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Experimental study on the ultimate bending resistance of steel tub girders with top lateral bracing

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ABSTRACT

This paper presents a series of experimental test results on the flexural resistance of a steel tub girder with top lateral bracing. Three test girders were fabricated with high tensile strength SM570 TMC (nominal yield strength, $F_y = 460$ MPa) steel plates. The test girders had a half-size cross section of practical bridge girders whose depth and length were approximately 1000 mm and 12,000 mm, respectively. The pure bending test was conducted on the tub girder specimens using a universal test machine. Incremental nonlinear analyses were also performed on the tested girders and compared with the tested results. The incremental nonlinear analysis with finite element modeling was confirmed to be applicable to simulating inelastic buckling behavior and evaluating the ultimate bending strength. The effect of cross-frames and top lateral bracings on flexural strength was then discussed. The flexural resistance capacity specified in the AASHTO LRFD design specifications was compared with the evaluated ultimate strengths, and the validity of the design specifications was verified.

1. Introduction and background

Composite box girders are frequently used for curved bridges for their superior torsional stiffness, economy, fabrication advantages, aesthetic appearance, etc. A box girder type called steel tub girder is generally known as an improved variant because it has a more efficient composite section with concrete slab as shown in Fig. 1. More detailed design guides have recently been published in AASHTO LRFD 3rd ed. [1] and the NSBA proposed design guideline [2].

Prior to the hardening of the concrete deck, the steel tub girder of an open section type has significantly lower torsional stiffness than that of the composite closed section. Moreover, the non-composite tub girder must sustain the entire construction load including the wet concrete. Since the top flanges are compressed, and the depth of the web in compression is largest during this construction step in the AASHTO LRFD specifications [1], the non-composite section is susceptible to lateral–torsional buckling. Therefore, a critical construction stage of these girders is the duration of the casting of the concrete deck. Given the vulnerability to lateral torsional buckling in the non-composite state, the flexural resistance of the steel tub girder during this step could be significantly affected by the spacing between brace points, i.e., unbraced length. To provide a nodal brace point against lateral torsional buckling for this critical stage, top lateral bracings and interior cross frames are inevitably installed. Top lateral bracings make the open-top trapezoidal section into a pseudo-box section, thereby increasing the torsional stiffness tremendously. Hence, top lateral bracings are mandatory in horizontally curved tub girders. They are also needed in tangent girders for the unintended and/or torsional loads that are unaccounted for as reported by Chen et al. [4].

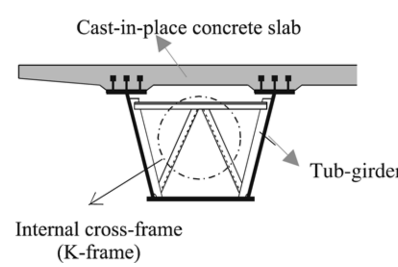

Fig. 1. Typical cross section of composite steel tub girders.

In AISC LRFD, bracing members are usually classified as lateral bracing and torsional bracing [3]. Since the top lateral bracings of the tub girders are directly connected to the flange in compression to sustain the lateral displacement, they will most probably act as the brace point against the lateral torsional buckling of tub girders.

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Note, however, that the top lateral bracing is designed mainly to increase only the torsional stiffness of tub girders [2] by making the U-shaped open tub girders as a quasi-closed box section. According to the NSBA design guideline [2], the internal cross-frames, not the top lateral bracings, should be utilized as brace points to prevent girder top flanges from buckling. Moreover, Article 6.11.3.2 of the AASHTO LRFD specifications [1] stipulates that the provisions of the I-section girder shall be applied only to the top flanges of tub sections for critical stages of construction, and that the unbraced length should be taken as the distance between interior cross-frames or diaphragms. It is also remarked in the commentary of Article 6.11.3.2 that "top lateral bracing attached to the flanges at points where only struts exist between the flanges may be considered as brace points at the discretion of the engineer".

In addition, the test results obtained by Chen et al. [4] suggested that the bending capacity of the tub girder could be less than the nominal flexural resistance specified by the AASHTO LRFD design specifications [5] when test specimens were braced only by the top lateral bracing. The experimental studies by Chen et al. [4] were conducted on a series of scaled test models of a U-shaped girder with the X-brace truss system or metal deck panels fixed to the top flanges. The detrimental effects of shortening in the top lateral bracing were also found to decrease the U-shaped girder bending capacity. Current design provisions for U-shaped girders consider the brace points as unyielding support. For the test case, the experimental load capacity was 25% less than the nominal flexural resistance calculated using the design specifications [5].

The cross-frames installed in between the I-shaped girders act as the brace points to prevent the girder flanges from buckling in compression. It is unlikely that the I-shaped girders, and the internal cross-frames of box girders installed in an inner section, will maintain the original cross-sectional shape against sectional distortion and effectively control distortional stresses. According to the AASHTO Guide specifications for curved girder bridges [6], the interior cross-frames should be installed with proper space and sufficient rigidity to limit the distortional-to-bending normal stress ratio to less than 10% and it is also stipulated that the maximum cross-frame spacing should not exceed 10 m (30 ft) in all horizontally curved tub girders. Therefore, the required spacing for interior cross-frames may differ from what is required as brace points which should be more compact to establish an unbraced design length such as the strut spacing of the top lateral bracing system.

Note that bracing members are no longer utilized once the concrete deck has cured as they could represent a significant portion of a girder steel's weight and cost; hence, the need to minimize them. Still, there is no existing codified design method to consider the top lateral bracings as the brace points of the non-composite tub girder design. Moreover, the structural stability of the non-composite tub girder under positive bending as usually encountered during the concrete deck construction stage has not been properly addressed in previous research.

As such, verifying the flexural strength of the non-composite steel tub girders and comparing them with those specified in the design specifications such as the AASHTO LRFD [1] served as a strong motivation for the authors to conduct this study. At the same time, investigating whether the top lateral bracings could perform as brace points for the non-composite tub girder sections in positive flexure was required to illustrate that the unbraced length of the steel tub girder could be determined based on the strut spacing of the top lateral bracings. The objective of this experimental study was to investigate the following:

(1) Inelastic buckling of non-composite tub girders at failure

(2) Experimental and analytical evaluation of ultimate flexural resistance in positive flexure

(3) Validity of top lateral bracings as brace points for the determination of unbraced length.

Fig. 2. Fabrication of test specimens.

An approach to estimating the forces in the lateral bracing members due to flexure and top-flange bending stresses was recently proposed by Fan and Helwig [7]. They found that the current design method based on the EPM (equivalent plate method) developed by Kollbrunner and Basler [8] underestimated the member forces of the top lateral bracing. They attributed the difference to the neglected effects of girder vertical bending and erroneous assumptions in terms of the lateral force components of applied loading due to sloping webs. Based on the equations proposed by Fan and Helwig [7], a realistic section of the top lateral bracing could be selected for the steel tub girder models in this study. Previously recommended design guides [9] (Highway, 1975) were also used as reference.

Test specimens of the non-composite tub girders and experimental set-up are presented followed by the results of the bending test. The ultimate flexural behaviors of non-composite tub girders are represented through the test results and finite element analyses. The ultimate flexural strengths from the bending test and finite element analysis of the tub girder models are then compared with the currently available design specifications. The last section of this paper summarizes the findings of this study.

2. Test specimens and set-up

2.1. Steel tub girder specimens

Three tub girder models were prepared with various strut spacings as shown in Fig. 2. The total length of the test model was 12,000 mm. In particular, the middle part of 7200 mm served as the specimen region subjected to uniform bend-loading. The depth of the girder was 1017 mm. The general dimensions and properties of