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Experimental Study of Steel Tub Girders with Partial Top Lateral Bracing

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Abstract
Steel box girder systems, which consist of steel tub girders with a cast in-place concrete deck on top, are a popular alternative for straight and horizontally curved bridges due to their high torsional stiffness and aesthetic appearance. However, steel tub girders possess a relatively low torsional stiffness during transport, erection and construction because of the thin-walled open section. Additionally, during the casting of concrete, the top flanges of the tub girder are in compression in the positive moment region and they are susceptible to lateral torsional buckling (LTB). Usually, top flange lateral bracing, in the form of a horizontal truss, is fully installed along the steel tub girder to prevent flanges from buckling and to increase the torsional stiffness of the girder. However, the horizontal truss is mainly effective near the ends of the girders where the shear deformations are the largest. The contribution of the top lateral bracing to control lateral torsional buckling is notably reduced at the mid-span region. This paper provides an overview of on an ongoing research study focused on improving the efficiency of steel tub girders by investigating the impact of the girder geometry and bracing details on the behavior of the girders. The study includes large-scale experimental tests and parametric finite element analytical (FEA) studies. This paper highlights the experimental tests. The efficiency of the horizontal truss is assessed by conducting multiple elastic-buckling tests on a steel tub girder with different amounts of top lateral bracing along the girder. A tub girder is subjected to combined bending and torsion using eccentric loads applied by gravity load simulators. The goal of the study is to improve the efficiency of steel tub girders by defining adequate amounts of bracing without undermining their structural performance.

1. Introduction
Steel trapezoidal box girders have become a popular alternative for straight and curved bridges. The girders, often referred to as "tub girders", consist of a single bottom flange, two sloping webs and two top flanges. The smooth profile of the girder provides an aesthetically appealing

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bridge that also possesses several structural advantages compared to other girder types. As a result of the large torsional stiffness, the girders are a popular choice in horizontally curved systems where the bridge geometry leads to large torsional moments. However, during construction the girders are an open section and generally require extensive bracing. The primary bracing systems consist of plate diaphragms at the supports, a top flange lateral truss, and intermediate internal and external K-frames (Fig. 1)

Figure 1 - Bracing systems in twin tub girder during construction

Though tub girders have mainly been used on horizontally curved bridges where concrete girders are not viable due to the longer span lengths, steel tub girders have shown to be feasible for straight bridges with span lengths normally reserved for concrete girder systems. A relatively shallow application of the straight steel tub girders was recently used by the Texas Department of Transportation in the Waco District (Fig. 2). The resulting bridge provided an aesthetically appealing structure that satisfied a demanding vertical clearance requirement and was cost-comparable with precast concrete girders. This shallow tub girder application demonstrates that steel trapezoidal box girders offer a viable alternative that should be considered for a wider variety of bridge applications. To augment the viability of the tub girders in straight bridges, improved girder geometries and bracing details may lead to improved economy and structural efficiency. Details that are being investigated in this research study include the spacing between internal K-frames, the layout of the top lateral truss, and the geometry of the steel tub girders. Common geometrical practices for the tub girders consist of a 4V:1H web slope and the top flanges centered over the webs. A flatter web slope can lead to increased lateral coverage of a single girder and may eliminate a girder line, thereby improving both the economy and efficiency of the girders during erection. In addition, offsetting the top flanges towards the inside of the tub girder can provide increased efficiency with respect to connections to the bracing systems. Three girders were fabricated for the testing program. The baseline girder has a web slope of 4V:1H with the flanges centered over the webs. An additional specimen also has a 4V:1H web slope with the top flanges offset towards the inside of the girders, while the final specimen has a web slope of approximately 2.5V: 1H and top flanges centered over the web. All of the internal K-frames and top lateral truss members are bolted to facilitate variations of the bracing that is provided. While the experimental and computation studies will focus on the behavior of all three girders, this paper focuses on the baseline girder with the 4V:1H web slope and the top flanges centered over the webs. The results from the tests conducted to date are summarized in this paper.

The experimental studies will include pure bending and well as combined bending and torsion for the applied loading. Straight bridges possess lower torsional demands than horizontally curved bridges; thus, partial application of top lateral bracing along the girder may be enough to provide sufficient restraint to control lateral-torsional buckling (LTB). The top lateral bracing truss is effective in regions where the shear deformations are the maximum in contrast with the truss at mid-span region which does not significantly contribute to prevent lateral torsional buckling of the tub girder.

Figure 2 - Shallow Tub Girder System from Waco District

2. Test of Full Scale Specimen

2.1 Description of Specimen

The current paper presents the experimental results obtained during the study of straight steel tub girder using the baseline girder configuration with a 4V:1H web slope and the top flanges centered over the webs. The design of the steel tub girder was carried out following the requirements of the Section 6.11 of the AASHTO 2012 specifications for straight and curved tub girders. The baseline girder was designed and fabricated according to current engineering practices. A description of the most important factors for the design of the specimen are discussed in the following subsections.

2.1.1 Tub Girder Geometry

The specimen span (L) was defined based on various parameters such as laboratory space, span-to-depth ratio L/D of the girder, and flexural and torsional flexibility of the girder. Because the girders were desired to be used in multiple tests, many of the proportions were selected so that the girders would remain elastic during the buckling and combined bending and torsion tests. Based on that, the clear span L of the simply supported specimen was selected to be 84 ft. Also, the girder depth D was defined as 3 ft. In consequence, the span-to-depth ratio of the steel tub girder was equal to 28 which is comparable to that suggested by AASHTO section 2.5.2.6.3 for simply supported beams (L/D=25).

