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FE model to simulate bond-slip behavior in composite concrete beam bridges

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A B S T R A C T

This paper introduces a numerical model to simulate bond-slip behavior in composite beam bridges. Based on a linear bond stress-slip relation along the interface, the slip behavior is implemented into a finite element formulation. An adoption of the numerical model makes it possible to consider the slip behavior even in a beam element defined by two nodes only. The slip behavior can be determined from the force equilibrium, a constant curvature distribution and the piecewise linear distribution of the bending moment. Finally, Correlation studies between numerical results and experimental values were conducted to verify the validity of the proposed model.

1. Introduction

Composite structures are generally constructed by placing slab concrete on steel girders or pre-cast concrete girders, and various types of shear connectors are used to carry some reserved load above what is expected under normal use while achieving the monolithic behavior of a structure. Composite concrete beam bridges integrated with pre-cast or cast-in-place concrete girders are no exception. The structural behavior of the composite member becomes more complicated due to different material properties of slab and girders and the slip behavior between these two structural components. Because bond-slip is usually present at various loading conditions, regardless of the differences in design assumptions, such as the perfect bond and partial bond, an exact evaluation of the slip behavior along the interface between the slab and girders must be accomplished to determine the reduction in both the strength and serviceability of a structure.

Beyond numerous experimental studies on the bond-slip mechanism [1,12,13,15], many analytical approaches have been also attempted concerning a decrease in the resisting capacity and an increase in the deflection in composite concrete beams with partial shear connectors. Bradford and Gilbert [2] analyzed partially composite beams using an equivalent transformed section approach with the linear load–slip relation of a shear connector, and Dezi et al. [4] directly solved the governing differential equations by using the finite differential method to calculate the deflection change caused by the slip at the interface of the concrete slab and steel beam. These approaches yield very accurate results for partially bonded composite beams, but also have numerous restrictions in application such as the symmetric configuration and boundary conditions of a structure with no slip at midspan. In addition, Roberts [23] obtained slip and nodal displacements for typical composite beams with the finite difference method on the basis of the force equilibrium and compatibility condition. However, it is also true that the finite difference method usually creates some limitations in application to various structural systems because its solution procedure is strongly dependent on the governing equation and boundary conditions. Most recent studies, accordingly, have been conducted with the numerical approach [5,6,19–22,26,28].

To overcome these limitations in considering the bond-slip effect, a few numerical models have been proposed [5,19,21,22,26,28], but most of studies have been based on a double node concept to represent the relative slip between the concrete slab and beam [6]. In spite of easy application into the finite element formulation, this method leads to not only an increase in the number of degrees of freedom, but also to greater complexity in the mesh definition, especially in the case of a structure with numerous nodes and elements. In addition, the direct consideration of axial degree of freedom in an element stiffness matrix, to take into account the relative slip behavior along the interface, may cause the shear locking problem because of using different interpolation polynomials from those for the bending behavior, and Ranzi and Bradford [20] introduced a direct stiffness formulation to remove the locking phenomenon in composite beams structure.

This paper, accordingly, introduces a finite element (FE) model which can include the bond-slip deformation in a beam element whose deformation is defined by two end nodes, without taking the double nodes along the interface between the concrete slab

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and beam. A linear partial interaction theory is adopted in formulation, and the governing equations at an element are derived on the basis of continuous analytical solutions. After constructing the transfer matrix relation for a total structure with the compatibility conditions and equilibrium equations at each node, the nodal forces and displacements related to the slip behavior are calculated by the successive application of the governing equations for each element. Inclusion of the developed model into the conventional finite element formulation allows the simulation of bond-slip behavior, even in the beam element, without taking double nodes and does not cause the locking problem due to the direct consideration of axial deformation. The reliability for the proposed model is verified by comparing the analytical predictions with results from experimentation and previous analytical studies.

2. Material properties

In order to formulate the constitutive relationships in a layer of composite beam elements, the following simplified assumptions have been made: (1) the element is divided into imaginary layers to describe the different material properties; (2) plane sections remain plane to represent the linearity in the strain distribution on any section; (3) the Timoshenko beam theory, which takes into account the transverse shear deformation, is the basis; and (4) the constitutive materials are assumed to carry uniaxial stress only.

