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Experimental Study on the Interaction of Partial Top Lateral and K-Frame Bracing on Tub Girders

Stalin Armijos Moya[1], Yang Wang[2], Todd Helwig[3], Michael Engelhardt[4], Patricia Clayton[5], Eric Williamson[6]

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 upper portion the tub girder is in compression in the positive moment region and the girder is susceptible to lateral torsional buckling (LTB). Usually, top flange lateral bracing (TLB), in the form of a horizontal truss, is installed along the entire length of the steel tub girder to increase the torsional stiffness of the girder and to prevent LTB. However, for straight or nearly straight girders, 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. Also, internal K-frames are placed to control cross-sectional distortion. 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 both the experimental tests and part of the analytical study. The interaction between partial top lateral and K-frame bracing systems is assessed by conducting multiple elastic-buckling tests on three steel tub girders with different amounts of top lateral bracing along the girder. Interaction between these two types of bracing systems was observed with variations in the forces of the top lateral truss diagonals and struts when the configuration of internal K-frames was altered. The three tub girder specimens were also subjected to vertical bending and combined bending and torsion using concentric and eccentric loads, respectively, applied by gravity load simulators. The goal of the study is to improve the efficiency of steel tub girders by optimizing the bracing while maintaining adequate safety.

[1] Graduate Research Assistant, The University of Texas at Austin, <starmijos@gmail.com>
[2] Graduate Research Assistant, The University of Texas at Austin <yangwang.structure@utexas.edu>
3 Professor, The University of Texas at Austin <thelwig@mail.utexas.edu>
[4] Professor, The University of Texas at Austin <mde@mail.utexas.edu>
[5] Assistant Professor, The University of Texas at Austin <clayton@utexas.edu>
[6] Professor, The University of Texas at Austin <ewilliamson@mail.utexas.edu>

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 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 or due to the curvature, steel tub girders have also been shown to be feasible for straight bridges with span lengths normally reserved for concrete girder systems. Relatively shallow straight steel tub girders were 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-competitive 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 cross-sectional 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 economy. 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. In order to study the aforementioned-proposed details, three tub girders were fabricated for the experimental program. First, 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 (offset top flange girder), while the final specimen has a web slope of approximately 2.5V: 1H and top flanges centered over the web (flatter web girder). All of the internal K-frames and top lateral truss members are bolted to facilitate variations of the bracing in the experimental program. This paper focuses on the interaction between partial top lateral and K-frame bracing systems. The experimental studies included loading the girders in pure bending as well as in combined bending and torsion. The results from the experimental tests conducted to date are summarized in this paper. Finally, an analytical study to evaluate the interaction of these two bracing systems in a three span continuous bridge under construction sequence loads is presented.

Figure 2 - Shallow Tub Girder System from Waco District

2. Test of Large Scale Specimen

2.1 Description of Specimens

The current paper presents the experimental results obtained using the baseline girder, the girder with offset top flanges, and flatter web girder, previously mentioned. The baseline girder was designed and fabricated according to current engineering practices for straight and curved tub girders. The other two specimens were sized by conducting preliminary finite element analyses so that the girders are able to reach global elastic buckling (lateral torsional buckling) before any type of local buckling. All three test specimens were straight girders. However, as part of the study, the specimens were tested under combined bending and torsion by applying an eccentric vertical load, to simulate the force environment in a curved girder. Thus, while all of the specimens were straight, the test program was designed to obtain data to provide insights into the behavior of both straight and curved girders. A description of the most important factors for the design of the specimens are discussed in the following subsections.

2.1.1 Tub Girder Geometries

The specimen span (L) was defined based on various parameters such as laboratory space, span-to-depth ratio L/D of the girders, and flexural and torsional flexibility of the girders. 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. Consequently the span-to-depth ratio of the steel tub girders was equal to 28 which is comparable to that suggested by AASHTO (2012) section 2.5.2.6.3 for simply supported beams (L/D=25).

The separation between the top of the sloped webs was determined typical practices.. 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 (W/D) was 1.75, which is similar to values observed in current practice.

The major difference between specimens is the thickness of the cross-section plates, the location of the top flanges with respect to the webs, and the slope of the webs.

The flanges and webs of the three specimens were fabricated with the material AASHTO M270 (ASTM A709), grade 50W.

2.1.1.1 Baseline Tub Girder

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. Both the top flanges and the webs of the specimen are non-compact elements according to their slenderness ratio.

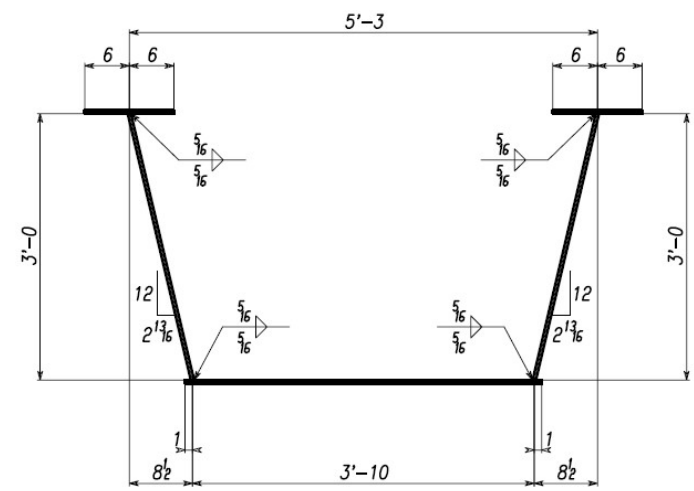

Figure 3 - Full-Scale Baseline Tub Girder Specimen - Cross Section

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, this thickness was deemed necessary to obtain the elastic-buckling response of the system based upon finite element studies. After the fabrication of the specimen, significant out-of-straightness of the plates was observed which is not typical of this type of girder. In fact, the top flanges had a wavy shape along the specimen which raised concerns about the potential for local buckling to occur before achieving elastic LTB of the system. As a result, during the tests, instrumentation was used to monitor the local buckling behavior of the plates.

This base line tub girder was built with two 12" wide top flanges which were centered to the center line of the sloped webs, as depicted in Fig. 3. Thus, the width-to-thickness ratio of the top flanges was equal to 13.71.

2.1.1.2 Offset Top Flange Tub Girder

Different from the base line tub girder, the offset top flange girder was built with two 13" wide top flanges which were connected to the sloped webs at 1" from the edges, leaving 12" of unstiffened plate (Fig. 4). The thickness of the top flanges was revised (relative to the baseline tub girder) due to their new location. Finite element analyses were carried out to define the thickness of the top flanges for this second specimen in order to assure an elastic behavior of the tub girder during the buckling tests to be performed at the laboratory. The top flange thickness was set equal to 9/16", resulting in a width-to-thickness ratio of the slender top flange equal to 21.33. Clearly, this ratio is not compliant with the current code requirements of flange slenderness, but limitations in the weight of the girder (due to handling inside of the laboratory) did not allowed thicker top flanges. The bottom flange and sloped webs were sized with 7/16" thick plates, similar to the baseline tub girder.

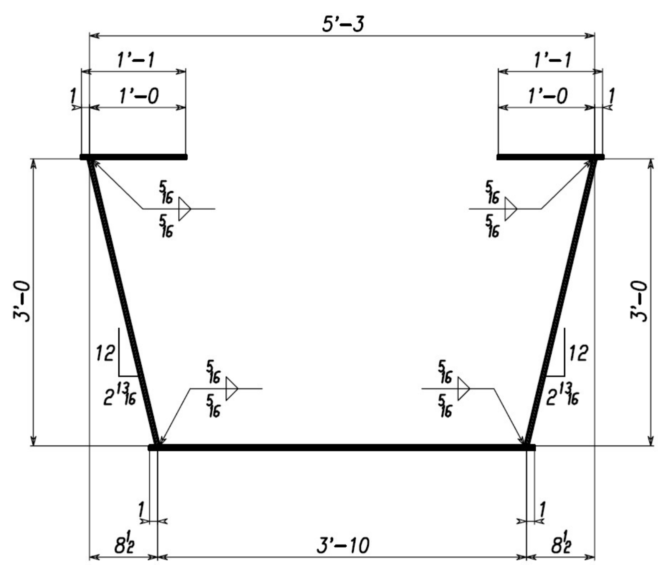

Figure 4 - Full-Scale Offset Top Flange Tub Girder Specimen - Cross Section

2.1.1.3 Flatter Web Tub Girder

Different from the previously mentioned tub girders, the slopes of the two webs of the third steel tub girder test specimen were set to be equal to approximately 2.5V:1H (Fig. 5), which exceeds the limit ratio according to section 6.11.2.1.1 of AASHTO (2012). The top flanges were centered to the center line of the sloped webs, as depicted in Fig. 5.

Similar to the baseline tub girder the flatter web girder was built with webs and flanges 7/16 in. thick in order to obtain elastic-buckling response of the system during the experimental tests.

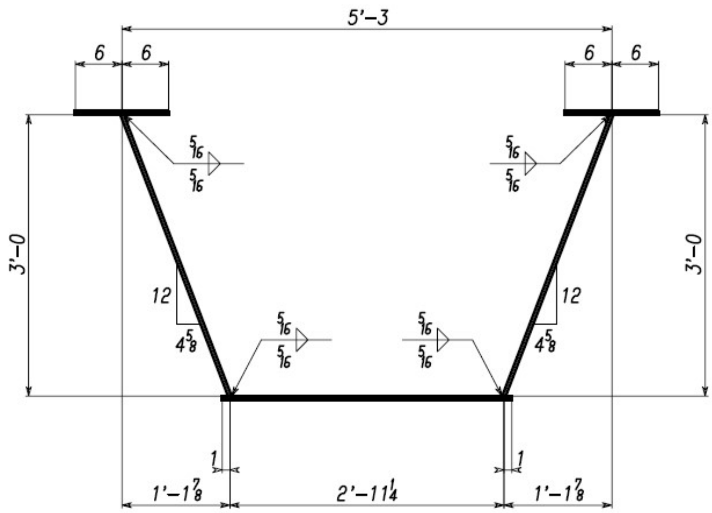

Figure 5 - - Full-Scale Flatter Web Tub Girder Specimen - Cross Section

2.1.1.4 Bracing Geometry

The spacing of the top lateral truss panel points was defined as 7 ft., generating 12 panels along the length of the beam (Fig. 6). As noted earlier, the internal K-frames can be installed or removed as desired to study the behavior of the girders as the bracing is varied. In a similar fashion, the top lateral truss diagonals can also be added or removed as 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. As an example of a bracing configuration, Fig. 6 shows a plan view of the baseline tub girder, where the first two panel points denote a "strut-only" and K-frame condition. Many other configurations were tested for the baseline specimen, as well as for the other two specimens.

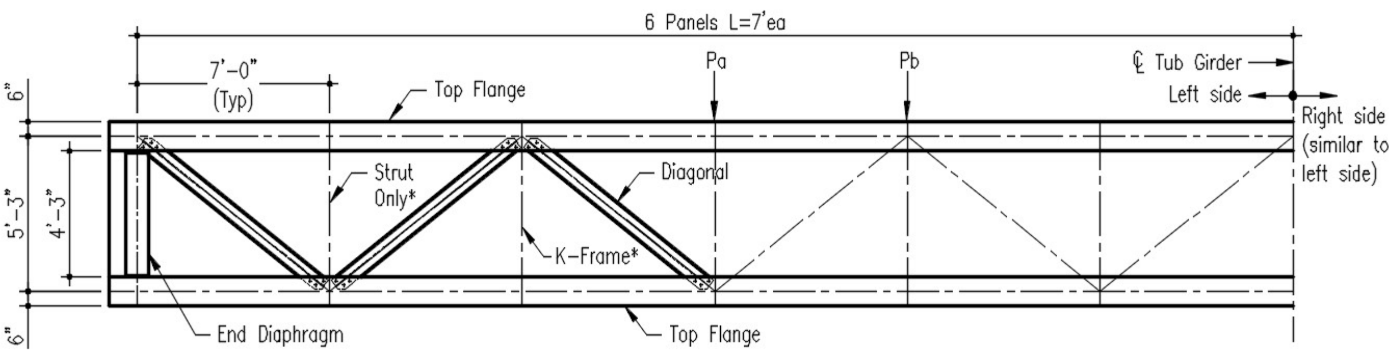

Figure 6 – Example of Bracing Layout - Half of Baseline Steel Tub Girder Specimen - Plan View

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 in the test specimens. The diagonals were designed to be directly connected to the top flanges to avoid gusset plates (Fig. 7). Bolted connections allowed 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 were 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 based on Helwig and Yura (2012). The angle between the diagonal and the top flange center lines is 37 degrees. Three diagonals were installed at each end of the steel tub girders 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 7 - Top Lateral Bracing System

The WT5x22.5 section used for the diagonals was checked to have enough capacity in tension and compression to remain elastic during the tests. Also, this WT 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 warping normal stresses less than 10% of the major-axis bending stresses. On the other hand, a 2 in diameter x-strong pipe (2.375 in. outside diameter and 0.218 in. wall 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.

2.1.3 Internal K-Frame Bracing

Formed by one strut (which is part of the top lateral truss) and two diagonals (Fig. 8), 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. x-strong) for facility during fabrication. The K-frame bracing elements were fabricated with ASTM A53 – Grade B steel. 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 panel points were evaluated during the experimental program.

Figure 8 - K-frame Bracing

2.2 Description of Test Setup

The test setup (Fig.9) 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 each specimen can rest 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 9 – Baseline Steel Tub Girder (No top lateral truss present) - Test Setup

Vertical loads over the steel tub girders are applied with two gravity load simulators (GLS) as shown in Fig.10. 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. Consequently, the GLS does not introduce a horizontal component of force to the girder, as the girder displaces laterally due to LTB. 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.

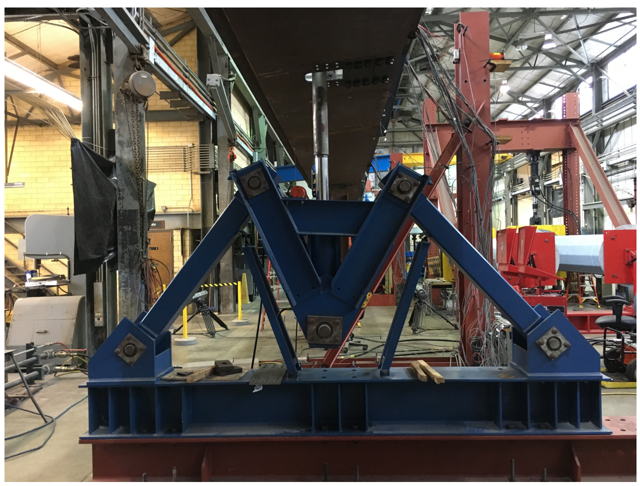

Figure 10 - Gravity Load Simulator (GLS) during test

The focus of this study is on both straight and horizontally curved girders. Although the research team considered fabricating horizontally curved girders, laboratory space limitations as well as the limitation of being able to test 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 of the tub girder that allows the load to be shifted laterally up to an eccentricity of 16 inches. Bolted cover plates were 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 600 ft. were possible.

2.3 Testing Procedure and Instrumentation

Prior to testing, initial imperfections of each 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 sides of the girder. Each specimen was resting over the north and south test setup supports when initial imperfections were measured on the east and west sides of the girders. The baseline girder showed an initial twist of 1.30 degrees (midspan) and a maximum out-of-straightness of about L/1300 (on top flange) towards the east. The girder with offset flanges presented an initial twist of about 1.60 degrees (midspan) and a maximum out-of-straightness of L/750 (on top flange) towards the west. Finally, the girder with flatter webs showed an initial twist of 2.30 degrees (midspan) and a maximum out-of-straightness of about L/500 (on top flange) towards the east. Initial imperfections were measured before every elastic-buckling test; however, these imperfections did not changed significantly 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 the construction phase, the range of stresses imposed over these sections are normally within the elastic range. AASHTO (2012) requires the girders during construction remain elastic. Elastic-buckling tests were carried out by applying loads to 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 vertical eccentric loads (to simulate horizontal curvature). For the positive bending tests, two vertical loads were applied at approximately quarter points of the beam (location denoted as “Pa” on Fig. 6). Henceforth, the load on each GLS will be referred to as load “P”. The combined vertical bending and torsional demands were obtained by applying vertical eccentric loads at 8 in. and 16 in. from the shear center location of the girders. Vertical loads with eccentricities of 8 in. and 16 in. were selected to simulate demand conditions produced by curvature on horizontally curved tub girders with radii of curvature equal to 1200 and 600 ft., respectively. The eccentric loads were applied so that torsional demands towards the west of the girders were imposed. The maximum total vertical load applied varied depending on the bracing configuration and the eccentricity. The maximum vertical load applied was 100 kips (2 point loads of 50 kips) with different load increments depending on the test.

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 an optical tracking system that captures the displacements of LED markers attached to the tub girder section. The vision system collected deflections with relatively high accuracy (error of about 0.01mm). Rotations were calculated from the measured deflections. These results are not part of the scope of the current paper, so that they are not reported herein.

To calculate the bracing forces, stresses in the cross-section of the bracing members were obtained using conventional resistance-based foil strain gages. Six strain gauges were installed at mid-length on every top lateral truss member (WT5x22.5). A linear regression method was used to calculate axial forces in the top lateral diagonals. Struts and diagonals of the K-frames were instrumented with strain gages at mid-length of the pipes, where a pair of gages were installed on opposite sides of the pipe to allow strains due to bending of the pipe to be separated from strains due to axial forces. Axial forces in these pipes were calculated by averaging the strains obtained with the opposite gauges.

2.4 Bracing Configuration

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

Each test was conducted with different amounts of top bracing diagonals at each end. Cases with 0, 1, 2, and 3 diagonals on each end of the simple supported girder were the four configurations of partial top lateral bracing studied. For each aforementioned top lateral bracing configuration (four bracing layouts), three different configurations of internal K-frame bracing were assessed. K-frames were located at every 2, 4, and 6 panel points for each configuration of top lateral bracing, which resulted in a total of 12 elastic buckling tests. These 12 configurations of top lateral and K-frame bracing were evaluated for the three cases of vertical loads (concentric, eccentric at 8”, and eccentric at 16”) producing a total of 36 elastic-buckling tests performed with the GLSs. The variation on the top lateral bracing forces with different K-frame layouts is evaluated and summarized in the following sections.

3. Experimental Results

A total load (2P) that represents construction loads was defined to compare forces in the top lateral bracing members. Assuming 0.8 kip/ft. as a uniform construction load that represents the weight of a concrete deck, stay-in-place forms, and construction loads, a maximum moment of 706 k-ft. would be expected during construction. In order to produce the same maximum moment, a load of 35 kips on each gravity load simulator (P) is required. Thus, a total load (2P) of 70 kips is the load at which the bracing forces were compared.

3.1 Top Lateral Bracing Forces on Straight and Horizontally Curved Tub Girders

To study the load distribution on partial top lateral bracing on straight and horizontally curved steel tub girders, the specimens were loaded under bending and torsional demands. The bracing force distribution observed under these two loading conditions is described in this section. Fig.11 shows the labels of the top lateral bracing diagonals used in the plots presented herein. Each tub girder contains 12 panels, which are defined as the area between adjacent struts. Truss diagonals S3, S2, S1, N1, N2, and N3 are located in panels 1, 2, 3, 10, 11, and 12, respectively.