The separation between the center lines of the top flanges was defined based on common practice and torsional stiffness of the girder. A distance W equal to 5 ft. and 3 in. was selected as the separation of the top of the sloped webs (Fig.3). The resulting width-to-depth ratio was 1.75, which is similar to values observed in current practice.

As noted earlier, the slopes of the two webs of the baseline steel tub girder were set to be equal to 4V:1H (Fig. 3), the limit ratio according to section 6.11.2.1.1 of AASHTO. Also, the thickness of the different plates that form the tub cross-section are compliant with the minimum requirements established in sections 6.11.2.1.2 and 6.11.2.2.2 of AASHTO. Both the top flanges and the webs of the specimen are non-compact elements according to their slenderness ratio. The flanges and webs were fabricated with the material AASHTO M270 (ASTM A709), grade 50W.

The thickness of webs and flanges was set equal to 7/16 in. This thickness is considerably smaller than commonly utilized in current bridge practice (usually equal or over 1 in). However, after running multiple finite element analyses, this thickness was necessary to obtain the elastic-buckling response of the system under the loading conditions defined for the study. After the fabrication of the specimen, significant out-of-straightness of the plates was observed which is not typical of this type of girders. In fact, the top flanges had a wavy shape along the specimen which arose concerns about potential local buckling issues before achieving elastic-bucking in the system. As consequence, during the tests, instrumentation was properly located to monitor the local buckling behavior of the plates during testing.

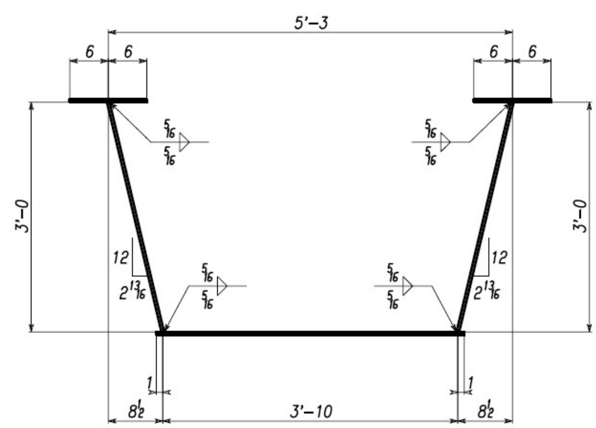

Figure 3 - Full-Scale Steel Tub Girder Specimen - Cross Section

The spacing of the top lateral truss panel points was defined as 7 ft., generating 12 panels along the length of the beam (Fig. 4). As noted earlier, the internal K-frames can be installed or removed as desired to monitor the behavior of the girders as a function of the bracing. In a similar fashion, the top lateral truss diagonals can also be added or removed at well. In the cases where the internal K-frames or top lateral truss diagonals are removed, top lateral struts between the two top flanges are maintained at a 7 ft. spacing to control separation of the top flanges. Fig.4 shows a plan view of the tub girder and the first two panel points denote a "strut-only" and K-frame condition.

