Rational Design of Top Lateral Bracing of Tub Girders

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ABSTRACT: While steel composite box girder bridges possess considerable torsional stiffness in their final completed stage, the absence of the deck slab during construction can make them vulnerable to large torsional deformations and instability. Recent collapse of the Marcy Pedestrian bridge during construction underscores this vulnerability. Thus providing for stability during initial construction as well as future re-decking is a key issue that must be considered in the design and detailing of these bridges. Top lateral bracing is the typical solution for providing the needed torsional stiffness during construction. Further, curved alignments can elevate the design of the top lateral bracing from a nominal provision to a primary load carrying system. The torsion and bending interaction associated with curved alignments inject an added dimension of complexity to the detailing of the top lateral bracing. This paper discusses the practical considerations and design optimization of top lateral bracing and provides a rational design basis.

INTRODUCTION

Steel-composite box girder superstructures are used in a wide range of applications with the number of boxes in cross section varied to suit the width of the roadway. Their remarkable rigidity and strength in resisting torsional moments makes them the structural form of choice for curved alignments and numerous other applications involving significant eccentric loading conditions. They also provide a pleasant and clean appearance and hence are a popular solution for bridges where aesthetics play an important role. However, steel tub sections of these box girders during construction can be quite vulnerable even to nominal loading conditions unless detailed properly. This is well illustrated by the Marcy Pedestrian bridge collapse during construction (Figure 1). This vulnerability of tub girders during construction is due to the following two factors:

Figure 1: Marcy Bridge collapse [5]

1. In the non-composite stage (without the deck slab) the steel tub sections by themselves lack any significant torsional stiffness

2. The shear center of the steel tub section (in the pre-composite stage - prior to concrete deck) is well below the elastic center of the section

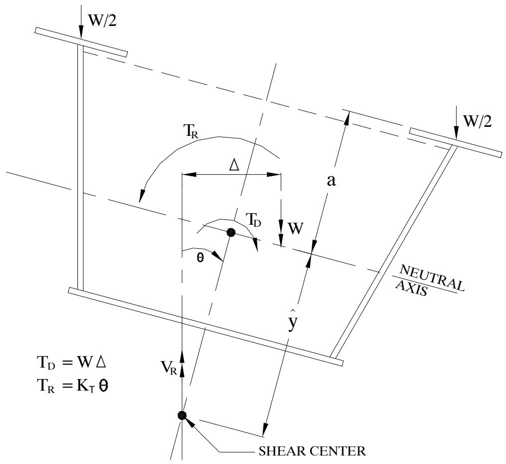


Figure 2: Top lateral bracing and tub-girder stability

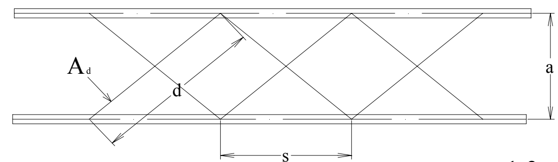
This is schematically illustrated in Figure 2, where even under perfectly symmetrical loading (W), a small rotation of the box section (θ) produces a disturbing moment T_D due to the horizontal offset Δ between the lines of action of the external load W and the location of shear resistance of the section V_R. In the absence of sufficient torsional stiffness, the section is incapable of developing a sufficient restoring moment, and divergent rotations due to small perturbations can result. For tub girder sections often the section modulus for lateral bending is larger than that for vertical bending. While the conventional wisdom suggests that such sections are incapable of developing instability due to lateral torsional buckling, it does not apply to tub girders due to the location of their shear center significantly below the neutral axis. This was first noted by Attard (1990). While the simplification in Figure 2 may suggest that the instability is driven by lack of statical-equilibrium, in actuality, the underlying structural mechanics parallels that of classical lateral torsional buckling.

The common arrangements of top lateral bracing systems used on tub girders are shown in Figure 3. These provide a pseudo closed box section by providing a mechanism for transverse shear flow at the top flange level. For engineering assessments, these are often represented as an equivalent steel plate between the top flanges. The equivalent plate thicknesses (t_e) for the respective arrangements can be obtained using the expressions shown with the diagrams (Heins, 1975). Once t_e is known the Saint Venant torsional constant can be computed using the following well known expressions. For no top lateral bracing – open section ($t_e = 0$):

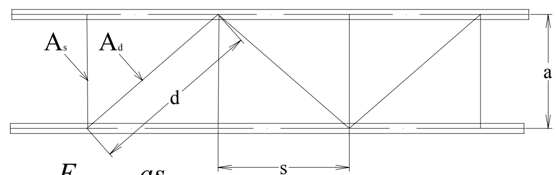
$$J_{open} = \frac{1}{3}\sum_{i=1}^{n} b_i t_i^3 \qquad 1.1$$

With top lateral bracing – closed section ($t_e \neq 0$):

