Journal of Constructional Steel Research 65 (2009) 1827–1835

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

journal homepage: www.elsevier.com/locate/jcsr

Bending behaviors of quasi-closed trapezoidal box girders with X-type internal cross-frames

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ARTICLE INFO

Article history:
Received 20 June 2008
Accepted 12 April 2009

Keywords:
Steel
Bracing
Cross frame
Quasi-closed box
Tub girders
Matrix equation

ABSTRACT

During the construction of composite trapezoidal box girder bridges, steel tub girders with top lateral bracing systems, so-called quasi-closed box girders, are expected to carry non-composite dead loads in addition to other construction loads. Although quasi-closed box systems with internal cross frames mainly serve to increase the torsional resistance of tub girders and preserve the original box shape, significant forces are developed in both top lateral and internal bracing members due to bending. The coupling action that occurs between the single-diagonal-type lateral bracing system and internal cross frames depends on the panel spacing of the internal cross frames. Although either internal K- or X-frames can be used in trapezoidal box girders, their interaction behaviors with top lateral bracing systems differ because of their different configurations. In this study, matrix equations were formulated to calculate the brace forces developed in both single-diagonal-type top lateral bracing and internal X-frame members in trapezoidal box girders subjected to bending action. Member forces computed using the new equations were then compared with those from three-dimensional finite element analyses, and an excellent correlation was found.

1. Introduction

Steel/concrete composite trapezoidal box girders are very widely used for both horizontally curved and straight girder bridges because of their superb torsional rigidity and favorable long-term maintenance costs. This type of structural system consists of one or more open top steel tub girders used in conjunction with a cast-in-concrete deck slab and welded shear connectors. These composite box girders are at their critical operating stage during construction because in addition to the wet concrete, the non-composite steel tub section must support the entire construction load. To address this issue, a top lateral bracing system is installed at the top flange level of the open top steel tub girder in order to form a quasi-closed box cross section, thereby increasing the torsional rigidity during construction. Various types of top lateral bracing systems commonly used for quasi-closed box cross sections are shown in Fig. 1. Because of the simplicity of fabrication, single-diagonal-type (Fig. 1(a)) bracing systems are more frequently considered for top lateral bracing systems than crossed-diagonal-type bracing systems (Fig. 1(b)). Although quasi-closed box systems with internal cross frames are utilized primarily to increase the torsional and distortional resistance of tub girders, significant forces are developed in both lateral and internal bracing members as a result of bending action. When this occurs, top lateral bracing systems enhance the resistance to lateral-torsional buckling of individual top flanges that are in compression in the positive moment region.

The distortional force components of applied loads cause the cross section of a box girder to distort from its original shape, which is resisted by internal cross frames spaced along the length of the girder. K-frames or X-frames are commonly found in trapezoidal box girders, as shown in Fig. 2. The intensity of the distortional warping stresses in box girders can be controlled by a judicious selection of spacing between adjacent cross frames. According to *AASHTO Guide Specifications* [1], the spacing of cross frames should be designed to ensure that the longitudinal warping stress in the box does not exceed 10% of the longitudinal stress due to vertical bending at the strength limit state. In practice, cross frames are usually provided at either one or two-panel spacing along the box girder because of the preferred angle of the lateral bracing members with the struts.

Fan and Helwig [2,3] made a considerable contribution to the understanding of the mechanics involved in lateral bracing systems and internal cross frames in quasi-closed box girders. After deriving general form equations for estimating the forces in both crossed diagonal type and single-diagonal-type lateral bracing systems induced by vertical bending and applied torque [2],

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0143-974X/$ – see front matter
doi:10.1016/j.jcsr.2009.04.014

Nomenclature

a	Web spacing of tub girder at bottom flange
A_D	Cross-sectional area of top lateral diagonal
A_S	Cross-sectional area of strut
A_X	Cross-sectional area of internal X-frame diagonal
b	Web spacing of tub girder at top flange
C_{bf}	Parameter for effective width of bottom flange for lateral bending
D	Total diagonal force in lateral bracing
D_{bend}	Diagonal force due to vertical bending
D_{dist}	Diagonal force due to distortion
D_{lat}	Diagonal force due to lateral force component
D_{tor}	Diagonal force due to torsion
E	Modulus of elasticity
h	Box girder depth
$I_{bf,e}$	Second moment of inertia of effective bottom flange with respect to vertical centroidal axis
I_{box}	Second moment of inertia of steel box with respect to horizontal centroidal axis
I_{tf}	Moment of inertia of top flange with respect to vertical centroidal axis
M	Bending moment
L_D	Length of lateral diagonal
L_X	Length of internal X-frame diagonal
L_S	Length of strut
Q_A, Q_B	interactive forces between the top flange and bracing members
S	Total strut member force
S_{bend}	Strut force due to vertical bending
S_{dist}	Strut force due to distortion
S_{lat}	Strut force due to lateral force components
S_{tor}	Strut force due to pure torsion
s	Spacing between struts
t_{bf}	Bottom flange thickness
u	Longitudinal deformation of top flange
v	Relative lateral displacement of top flange
W	Uniformly distributed vertical load
w	Relative vertical displacement of top flange
W_{lat}	Lateral components of uniformly distributed vertical load
y_b	Vertical distance between bottom flange centroid and neutral axis of box cross section
y_t	Vertical distance between top flange centroid and neutral axis of box cross section
α	Horizontal angle between diagonal and top flange
γ	Vertical angle between X-frame diagonal and vertical line
δ_D	Axial elongation of lateral diagonal
μ	Poisson's ratio and
φ	Vertical angle of inclined web of tub girder