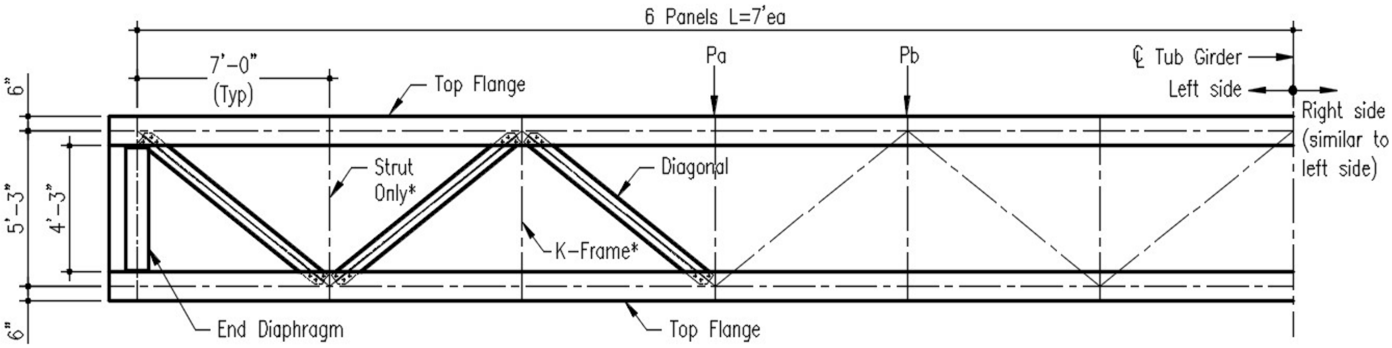

Figure 4 - Half of Steel Tub Girder Specimen - Plan View

2.1.2 Top Lateral Bracing

The single-diagonal type (SD-type) top truss was used as the top lateral system not only because it allows flexibility during construction and testing, but also because it is the most common type of lateral bracing used in current practice. The SD-type system is formed by single diagonals and struts connected to the tub girder top flanges through bolted connections. The diagonals have been designed to be directly connected to the top flanges to avoid gusset plates (Fig. 5). Bolted connections allow relatively simple addition or removal of the bracing elements depending on the experimental test to be conducted. The top truss diagonals were comprised of WT5x22.5 designed to be connected directly underneath the top flanges through three 3/4in. high strength bolts. Meanwhile, the struts are connected to a stiffener welded to the web of the tub girder through bolted connections made of 1/2 in. thick steel plates (material ASTM A-36). The vertical eccentricity between the top flange and the centerline of the strut is 3.75 in. which is an acceptable value (Helwig and Yura 2012). The angle between diagonal and top flange center lines is 37 degrees, which is close the approximate value of 45 degrees which often used in practice. Three diagonals were installed at each end of the steel tub girder in order to simulate the partial lateral bracing of the top flange. Different cases of partial top lateral bracing were tested by removing diagonal members of the horizontal truss at each end (4 different arrangements of lateral bracing).


Figure 5 - SD-Type Top Lateral Bracing System

A WT5x22.5 cross-section was defined for the diagonals, which was checked to have enough capacity in tension and compression to remain elastic during the tests. Also, this tee section is compliant with the slenderness ratio (AASHTO 6.9.3) and minimum cross-sectional area

(AASHTO C6.7.5.3-1) requirements, which are mandatory to ensure that the quasi-closed section will undergo normal stresses less than 10% of the major-axis bending stresses. On the other hand, a 2 in. pipe with 1/5 in. thickness was selected as the cross-section for the struts. Similar to the diagonals, the strut cross-section was sized to resist the axial demands calculated during the analysis and to satisfy slenderness requirements of AASHTO 2012 (AASHTO 6.8.4). The diagonals and pipes have been designed and fabricated with steel ASTM A705 – Grade 50 and ASTM A53 – Grade B, respectively.

2.1.2 Internal K-Frame Bracing

Formed by one strut (which is part of the top lateral truss) and two diagonals (Fig. 6), the K-frames were designed and fabricated accordingly to remain elastic during the experimental tests to avoid any type stability or overloading issues. The section of the strut was sized for the top lateral bracing system, and the same section has been adopted for the K-frame diagonals (2 in. pipe with thickness of 1/5 in.) for facility during fabrication. The K-frame bracing elements were fabricated with steel ASTM A53 – Grade B.

Three different arrangements of internal k-frames were tested for each configuration of top lateral bracing. K-frame bracing at every 2, 4 and 6 panels were evaluated during the experimental program.

Figure 6 - K-frame Bracing

2.2 Description of Test Setup

The test setup (Fig.7) was designed to test simply-supported straight tub girders under both pure positive bending and torsional loading conditions. The test setup consists of two steel supports 84 ft. apart over which the specimen rests as a simply supported beam. Each steel support consists of three 12 ft. long W36x135 rolled beams stacked vertically so as to raise the elevation of the test girders above the loading system. The support located on the south side of the laboratory floor is supported laterally with two diagonal braces to stiffen the test setup and simulate “pinned conditions”. The two braces are formed by 2L4x3x3/8” LLBB connected to the steel support and to the strong floor through bolted connections. The opposing support consists only of the stacked W36x135 sections and allow some flexibility to simulate a “roller”. Elastomeric bearings were used between the W36x135 support system and the girders.

Figure 7 - Steel Tub Girder - Test Setup

In addition to the vertical supports, three L-shaped reaction frames are positioned along the length of the tub girder to apply lateral loads to the test girder (Fig.7). The frames are comprised of W12x65 rolled sections and braced with 2-L4x3x3/8" angles. The purpose of the lateral load tests is to obtain data on the lateral stiffness of the tub girders with various bracing conditions that can be used to validate the FEA models for the parametric studies.

Vertical loads over the steel tub girders are applied with two gravity load simulators (GLS Fig.8). Each GLS is able to apply vertical loads up to 160 kips, and to keep the load vertical even if the ram moves laterally up to 6 in. The vertical loads were applied near the quarter points of the girder. Although the loading consists of point loads applied near the quarter points, the resulting moment diagram is similar to that caused by a distributed load from self-weight of the girder and concrete deck, which would be the critical load during construction. Each GLS is connected to a 13ft. long W12x79 rolled beam which is anchored to the strong floor of the laboratory. The vertical load from the GLS is applied with a hydraulic actuator that connects to a W18x143 load transfer beam that spans between the two top flanges of the tub girder specimens. Heat treated knife edges are used to transfer the load from the W18x143 beam to the top flanges of the tub girder. The clear distance between the tub girder bottom flange and lab floor is 9ft. which is adequate to position the girder above the gravity load simulators (GLS) without interference.

Figure 8 - Gravity Load Simulator (GLS)

The focus of this study is on both straight and horizontally curved girders. Although researchers considered fabricating horizontally curved girders, the expense of the specimens as well as the limitation of getting a single girder curvature was not desirable. Instead, the research team focused on a setup that allowed eccentric loading that can simulate the torsion from the horizontal curvature of the girder. A rectangular opening was cut into the bottom flange that allows the load to be shifted lateral up to an eccentricity of 16 inches. A bolted cover plate is used across the hole to minimize the opening. With the ability to offset the load to achieve a torque, girder geometries from straight to a simulated curvature of approximately 500 ft. is possible. In addition, lateral loads can be applied at the location of the L-shape reaction frames. Equal lateral loads were applied near to both, top and bottom flanges (Fig.9). Considering that the shear center of the steel tub girder is located below the bottom flange (13.2 in. below bottom flange), this loading condition also produces torsional demands over the girder. The loads were applied with hydraulic actuators connected to threaded rods reacting against the L-shape frames. A load cell is included in the threaded rods to measure the magnitude of the applied later loads. As noted earlier, the purpose of these tests is to gain data to compliment the simulated gravity load data. The lateral load data provides data on the lateral and torsional stiffness of the tub girders with various bracing configurations to assist in validating the FEA models. This data is complementary to the data gained during the simulated gravity load tests.