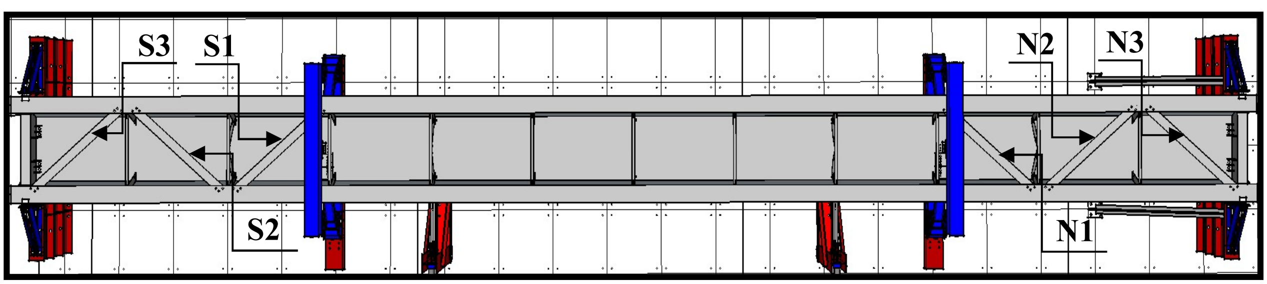

Figure 11 - Top Lateral Truss Labels - Plan View (N and S referring North and South supports, respectively)

3.1.1 Positive Bending Tests (Straight Tub Girder)

The gravity load simulators were used to apply vertical concentric loads near the quarter points of the girders to evaluate the load distribution on partial top lateral bracing under positive bending demands when different layouts of internal bracing (K-frames) were installed. Two gravity load simulators were used to apply vertical concentric loads (P) on the specimen. The forces for partial top lateral bracing were obtained for the 3 different configurations of partial horizontal truss (with 3, 2 and 1 diagonal on each end).

Fig.12 shows the total vertical load applied (2P) versus the axial force on each truss diagonal when the partial lateral bracing truss is formed by 3 diagonals on each end and when K-frames are installed at every 2 panel points in the baseline tub girder. Additionally, the total load (2P) at which the bracing forces are compared is marked with a dashed line on Fig.12. Considering the fact that the baseline girder had an initial twist towards the east of the tub, the bracing members N1, N3, S1, and S3 sustained compression forces; while the diagonals N2 and S2 (framed in the opposite direction) saw tensile forces. Although torsional demands were not directly imposed, axial loads were observed in the horizontal truss. The distribution of the braces forces along the length of the girder show larger bracing forces in the diagonals close to mid-span implying that vertical bending demands are dominant. The horizontal truss is connected to the top flange which is a region of high bending stresses. Thus, the top lateral diagonals experience the same axial strains as the tub girder because of compatibility, as described by Helwig and Fan (1999). Similar general force distributions along the length of the girders was observed when the K-frame layout was modified, even though variations in the internal forces distribution were observed.

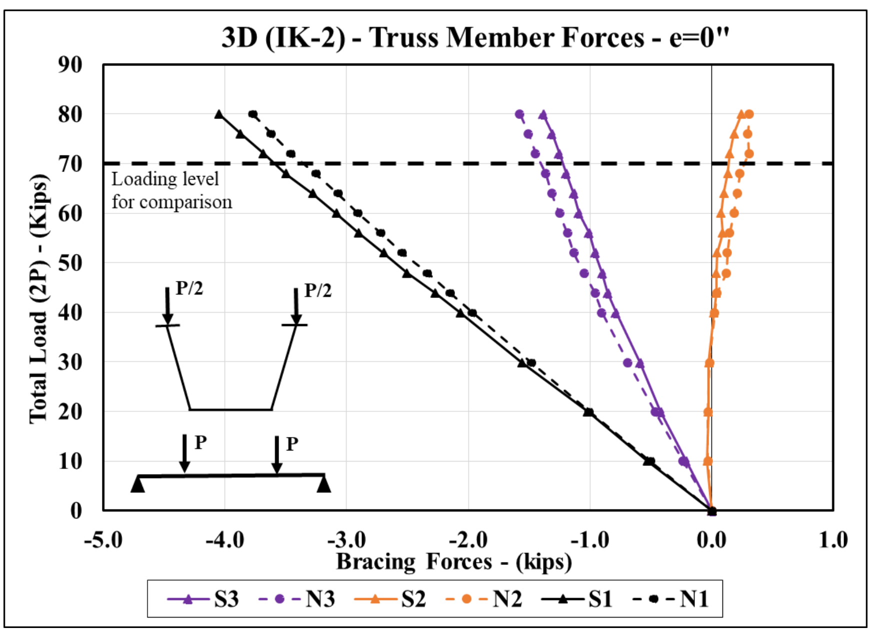

Figure 12 - Bracing Forces on Simple Supported Beam due to Vertical Bending - Baseline Tub Girder

Fig. 13 shows the top lateral bracing forces with the 3 different K-frame layouts under study. As previously mentioned, the larger bracing forces were observed closer to mid-span where the bending strains are larger. When K-frames were placed every 2 panels, the bracing forces in the panels 3 and 10 were the largest. However, after changing the K-frame configuration, redistribution of forces was observed. Diagonal forces in panels 1 and 12 (next the supports) changed by about 50%. The bracing forces in the diagonals of panels 2 and 11 went up about 150 to 400%; however, these forces were very small relative to the other bracing forces. On the other hand, bracing forces in panels 3 and 10 went down about 30%. When the internal bracing layout was changed from K-frames every 4 panels to every 6 panels, no significant change in top lateral bracing forces was observed.