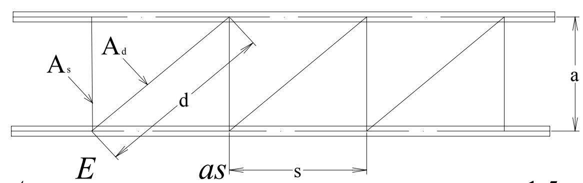
$$J_{closed} = \frac{4A_0^2}{\sum \frac{b_i}{t_i}} \qquad 1.2$$



$$t_e = \frac{E}{G}\frac{as}{\frac{d^3}{2A_d} + \frac{s^3}{6A_{tf}}} \qquad 1.3$$



$$t_e = \frac{E}{G}\frac{as}{\frac{d^3}{A_d} + \frac{2s^3}{3A_{tf}}} \qquad 1.4$$



$$t_e = \frac{E}{G}\frac{as}{\frac{d^3}{A_d} + \frac{a^3}{A_s} + \frac{s^3}{6A_{tf}}} \qquad 1.5$$

Figure 3: Common arrangements of top lateral bracing and equivalent plate thicknesses [2]

For analysis, a box girder is often represented as a structural spline and the Saint Venant torsional constant J is prescribed along with other axial, bending and shear section properties needed for describing the mechanical properties of the beam elements. However, the torsional behavior of a tub section cannot be adequately described without considering the effects of warping torsion. The relationship between the internal moment of resistance and the twist angle of the cross section (θ) at a given location (x) is given by:

$$T(x) = GJ\frac{d\vartheta}{dx} + EC_w\frac{d^3\vartheta}{dx^3} \qquad 1.6$$

Where C_w is the warping constant of the cross section. Determination of the shear center and the warping constant is fairly involved (Heins, 1975). As the FEM beam (frame) formulation lacks all higher order derivatives than dθ/dx of the rotation θ, the normal FEM formulation is incapable of capturing warping effects. This issue and the significant misalignment between the elastic center and the shear center contribute to the limitations involved in structural spline representation of tub girders in analysis. Alternatively, the use of a second beam element placed eccentric to the spline along the elastic center can be used as a modeling procedure where standard beam elements can be used for representing warping (Kumarasena et. al, 1989). However, this is rarely implemented in a design office environment.

Theoretically, tub girders on straight alignments do not have to resist any torsional moments in the non-composite stage, and consequently, it is regarded by some in the design community that top lateral bracing is not required for such cases. Where top lateral bracing have been provided, they are often sized to meet some nominal minimum slenderness requirements. However, as demonstrated later, the critical vertical load a tub section can carry prior to reaching lateral instability is directly related to the size of the top lateral bracing. The pre-composite DL acting on a tub section during construction can be a substantial part of the total design load, especially for longer spans. This makes the consideration of stability a key design issue. This is well demonstrated by the Marcy Pedestrian bridge experience. For curved alignments, in addition to maintaining stability, top lateral bracing must also resist primary forces crucial to maintaining statical equilibrium. In such cases, they could become substantial elements with sizable connections. Thus design optimization considering the torsion-bending interaction becomes an important practical issue.

After completion of the superstructure, the torsional stiffness contribution from the deck slab is considerably large in comparison to that of the top lateral bracing. For this reason, the additional forces in the bracing elements due to live load and other transient loads acting on the completed bridge structure are typically an order of magnitude smaller than due to dead loads during construction.

STUDY OBJECTIVES & APPROACH

As noted previously, top lateral bracing is a critical design element for tub girders in the pre-composite stage. They are tied to the critical vertical load that the tub girder can carry prior to reaching elastic instability. For curved alignments, top lateral bracing must also resist primary forces needed to maintain static equilibrium, and as shown later, additional design and detailing considerations are required to ensure satisfactory performance of the pre-composite tub girder during construction. However, the existing AASHTO design specifications do not fully address these issues and there is a certain lack of appreciation with respect to some of the key issues within the design community. The key objectives of the current study were to conduct a preliminary investigation in to the following:

1. Examine the stability of tub-girders on straight alignments under concentric gravity loads
2. Examine the effects of nominal eccentricities on stability of straight tub girders
3. Compare the common methods of computing cross section properties in torsion with FEM analysis based methods
4. Formulate a design criteria for stability for tub section on straight alignments based on theoretical and numerical studies
5. Examine how the curvature affects the behavior of tub girders during construction and see what additional design checks are needed in the presence of curvature

The pioneering work by Timoshenko (1961) explaining the mechanics of lateral torsional buckling of rectangular solid beam sections has been further developed for various loading, boundary conditions and specific design conditions by others (eg. Nethercot & Rockey, 1971). The present study is aimed mainly at design issues relating to the tub girders during construction when they possess only a small fraction of the final torsional stiffness of the completed structure. Additionally, in their pre-composite stage, the tub sections are typically subjected to a large proportion of the total design load without the benefit of the concrete slab, and could also be subjected to nominal eccentric loading conditions due to various factors. Considering the tub girder section shown in Figure 2 on a simple span of length L, it can be shown that the uniformly distributed concentric gravity load w_c corresponding to lateral torsional buckling is given by:

$$w_c = \frac{\beta}{\sqrt{(1+\frac{2a}{\hat{y}})}} \frac{\pi}{L^3} \sqrt{EIGJ + (\pi / L)^2 EIEC_w} \qquad 2.1$$

where β is a constant. A 3-dimensional finite element model of a simple span bridge layout as shown in Figure 4 was developed and analyzed under a uniformly distributed concentric load to validate the use of the above expression and to find the constant β . In developing the finite element model, the webs, top and bottom flanges of the tub section were modeled using shell elements and the transverse diaphragm elements were modeled using beam elements with appropriate section properties. The top lateral bracing was represented as a plate of thickness t_e between top of webs, modeled again using shell elements. The analysis considered geometric nonlinearity in all elements of the box girder. The equivalent plate elements representing the top lateral bracing were modeled as linear elements to prevent the buckling of these very thin elements due to in-plane bending of the box section.

