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Simplified method for predicting the deflections of composite box girders

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ABSTRACT

A simplified method for predicting the deflections of composite box girders with corrugated steel webs is presented in this paper. In the proposed method, the governing equations of the composite box girder bridge are derived based on the principles of the minimum total potential energy method. The vertical deflection of the composite box girder bridges with corrugated steel webs is obtained by solving the governing equations with the associated boundary and load conditions. The accuracy and efficiency of the proposed method are validated for three composite box girders with corrugated steel webs (single-cell and double-cell box girders) with the results obtained based on the finite element method.

1. Introduction

A new type of composite box girders with corrugated steel webs has recently been developed. The top and bottom slabs of the composite box girder are made of reinforced concrete, and the web is made of corrugated steel plates. The composite box girders with corrugated steel webs are aesthetically pleasing and attractive from the viewpoint of both construction, time saving, and cost effectiveness. Extensive theoretical and experimental studies have been performed on composite box girders with corrugated steel webs. Hassanein and Kharoob [1,2] and Zevallos et al. [3] focused on the shear strength and shear stability of bridge girders with corrugated webs using realistic imperfection and proposed the design shear strength formula. Kim et al. [4,5] introduced a flexural behavior model for the prestressed composite beams with corrugated webs and verified the method by presenting the contrast experimental study. Kövesdi et al. [6] made numerical investigations for the determination of the patch loading resistance and the geometric parameters, which influence the patch loading resistance. Lee et al. [7] evaluated the structural performance of prestressed composite girders with corrugated webs by conducting experiments with different prestress levels, tendon layout patterns, welding methods, and shear connectors. The accordion effect in corrugated webs [8], stress distribution in the flanges [9], fatigue life of girders with trapezoidal corrugated webs [10], and structural safety of girders with corrugated webs [11,12] have also been investigated in recent years. Jiang et al. [13] reported a summary of the research and developments in the area of composite box girders with corrugated steel webs.

Serviceability performance is an important consideration in the design of composite box girders with corrugated steel webs. To ensure the serviceability requirement, it is necessary to accurately predict the deflections of composite box girders with corrugated steel webs. This problem can be solved by the finite element method (FEM). However, the use of FEM is usually computationally too intensive with the increase in structural size, and for complex composite box girders with corrugated steel webs, input preparation is time-consuming. Therefore, it is desirable to develop a simpler and more consistent theoretical method for predicting the deflections of composite box girders with corrugated steel webs.

To reduce the computation effort, researchers have proposed simplified methods for the analysis of composite structures [14–21]. However, to the authors' best knowledge, a simplified manual calculation technique has not yet been developed to predict the deflections of composite box girders with corrugated steel webs.

The objective of this study is to develop a simplified analysis method for predicting the deflections of composite box girders with corrugated steel webs. To this end, longitudinal displacement

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of concrete slabs in composite box girders with corrugated steel webs is described. Then, the total strain energy of composite box girders with corrugated steel webs is calculated. The governing equations of composite box girders with corrugated steel webs, based on the principle of minimum total potential energy, are derived. The vertical deflection of the composite box girder bridges with corrugated steel webs is obtained by solving the above governing equations with the associated boundary and load conditions. The simplified method is validated with the results of the finite-element analysis conducted on three different composite box girders with corrugated steel webs.

2. Assumptions

Consider a typical composite box girder with corrugated steel webs like the one shown in Fig. 1, which is subjected to flexure in the XZ plane under distributed load $q(x)$. An orthogonal reference frame $\{o;x,y,z\}$ is introduced: the x-axis is parallel to the beam axis, and the vertical plane YZ is the plane of geometric, material, and load symmetry of the structure. Fig. 2 shows a typical corrugation configuration composed by a series of longitudinal and inclined sub-panels. The following assumptions are made in the analysis:

(1) The concrete slabs and corrugated steel webs behave in a linear-elastic fashion.
(2) Due to the longitudinal flexibility of a corrugated web, its contribution to the flexural resistance is negligible, and, thus, the primary bending moment is assumed to be carried entirely by the slabs.
(3) From the assumptions of the thin walled beam theory, the primary shear is assumed to be carried entirely by the webs.
(4) Only the top and bottom concrete slabs are effectively considered to resist the axial forces and bending moments acting on the box girder.
(5) The strains, deformations, and deflections are small, and thus equilibrium is formulated in the undeformed state.
(6) The warping distribution is assumed to remain constant over the depth of the concrete slabs.
(7) The effect of all tendons on the flexural, shear, and torsional behavior of structures is ignored.

