Engineering Structures 152 (2017) 559–578

Contents lists available at ScienceDirect

Engineering Structures

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

Analytical solutions for composite beams with slip, shear-lag and time-dependent effects

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ARTICLE INFO

Article history:
Received 23 February 2017
Revised 17 July 2017
Accepted 31 August 2017

Keywords:
Steel-concrete composite beam
Analytical model
Space-exact solution
Slip
Shear-lag
Shrinkage and creep

ABSTRACT

In this paper, a new solution method is proposed to solve the one-dimensional analytical model of composite beams which is able to simulate the effects of interface slippage, and shear-lag and time-dependent effects. This method involves a solution of space and time variables. To enhance the accuracy of the solution, a space-exact analytical solution rather than the widely used space-approximate numerical solutions is adopted in the model. Furthermore, a step-by-step method which excels the method with single-step algebraic equations is used for the prediction of the time variables. A recursion method is then developed to solve the governing differential equation systems at each time step. The effectiveness and accuracy of the proposed method are validated by using the available test results of instantaneous and long-term tests on composite beams. The validated solution method is applied to time-dependent solutions, including vertical deflection, interface slippage, warping displacement due to shear, and stresses. The results show that concrete shrinkage and creep effects have a significant influence on the structural response of the beams. The characteristics of the shear-lag effects of concrete slabs are closely related to the placement of the prestressing wires. Finally, the solutions of the model that uses a general step-by-step method and that which uses single-step algebraic equations are compared. It is found that the latter can well predict the time-dependent behaviors of composite beams, except for the warping displacement due to shear of the simply supported beam.

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1. Introduction

Steel-concrete composite beams have been widely used for the construction of buildings and bridges. These composite beams can fully utilize concrete slabs and steel girders to resist internal compression and tension respectively, especially under a sagging moment. To enable composite action, shear connectors are used to couple the concrete slabs and steel girders together. However, the deformability of the shear connections causes slippage at the interface between a concrete slab and steel girder, thus leading to a decrease in flexural stiffness of the beam. Besides interface slippage, the shear-lag effects on the slabs lead to non-uniform stress distribution, especially for composite beams with a wide concrete slab. However, there are both positive and negative shear-lag effects on wide slabs [1–4]. In terms of the former, the stress at the slab-web intersections is greater than that on other parts of the slab, while in terms of the latter, the stress at the slab-web intersections is less than that on the other parts. Due to the non-uniform distribution of stress, neglecting shear-lag effects may result in underestimation of the actual stress on certain parts of a concrete slab. Zhu et al. [5] reported that the placement of prestressing wires can also significantly influence the characteristics of shear-lag effects. Therefore, to accurately simulate the real behavior of composite beams, shear-lag effects along with the effects of interface slippage must be considered. Besides the aforementioned effects of spatial kinematics, time-dependent effects due to creep and shrinkage of concrete have always been a key issue of composite beams. These effects can cause deformations and internal forces to change with time.

In analyses of the structural behavior of composite beams that take into consideration the effects of interface slippage, and shear-lag and time-dependent effects on composite beams, one-dimensional models [6–10] have been widely used. To solve the models, space and time variables are evaluated. To solve the space variables, four displacement functions, including the longitudinal displacements of concrete slabs and steel girders, vertical displacements and the intensity functions of the entire beam, should be incorporated into virtual-work equations. The finite difference method (FDM) [6] and finite element method (FEM) [9] are often

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https://doi.org/10.1016/j.engstruct.2017.08.071
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utilized to solve numerical equations. Alternatively, Sun and Bursi [11] proposed an analytical approach to solve for the space variables and derived a closed-form solution to account for slip and shear-lag effects. Undoubtedly, the results from using the closed-form approach are more precise, while minor numerical errors are prevalent when using FDM or FEM due to spatial discretization.

To derive solutions for time variables, general step-by-step methods and methods that use single-step algebraic equations are commonly found in the literature. These solution procedures require the use of a numerical time integration procedure to transform a hereditary integral relationship into a time-discretized constitutive relationship which is easy to handle in the solution algorithms. The methods that use single-step algebraic equations, such as the effective modulus (EM) [12], mean stress (MS) [13] and age-adjusted effective modulus (AAEM) [14] methods, utilize various quadrature formulae to handle the numerical integration, of which the stress history can be neglected but the accuracy is compromised. In contrast, Bazant [15] proposed a general step-by-step method to handle numerical integration by using the trapezoidal or the midpoint rule. The shortcoming of this method is that the entire stress history at each time point needs to be stored during the solution procedure. Thus, the solution time and computational cost are higher when compared to other methods. However, this problem is now addressed due to new developments in computational technology.

The above literature review indicates that combining an analytical closed-form approach to handle the space variables and a general step-by-step method to evaluate the time variables can provide the most accurate predictions for the time-dependent structural behavior of composite beams. This solution method is not available yet and worthy of investigation in this paper.