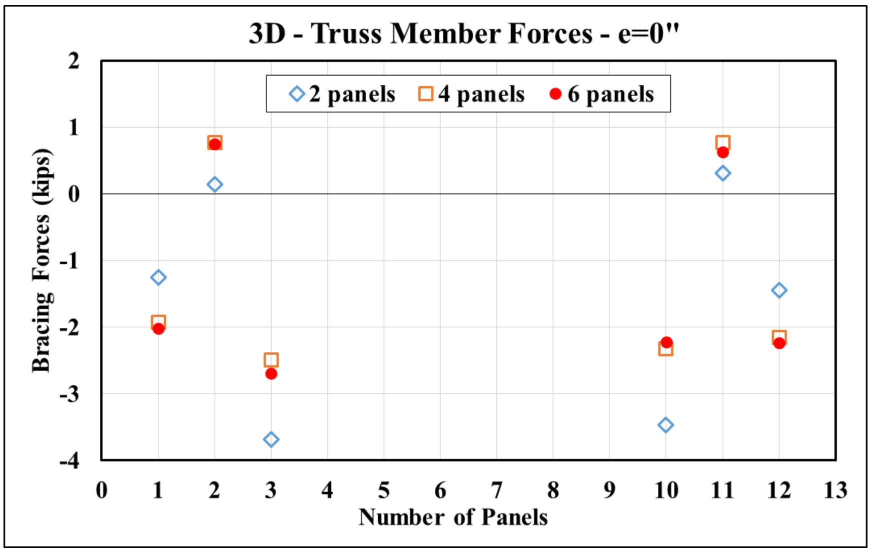

Figure 13 - Top Lateral Diagonal Forces for Different K-frame Layouts (3 Diagonals) - Baseline Tub Girder

Although there was a redistribution of forces in the bracing systems when the K-frame layout was modified, the general response of the tub girders was very similar. The torsional stiffness of the girder was not highly affected when modifying the internal bracing layout. The twist angles at mid-span of the baseline girder when K-frames were placed at every 2, 4, and 6 panels were 0.043, 0.046, and 0.042 degrees, respectively.

This redistribution of loads shows a clear interaction between the top lateral bracing truss and the internal K-frames. When K-frames were placed every 2 panels, one of these internal frames was located between panels 2 and 3, and panels 10 and 11. The strut and diagonals of the aforementioned K-frame sustained loads of about 2.4 kips (tension) and 1.0 kip (tension and compression), respectively. When K-frames were placed every 4 and 6 panels, the previously mentioned K-frame was not present and only the horizontal strut was left (K-frame diagonals were removed). The force in that strut was about 1.15 kips (tension) which is about 50% the force that the strut sustained when K-frames were placed every 2 panels. In the absence of the K-frame diagonals, the forces are absorbed by the stiffer members (WTs) which produced an increment in the load sustained by the top lateral diagonals in panels 1, 2, 11, and 12.

Additionally, the change in K-frame layout from every 4 to every 6 panels did not produced significant changes in top lateral bracing forces. This effect shows that the top lateral truss can interact with the K-frames only if the internal braces are located in the regions where partial top lateral bracing is placed; specifically, between panels with top lateral diagonals.

Fig. 14 shows the top lateral bracing forces when 2 top lateral diagonals were placed on each end with the 3 different K-frame layouts. Clearly, this arrangement of top lateral bracing members was less sensitive to force redistribution than when 3 diagonals were placed. The variation of axial forces in panels 1 and 12 were between 5 to 11%, and the forces in panels 2 and 11 varied about 6 to 18%, which is significantly less than what was observed in Fig. 13. With no K-frame inside the region of partial top lateral bracing, the interaction between these two bracing systems is smaller. When 1 truss diagonal was placed at each end, the axial forces varied about 1 to 3%.

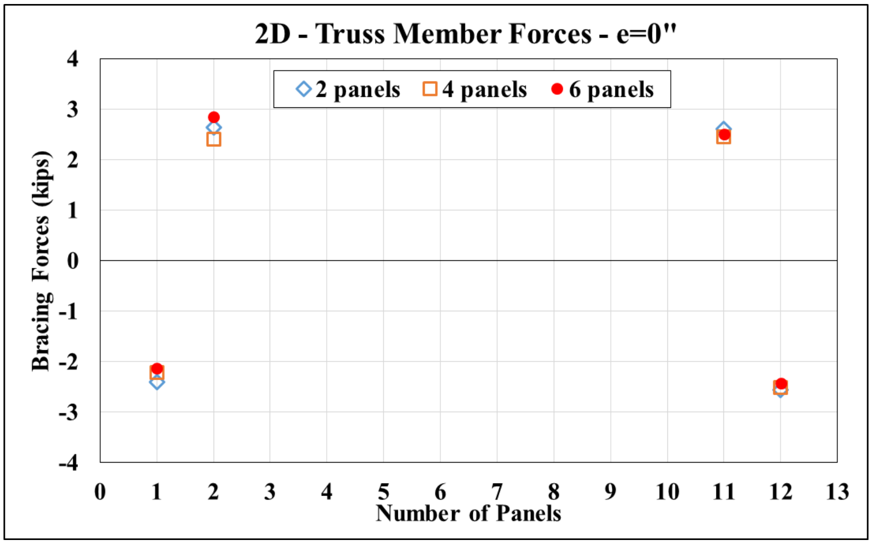

Figure 14 - Top Lateral Diagonal Forces for Different K-frame Layouts (2 Diagonals) - Baseline Tub Girder

3.1.2 Bending plus Torsion Tests (Horizontally Curved Tub Girder)

The gravity load simulators were used to apply eccentric vertical loads near the quarter points of the girders. Eccentric loads at 8 in. and 16 in. from the shear center of the section were applied to simulate the demands on horizontally curved bridges with radii of curvature of 1200 and 600 ft., respectively.

Fig.15 shows the total vertical load applied (2P) versus the axial force on each truss diagonal when the partial lateral bracing truss is formed by 3 diagonals on each end and when K-frames are installed every 2 panel points in the baseline tub girder. Fig. 15 shows the bracing forces when eccentric vertical loads were applied at 16 in. from the shear center. The eccentric vertical loads were applied so that torsional moments towards the west of the tub were applied; in fact, opposite to the initial twist of the girder. Based on that, the bracing members N1, N3, S1, and S3 sustained tensile axial forces; while the diagonals N2 and S2 (framed in the opposite direction) experienced compression axial demands. The distribution of the braces forces along the length of the girder showed larger bracing forces in the diagonals closed to the supports; while the diagonals close to mid-span showed lower axial forces. This distribution of axial forces implies that the torsional demands are dominant instead of the vertical bending. The larger torsional demands are expected to occur at the supports where the warping deformations are expected to be larger. Once the top lateral diagonals are engaged, they restrain the shear deformations associated with warping, and as a result, the truss diagonals neat the girder ends experienced higher axial forces than the ones near mid-span.