3. Proposed simplified analysis method

The proposed method essentially consists of four steps: description of the longitudinal displacement of concrete slabs, calculation of the total strain energy, derivation of the governing equations, and prediction of the deflections. In the first step, the longitudinal displacement caused by the bending deflection of concrete slabs, the longitudinal displacement caused by the shear deflection of corrugated steel webs, and the longitudinal displacement caused by the shear lag effect of box girders are calculated respectively to describe the total longitudinal displacement of concrete slabs. In the second step, total strain energy of composite box girders with corrugated steel webs is calculated. Then, the principle of minimum potential energy is used to develop the governing equations. In the last step, with the associated boundary and load conditions, the vertical deflection of the composite box girder bridges with corrugated steel webs can be obtained by solving the above governing equations. The details of the four steps are described below.

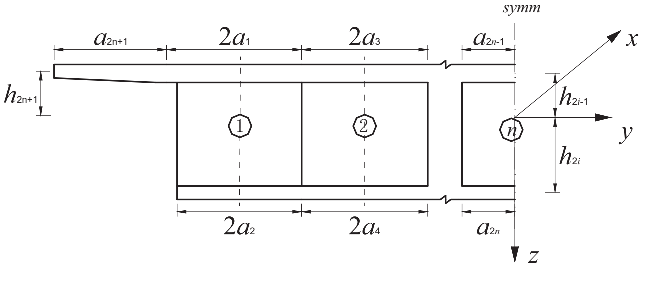

Fig. 1. Cross-section of single-box multi-cell corrugated box girder.

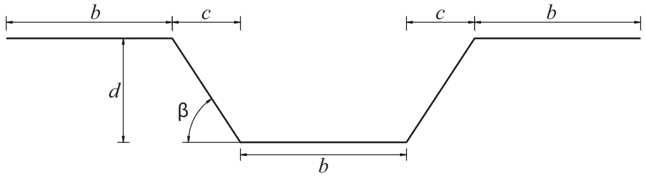

Fig. 2. Corrugation configuration and geometric notation of corrugated steel webs.

3.1. Description of longitudinal displacement

The longitudinal displacement of concrete slabs in composite box girders with corrugated steel webs, $U(x,y,z)$, consists of the longitudinal displacement caused by the bending deflection of concrete slabs, $U_1(x,y,z)$, the longitudinal displacement caused by the shear deflection of corrugated steel webs, $U_2(x,y,z)$, and the longitudinal displacement caused by the shear lag effect of box girders, $U_3(x,y,z)$

$$U(x,y,z) = U_1(x,y,z) + U_2(x,y,z) + U_3(x,y,z) \tag{1}$$

According to the EB (Euler-Bernoulli) theory, $U_1(x,y,z)$ can be expressed as

$$U_1(x,y,z) = z \cdot \omega'(x) \tag{2}$$

where $\omega(x)$ is the vertical deflection of the box girder corresponding to the elementary beam; $(\prime) = (\frac{d}{dx})$;

$U_2(x,y,z)$ can be expressed as

$$U_2(x,y,z) = -z \cdot \alpha(x) \tag{3}$$

where $\alpha(x)$ is the angle of rotation of the cross-section caused by the shear deformation of corrugated webs and can be defined as

$$\alpha(x) = \frac{Q(x)}{G_w A_w} \tag{4}$$

where $Q(x)$ is the vertical shear force of the girder; A_w represents the shear area of the corrugated steel webs, $A_w = (n+1)t_w h_w$; h_w represents the web depth; t_w stands for the web thickness; n is the number of cells; and G_w is shear modulus of corrugated steel webs calculated using the formula proposed by Johnson and Cafolla [22] as $G_w = G\frac{b+c}{b+c\sec\beta}$ (see Fig. 2).

With the assumption that the warping distribution over the depth of the concrete slabs is constant, longitudinal displacement caused by shear lag effect of box girders, $U_3(x,y,z)$ is given as

$$U_3(x,y,z) = z \cdot \xi(y)u(x) \tag{5}$$

where $u(x)$ is the maximum angular rotation function caused by the shear lag effect and $\xi(y)$ is the warping displacement function for the shear lag and is expressed by the following three parabolic branches: