Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Orlando, Florida, April 12-15, 2016

The Impact of Girder Geometry and Bracing Details on the Stability of Steel Tub Girder

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Abstract

Steel tub girders (trapezoidal box girders) are often used in straight and horizontally curved bridges due to their aesthetic potential as well as large torsional stiffness of the composite closed-box section. However, while the girders are stiff in the fully constructed condition, extensive bracing is necessary during construction to improve the torsional stiffness of the girders. The commonly used bracing systems consist of a top lateral truss as well as internal and external cross frames or diaphragms, both of which are relatively expensive to fabricate. This paper documents preliminary results of an ongoing research project focused on improved details for bracing in trapezoidal box girder systems. The study consists of parametric finite element analyses and laboratory testing. The modifications to existing details include the alteration of both the girder geometry and bracing layout. While both of these modifications can improve the efficiency of the fabrication, there are also significant concerns on the impact on the global and local stability of the girders during construction. This paper documents the results to date on the research study focused on evaluating the impact of geometrical and connection details on the stability performance of the girders.

1. Introduction

Steel tub girders such as those shown in Figure 1 are a form of built-up girders consisting of two top flanges and two sloping webs joined by a common bottom flange. The girders have been widely used for straight and horizontally curved highway bridges. During construction, the open girders are a torsionally-flexible steel section that requires extensive bracing to resist the loads applied during erection and construction. The braces help to control the buckling of individual girders as well as improving the system lateral or torsional stiffness both during construction and in service. In many cases, the absence of proper bracing has caused local or global bridge failures due to instabilities. The lack of a top lateral diagonal truss resulted in the 2002 Marcy pedestrian bridge

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collapse during construction in New York, leading to casualties and economical loss. When the concrete deck placement progressed to approximately mid-span, the tub girder failed by lateral torsional buckling.

Figure 1: Bracing Systems for Twin Tub Girders During Construction

Offset in strut/internal K-frame **Large gusset plate utilized so working lines intersect**

Excessive use of internal K-frames. **Excessive use of external K-frames.**

Figure 2: Inefficient Tub Girder Bracing Details

One of the inefficiencies with the bracing systems that are utilized in tub girders is that much of the bracing is primarily necessary during construction. Although the many of the braces do not play a significant role in the final bridge, the resulting connection fabrication can significantly increase the cost of the girders. The problem is exacerbated by poor details that lead to expensive and inefficient connections in the girders. Complex connection geometry and excessive bracing and gusset plates are sometimes used in tub girders (Fig. 2) (Helwig and Yura 2012). Furthermore, the AASHTO design provisions for tub girders can result in limitations on the cross-section proportion and bracing details providing no well-documented research evidence or study results of the tub girder buckling behavior. All these factors can reduce the efficiency and competitiveness of a tub-girder systems compared to other bridge types. To augment the viability of tub girders, the Texas Department of Transportation has sponsored a research study to improve the understanding of the behavior of tub girders and to enhance the economic and structural advantages through improved detailing. This paper documents the results of the ongoing study that has focused on parametric finite element studies on the impact of different girder geometric parameters and bracing details on the stability of steel tub girder. The results to date have been used to proportion test specimens that will be used in full scale laboratory tests.

2. Torsional Stiffness of Steel Tub Girders

Lateral-torsional buckling (LTB) is a failure mode that is often critical for steel girder systems during construction. The failure mode can control tub girders if insufficient bracing is utilized. The top lateral trusses create a quasi-closed girder and significantly increase the torsional stiffness so that LTB is not a concern. Based on the Equivalent Plate Method (Kollbrunner and Basler 1969), the top lateral truss system can be simulated as a fictitious plate and thickness of the plates can be determined for different bracing layout so that the torsional properties of the box can be approximated during the structural analysis. The improvement of the torsional stiffness is reflected in the torsional constant as shown in Table 1. The stiffness of a quasi-closed box girder can be more than 1000 time larger than a comparable open section, due to the larger torsional constant. While the role of the top lateral truss is clear in horizontally curved girders that experience large torsion, the role is not as clear in straight girder applications. For straight girders, the role of the top lateral bracing requires further clarification to define the bracing necessary to control LTB.

Table 1: Torsional constant J

Open section[1]	Closed section[2]
$J = \frac{1}{3}\sum_i b_i t_i^3$	$J = \frac{4A_0^2}{\sum_i b_i t_i}$

1. b_i and t_i are the respective width and thickness of the plate elements.
2. A_0 is the enclosed area of the cross section of the tub girder, and the denominator is the summation the width-to-thickness ratios of each plates

The warping torsional component can be expressed as:

$$T_W = EC_W \frac{d^3\phi}{dx^3} \tag{1}$$

where E is the modulus of elasticity, and C_W is the warping constant. Warping constant C_w of tub section can be determined following the process developed by Widianto (2003). Considering the sections shown in Figure 3, the effect of the top lateral truss on the section torsional properties are represented in Table 2. In the example, the equivalent plate thickness t_{eq}=0.05 in. with a Warren-type W4×12 for top diagonal and 2 in. diameter pipe for the strut. Reviewing the properties in Table 2, the torsional constant, *J,* for the quasi-closed section in this example is 2240 times greater than the open-section torsional constant.