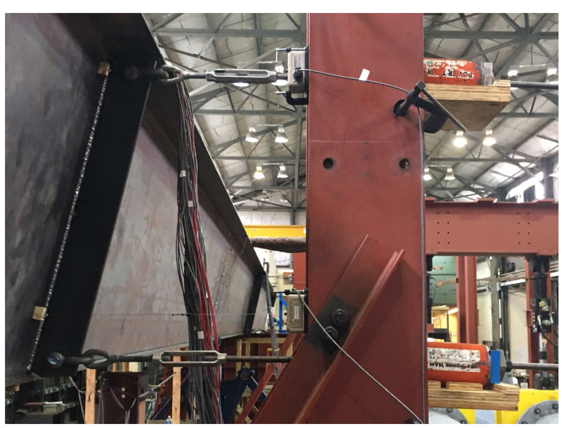

Figure 9 - Lateral Loading Test Setup

2.3 Testing Procedure and Instrumentation

Prior to testing, initial imperfections of the steel tub girder were measured. Two wires (piano wire) were extended between the test setup supports at 6 in. from both edges of the bottom flange. The taut wires served as reference point to measure lateral and vertical out-of-straightness of the tub girder. Measurements were collected at every 7 ft. on both lateral sides of the girder. Initial imperfections were measured before every elastic-buckling test; however, these imperfections did not changed drastically from test to test with maximum variations of the order of ±0.1in.

Since the critical stages for both stability and lateral/torsional flexibility of steel tub girders generally occur during construction phase, the range of stresses imposed over these sections are normally within the elastic range. AASHTO requires the girders during construction to remain elastic. Elastic-buckling tests were carried out by applying loads in the specimen to keep stresses lower than 60% of nominal yield stress (30 ksi). This maximum stress limit was set to consider the impact of residual stresses and initial imperfections in the response of the tub girder and to ensure that the girders remained elastic.

Two types of loading conditions were studied: vertical positive bending and combined bending and torsion due to both vertical and lateral loads, respectively. For the lateral loading tests, four horizontal loads were applied, 2 at each reaction frame located at the third points of the girders (location denoted as "Pb" in Fig. 4). The maximum total lateral load applied was 20 kips (4 point loads of 5 kips) at increments of 1 kip (1/4 kip increment on 4 loading points). For the positive bending tests, two vertical loads were applied at approximately quarter points of the beam (location denoted as "Pa" on Fig. 4). The maximum vertical load applied was 80 kips (2 point loads of 40 kips) at increments of 5 and 2 kips (2.5 and 1 kip increment on 2 loading points).

Horizontal and vertical deflections of the steel tub girder were measured at third points of the tub length (28 ft. and 56 ft.) and at mid-span (42 ft.). The deflections at third points were obtained with string potentiometers, while the deflections at mid-span were collected with infrared cameras that are able to capture signal from LED markers attached to the tub girder section. The infrared vision system collected deflections with relatively high accuracy (error of about 0.01in). Rotations were calculated from the measured deflections. Regarding sign convention in subsequent graphs, negative lateral displacements represent movements to the East, while positive displacements represent movements to the West.

Stresses at multiple points of the specimen were obtained using conventional resistance-based foil strain gages on both faces of the web, top and bottom flange plates. Strain gages were also used on the bracing members; however, the scope of this paper does not consider the response of bracing members. Bracing member data will be presented in a subsequent paper.

2.4 Bracing Configuration

In order to measure the effectiveness of partial top lateral bracing, different bracing layouts were tested on the same tub girder under the same loading conditions.

First, four lateral loading tests were performed in the specimen. Each test was conducted with different amounts of bracing diagonals at each end of the tub so that the effectiveness of this type of bracing can be evaluated. Cases with 0, 1, 2, and 3 diagonals on each end of the simple supported beam were the four configurations of top lateral bracing evaluated in the study. K-frames were positioned at every two panels for these four tests.

Following the lateral load tests, twelve vertical positive bending tests were carried out. For each aforementioned top lateral bracing configuration, three different configurations of internal K-frame bracing were assessed. K-frames were located at every 2, 4, and 6 panels for each configuration of top lateral bracing, which resulted in a total of twelve tests. The impact of each bracing system in the response of the specimen is evaluated and summarized in the following sections.

2.4 Overall Behavior

As expected, the steel tub girder responded elastically under the applied loads as indicated by the linear strain gauges and the deflection measurements. Initial imperfections did not significantly change from test to test. The vertical and horizontal deflections measured at the third points were similar and consistent with tests obtained at mid-span. No local buckling of the plates was observed during the tests.