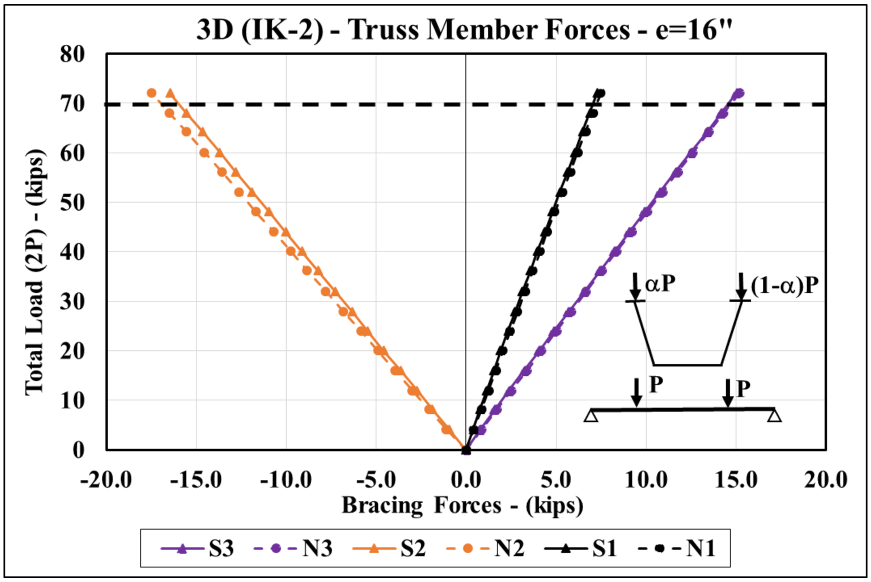

Figure 15 - Bracing Forces on Simple Supported Beam due to Combined Bending & Torsion - Baseline Tub Girder

Fig. 16 shows the top lateral bracing forces with the 3 different K-frame layouts under study. As previously mentioned, larger bracing forces were observed close to the supports where the larger warping demands occur. When K-frames were placed every 2 panels, the bracing forces in panels 1 and 12 (tension), and 2 and 11 (compression) were very similar; while the forces in panels 3 and 10 (tension) were about 50% of the forces in panels 1 and 12. However, after changing the K-frame configuration, redistribution of forces was observed. Diagonal forces in panels 1, 2, 11 and 12 dropped about 10 to 19%. Correspondingly, bracing forces in panels 3 and 10 went up about 50%. When the internal bracing layout was changed from K-frames every 4 panels to every 6 panels a maximum variation of about 5% in the truss forces was observed.

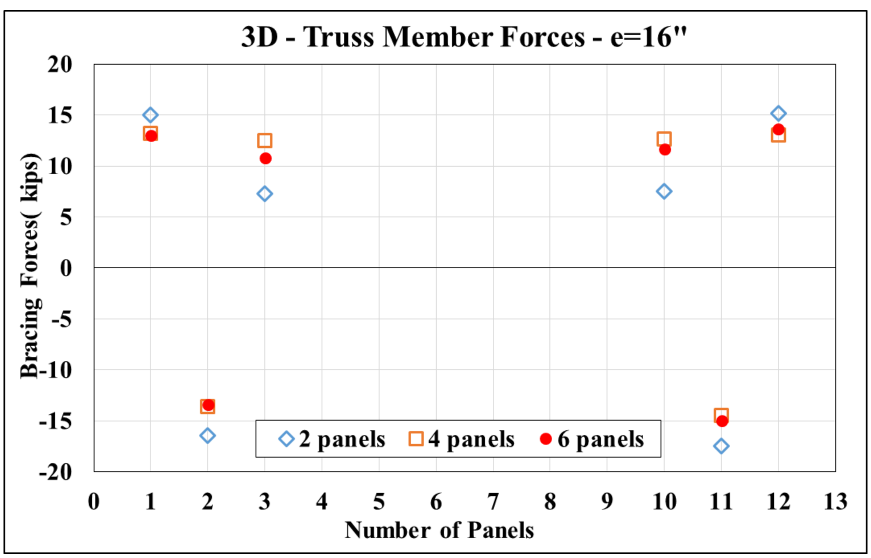

Figure 16 - Top Lateral Diagonal Forces for Different K-frame Layouts (3 diagonals) - Baseline Tub Girder

The general response of the tub girders showed minor variations. The twist angles at mid-span of the baseline girder when K-frames were placed at every 2, 4, and 6 panels were 0.31, 0.41, and 0.58 degrees, respectively. As a result, the forces in the bracing members are comparable.

Clearly, the interaction between the top lateral bracing truss and the internal K-frames is still present when torsional demands are dominant. When K-frames were placed every 2 panels, the internal K-frames located between panels 2 and 3, and panels 10 and 11 showed higher axial forces than with the other K-frame distributions. The strut and diagonals of the aforementioned K-frame developed forces of about 6.0 kips (tension) and 4.60 kip (tension and compression), respectively. When K-frames were placed every 4 and 6 panels, the previously mentioned K-frame was not present and only the horizontal strut was left (K-frame diagonals were removed). The force in that strut was about 1.50 kips (tension) which is about 25% of the force that the strut sustained when K-frames were placed every 2 panels.

Fig. 17 shows the top lateral bracing forces when 2 top lateral diagonals were placed at each girder end with the 3 different K-frame layouts for the eccentric loading case. Compared to the case where 3 diagonals were placed, this layout of top lateral bracing diagonals experienced less force redistribution. The variation of axial forces in panels 1 and 12 were about 21%, and the forces in panels 2 and 11 varied about 3 – 5%, which is significantly less than what was observed in Fig. 16. With no K-frame inside the region of partial top lateral bracing, the interaction between these two bracing systems is smaller.

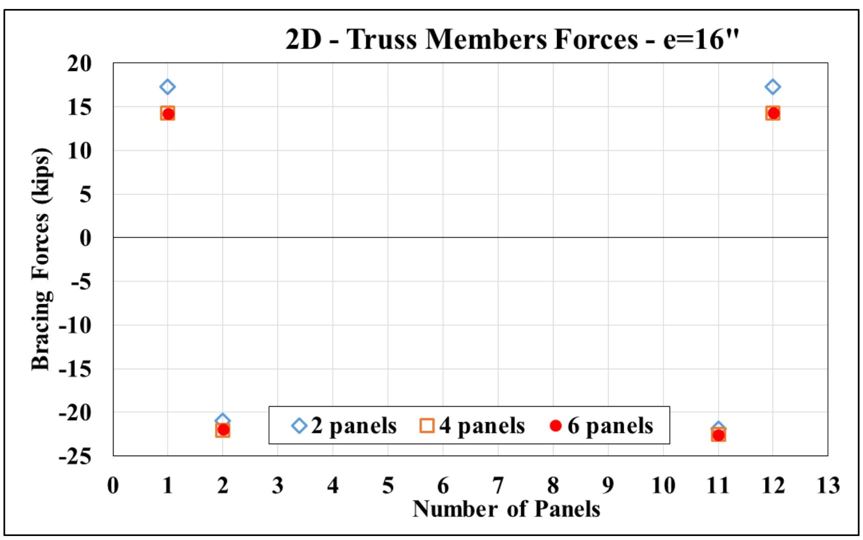

Figure 17 - Top Lateral Diagonal Forces for Different K-frame Layouts (2 diagonals) - Baseline Tub Girder

Although the results presented herein were for the baseline tub girder, similar trends in response was observed for the other two specimens under concentric and eccentric loading.