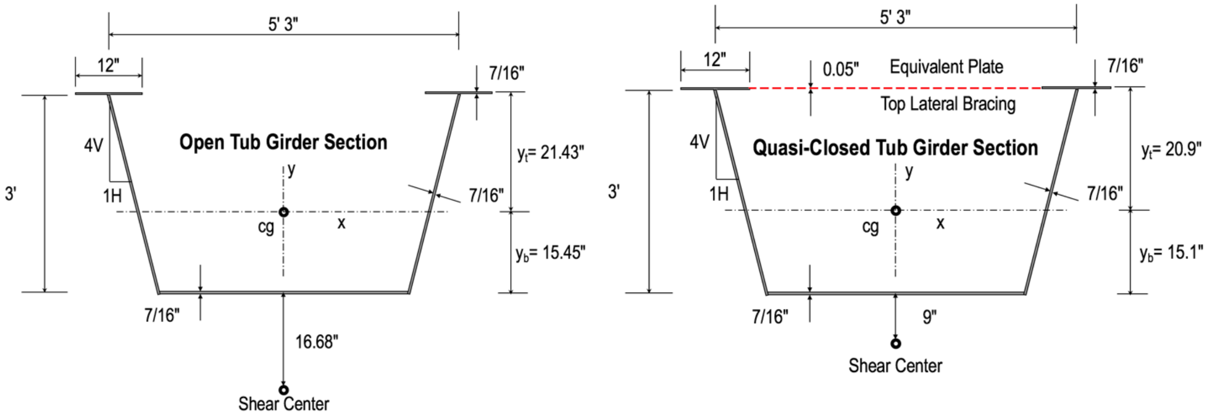


Figure 3: 84ft. Steel Tub Girder Model 1 Cross Section and Shear Center Location

Table 2: Numerical Example of Tub Girder Section Torsional Properties

Section Property	I_x -in^4	I_y -in^4	J -in^4	C_w -in^6
Open Section	1.37×10^6	4.22×10^4	4.0	4.28×10^6
Quasi-Closed Section	1.38×10^6	4.22×10^6	8950	2.29×10^6

The girder cross section shown in Figure 3 was used in the initial finite element analysis that is presented later the paper. This example indicates that the St. Venant torsional stiffness dominates the behavior of quasi-closed tub girders. For either a quasi-close tub girder or a fully composite tub girder, the behavior is dominated by Saint-Venant torsion due to the closed cross section. Due to the very large torsional stiffness of the closed sections, LTB is not generally a concern in the girders. However, for straight tub girders, the necessity of providing the top lateral truss all along the girder length is not clear. Improved efficiency may be obtained by providing the top truss at selected regions where it is the most efficient. However, the LTB behavior of the tub girders are not well understood, particularly with only partial bracing.

2.1 Buckling behavior of Steel Tub Girder

Two possible stability limit states for tub girders include local and global (LTB) buckling. Local buckling depends only on the dimension of compression elements in the cross section. While the local buckling can be controlled by limiting the slenderness ratio of the compression elements, very little guidance is provided on the LTB behavior of the tub girders. A typical tub girder cross section as shown in Fig. 3, is singly symmetric about its vertical axis and primarily bent about its weak axis because I_y / I_x=3. In the absence of a top lateral truss, this section is prone to lateral instability because of the small top flanges and the shear center location. Based on the formula for critical moment of a singly-symmetric section subject to uniform moment (Galambos 1968), the elastic lateral buckling capacity for tub girders is given by the expression below:

$$M_{cr} = \frac{\pi^2 E I_y}{L_b^2}\left[\frac{\beta_x}{2} \pm \sqrt{\frac{\beta_x^2}{4} + \frac{GJ}{EI_y}\left(\frac{L_b}{\pi}\right)^2 + \frac{C_W}{I_y}}\right] \tag{2}$$

where β_x is the mono-symmetric constant associated with section symmetry and L_b is the unbraced length. For tub girders, β_x is negative since the top flange area is less than the bottom flange area.

In the positive moment region (top flanges in compression), the plus sign will be used in front of the radical term.

There are several factors that may affect the direct application of Eq. 2. First, this equation was derived for uniform moment loading case. For cases with moment gradient, a moment gradient factor (C_b) is often applied to the uniform moment solution. The impact of moment gradient on the behavior of tub girder sections has not been widely studied, nor has the impact of load position. Another unclear condition in the use of Eq. 2 is the value of L_b that should be used.

2.2 Impact of Tub Girder Details on Structural and Fabrication Efficiency

From Eq. 2, it can be concluded that the global stability of the tub girder system can be improved by either altering the girder geometry or by providing an effective bracing system to reduce the unbraced length of the girders.

2.2.1 Girder Geometry-Web Slope

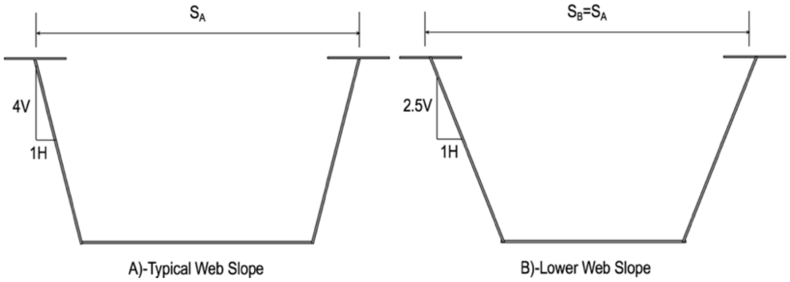


Figure 4: Tub Girder Web Slope

AASHTO Sections 6.11.2.1.1 allows both vertical and sloped webs. The web slope is limited to a ratio no less than 4V:1H (4 Vertical to 1 Horizontal) as depicted in Fig. 4A. The AASHTO Commentary (2014) attributes the use of sloped web to reduce the width of bottom flanges. AASHTO Section 6.11.2.3 provides some further explanation on this restriction of web slope associated with the use of the live load distribution factor in the simplified analysis method. If a refined analysis approach is used, this restriction may not apply (Chavel & Carnahan 2012). One possible alternative would be to use of a lower web slope keeping same top flange separation, such as the 2.5V:1H slope depicted in Fig. 4B. The benefits of using a lower web slope is to increase the cover width of the girder relative to the bridge width. In bridges that utilize several tub girders across the width, the flatter web slope may result in fewer girder required.

