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Distortion analysis of non-prismatic composite box girders with corrugated steel webs

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ABSTRACT

In this study, the distortion effect of non-prismatic composite box girders with corrugated steel webs (CBGCSWs) is theoretically analysed under eccentric loads during the elastic stage. Considering the mechanical properties of corrugated steel web, a governing differential equation for distortion is derived for non-prismatic CBGCSWs. The differential equation is solved using the Newmark method to obtain the distortional warping normal stresses of angular points. The feasibility of the proposed theoretical method is validated by the finite element (FE) method. The proposed method is then applied to examine the effects of the number of diaphragms (N), girder length (L), girder width (b), shortest girder height ($h_{\min}$) and girder height ratio (ξ) on the maximum ratio of distortional warping normal stress to longitudinal bending normal stress (distortion-to-bending stress ratio, ζ) of non-prismatic CBGCSWs. Based on the results of the parametric study, a diaphragm spacing equation is developed for determining the diaphragm spacing of non-prismatic CBGCSW bridges to reach the desired distortion-to-bending stress ratio. The presented equation can be further used as a reference to design the diaphragm spacing of this type of bridge.

1. Introduction

The composite box girders with corrugated steel webs (CBGCSWs) exhibit many advantages over traditional concrete box girders, e.g., light self-weight and complete avoidance of web cracking [1]. Therefore, this composite structure has been widely applied in bridge engineering, especially in Japan and China. In particular, non-prismatic CBGCSWs are more commonly used in long-span bridges than prismatic ones due to their superior stress distribution and spanning capacity [2-5]. In recent years, numerous studies have been conducted to investigate the shear stress distribution [2], flexural behaviour [6,7], torsional response [8-10] and stress increment of the unbonded pre-stressing tendons [11] of this structure as well as the shear strength and design of corrugated steel webs (CSWs) [12-16]. However, little effort has been dedicated to investigating the distortion effect.

Under eccentric loadings, box girders generate distortion in addition to bending and torsion, thereby inducing distortional warping normal stresses (hereafter denoted by distortional stresses for simplicity) and transverse bending normal stresses. In this case, the distortion is likely to be the main source of total warping stresses. Moreover, the transverse bending normal stresses caused by distortion may have the same order of magnitude as the longitudinal bending stresses [17,18]. Over the past several decades, many investigations have examined the distortional behaviour of conventional concrete box girders [19-22]. However, the distortional behaviour of CBGCSWs is significantly changed by replacing the concrete webs with CSWs. On the one hand, the out-of-plane stiffness of CSWs is relatively smaller than those of the top and bottom concrete flanges. Thus, the cross section can be transversely schematized as hinged at the junctions; consequently, the resistance to distortion provided by the cross-sectional frame is severely weakened. On the other hand, the longitudinal warping stiffness of the cross section is also reduced by the poor ability of CSWs to resist axial forces (i.e., the "accordion effect" of CSWs) [23,24]. For these reasons, the cross sections of CBGCSWs tend to distort more easily than those of concrete box girders. Therefore, the distortion plays a more important role in CBGCSWs than in concrete box girders.

Although the CBGCSWs are more highly influenced by distortion than concrete box girders, as previously stated, research on distortion effect of CBGCSWs is rare. Li [25] analysed the distortional behaviour of prismatic CBGCSWs based on the principle of minimum

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potential energy. Yang et al. [26] derived a distortion differential equation for prismatic CBGCSWs. However, these studies focused on the prismatic CBGCSWs. However, because of the variable cross section, the coefficients of differential equation for distortion of non-prismatic CBGCSWs vary along the girder length. In this case, the differential equation cannot be solved by the methods used in prismatic members (e.g., the initial parametric method). Therefore, a theoretical method to analyse the distortion effect of non-prismatic CBGCSWs must be developed.

This study aims to theoretically analyse the distortional behaviour of non-prismatic CBGCSWs during the elastic stage and develop a diaphragm spacing equation for this structure. The present article is organized as follows. In Section 2, a governing differential equation is derived to describe the response of non-prismatic CBGCSWs to distortion. The Newmark method is then utilized to solve the differential equation. In Section 3, three examples for different types of CBGCSWs are presented to demonstrate the applicability and accuracy of the proposed method. Section 4 investigates the effects of different parameters, including the number of diaphragms (N), girder length (L), girder width (b), shortest girder height ($h_{\min}$) and girder height ratio (ξ), on the distortion-to-bending stress ratio. Section 5 develops a diaphragm spacing equation for non-prismatic CBGCSWs bridges using a multiple nonlinear regression analysis. This study is briefly summarized in Section 6.