Finally, in order to extent the results obtained in the experimental study, an analytical study was performed, and is described below.

4. Analytical Study

Three-dimensional FE models of the tub girder specimens were created using a commercial finite element software (ABAQUS) and then validated with the experimental data. Following this validation process, a finite element model of a typical three-span continuous curved girder was created in order to expand the results obtained in the experimental study. The model was used to study the behavior of tub girders with partial-length bracing. The results presented herein focus on the interaction of the top flange lateral bracing and internal K-frames. These analyses considered construction loads and the sequence of loading during the concrete deck casting.

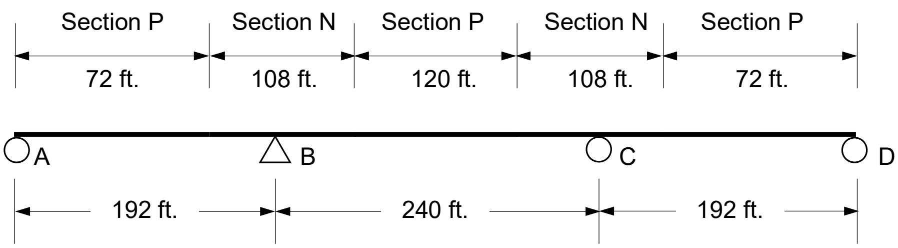

Figure 18 - Continuous Bridge - Longitudinal Dimensions

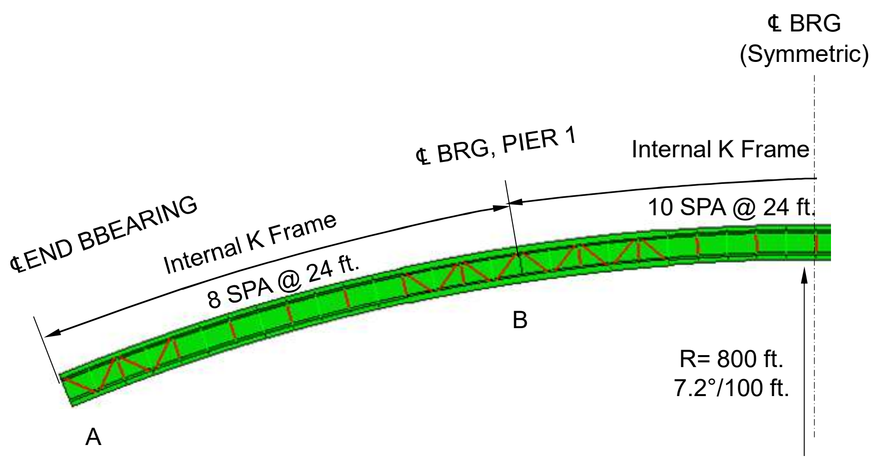

Figure 19 - Half of the Symmetric Three-Span Bridge - Plan View

The three-span horizontally curved girder shown in Fig. 18 and 19 was selected for the analytical study. The radius of curvature of the girder is 800 ft. which results in a 7.2° subtended angle for every 100 ft. of girder length. The girder is non-prismatic with two cross-sections, Sections P and N, which are used in positive and negative moment regions, respectively (Fig.20). Distributed loads were applied on each top flange to simulate gravity loads from wet concrete, forms, deck overhang, and other construction loads. The horizontal top lateral truss is a single diagonal type with 52 panels along the length of the bridge and a panel size of 12 ft. Torsional demands on the girder are caused by the horizontal curvature. The top flange lateral diagonals were modeled with WT5x30 sections; while the horizontal struts were defined as L5x5x0.5 members. K-frame diagonals were assigned the same section as the struts. Shell elements (S4R) were used to model the tub girder section plates; while beam elements (B31) were used to model the top flange truss and internal K-frames. The assumed deck casting sequence is shown in Fig.21 below.