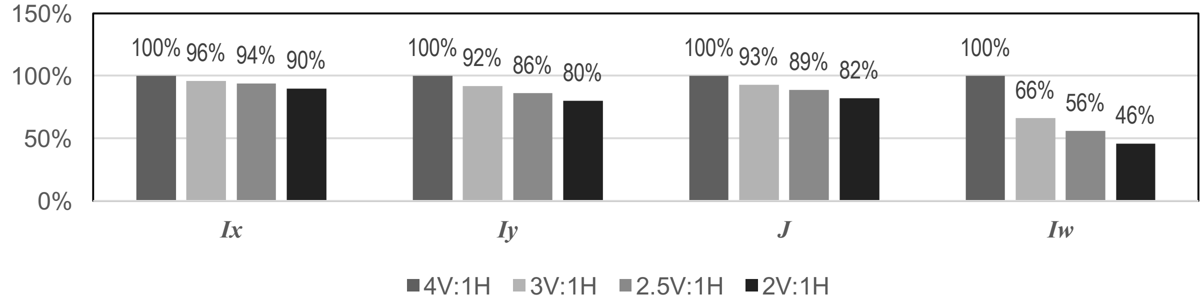
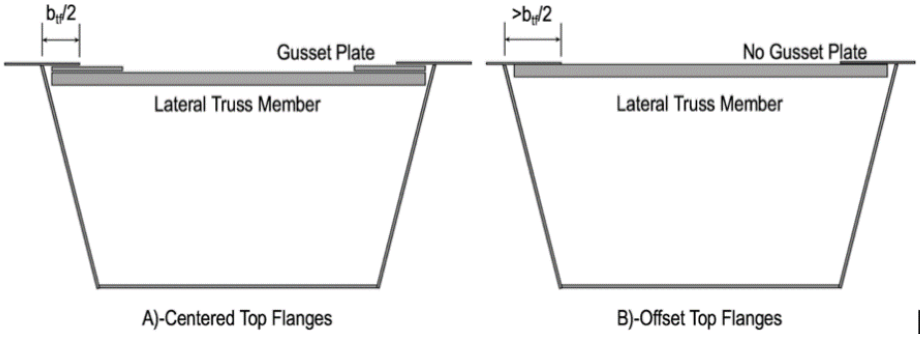


Figure 5: Tub Girder Section Properties with Various Web Slopes

As presented in Fig. 5, compared to the section properties of tub girder with standard web slope, the moment of inertia I_x merely decreases by 4~6% with a lower web slope, while moment of inertia I_y decreases by 8~20%. Web slope change has greater impact on the torsional properties of the section: the torsional constant J drops by 7~18% with a lower web slope, while the warping constant C_w can be reduced by up to 54%. The effect of web slope change on the buckling capacity will be shown in Section *3.2*.

2.2.2 Bracing Details

2.2.2.1 Bracing Connection Details-Top Flange Offset



A)-Centered Top Flanges

B)-Offset Top Flanges

Figure 6: Offset in Top Flanges

Typically, top lateral trusses are detailed such that the working lines of diagonals and struts intersect. Therefore, relatively large gusset plates as in Fig. 6A are required, which leads to poor load transfer and additional fabrication costs. A possible improvement would be to connect the top lateral truss members directly to the top flange. However, sufficient flange width is needed to achieve this connection detail. Because large flanges are not normally needed for construction moments, plate widths for the top flanges are often relatively small (b_{top} = 12 in. ~ 16 in.). AASHTO Section 6.11.2.1 specifies that the top flanges must be centered on the webs. This geometry requirement leaves only half of the top flange width ($b_{top}/2$) (Fig. 6A) available for the connection, which can create geometric problems in the connection fabrication. A potential enhancement of the top lateral bracing connections could be possible if the top flanges are offset towards inside of the box (Fig. 6B). The larger flange width over the inside of the web will provide much better efficiency in detailing a bolted (or welded) connection with the top lateral truss members. However, the larger length of the flange will obviously make the flange more susceptible to local buckling.