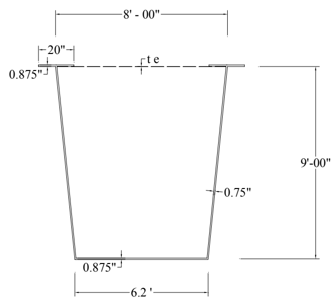
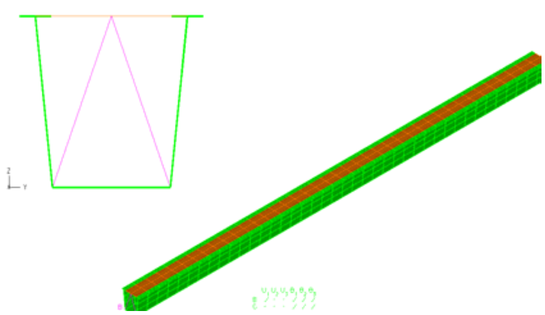


Figure 4: Details of the tub girder section and the FE model



One half of the uniformly distributed load was applied along the top of each web, and the load intensity was increased until instability was reached. The loading direction was kept vertically downwards throughout the model deformation process. The values of the critical load was obtained for no top lateral bracing (t_e = 0) as well as a series of various equivalent plate thicknesses as described later.

As the reliable computation of section properties is important to the application of this approach in a design environment, the 3-dimensional finite element model was also used in investigating the commonly used methods of calculating the section properties of a tub section with top lateral bracing. The same basic model (with appropriate modifications) was also used in examining the following:

- The effect of nominal eccentricity (by varying the intensity of the uniformly distributed load on the two webs to produce a 5% eccentricity)

- Effect of curvature on tub girder behavior and stability (for R = 1150, 750 and 400-ft radii of curvature)

RESULTS OBTAINED

DETERMINATION OF SECTION PROPERTIES - Section properties associated with bending of the section are straightforward[1] and the computed values provide good correlation with the behavior of the section. However, the derivation of section properties for torsional properties including the shear center and warping constant is somewhat involved (Heins, 1975). Table 1 lists the section properties of the tub section with different values of equivalent plate thicknesses for top lateral bracing. Torsional section properties were obtained from several different computational procedures and also using the FEM model. It can be seen that the magnitude of C_w obtained using the two different analytical methods (Notes 1 & 2) are wide apart. The use of these C_w values resulted in very large predicted buckling loads compared to those obtained from the 3D FEM models. In order to resolve this difficulty, FEM models were used to obtain the torsional and warping properties as in Note 3. As reported in Table 1, the warping constant C_w obtained from this FEM procedure was considerably smaller than those obtained from the analytical methods. However, a relatively good correlation between the torsional constant J and the location of the shear center was observed between the analytical and computational procedure based on the FEM models.[2]

[1] These parameters include the location of the elastic center y_{cg} and Izz and Iyy for in plane and out plane bending

[2] It must be noted that there is considerable departure of the value of J obtained from the FEM procedure from that obtained from closed form solutions for very small t_e (< 0.0003"), and that the two procedures yields practically the same result for larger t_e (> 0.0027").

Table 1: Section Properties of Tub Sections

Section		Bending Properties			Torsional Properties						
ID	t_e (in)	I_{yy} (ft^4)	I_{zz} (ft^4)	y_{cg} (in)	J (in^4)		C_w (ft^6)			y_{sc} (in)	
					Note 1	Note 3	Note 1	Note 2	Note 3	Note 1	Note 3
1	0.0	21.4	19.7	47.8	402	56	121	8471	144	99.9	95.1
2	0.0001	21.4	19.7	47.8	755	353	6230	3223	142	99.4	93.9
3	0.0003	21.4	19.7	47.8	1457	1060	6220	3206	139	99.3	93.2
4	0.0006	21.4	19.7	47.8	2508	2110	6200	3181	136	99.2	93.4
5	0.0009	21.4	19.7	47.8	3556	3160	6180	3159	134	99.0	91.7
6	0.0027	21.4	19.7	47.8	9773	9430	6070	3015	125	98.0	101.1
7	0.0055	21.4	19.7	47.8	19215	19000	5900	2795	118	96.5	89.0
8	0.0110	21.4	19.7	47.8	36997	37210	5580	2419	113	93.7	108.4
9	0.0197	21.4	19.7	47.8	63223	64540	5110	1927	117	89.5	
10	0.0330	21.4	19.7	47.8	99366	103140	4490	1366	148	83.5	

Notes (Table 1)

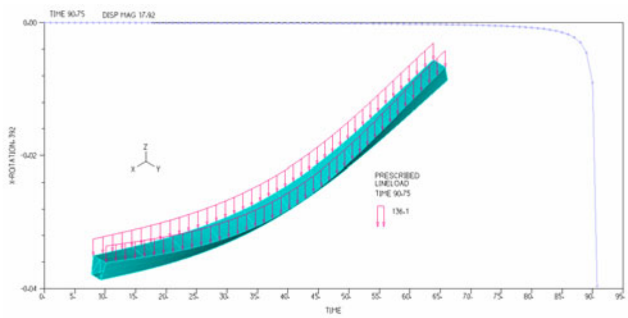
1. Using expressions for J for open and pseudo-closed sections (equations 1.1 and 1.2) and method referenced in [2] for warping properties
2. Using the method outlined by Heins, 1975
3. Using FEM models as outlined by Kumarasena et al. 1989

Table 2: Comparison of Equivalent Plate (t_{eq}) and Actual Bracing (Figure 3)

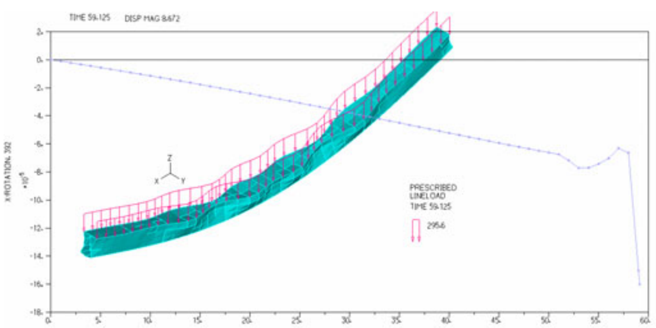
Bracing Arrangement (Figure 3)		Rotations Obtained (rad)		Comparison
ID	t_e (in)	Equivalent Plate θ_{teq}	Bracing $\theta_{bracing}$	$\theta_{teq}/\theta_{bracing}$
(a)	$t_e = \frac{E}{G}\frac{as}{\frac{d^3}{2A_d}+\frac{s^3}{6A_{tf}}} = 0.260$	7.48×10^{-3}	7.47×10^{-3}	1.001
(b)	$t_e = \frac{E}{G}\frac{as}{\frac{d^3}{A_d}+\frac{2s^3}{3A_{tf}}} = 0.0822$	11.46×10^{-3}	11.56×10^{-3}	0.991
(c)	$t_e = \frac{E}{G}\frac{as}{\frac{d^3}{A_d}+\frac{a^3}{A_s}+\frac{s^3}{6A_{tf}}} = 0.0521$	16.12×10^{-3}	15.17×10^{-3}	1.062

The expressions for obtaining t_e for the different top lateral bracing arrangements (equations 1.3 to 1.5) were also tested using the 3D FEM model by explicitly modeling the top lateral bracing elements and comparing the rotation under a given torque with that obtained when the bracing elements were represented with an equivalent plate computed using the referenced equations. As shown in Table 2, the correlation between the results from the two models appears to be quite good. In testing the above expressions for t_e with the FEM model, the following properties were assumed for all three of the bracing systems: E = 29,000 ksi, G = 11,000 ksi, a = 8 ft, s = 5 ft, d = 9.43 ft, b_{tf} =1'-8", t_{tf} =7/8", A_{tf} =0.122 ft^2, As = Ad = 8 in^2 (L 6x6x3/4). The results show that, for the same bracing elements, the bracing system (a) is twice as effective as system (c) in effecting torsional rigidity to the tub section.

BUCKLING LOADS FOR STRAIGHT ALIGNMENTS - Elastic buckling loads for straight alignments were obtained using the 3D FEM model as described previously. As the load was increased from zero up to a maximum (set sufficiently high so failure would result before reaching this max load) in equal time steps, the total load at any point is proportional to time. Figure 5 illustrates the results obtained for two different equivalent plate thicknesses. Figure 5(a) shows the tub girder section reaching failure in elastic lateral torsional buckling for t_e = 0.0006 in. As the equivalent plate thickness is increased, the failure mode changes to that of local plate buckling as shown in Figure 5(b). In order to see if there is a critical torsional stiffness above which the lateral torsional buckling would not occur, FEM models were analyzed with increasingly larger values of the equivalent plate thicknesses t_e until the predicted critical buckling loads reached well above the capacity of the box section in bending. Premature failure of the box section due to local plate buckling of the tub section was artificially prevented by modifying the plate thicknesses of the tub section by a factor α >1 ($t_{modified}$ = αt) and reducing the elastic modulus by the same factor ($E_{modified}$ = E/α).