The amount of top lateral bracing on the tub girder had a significant impact in the torsional stiffness of the specimen. By adding a couple of top diagonals at each end of the tub, the LTB capacity of the specimen was significantly improved. On the other hand, internal K-frame bracing, and its configuration did not have important impact on the LTB behavior. This behavior is consistent with observations from previous failures (Marcy Pedestrian Bridge) as well as recent studies on the system buckling mode for narrow I-girder systems (Helwig and Yura, 2012).

A more detailed summary of experimental findings is presented in the next section.

3. Experimental Results

3.1 Impact of Partial Top Lateral Bracing Distribution

To study the effect of partial top lateral bracing on straight steel tub girders, the specimen was loaded under bending and torsional demands. The response of the specimen under these two loading conditions is described in this section.

3.1.1 Lateral Tests

The lateral load tests resulted in both lateral and torsional loads applied to the specimen at the 2 third points along the beam. The moments were imposed to the girder by applying equal horizontal loads P as described in Fig. 10. The torsional moment was calculated with respect to the shear center of the open tub girder. To assess the bracing effectiveness, lateral displacements (δ) and twist of the section (β) under the aforementioned demands were compared for different scenarios of partial top lateral bracing.

Fig.10 shows the relationship between lateral displacement at mid-span of the tub (δ) and the total lateral load applied on the specimen (4P). As expected, the steel tub girder without any diagonals in the top lateral bracing is the most flexible system (approx. lateral stiffness of 3.82 kips/in) which is represented by the dotted line with squares. By adding a bracing diagonal on each end of the tub (dotted line with hyphens), the lateral stiffness improves significantly by a factor of almost 3 (~10.97 kips/in); while, by having two bracing diagonals at each end (dotted line with diamonds) produces a lateral stiffness enhancement of approximately 6 times (~23.19 kips/in) in comparison with the unbraced case. Finally, the lateral stiffness increases to about 32.51 kips/in (dotted line with triangles) when the tub girder was tested with three diagonals at each end (lateral response improved by a factor of about 8.5). In addition to improving the lateral stiffness, the diagonals significantly improve the torsional stiffness as well.

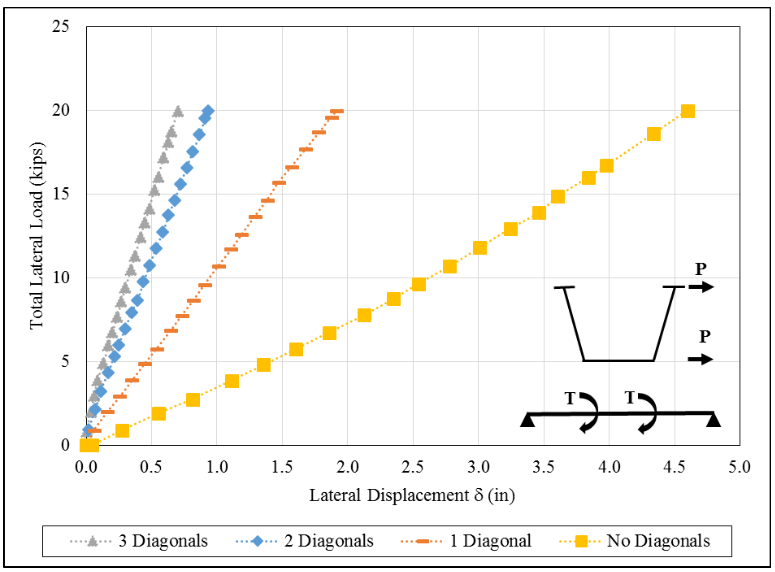

Figure 10 – Total Lateral Load versus Lateral Displacement

Fig.11 presents the angle of twist at mid-span (β) with respect to the applied moment T for the four different configurations of top lateral bracing. Similarly, the torsional stiffness of the specimen improves considerably with the addition of the bracing diagonals at the supports. The torsional stiffness of the unbraced tub girder (~3900 kips-in/rad) is improved in a ratio of about 3, 8 and 13 when adding one, two and three diagonals, respectively, at the ends of the girder. This trend shows that the braces near the ends of the section are the most efficient at enhancing the lateral and torsional stiffness of the girders and the efficiency decreases with increasing distance from the ends of the section. For a given torsional/lateral stiffness demand, the amount of bracing near the ends of the section should be determined and inefficient braces near midspan should not be needlessly provided.