2. Establishment of analytical model

2.1. Kinematic analysis

The geometry and notations of a typical steel-composite beam with uniform cross-section are illustrated in Fig. 1. It should be noted that the Euler-Bernoulli kinematic assumption of plane sections that remain plane after bending is adopted in the model for the steel girder only but not for the reinforced concrete (RC) slab. To account for the kinematic behavior of the shear-lag of an RC slab, intensity and distribution shape functions are introduced. To simulate the interfacial slip, the RC slab and steel girder are assumed to have different longitudinal displacements, but have the same vertical displacement.

By adopting the kinematic assumptions presented in the last paragraph as well as the coordinate system and the notations depicted in Fig. 1, the displacement field for the RC slab and steel girder is expressed in Eq. (1):

$$\mathbf{u}(x,y,z,t) = \begin{cases} v(z,t)\mathbf{s}_j + [w_c(z,t) - (y-y_c)v'(z,t) + f(z,t)\psi(x)]\mathbf{s}_k \\ \quad \forall(x,y) \in \bar{A}_c, z \in [0,L] \\ v(z,t)\mathbf{s}_j + [w_s(z,t) - (y-y_s)v'(z,t)]\mathbf{s}_k \\ \quad \forall(x,y) \in \bar{A}_s, z \in [0,L] \end{cases} \tag{1}$$

where $\boldsymbol{s_i}$, $\boldsymbol{s_j}$, $\boldsymbol{s_k}$ are the unit vectors of the coordinate axes, as shown in Fig. 1; $\bar{A}_c$ and $\bar{A}_s$ represent closures of the domains in the x-y plane for the RC slab and steel girder respectively; y_c and y_s are the y coordinates of the cross-sectional centroid of the RC slab and steel girder respectively; primes denote partial derivatives with respect to the z coordinate; $v(z,t)$ is the vertical displacement of the whole cross-section at time t; $w_c(z,t)$ and $w_s(z,t)$ are the longitudinal displacements of the RC slab and steel girder at time t respectively; $f(z,t)$ is an intensity function of the warping displacement due to shear of the RC slab at time t, and $\psi(x)$ is the distribution shape function of the warping displacement due to shear of the RC slab and presented in Eq. (2). According to the study of Dezi et al. [6], a quadratic polynomial can be utilized as the expression of the shape function $\psi(x)$ with sufficient accuracy. Since the shear flow at the slab edge should be 0 ($\psi_{,x}(\pm b_c) = 0$), the expression of $\psi(x)$ is as follows by removing the constant term

$$\psi(x) = \begin{cases} \left(\frac{x}{b_c}\right)^2 + 2\frac{x}{b_c} & -b_c \leqslant x \leqslant 0 \\ \left(\frac{x}{b_c}\right)^2 - 2\frac{x}{b_c} & 0 < x \leqslant b_c \end{cases} \tag{2}$$

The distribution shape function ψ permits the simplification of the expression of the interface slippage $\Delta(z,t)$ at time t as

$$\Delta(z,t) = w_s(z,t) - w_c(z,t) + v(z,t)'h \tag{3}$$

where h is the distance between the centroid of the RC slab and steel girder.

2.2. Balance condition

The structural behavior of a deformable beam at time t must satisfy three basic conditions, which are compatibility, equilibrium and material constitutive relationships.

(1) Compatibility conditions

By using Eq. (1), the following non-vanishing strain components can be computed for an RC slab and steel girder respectively:

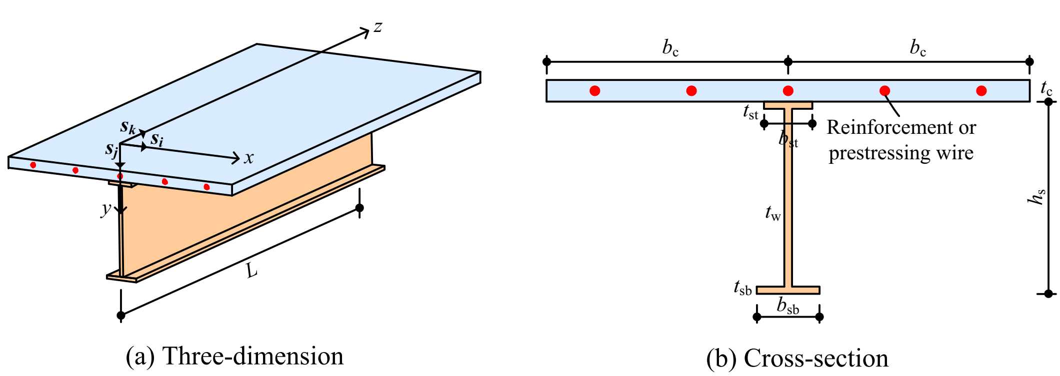

Fig. 1. Geometry and notations of steel-concrete composite beams.

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