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Modified steel bar model incorporating bond-slip effects for embedded element method

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HIGHLIGHTS

- A simple embedded element is introduced to consider interactional effect.
- The elastic modulus of steel and its yield stress is reduced in model.
- Effects of various parameters pertaining to concrete and steel were examined.
- Elastic modulus of the steel is reduced to consider the bond-slip effects.
- The model can be used in complex structures with simplicity.

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ABSTRACT

The interaction between the steel bar and concrete is one of the most important issues that control the efficiency of the composite behavior. Accurate evaluation of the interaction between the reinforcement and the surrounding concrete can lead to more reliable finite element models. The implementation of a modified steel bar model in embedded elements to consider the bond-slip phenomenon is presented in this study. The procedure includes the addition of equivalent bond strain to the strain of the steel bar. This leads to a decrease in the effective stiffness of steel bar in the layered model. Validation of the modified steel bar model with existing experimental results demonstrates that the model is capable to consider the bond effects in embedded elements for use in analysis of reinforced concrete structure. A comprehensive parametric study is accomplished to obtain the influence of parameters such as concrete and steel properties, bar diameter, reinforcement ratio and confinement conditions on modification factors. Results revealed the significant effect of bond-slip on total behavior of the member.

1. Introduction

In construction, steel reinforced concrete (RC) is widely used as a structural material in the world. The interaction between the reinforcement and the surrounding concrete has important effect on design procedure, and therefore is of great interest to researchers. This phenomenon strongly influences the behavior of reinforced concrete members and controls the structural efficiency of a RC element. Bond stresses between the reinforcing bars and concrete is a function of slip, which is associated with the difference between the strains in concrete and the reinforcing bar. The Bond-slip diagram demonstrates the variation of the bond stress with respect to slip in the interaction boundary between two materials. A numerical model that can closely simulate the interaction effect is required for proper evaluation of concrete–bar interaction. Presence of the bar in the concrete enhances the strength and stiffness of the composite element.

There are two common types of element used in the modeling of the composite behavior. In an accurate model denoted by "discrete element", the concrete and steel parts are considered separately. In the other model called "embedded element", the reinforcing bar is considered as an additional axial component like stiffening fiber embedded in concrete element and its nodal displacements are consistent with those of the concrete elements [1]. This model assumes perfect bond between concrete and bar with no slip.

Although the discrete model is more precise than the embedded model, using this type of model leads to restrictions on mesh generation and also increase in the number of required mesh. Therefore, the convergence of the model is very time-consuming and

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the procedure is not applicable for large systems. In contrast, the embedded element needs less time and is applicable for larger and more complex structures.

Until now, different methods have been employed for considering bond-slip effects in finite element analysis. Ngo and Scordelis [2] have used bond-link model to account for bond-slip in FE analysis for which a node of concrete is connected to a node of steel rebar and the link element has no physical dimension. In the other work, Groot et al. [3] have defined an area between concrete and steel bar, called bond- zone, to consider the bond-slip property. Different kinds of interactions such as translation and rotation can be considered in this method. This method is not appropriate for complex systems with large number of nodes, which lead to increase in the degree of freedom for the whole model.

Kwak and Filippou [4] have proposed a modified model to develop bond-link element. In their model, the stiffness of the reinforcing steel element has been reduced due to the bond-slip effect with no double nodes for defining bond element. Although the method was simple, some of the influential parameters cannot be considered in their method. Monti et al. [5–7] have used the force-based fiber element presented by Spacone et al. [8] to consider the bond-slip effect in reinforcing bar model. The sum of the steel strain and the anchorage slip strain was used as the fiber section strain. However, the effective strain of bond has not been precisely computed in this model and also the location of cracks has been neglected. Kwak and Kim [9] have presented modified steel bar model in analysis of RC frame under cyclic load. In this model, the strength and elastic modulus of steel reinforcing bar were modified. The procedure of the computation was accurate. However, the method needs much computational effort to be implemented for complex systems.

Zhou et al. [10] have used embedded bond-slip model for soil–nail interaction. In their study, two user-defined 4-node plane interface elements were defined along the soil–nail contact. Although with this new method, the shear deformation along the soil–nail interaction can be obtained in the normal and tangential directions, but the number of nodes and also the degrees of freedom increased which lead to much time for processing.