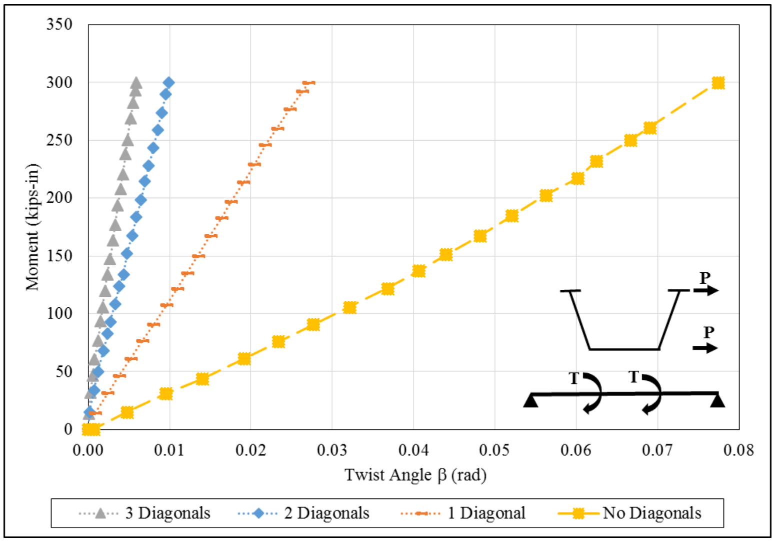

Figure 11 – Torsional Moment versus Twist Angle

3.1.2 Positive Bending Tests

The gravity load simulators were used to apply vertical loads near the quarter points of the girders to evaluate the effectiveness of partial top lateral bracing to resist lateral torsional buckling. Two gravity load simulators were used to apply vertical concentric loads on the specimen. Similar to the lateral tests, lateral displacements (δ) and twist angles (β) at different load levels are compared for different configurations of partial top lateral bracing.

Fig.12 shows the total vertical load applied (2P) versus the lateral displacement of the specimen (δ) when the specimen was tested with 0, 1, 2 and 3 bracing diagonals at each end. The tub girder without top lateral bracing presented an elastic lateral torsional buckling response during the test which can be observed by the nonlinear response of the load versus deflection curve. The lateral torsional buckling of the system reduced the torsional stiffness of the specimen at every single load step due to the lateral displacement induced on the girder. Clearly, the lateral torsional buckling resistance controls the behavior of the girder. However, the capacity to resist LTB is significantly improved with the addition of diagonals at the ends of the girder. The system without diagonals had a maximum lateral displacement of 2.90 in. at 80 kips of total load, while the specimen with 1 diagonal per end had a maximum lateral displacement of 0.20 in at the same load step. The torsional stiffness is highly improved with a single diagonal at each end, as shown in the results of the lateral tests. By adding a second diagonal per end the torsional stiffness of the tub improves in a ratio of 5 with respect to the response of the tub with 1 diagonal. The tub girder with three diagonals per end did not show a significant improvement in torsional stiffness with respect to the previous case. Instead, the three diagonals per end produced a shift in the direction of lateral movement (shift of mode shape). Clearly, the first diagonal on each end of the specimen produced the most significant improvement in the resistance to LTB, while additional diagonals were not as effective at improving the behavior. As expected, the experimental results demonstrated that the the effectiveness of the top lateral bracing is lower with increasing distance from the ends of the girders.

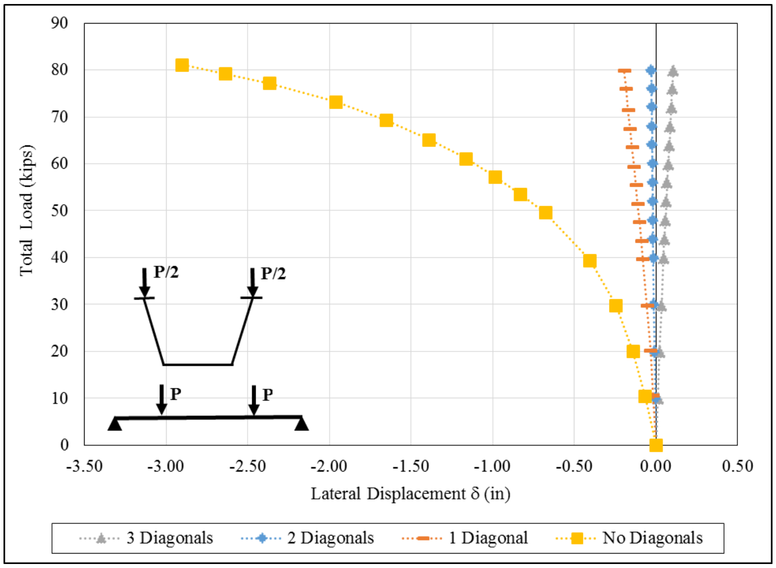

Figure 12 – Total Vertical Load versus Lateral Displacement

Fig.13 presents the total vertical load (2P) applied versus the twist angle (β) on the tub girder for the four different arrangements of top lateral bracing. As observed in Fig.12, the most important improvement in the torsional stiffness of the specimen is achieved when 1 diagonal is added at the ends of the tub girder. The addition of extra diagonals enhances the LTB resistance, but at a much lower increment compared to the first diagonal. As depicted in Fig.13, when the specimen was tested with 3 diagonals, the rotation of the tub girder actually had a change in rotational sign which implies a high resistance to lateral torsional buckling. While the change in rotational sign may seem counter-intuitive, it is important to note that this is just the twist that occurred at mispan. The load was applied near the quarter points and the bracing simply impacted the mode shape of the girder. The partial bracing tests demonstrate that full top lateral bracing along the girder is not needed to control LTB; instead, partial top lateral bracing can be provided in these cases to control LTB in straight tub girders with concentric loads. Additional tests and review of the data will be continued to develop recommendations on the necessary bracing to control LTB.