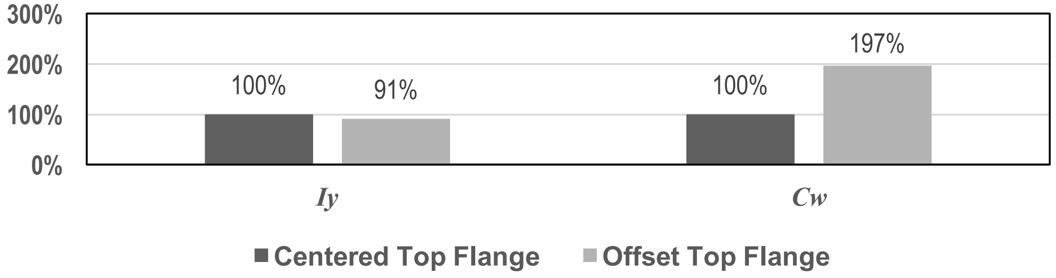


Figure 7: Section Properties Change with Top Flange Offset

From Fig.7, compared to the tub section with top flanges centered on the webs, moment of inertia I_y deceases by 9% and the warping constant is almost 2 times the original value. Therefore, the LTB may not be the limit state for section with top flange offset. However, local buckling issues of the top flanges can control the buckling behavior since offsetting the top flanges increases the unsupported top flange width. The effect of top flange offset is presented in Section *3.3*.

2.2.2.2 Bracing Layout

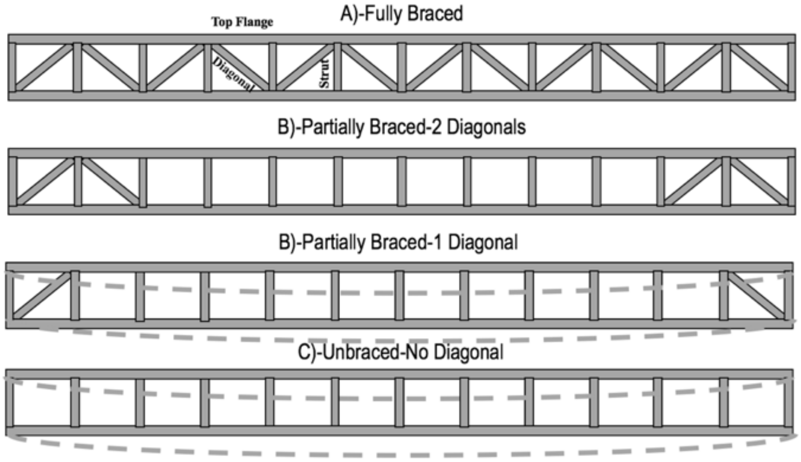
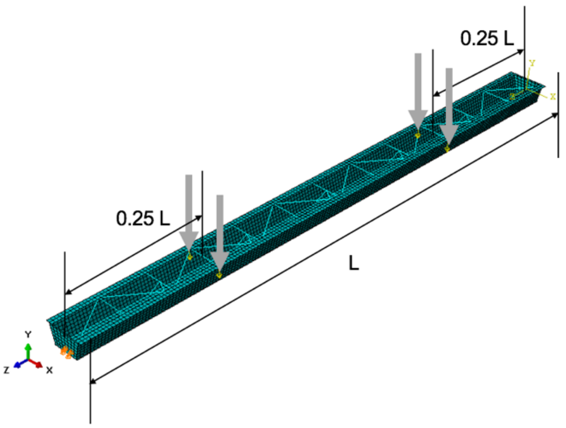


Figure 8: Reducing the Number of Top Diagonals Trusses

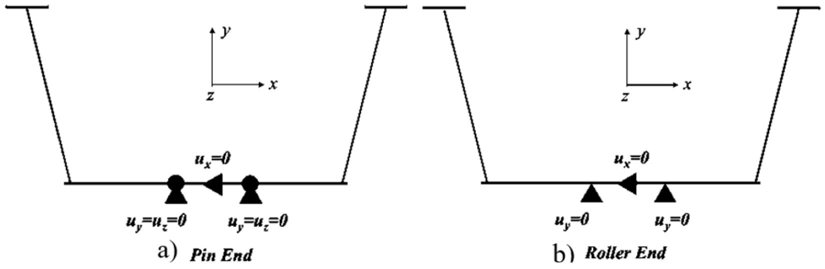
As noted earlier, the proper value of L_b can be difficult in tub girder since it is not clear of the role between the internal cross-frames, external intermediate cross-frames (if any) and the top lateral truss details. If a properly detailed top lateral truss is provided all along the length, LTB is not likely an issue due to the very large torsional stiffness of the girder as outlined earlier. However, in straight girder applications, the top lateral truss is not likely required all along the length. For horizontally curved applications, the top lateral diagonal braces are generally provided along the entire length as shown in Fig. 8A. However, partial top lateral bracing near the support ends as in Fig. 8B & C may be a more effective option for straight tub girder since the maximum shear deformations are developed near the end regions. The truss diagonals near the mid-span region do not significantly contribute to the LTB resistance of the tub. The dashed lines in Fig. 8B & C represent the likely buckled shape of a tub girder. The impact of different bracing configurations on the response of straight and curved tub girders is presented in Section *3.4.*