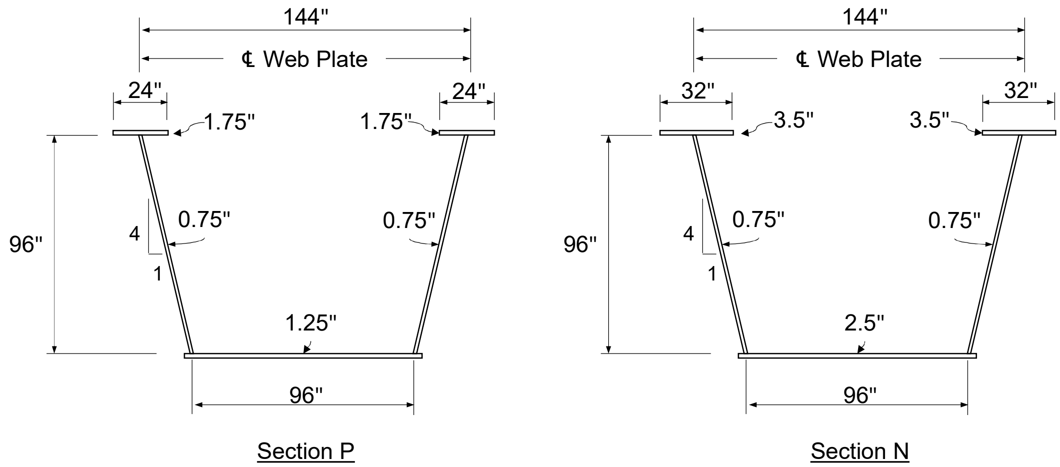

Figure 20 - Continuous Bridge - Cross-Sections

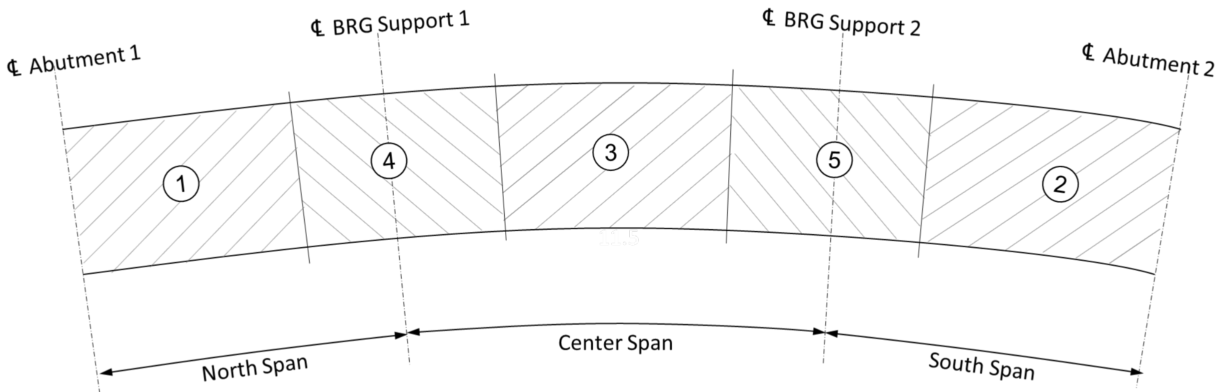

Figure 21 - Deck Casting Sequence

To represent the partial top lateral bracing, 50% of the total top lateral diagonals were provided, as shown in Fig. 19. Only the truss diagonals in the negative moment region and near the end supports were retained. Analysis were performed with K-frames located at every 2 and every 4 strut panel points (24 ft. and 48 ft. spacing between internal K-frames, respectively) keeping the same amount of top lateral diagonals. The results presented below focus on the brace force interaction between top lateral truss diagonals and K-frame diagonals.

Fig. 22 shows the forces of the partial top lateral bracing system when K-frames were placed every 2 and every 4 panels. Similar to the results obtained in the experimental study, a variation in the top lateral truss forces was experienced when the amount of K-frames was reduced. The increment of axial forces in the top lateral diagonals ranges from 0.6 to 15%. Besides the diagonals, some of the axial forces in the struts that comprise the horizontal truss dropped up to 70% when the K-frame layout was modified from K-frames every 2 to every 4 panels, as shown in Fig.23. Clearly, the interaction of these two bracing systems can be observed not only in experimental tests, but also in more realistic applications. Although the variation in axial forces (diagonals) is not as large as the ones experienced in the experimental study, other configurations of K-frames may produce more significant variations in top lateral bracing forces. This variable will be considered for future parametric analytical studies.

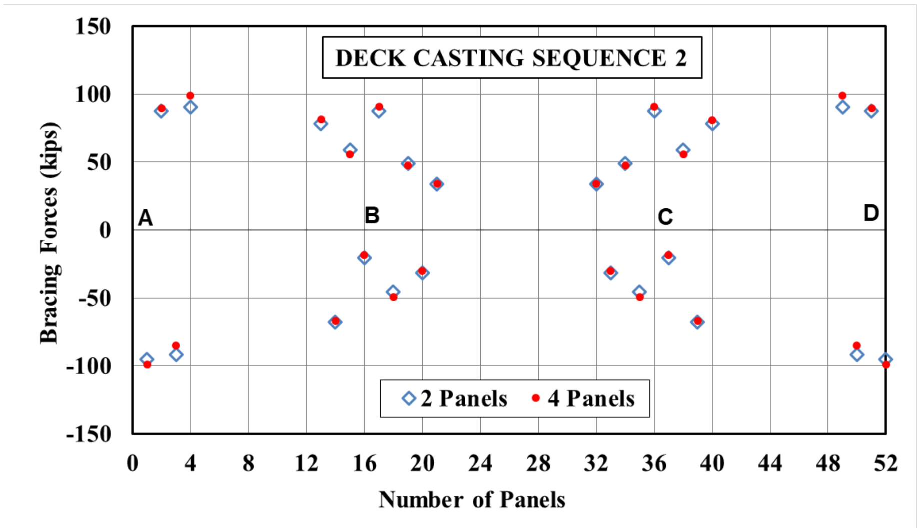

Figure 22 - Top Lateral Bracing - Axial Forces in Diagonals

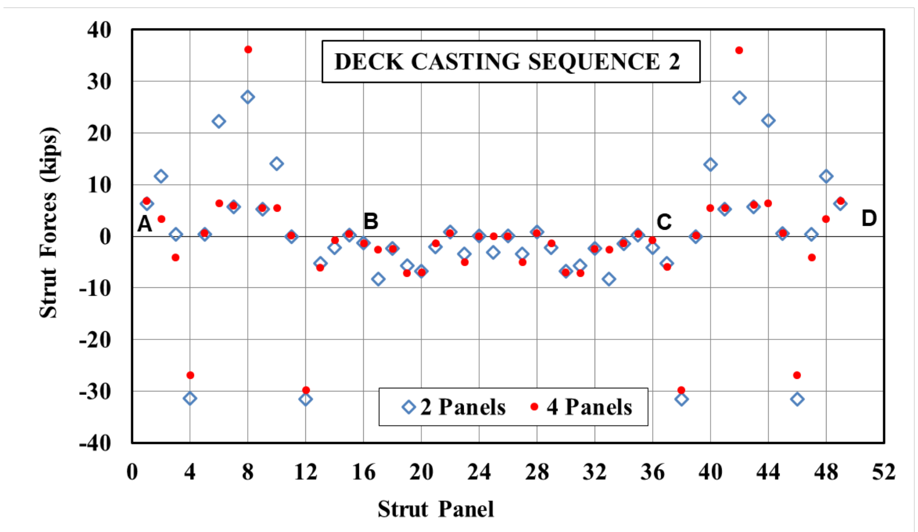

Figure 23 - Top Lateral Bracing - Axial Forces in Struts

5. Conclusions

This paper documents some results of an experimental and analytical study to evaluate the interaction of top lateral bracing and internal K-frames in straight and horizontally curved 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 impact of different configurations of top lateral and internal bracing in straight and horizontally curved tub girders. The major findings are as follows:

- Experimental tests showed that the partial top lateral bracing systems interact with internal K-frames when a tub girder is subjected to either vertical bending or torsional demands. Modifications in the configuration of internal K-frames caused changes in the axial forces of the horizontal truss members. The variation in forces measured in the diagonals and struts of the horizontal truss were as high as 50% to 70%, depending on the level and the type of demand.

- When K-frames were not installed in the zones of partial top lateral bracing, rearranging the internal bracing layout did not produce significant variation in the diagonal forces of the horizontal truss.

- An analytical studied that considered construction sequence showed that the interaction between top lateral bracing and K-frames can be observed not only in experimental tests but also in more realistic applications.

6. Acknowledgement

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