1.1. Research significance

Although the bond effects on the mechanical behavior of embedded model were studied in some papers, a simple method to be used in common finite element software has been rarely employed in previous works.

In this study, a modified steel bar model is developed to consider the bond-slip effects in the embedded element. This modified simple embedded element can be used in large complex composite structures to obtain reliable and precise results in finite element model. According to the simplicity of the method, a comprehensive parametric analysis is employed to determine the influence of various effective parameters.

2. Modified steel bar model

Relative displacement between concrete and steel bar can make the composite behavior more ductile. In fact, displacement of the RC members is controlled by the bond behavior. In this field, Cashell et al. [11] have shown that a relatively high bond stress causes the member to fail at an early stage whereas a lower bond results in a substantially larger failure displacement. Therefore, it is essential to develop an efficient new model to consider the bond-slip effects in finite element modeling. The stress–strain relation of a steel rebar is usually shown by a bilinear curve with an explicit yield stress, f_y. Many stress–strain models for steel bar embedded in concrete have been proposed based on experimental and analytical methods. Belarbi and Hsu [12] have described a linear stress strain relationship of steel bar model from experimental data in which the real yield strength of steel bar embedded in concrete, f_y^* can be obtained from:

$$\frac{f_y^*}{f_y} = (0.93 - 2B) \tag{1}$$

where the effective yield stress is a function of $B = (f_{cr}/f_y)^{1.5}/\rho$. In this equation, ρ is the reinforcement ratio and f_{cr} represent the tensile cracking stress of concrete at cracking strain of about 8×10^{-5}.

In addition to the yield stress, the stress–strain relationship is modified is this study. To this aim, the equivalent strain of bond-slip effect is added to the strain of steel reinforcing bar. As shown in Fig. 1, the total deformation of steel rebar is assumed to be sum of its own mechanical strain, and the displacement related to the slip.

In order to describe the principles of method, consider a reinforced concrete member in bending. As shown in Fig. 2(a), the distance between two adjacent cracks in the member is denoted by S_r. The concrete located between the bending cracks participates in the tensile strength of the cross section. However, in the cracked section, the concrete has no effect on the tensile strength and the tension force is entirely transferred to the steel reinforcing bar. So according to Fig. 2(b), the stress concentration occurs at the cracked section. There is no bond stress between concrete and rebar at the cracked section, which causes the strain and also the stress concentration. According to the principle features of the modified embedded model, the modified elastic modulus of steel reinforcing bar can be written as:

$$E_s^* = \frac{f_y^*}{\varepsilon_s + (\delta/l)} \tag{2}$$

where f_y^* is the effective yield stress of the steel bar which can be obtain from Eq. (1), ε_s is the strain of the steel bar corresponding to the stress of f_y^* in steel bar model and δ is the maximum slip of the steel bar. In Eq. (2), l is the transmission length of bond strength between the steel bar and the surrounding concrete. As depicted in Fig. 3, the maximum slip of the steel rebar in RC members depends on the failure conditions [13–15], which is a function of several important parameters such as steel diameter, concrete cover of reinforcement and confinement conditions of reinforcement. Nevertheless, in CEB-FIP Model Code 1990 [16], the slip at peak of bond-slip curve corresponding to the maximum bond stress was described by parameter S_1, which has 2 constant values, 0.6 mm for unconfined concrete and 1.0 mm for confined concrete. A more precise estimation of the maximum slip has been presented by Wu and Zhao [17] who expressed the slip at peak of bond-slip curve as:

$$\delta = \frac{0.7315 + K}{5.176 + 0.3333K} \tag{3}$$

where

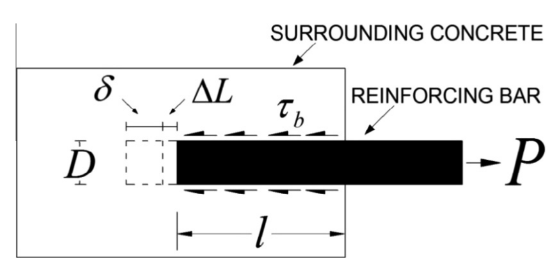

Fig. 1. Steel rebar in concrete.