3. Finite element analysis

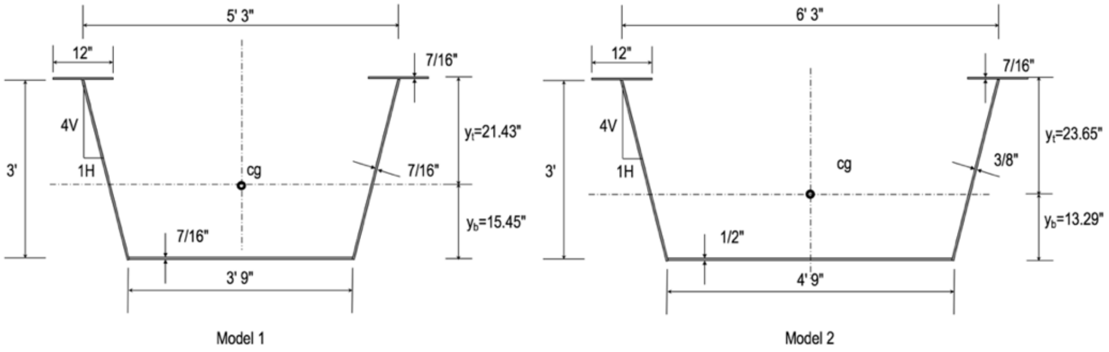
3.1 Finite Element Model Description



A)-3D Tub Girder Model



B)-Boundary Condition



C)-Model Cross Section Geometry

Figure 9: Finite Element Tub Girder Model in ABAQUS

Steel tub girder models were created using the commercial finite element program ABAQUS (ABAQUS 2014) as shown in Fig. 9. The tub girder model was composed of 4-node shell elements, ABAQUS type S4R. This type of element is suitable for modeling thin-walled structures and has a two-dimensional geometry with the thickness of the plate as an input. There were 2 elements on each top flange, 6 elements on each web and 8 elements on the bottom flange. 3D beam elements, ABAQUS type B31, were used for all the bracing members including top lateral diagonals, struts and internal K-frames. Section profiles and element orientation are defined for these of element. The models were simply supported. End diaphragms were provided at both ends to prevent section twisting and warping. The role of the first series of analyses was to assist in the design of a setup for full scale laboratory tests. The goal of the research was to test both straight and horizontally curved girders. Due to the high cost of horizontally curved girder, the decision was made to utilize straight girders and to offset the load by various amounts, leading to a torque on the girder systems. For a given offset (depicted in Figure 10) the loads were applied at the flange to web juncture. The loads were applied at the quarter points of the simply-supported tub girders to give a moment distribution somewhat representative of a uniformly distributed load.

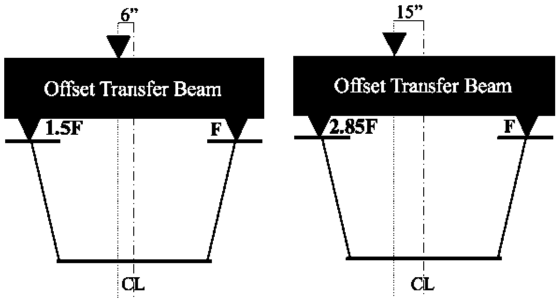


Figure 10: Eccentric Loading to Represent Horizontal Curvature

The correlation between the loading eccentricity and horizontal curvature is based on torsional moment and the section deflection distribution. The results are given in Table *3* below.

Table 3 -Load Eccentricity *e* vs. Equivalent Radius of Horizontal Curvature *R*

Load eccentricity *e* -in.	6	15
Load ratio between the top flanges	1.5	2.85
R_{eq}-ft.	~560	~260

Eigenvalue and large displacement analyses were performed on the steel tub girder models. An initial imperfection of $L/1000$ was included in the nonlinear geometry analysis. The two tub girder models were modified to account for different configurations. The FEA results were compared with the solution from Eq. 2. Since Eq. 2 only gives the critical moment under uniform moment, a moment gradient factor C_b was used to consider the quarter-point loading moment diagram. For singly symmetric section with two concentrated loads placed symmetrically at aL from each end of the span C_b =1.04.

3.2 Effect of Lower Web Slope

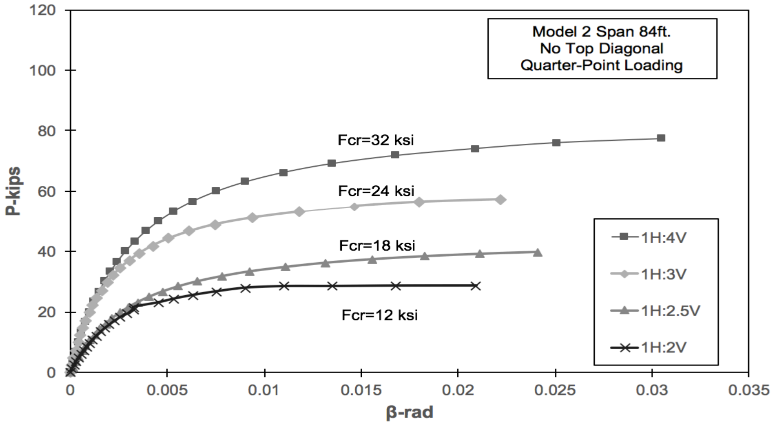


Figure 11: P vs. β with Different Web Slope Ratio

The effect of the lower web slopes on the buckling behavior was studied on Model 2. Fig. 11 shows the applied load and mid span section twisting curve with different web slopes less than code specified limit. Although from Section *2.2.1*, it can be seen that section torsional properties, especially the warping constant, drop significantly, these curves start increasing linearly only with two different slopes, indicating that there is no notable torsional stiffness difference between a web slope of 4 and 3 or 2.5 and 2. However, a switch from 4 to 2.5 causes nearly 50% loss of the original torsional stiffness. It should be noted that in the test beams the girder width between the tops of the webs were maintained at 63 inches. This was done to facilitate the reuse of braces between specimens. In an actual bridge, the flatter slope will usually be used to increase the cover width of the girder (ie. fewer girders across the width of the bridge) and as a result, the impact on the torsional stiffness will likely be larger compared to a 4V:1H web slope.

3.3 Effect of Top Flange Offset

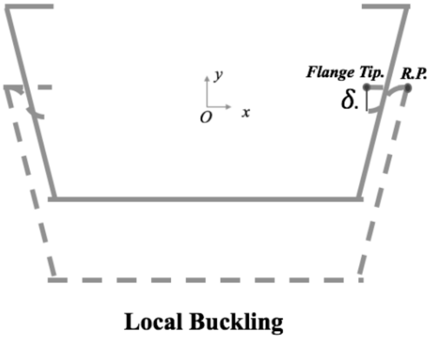


Figure 12: Local Buckling of Offset Top Flange

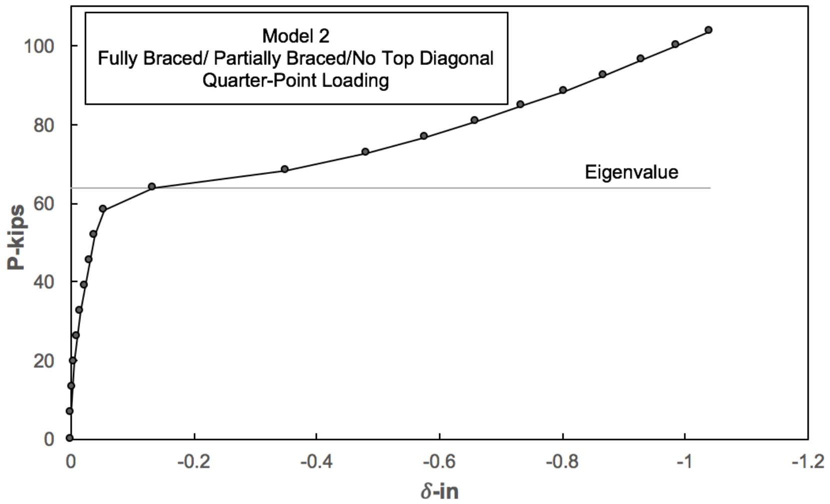


Figure 13: Lateral Bending Effect of Top Flange Offset

Offsetting the top flanges increases the unsupported flange length will increase and doubles the original flange slenderness ratio $b/(2t)$. The lateral bending effect of top flange can be measured by the relative vertical displacement between flange tip and web-flange conjuncture (see Fig. 12). Regardless of different top lateral bracing layout, local flange buckling will dominate the behavior. The elastic critical load for local buckling is 64 Kips. As in Fig. 13, these two points deflect vertically together at the beginning. Once local buckling occurs, the relative vertical displacement tends to increase rapidly. Since local buckling depends only the flange dimensions. This effect can be avoided by selecting proper top flange thickness. In this example, when ¾ in. top flanges were used in the model, the buckling mode shifted to LTB. Although the use of a larger top flange to control flange local buckling may require more material, additional savings are possible with simplified connection details.

3.4 Effect of Top Lateral Truss Layout

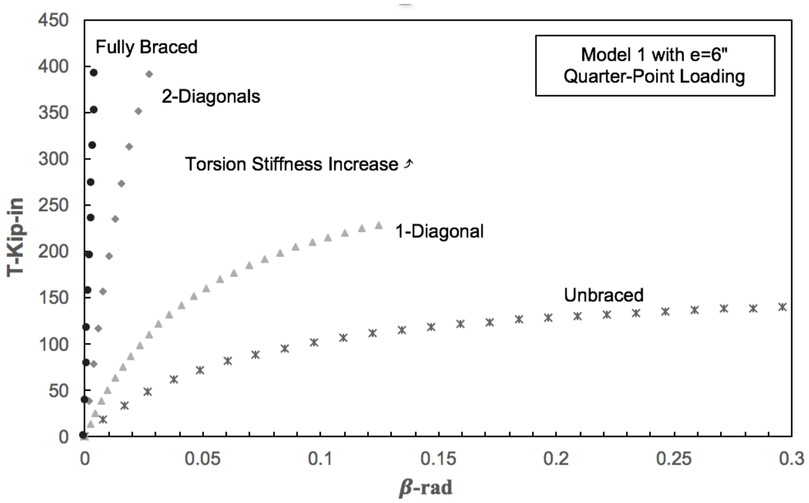


Figure 14: A) Torsional Response with Different Top Lateral Bracing Layouts (e=6")

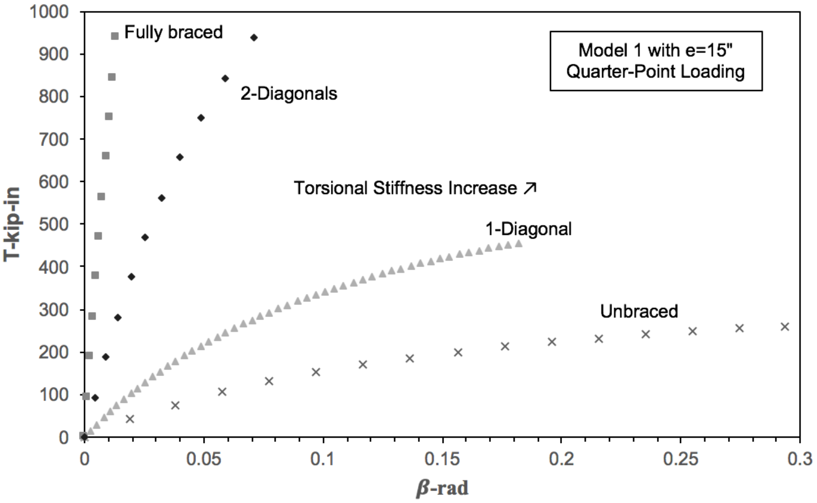


Figure 14: B) Torsional Response with Different Top Lateral Bracing Layouts (e=15")