(a) t_e = 0.0006 in, elastic lateral torsional buckling precipitates tub girder failure



(b) t_e = 0.0110 in, local plate buckling precipitates tub girder failure

Figure 5: Straight tub girders with top lateral bracing under increasing vertical load

The observed relationship between the intensity of the UDL applied to the tub section and the rotation at mid span of the tub section for different values of t_e is shown in Figure 6. The occurrence of instability at the critical load corresponding to each t_e analyzed is seen clearly from this plot. Lateral torsional buckling was observed at loads well above that sufficient to produce yielding of the tub section due to in-plane bending.

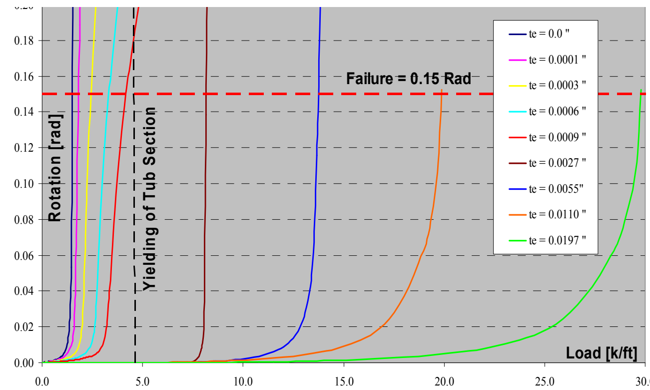


Figure 6: Rotation vs. load for straight tub girders with top lateral bracing

For consistency, the critical buckling load for each of the cases was taken as the UDL corresponding to a torsional rotation of 0.15 radians at mid-span. As noted previously, the cases with equivalent plate thickness exceeding 0.009" correspond to critical buckling loads exceeding the elastic capacity of the tub section. While the failure method remains as lateral torsional buckling well beyond the capacity of the girder provided that yielding and local plate buckling are prevented (by artificial means), the buckling loads thus obtained does not very well fit a type of curve described by equation 2.1 along the full range of t_e examined. However, it was found that the simplified expression given in equation 3.1 fits the lower end of the observed buckling loads fairly well with β = 4.6. It can also be noted that this lower range of t_e is also the range corresponding to practical design scenarios.

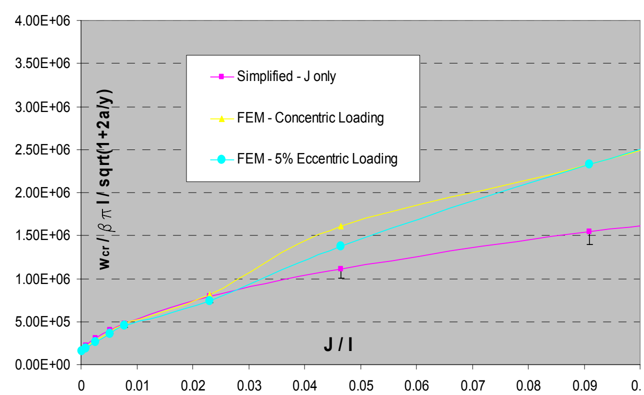


Figure 7: Buckling Load for Tub Section vs. Stiffness Ratio with β = 4.6

$$w_c \approx \frac{\beta}{\sqrt{(1+\frac{2a}{\hat{y}})}} \frac{\pi}{L^3} \sqrt{EIGJ}$$ 3.1

$$= \frac{\pi\beta}{\sqrt{(1+\frac{2a}{\hat{y}})}} \frac{I}{L^3} \sqrt{EG(J/I)}$$

The buckling loads obtained under a nominally eccentric loading (5%) are also in Figure 7. It can be observed that the reduction in the buckling load due to the assumed nominal eccentricity of 5% was not significant.

EFFECT OF CURVATURE - Figure 8 show the load vs. rotation for a curved alignment with a radius of 1150-ft for a given equivalent plate thickness. Horizontal curvature makes the development of box displacements and rotations more pronounced but gradual. Increasing the horizontal curvature was also observed to considerably reduce the critical load corresponding to instability (w_c). However, large rotations were observed at load levels significantly below w_c. As excessive rotations can lead to complexities during construction, for curved alignments, it appears that a more appropriate design basis for top lateral bracing can be based on limiting rotations during construction than the critical buckling load itself. Heins (1975) describes how the force deformation relationships can be derived for a given horizontally curved box girder. However, the method is fairly complicated. An approximate expression for rotation at mid span as given in equation 3.2 can be obtained for the linear elastic rotation at mid span:

$$\vartheta_0 = -\frac{\omega R^2 \left(\frac{1}{2}\sin 2\alpha_0 - \alpha_0 \cos^2 \alpha_0\right)}{\left(\frac{\pi}{L} JG - \frac{\pi^3}{L^3} EC_w\right)}$$ 3.2

$$\approx -\frac{\omega R^2 \left(\frac{1}{2}\sin 2\alpha_0 - \alpha_0 \cos^2 \alpha_0\right)}{\left(\frac{\pi}{L} JG\right)}$$