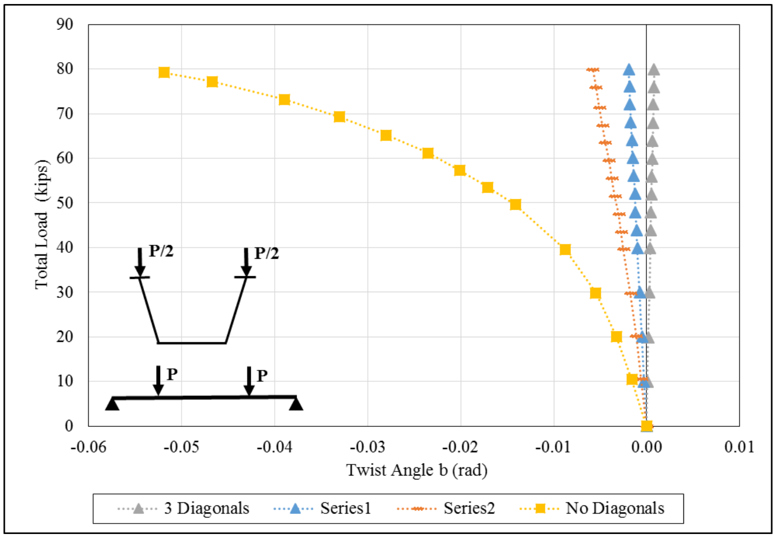

Figure 13 – Total Load versus Midspan Twist Angle

3.2 Impact of Internal K-frame distribution

The main function of internal K-frame bracing systems is to restrain distortion of the cross-section under torsional loads (Fan and Helwig – 2002). Torsional demands in straight tub girders are small which implies that distortional effects are low. The effectiveness of internal K-frame bracing in straight tub girders was evaluated by conducting positive bending tests on the specimen with different configurations of internal bracing. The specimen response with K-frames at every 2, 4, and 6 panels was evaluated in this phase of the study.

Fig.14 shows the total vertical load (2P) versus the lateral displacement (δ)of the specimen with no top lateral bracing and three different configurations of internal K-frames. The tub girder with internal bracing at every 4 and 6 panels show the same response with no major variation in the torsional stiffness. Though the specimen with K-frames every 2 panels presents higher torsional stiffness for lower load levels, the impact on the response tended to be similar to the aforementioned two cases at higher loads. Elastic lateral torsional buckling was observed during this test. The relative insensitivity of girder response to the internal K-frame spacing is similar to previous observations in the case of the Marcy Pedestrian Bridge failure (Yura and Widanto, 2005), as well as the system buckling mode of narrow I-girder systems (Yura et. al, 2008).

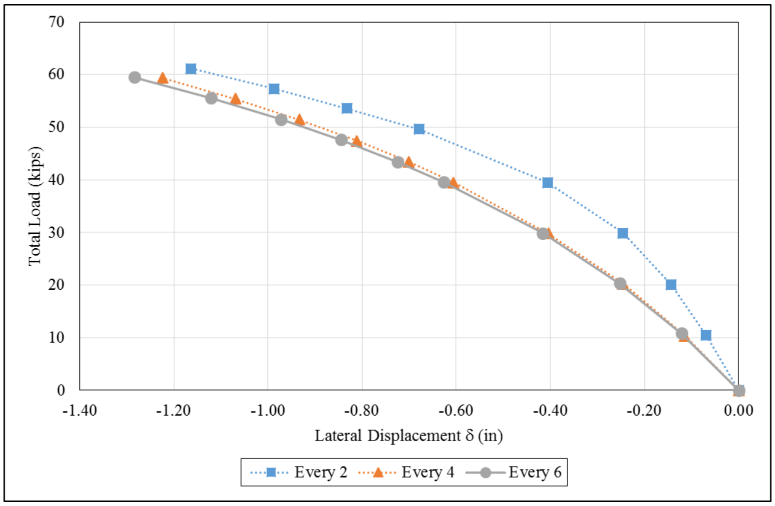

Figure 14 – Total Load versus Lateral Displacement - Different K-frame Configuration (No Top Truss Diagonals)

Fig.15 presents the total load versus the twist angle (β) of the specimen with no top lateral truss bracing and three different configurations of internal K-frames. Similar to Fig.14, the specimen with K-frames every 4 and 6 panels show very similar torsional response. The specimen with internal bracing every 2 panels showed higher initial torsional stiffness at lower applied loads, but similar torsional stiffness to the other two cases at higher loads. Clearly, the contribution of internal K-frames to resist LTB is minimal and their arrangement inside of the tub has relatively small impact in the global response of straight tub girders.

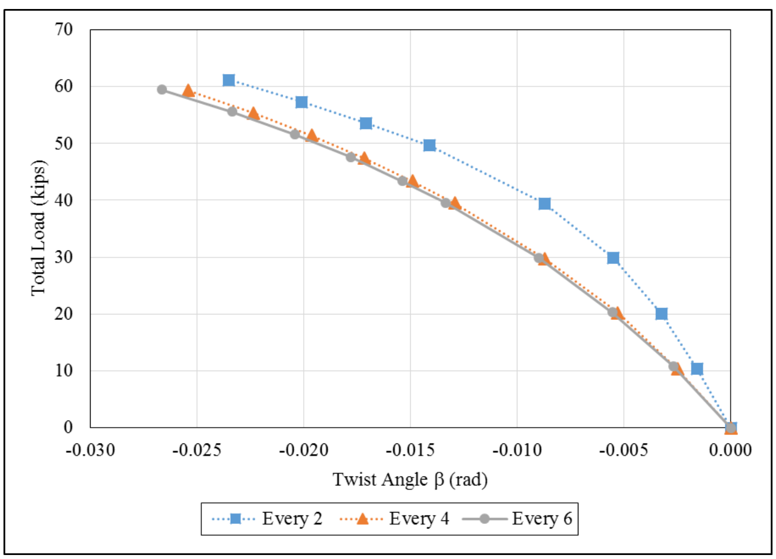

Figure 15 – Total Load versus Twist Angle - Different K-frame Configuration (No Top Truss Diagonals)