To study the effect of different top lateral diagonal layouts on the behavior, combined bending and torsion were applied on model 1 with eccentric point load. The corresponding torsional response (applied torque vs. angle of twist at mid span) with eccentricities of 6 in. and 15 in. are presented in Fig. 14-A & B. Various top lateral bracing layouts have been illustrated in the Section *2.2.2.2*. While the torsion moments of the applied eccentricities are different in magnitude, the general trends in the torsional response are the same. For the cases with full braces and with 2 diagonals provided at each support end, extremely high torsional stiffness of the girder can effectively control section twisting and prevent girder instability. Significant drop in torsional stiffness can be found with only one diagonal kept at the ends and the unbraced case. Without sufficient top lateral bracing, the girder can experience excessive amount of twisting and fails by LTB at a very low applied torque. The difference in torsional stiffness among these cases tends to intensify as the applied torque increases. This indicates, while removal of top lateral truss does not significantly affect straight girders, the use of partially braced layouts for curved girder should be cautiously considered based on the actual torsional moment demand. In addition, the distribution of torsional and bending moments on continuous girder systems will be highly variable during construction, which can complicate decisions on which top truss diagonals to leave out. Therefore, the use of partial bracing is primarily targeting straight girder systems.

4. Future Full Scale Experiment

Full-scale laboratory testing will be carried out to demonstrate the impact of improved details on the behavior and validate parametric study results from FEA. Based on the conclusion obtained in the previous section, four test specimens have been properly proportioned to achieve the desired elastic buckling behavior. Two primary variables will be investigated: 1) offsetting the flanges on the webs and 2) using a flatter web slope. All the four specimens have a span length of 84 ft. and depth of 3 ft as depicted in Fig. 15.

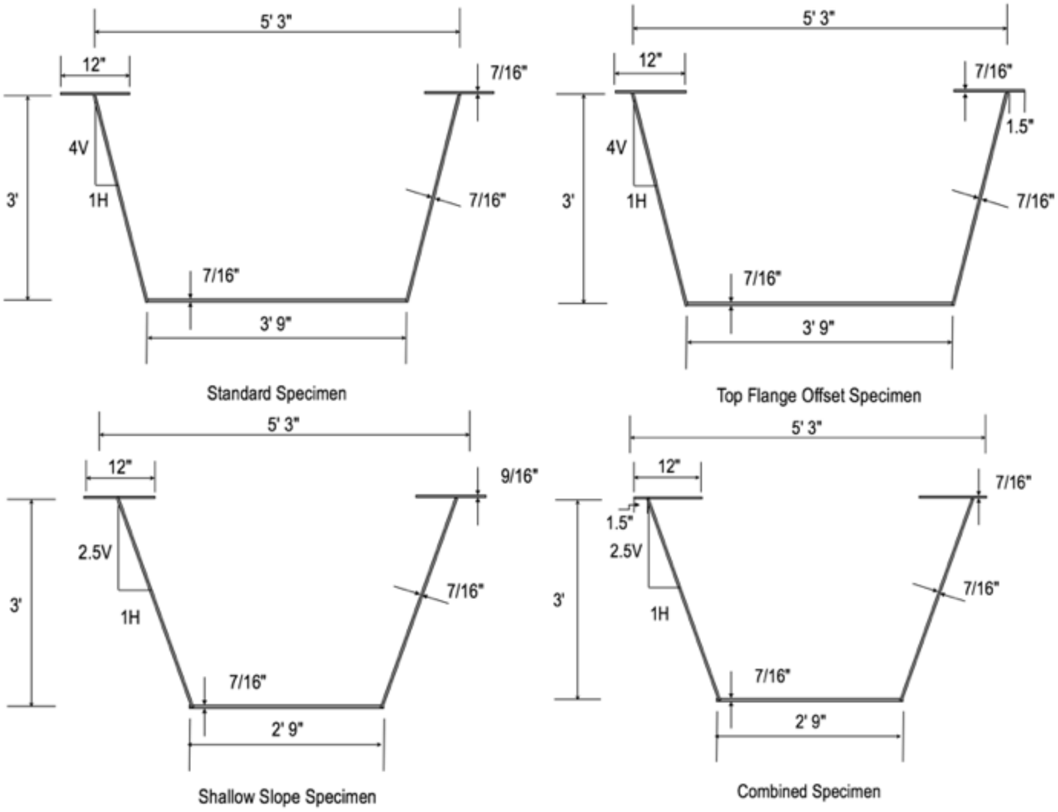


Figure 15: Lab Test Specimen Design

The angle of twist will be the primary test measurement to serve as the direct indicator of section torsional stiffness. Test loading case will include both the pure bending and combined bending & torsional loading. The specimens will be simply supported. Combined bending and torsion will be achieved by using two gravity load simulators (GLSs) each with a capacity of 160K. The gravity load simulators allow the load point to displace vertically and laterally with negligible restraint, thereby correctly simulating the effect of gravity loads on the structure. The gravity simulators will be located at approximately quarter points of the girder (24% of the span from the support) to simulate a bending moment diagram of uniformly distributed load.