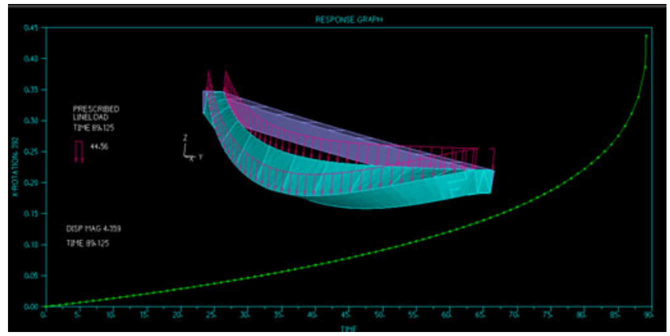


Figure 8: Load vs. rotation at mid-span with horizontal curvature (R=1150-ft)

Where w id the UDL and $2\alpha_0$ is the included angle made by the span L at the center of horizontal curvature. Comparison of rotational responses obtained for curved alignments using linear FEM analysis and geometric nonlinear analysis show that the non-linearity in the transverse rotations can be significant. An empirical correction to the linear elastic solution to include the non-linear effects in the following form gives good agreement with the observed amplification of transverse rotations due to non-linearity.

$$\vartheta_{0,NL} = \frac{1}{\left(1-\frac{\omega}{\omega_{CR}}\right)^2} \vartheta_{0,L}$$ 3.3

where w is the uniformly distributed load including the self weight of the girder and w_{cr} is the critical UDL for lateral torsional buckling if the tub girder section was spanning along the chord (straight line alignment).The results obtained in this study show that the above expressions can reasonably approximate the rotational response at the mid span location of a simply supported curved tub girder under concentric uniformly distributed load (Figure 9) for rotations less than about 0.2 radians.

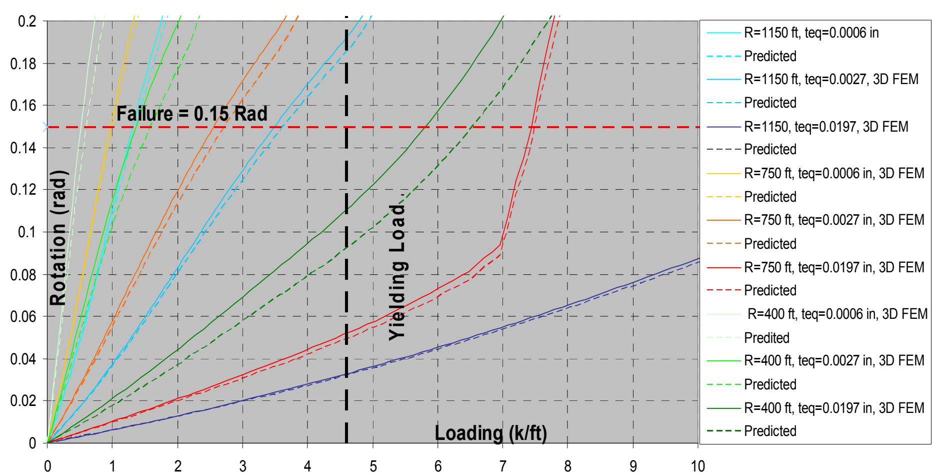


Figure 9: Vertical UDL vs. mid-span rotation for curved alignments

CURVED ALIGNMENTS & BENDING-TORSION INTERACTION

As noted previously, top lateral bracing for a tub girder on a horizontally curved alignment must be specially designed as other primary elements considering the actual design forces induced in these elements due to the design loading conditions. The factors contributing to primary forces in top lateral bracing elements during construction include:

1. Longitudinal Bending – depending on bracing configuration

2. Torsional Moments – Due to horizontal curvature

Practically all of the design forces in top lateral bracing elements are induced in the non-composite stage while resisting the weight of green concrete slab and other construction loading (if any). These forces then are locked in as the slab gains strength. Any increase in these forces due to external loads during service (including live load) is fairly small. Top lateral bracing can also develop primary design forces under deck replacement scenarios due to the following factors:

1. Eccentric dead loads due to partial (staged) removal of the deck slab in cross section

2. Live loads on partially removed deck under temporary traffic management conditions.

These are project specific scenarios and can vary in scope and depth depending on the project specific design conditions and criteria assumed for future staging of deck replacement and are outside the scope of the present discussion.

LONGITUDINAL BENDING - Several commonly used top lateral bracing layouts are shown in Figure 3. Depending on the framing configuration, bracing elements framed to different longitudinal locations of the top flanges of the tub section experience strains due to displacement compatibility. This produces stresses in any of the “diagonal elements” of the top lateral bracing members similar to the stresses in the top flanges due to longitudinal bending.

Examining the different arrangements of top lateral bracing shown in Figure 3, the layout shown in 3(a) (and also K-bracings) does not develop significant strains due to longitudinal bending. This is due to the absence (or the flexibility) of transverse strut elements. However, layouts in figures 3(b) and (c) include diagonal members that directly connect the strut members at different longitudinal locations. The displacement compatibility would result in significant forces in the bracing elements in such cases. The magnitude of the forces developed in the bracing members for a given top flange stress for configurations 3(b) and (c) are identical. While K-bracing arrangements avoid the development of forces due to longitudinal bending, these do not readily lend themselves to an optimal layout for curved alignments (discussed later) and may be more suitable for large boxes due to the geometry and the layout of connections.