2. Theoretical method

This study focuses on non-prismatic single-cell CBGCSWs with a rectangular shape under eccentric loads, as shown in Fig. 1. The following assumptions are adopted:

(1) The plane sections of the top and bottom concrete flanges remain planar under bending. Therefore, the deflections and bending stresses of the concrete flanges can be calculated using elementary beam theory.
(2) Because the wall of the box girder is thin, the variation in stress along the wall thickness can be ignored. Thus, both the distortional and shear stresses can be considered uniformly distributed along the wall thickness.

2.1. Distortional loads

By decomposing the eccentric loads, as illustrated in Fig. 2, the distortional loads can be obtained as

$$V_d(x) = \frac{P(x)}{4} \tag{1a}$$

$$H_d(x) = \frac{P(x)b}{4h(x)} \tag{1b}$$

where $V_d(x), H_d(x)$ are the vertical and horizontal components of distortional loads, respectively; $P(x)$ is the eccentric load; $h(x)$ is the distance between the centre lines of the top and bottom concrete slabs; and b is the distance between two webs, which is assumed to be constant along the girder length.

2.2. Cross-sectional deformation due to distortion

Fig. 3 shows the deformed shape of the cross section due to distortion. The solid line indicates the transverse bending deformation, which induces transverse bending normal stresses. The dotted line represents the distortional warping deformation, which causes longitudinal distortional stresses. $\Delta h_o(x), \Delta h_u(x)$ are the horizontal and vertical displacements of the angular points, respectively. The distortional angle, $\gamma(x)$, is used to describe the cross-sectional deformation, which is expressed as

$$\gamma(x) = \frac{2\Delta \upsilon(x)}{b} + \frac{2\Delta \chi(x)}{h(x)} \tag{2}$$

where

$$\Delta \chi(x) = \frac{\Delta h_o(x) + \Delta h_u(x)}{2}. \tag{3}$$

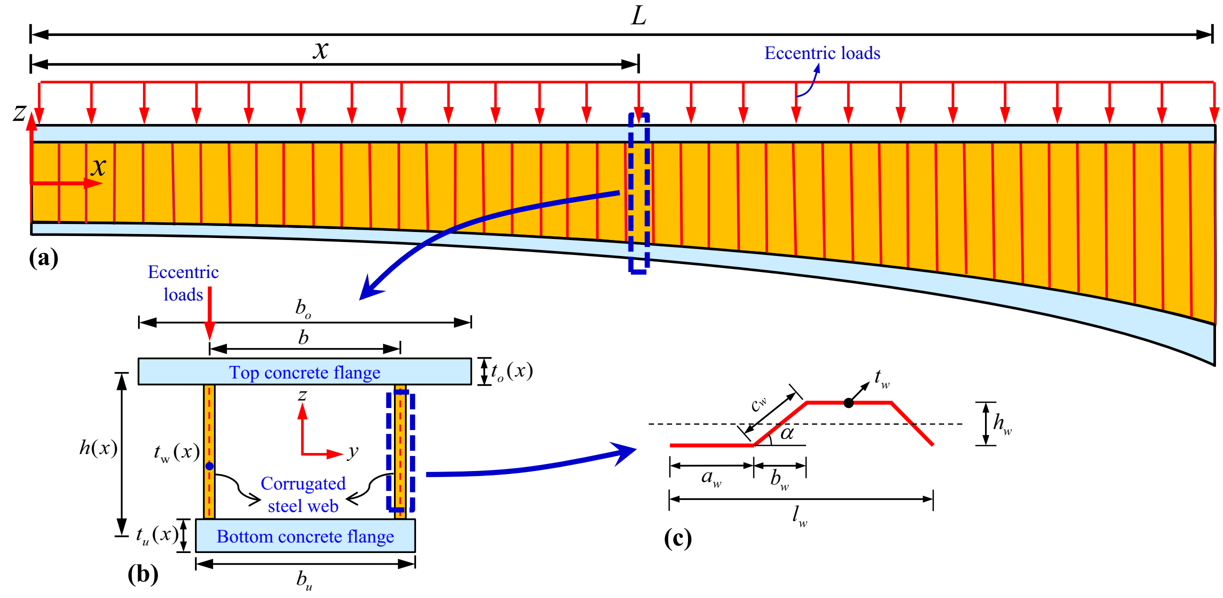

Fig. 1. Non-prismatic CBGCSWs subjected to eccentric loads for distortion analysis: (a) elevation; (b) cross section; and (c) CSWs.