Fig.16 and Fig.17 show the respective total load (2P) versus the lateral displacement (δ) and twist angle β with partial top lateral bracing (1 diagonal at each end). The difference between the torsional responses of the tub girder with different k-frame arrangements is minimal when 1 diagonal is included at each end. Although the curves are different, the magnitudes of the lateral displacements and girder twists are extremely small. The values are so small that the case with closer spacing (every 2 panels) resulted in slightly larger lateral displacements than the other two cases. The reason for this anomaly may be the resolution of the instrumentation or perhaps slight changes in the initial imperfection in the girder/loading system between the tests. Basically, the K-frame bracing system becomes less effective in straight steel tub girders under pure positive bending, and there is no major change in its torsional behavior when the number of internal braces is reduced. Similar effect was observed in the specimen with top lateral bracing including 2 and 3 diagonals at each end.

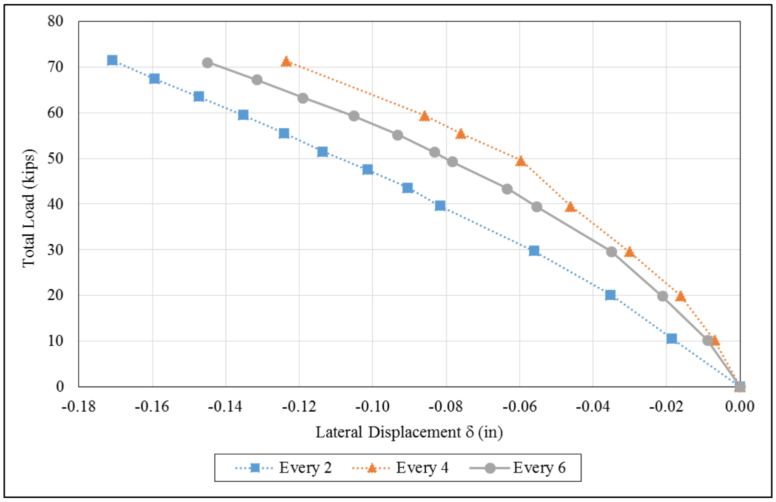

Figure 16 – Total load versus Lateral Displacement - Different K-frame Configuration (1 Top Truss Diagonal at Each End)

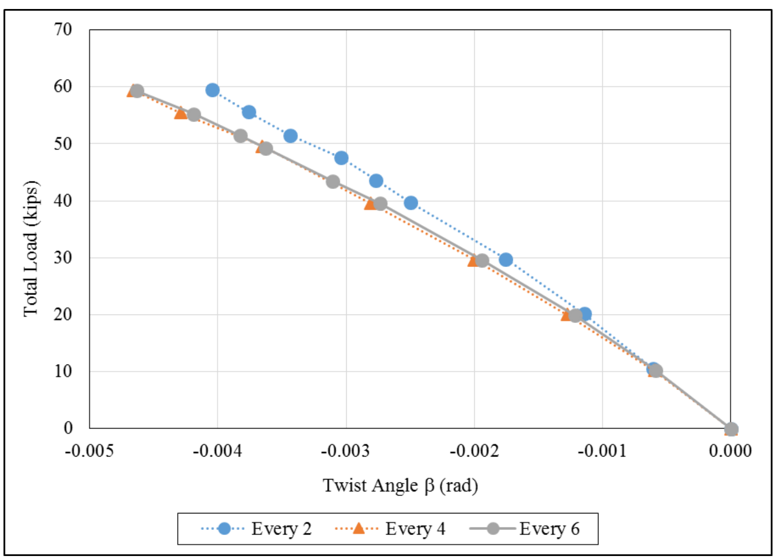

Figure 17 – Total Load versus Twist Angle - Different K-frame Configuration (1 Top Truss Diagonal at Each End)

5. Conclusions

This paper documents the results of the first phase of an experimental study to evaluate the efficiency of top lateral bracing and internal K-frames in straight tub girders. An 84-foot-long steel tub girder was subjected to elastic-buckling tests under positive bending and torsional demands with the purpose of evaluating the effectiveness of different configurations of top lateral and internal bracing in straight tub girders. The major findings obtained in the first phase of the study are:

- Experimental tests showed that the top flange lateral bracing systems are more effective in the region near to the supports of straight girders where shear deformations are at the maximum. The LTB capacity of the straight tub girders was significantly improved by adding 1 top truss diagonal at each support. The inclusion of subsequent diagonals resulted in significantly smaller increments in the capacity as the distance to the diagonals increased. Thus, top lateral diagonals located near mid-span add little to no benefit in the LTB behavior and likely at increasing the torsional stiffness of the girder.
- Internal K-frames provide minimal contribution to resist LTB in straight tub girders in comparison to top lateral bracing. Due to lower torsional demands, internal K-frames are less effective along straight tub girders. Thus, the number of K-frames, and their distribution along the straight girder, did not demonstrate a significant impact in the torsional response of the steel tub girder.

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