2.1. Concrete

Since the bending behavior of RC beams subjected to monotonic loadings is much more affected by the tensile rather than by the compressive behavior of concrete, the stress–strain relation in compression is not of primary interest. Among the numerous mathematical models currently used in the analysis of RC structures, the monotonic envelop curve introduced by Kent and Park [8] and later extended by Scott et al. [24] is adopted in this paper because of its simplicity and computational efficiency. In this model, as shown in Fig. 1(a), the monotonic concrete stress–strain relation in compression is described by three regions:

$$\sigma_c = Kf'_c\left[2\left(\frac{\varepsilon_c}{\varepsilon_{c0}}\right) - \left(\frac{\varepsilon_c}{\varepsilon_{c0}}\right)^2\right], \quad \varepsilon_c \leqslant \varepsilon_{c0}, \tag{1}$$

$$\sigma_c = Kf'_c[1 - Z_i(\varepsilon_c - \varepsilon_{c0})], \quad \varepsilon_{c0} \leqslant \varepsilon_c \leqslant \varepsilon_u, \tag{2}$$

$$\sigma_c = 0.2Kf'_c, \quad \varepsilon_c \geqslant \varepsilon_u, \tag{3}$$

where

$$\varepsilon_{c0} = 0.002K, \quad K = 1 + \frac{\rho_s f_{yh}}{f'_c}, \tag{4}$$

$$Z_i = \frac{0.5}{\frac{3+0.0284f'_c}{14.21f'_c-1000} + 0.75\rho_s\sqrt{\frac{h'}{s_h}} - 0.002K} \quad (i = 1, 2), \tag{5}$$

where ε_{c0} is the concrete strain at maximum stress, K is a factor which accounts for the strength increase due to confinement, Z_i is the strain softening slope, f'_c is the concrete compressive strength in kg/cm^2 (1 kg/cm^2 = 0.098 MPa), f_{yh} is the yield strength of the stirrups in kg/cm^2, ρ_s is the ratio of the volume of hoop reinforcement to the volume of the concrete core measured to the outside of the stirrups, h' is the width of the concrete core measured to the outside of hoops or ties, and s_h is the center to center spacing of tie or hoop sets.

In the case of RC beams whose behavior is greatly dominated by bending, the compression region is not seriously influenced by the effect of mesh size, unlike the tensile region, because most stress and strain values are in the elastic region, which extends to the ultimate resisting capacity of the structure. On the other hand, the tensile region is dominantly affected by the mesh size of an element owing to the micro-crack distribution concentrated in a fracture process zone, which may be small compared to the size of the finite element mesh [10]. Accordingly, it is assumed that concrete is linearly elastic in the tension region. Beyond the tensile strength, the tensile stress decreases linearly with increasing principal tensile strain (see Fig. 1(b)). Ultimate failure is assumed to take place by cracking when the principal tensile strain exceeds the value $\varepsilon_0 = 2G_f \cdot \ln(3/b)f'_t \cdot (3 - b)$ shown in Fig. 1(b), where b is the element length and G_f is the fracture energy that is dissipated in the formation of a crack of unit length per unit thickness and is considered a material property. The value of ε_0 is derived from the fracture mechanics concept by equating the crack energy release with the fracture toughness of concrete G_f. The experimental study by Welch and Haismen [29] indicates that for normal strength con-

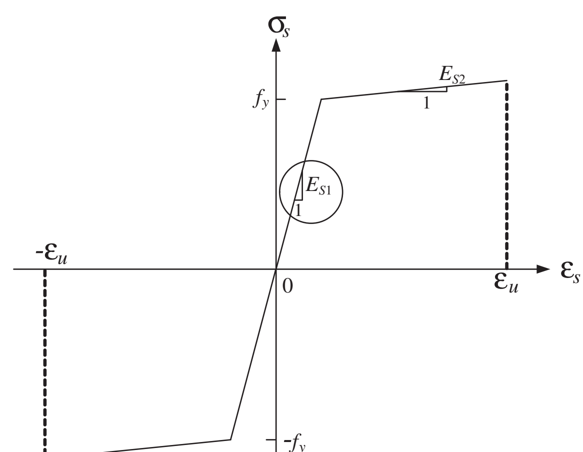

Fig. 2. Stress–strain relation of steel.

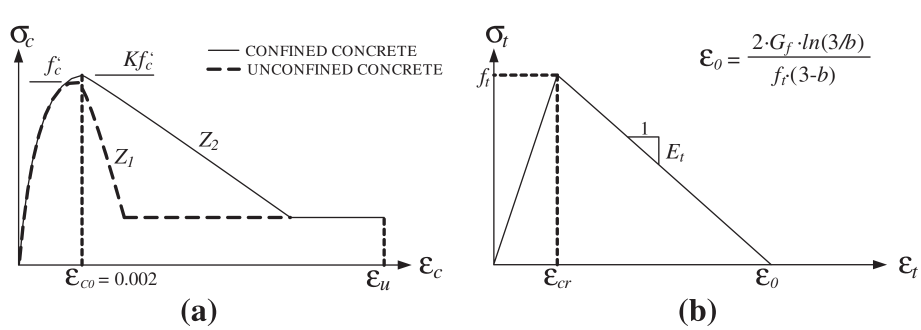

Fig. 1. Stress–strain relation of concrete: (a) compressive region and (b) tensile region.