The forces in the diagonals are compressive in the positive moment areas and are tensile in the negative moment areas. As the loading is strain induced, the bracing elements themselves should not fail assuming tub girder flanges have been properly sized[3], but the connections can fail due to overload.

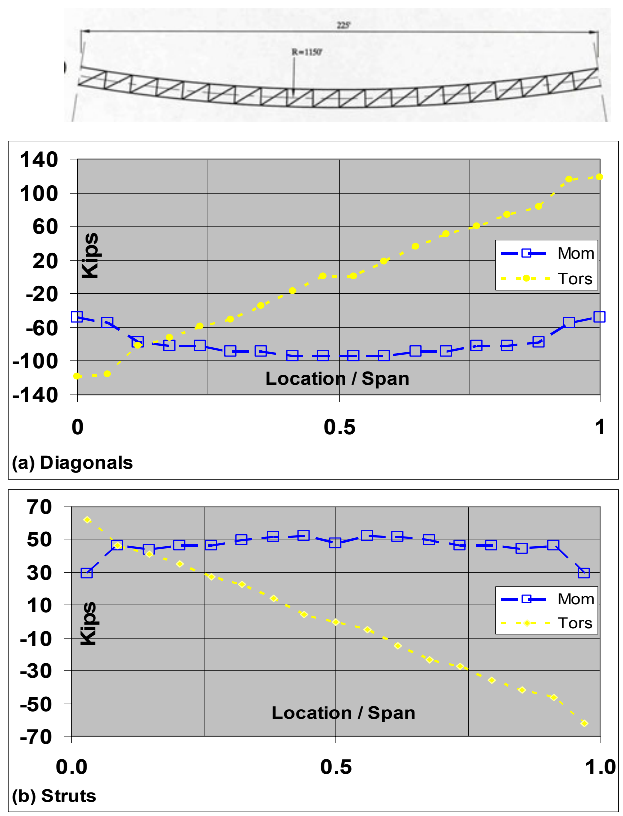


Figure 10: Forces Due to Longitudinal Bending & Torsion in Bracing Elements

[3] Except slight out-of plane buckling in compression at the limiting load under elastic buckling which may render them ineffective for the intended purpose

If a computer model that include the top lateral system was used in analysis, the forces and stresses reported for the top flanges would reflect the participation of the top lateral bracing system in resisting longitudinal bending effects. If flanges are designed for these reduced stress levels it is crucial that the bracing members and connections be properly sized.

Conservatively, the top flange can be sized for the sum effect of the forces resisted by the flange and the bracing while designing bracing for the portion of the load carried by them.

TORSIONAL MOMENTS **-** The governing torsional moments in horizontally curved box girders during construction are due to self weight of the tub section and the weight of wet concrete and other construction loadings (during casting of the deck). These are primary load effects that must be resisted to maintain statical equilibrium and stability. This non-composite DL during construction typically represent a very large proportion of the total DL which often is significantly large in comparison to LL effects for medium to long span boxes. Thus, depending of the radius of curvature and span length, the force levels produced in top lateral bracing can produce extremely demanding design conditions.

However, as discussed later under the design optimization example, it can be shown that the lateral bracing elements can be arranged such that the effects of torsion and bending are opposing one another, producing an optimal arrangement. This results in a significant reduction in the magnitude of the design forces and also reduces lateral bending of the top flanges of the box section.

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DESIGN OPTIMIZATION

Axial forces in top lateral bracing due to longitudinal bending and torsional moments are proportional to the magnitude of these moments at a given section. Thus the force components in top lateral bracing due to bending and torsion, when identified separately, follow the shape of the respective moment / torsion diagrams. Figure 10 shows these components for a lateral bracing layout for a 225-ft simple span box girder with an 1150-ft radius horizontal curvature.

The direction of the axial forces in diagonal members (compression vs. tension) due to longitudinal bending depends only on the sign of the bending moment (positive vs. negative) and is independent of the relative orientation of the diagonals. For example, the diagonal elements for bracing layouts shown in Figures 11 (a) to (c) would have the same internal stress level corresponding to a given top flange stress. The direction of forces in the diagonal bracing due to torsion however depends on the relative orientation of the bracing element with respect to the direction of the torsional moment. This is observed by the asymmetric nature of the force diagrams due to torsion shown in Figure 10. This allows us to select an optimal bracing layout by examining the bending and torsion diagrams for a given bridge and then orienting the diagonal bracing elements in such a way that the forces due to the two actions bending and torsion are in opposing directions.