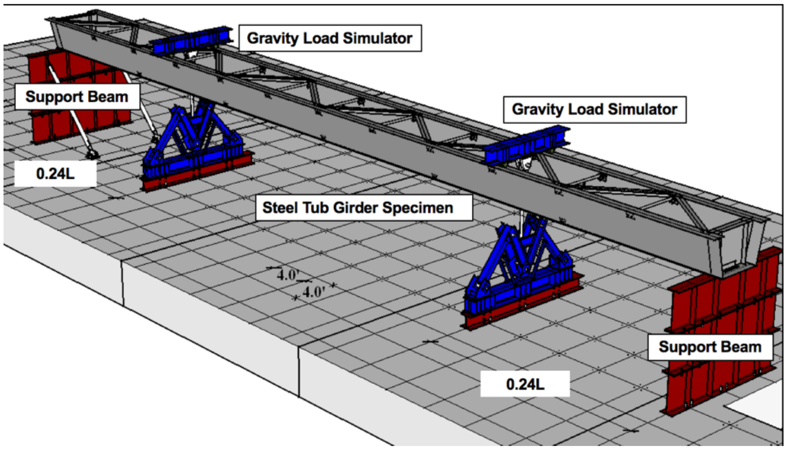


Figure 16: Laboratory test setup

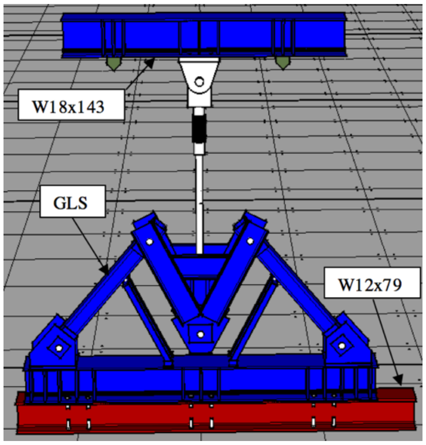


Figure 17: Gravity Load Simulator

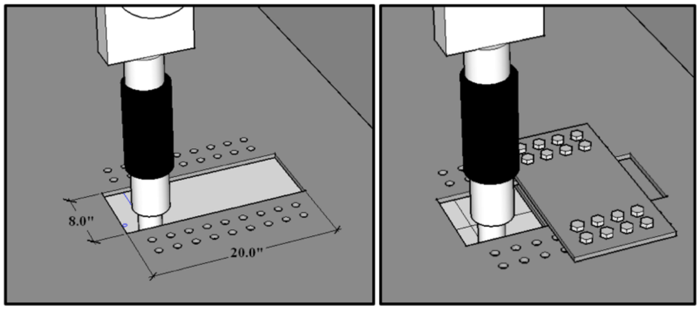


Figure 18: Slot on the Bottom Flange

Torsional loading will be achieved by applying an eccentric load through a W18×143 transfer beam as depicted in Fig. 17. The loading eccentricity can be adjusted by shifting the ram location along a slot cut on the girder bottom flange. This slot allows the ram to move laterally to impose different eccentricities during testing. To avoid any localized stress concentration near the slot, bolted plates will be used as depicted in Figure 18.

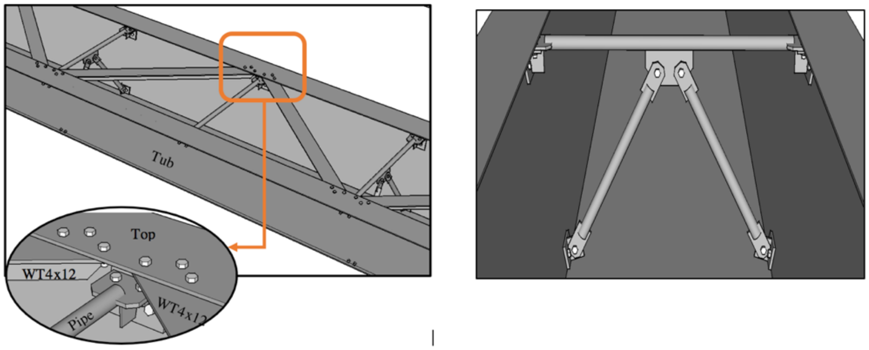


Figure 19: Bolt-connected Bracing System

Bracing members will be bolt-connected to the section so as to allow a variety of configurations to be evaluated.

5. Conclusions

This paper documents preliminary parametric study results of an on-going research study focused on improved tub girder details. Studies were performed using a 3D finite element model incorporating geometric nonlinearities. The models were developed to consider different configurations of girder geometry and bracing details. Predictions from this study were also compared with an elastic buckling solution. It can be concluded from the results presented in this paper that the global lateral torsional buckling capacity of steel tub girder can be affected with lower web slope. Offsetting the top flange can lead to local instability but can be prevented by optimizing the flange slenderness ratio. In the consideration of different top lateral bracing layout, improved efficiency may be possible with partial bracing configurations – particularly on straight girder systems. Providing minimum number of top diagonals can still maintain a very high torsional stiffness; however, the actual torsional demand, needs to be considered. Based on these conclusions, test specimens and a set-up have been properly designed for future laboratory tests. The future directions of the study include both full scale laboratory testing and parametric FEA analysis.

Acknowledgments

This research is supported and funded by the Texas Department of Transportation (Project: 0-6862). The authors gratefully appreciate their financial and technical support.

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