they went on to separate the pure torsional components and distortional components from the torsional loads applied to tub girders and suggest equations for computing internal K-frame member forces [3]. Topkaya et al. [4] studied the performance of different top lateral bracing systems to determine the most efficient bracing configuration for curved box girder bridges. Kim and Yoo [5] extended Fan and Helwig's treatment, finding that significantly different responses take place in box girders braced with a single-diagonal-type bracing system and those with a crossed diagonal type bracing system and developing more accurate analytical equations for estimating the brace forces developed in quasi-closed box girders with a single-diagonal-type bracing system. Kim and Yoo [6] also found that significant coupling actions occur between a single-diagonal-type lateral bracing system and internal K-frames placed at odd numbered panel spacing. They reported that the inclusion of this interaction results in member forces up to 30% higher than for even-numbered panel spacing. Although the primary role of internal cross frames is to resist the distortional force component of torsional loads, member forces are also developed in cross frames due to the interaction under vertical bending, even in the absence of any torsional loads [7].

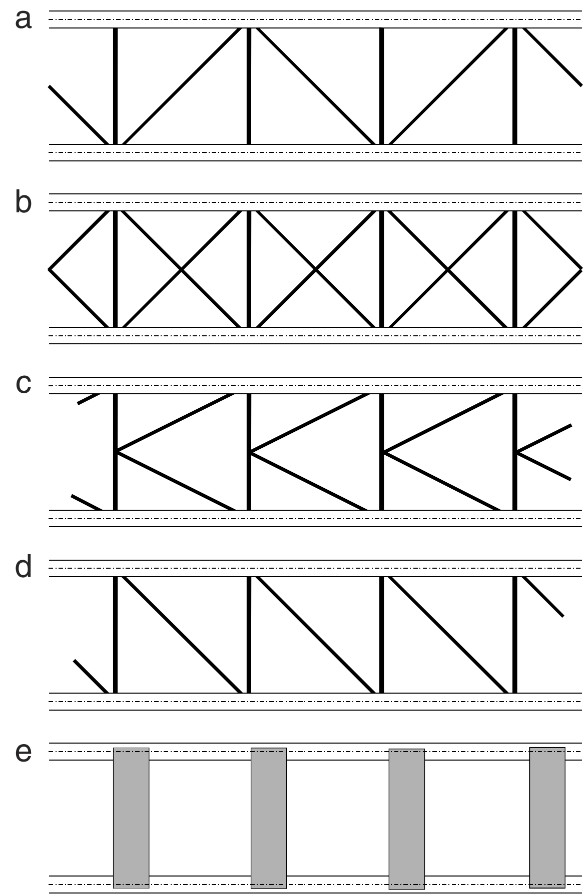

Fig. 1. Various types of top lateral bracing systems for quasi-closed steel box girders.

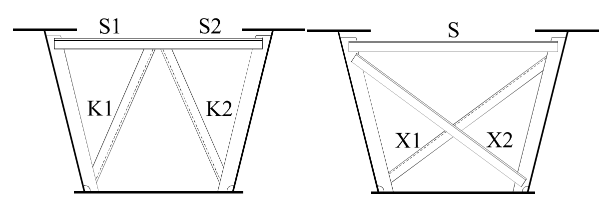

Fig. 2. Internal cross frames; (a) K-frame type: (b) X-frame type.

As noted previously, although both K-frames and X-frames are commonly used in trapezoidal box girders, they experience fundamentally different interactions with top lateral bracing systems. In the case of internal K-frames, the struts of the lateral bracing system also act as top transverse members of the internal K-frames. Superimposing the strut forces due to its function as an internal K-frame and as a transverse member of the top lateral bracing system produce the resultant member forces S1 and S2 shown in Fig. 2(a), which cannot be the same for simple equilibrium. Consequently, two different strut forces act at the