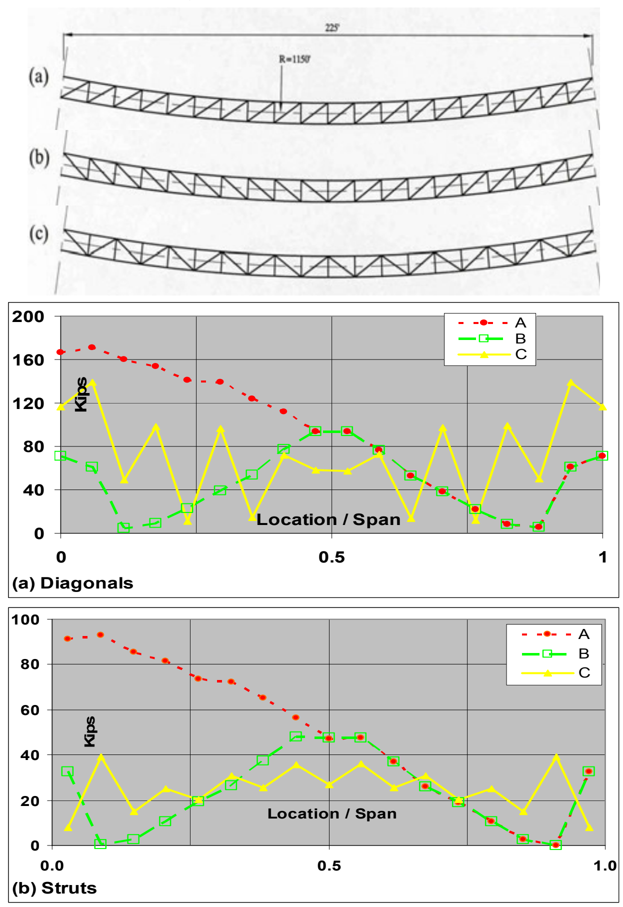

Figure 11: Design Optimization under Longitudinal Bending & Torsion

This is illustrated in Figure 11 where the magnitude (only) of the axial forces for several different bracing arrangements are shown for the box geometry (225-ft span, 1150-ft radius) described previously. It can be seen that the forces corresponding to the optimal arrangement shown in Figure 11(a) is nearly 50% of the force levels corresponding to the others. The optimized layout also produces least lateral bending of the top flanges and this is an added benefit.

For curved alignments, this optimized diagonal layout places them in the same orientation in both boxes. The resulting asymmetric configuration of the top laterals with respect to the longitudinal bridge axis produces a horizontal movement of about 2" towards the outer curvature (for the case discussed). While this cannot be avoided in curved alignments, for straight alignments, placing top laterals in opposing directions in adjacent boxes eliminate this horizontal response.

DESIGN RECOMMENDATIONS

Based on the above study, the following recommendations can be made for the design of top lateral bracing of tub girder sections.

1. The tub girder sections require top lateral bracing to ensure stability during construction irrespective of the alignment (straight vs. curved)

2. The safe design load for a tub girder (with a given bracing configuration) during construction can be estimated using the following approximate equation:

$$w_{cr} \approx \frac{4.6\pi}{FS\sqrt{(1+\frac{2a}{\hat{y}})}}\frac{I}{L^3}\sqrt{EG(J/I)}$$

   where $J = \frac{4A_0^2}{\sum \frac{b_i}{t_i}}$ and

   FS is a suitable factor of safety

3. For curved alignments, the critical buckling load is considerably reduced. However, excessive rotations develop before reaching instability, and providing sufficient bracing for control of deflections is a more appropriate design consideration for curved alignments. The girder rotations for curved tub girders during construction can be approximated using

$$\vartheta_0 = -\frac{\omega R^2\left(\frac{1}{2}\sin 2\alpha_0 - \alpha_0\cos^2\alpha_0\right)}{\left(\frac{\pi}{L}JG\right)\left(1-\frac{\omega}{\omega_{CR}}\right)^2}$$

   where w_{cr} is obtained from the previous equation for the critical load for a straight alignment.

4. The orientation of the top lateral bracing has a significant effect on the forces induced in these elements due to combined action of longitudinal bending and torsion. The optimization of the bracing layout can reduce the forces resulting in these elements by as much as 50%, thus improving the design as well as facilitating manageable connection details.

REFERENCES

[1] Attard, M.M, General Non-Dimensional Equation for Lateral Buckling, Thin-Walled Structures, Vol. 9, no. 1-4, pp. 417-435, (1990).

[2] Heins, C.P., Bending & Torsional Design in Structural Members, Lexington Books (1975)

[3] Karl Frank & Widianto, Mse, Lateral Torsional Buckling of Straight Steel Trapezoidal Box Girders during Construction, Karl Frank & Widianto, Mse, Proceedings of AASHTO T-14 Meeting, July 2004, Baltimore, Maryland.

[4] Kumarasena, et al, Deer Isle Bridge: Efficacy of Stiffening Systems, Jnl. of Structural Engr. Div., ASCE (1989)

[5] Marcy Bridge Collapse – News items on www.uticaod.com/news/specialreports/marcybridge/archive.htm

[6] Nethercot D.A and K.C. Rockey, A Unified Approach to the Elastic Lateral Buckling of Beams, The Structural Enginner (1971)

[7] Timoshenko S.P and J.M Gere, Theory of Elastic Stability, Engineering Societies Monographs, McGraw-Hill (1961)