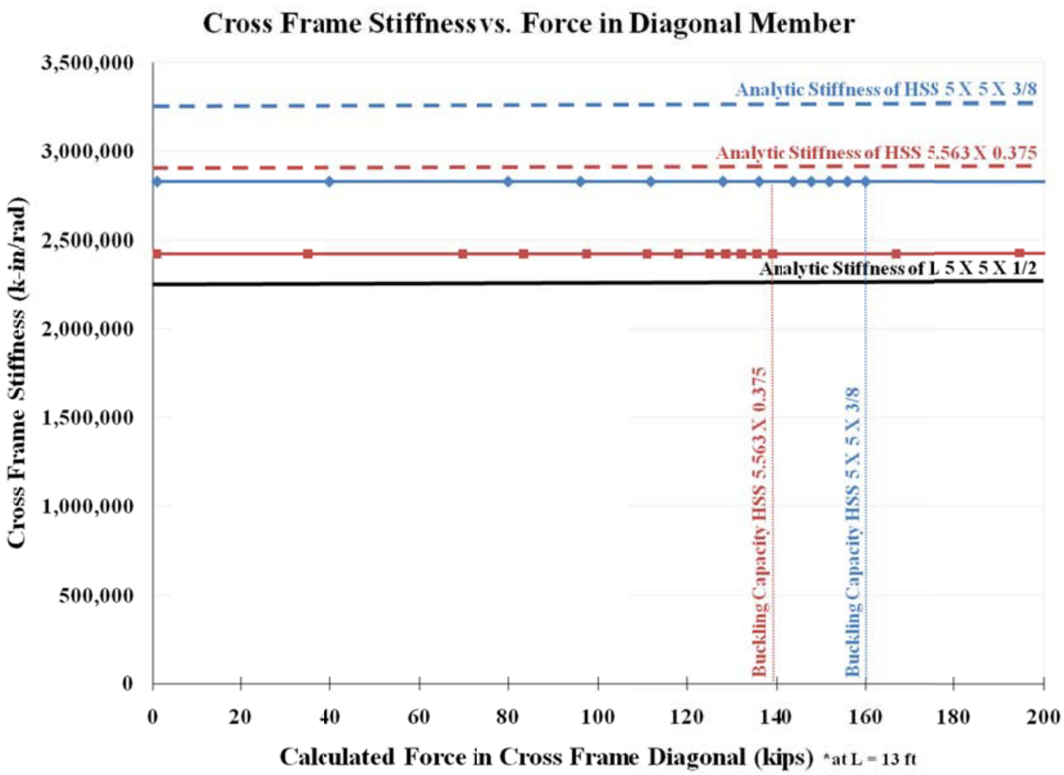

Figure 9: Finite Element Cross Frame Stiffness vs. Calculated Force in the Compression Diagonal

From the plot in Figure 9, it is observed the cross frame stiffness does not vary significantly as the force in the compression diagonal nears the pinned-end buckling capacity for both the square and round tube systems (HSS 5 x 5 x 3/8 and HSS 5.563 x 0.375 members, respectively). While the ANSYS predicted stiffnesses for these members are lower than the analytical solutions (as discussed in Section 4.2.2), the stiffnesses for the compression diagonal are consistent with those obtained for the tension diagonal (given in Table 4), with a slight decrease of 3-5% due to the application of the initial imperfection. By using the design method set out in Section 3 of this paper, the brace stiffness at the tube capacity given in Table 2 exceeds the brace stiffness calculated using the corresponding angle member cross frame. One potential explanation as to the strength of the tube in compression is the diagonal was sized using the girder spacing and web-depth rather than the actual length of the diagonal, which is shorter. Secondly, the buckling capacity was based on that for pinned ends while the actual connection provides some joint restraint.

Conclusions

Line element and shell element cross frame models can be very useful in understanding cross frame stiffness behavior. When considering the planar cross frame problem, these models produce values of the brace stiffness within reasonable accuracy of the available analytical solutions. However, by more accurately modeling the cross frame geometry and including effects such as shear lag in the connections and out-of-plane deformations, preliminary finite element analyses predicted brace stiffnesses that were significantly less than those calculated using the analytical solutions.

Using the shell element model to compare out-of-plane deformations, it was observed the deformations for the tubular cross frame system were an order of magnitude less than for the angle cross frame system, even when including both the tension and compression angle diagonals. One contributing factor to the reason angle cross frames may still provide adequate bracing is that the inclusion of the compression angle helps to increase the cross frame stiffness, relative to the tension-only system.

Finally, when considering the compression diagonal tubular cross frame system, the brace stiffness decreases as the force in the diagonal approaches the buckling load of the member. However, by following the proposed method for sizing the tubular diagonal, the axial brace stiffness of the tubular cross frame system still exceeds the corresponding angle system.

Acknowledgments

The authors would like to thank the Texas Department of Transportation for sponsoring this project to improve cross frame details in steel bridges as well as for their continued support of research at the University of Texas. We would also like to recognize Michelle Romage who serves as the project director for TxDOT.

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