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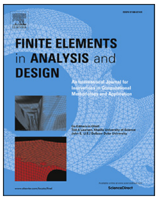

Modeling reinforced concrete structures using coupling finite elements for discrete representation of reinforcements

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ABSTRACT

This paper presents an alternative methodology to represent rebars and their bond-slip behavior against concrete based on coupling finite elements. Among the main features and advantages of the proposed technique are: (i) the coupling between the two independent meshes for concrete and reinforcement does not introduce any additional degree of freedom in the global problem; (ii) both rigid and non-rigid coupling can be used to represent the particular cases of perfect adherence and general bond-slip behavior, respectively; (iii) rebars of arbitrary geometry and orientation can be modeled; (iv) the methodology can be applied to 2D and 3D problems and (v) the formulation can be adapted to other type of finite elements and implemented easily in any existing FEM code. Constitutive models based on continuum damage mechanics are used to represent the concrete behavior and concrete-rebar interaction. A number of numerical analyses are performed and the results obtained show the versatility and accuracy of the proposed methodology.

1. Introduction

It is well known that to achieve an accurate and efficient modeling of the nonlinear behavior of reinforced concrete structures by the Finite Element Method (FEM), three important components must be appropriately represented: concrete, steel reinforcement and the bond-slip between steel and concrete. Regarding the latter component, since the thickness of the interface between the two materials is usually very small compared to the typical dimensions of the structural member, the computational analysis involves different scales.

A first alternative to model the interface in 3D can be achieved by using the same solid finite elements also employed for the other components – concrete and steel reinforcements. This strategy, however, involves a high computational cost and a complex finite element mesh due to the refinement needed in the neighborhood of the interface. In addition, the cross-section of the steel rebars is much smaller than the general dimensions of the structural member, which precludes using solid elements to represent the reinforcements (see, e.g., Refs. [1,2]) due to the mesh complexity, particularly when the reinforcement ratio of the structural member is considerably large.

To reduce the computational costs of 3D models, a strategy for modeling steel/concrete interaction based on a multi-fiber approach has been proposed by Richard et al. [3]. In their model, the steel/concrete interaction and reinforcement bars are homogenized and the kinematic assumptions are added to relate the global nodal displacement (beam element) to the local strains (cross section). Degenerated finite elements can also be applied to model steel concrete interaction, as employed for Richard et al. [4] for three-dimensional analysis. Recently, interface finite elements with high aspect ratio have been proposed by Rodrigues et al. [5] to describe the interaction between rebars (discretized using one dimensional finite elements) and concrete (represented by three-noded triangular finite elements). In this approach, a continuum damage model is applied to describe the interfaces between the two components. Lastly, one dimensional finite elements are also frequently applied to model both rebars and interfaces. In such models, the behavior of the steel/concrete interface is treated as discrete or embedded formulation to represent the reinforcement bars.

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Smeared, discrete and embedded models can be used to represent the steel rebars. The first model is particularly suitable for modeling distributed reinforcement, since it is based on the assumption that the reinforcements are distributed uniformly with a particular orientation angle over the concrete element. Hence, this formulation is very appealing for modeling concrete structures such as membranes [6,7], shells [8–10] and plates [9–11]. In addition, since it is usually assumed perfect bond between concrete and reinforcements, the constitutive relations are derived using the homogenization theory and, consequently, the reinforcement does not have an explicit discrete representation.

On the discrete and embedded models, the reinforcement layout is explicitly handled. Such models are suitable for applications in which the steel reinforcements are located sparsely. The basic difference among them lies is the way concrete and reinforcement layout are coupled. The discrete model was cited for the first time by Ngo and Scordelis [1]. In this model, the steel reinforcements are connected directly to the adjacent concrete element nodes. Therefore, the major drawback is related to the fact that the concrete mesh does depend on the layout of reinforcements adopted. On the other hand, no special finite elements are required for establishing the connection, since the contribution of the reinforcement to the global stiffness matrix is automatically achieved. E-Mezaini and Çitipitioğlu [12] propose a technique to overcome the problem of mesh dependency, in which isoparametric elements with movable side nodes are applied to concrete, in which case the reinforcement layout can be positioned arbitrarily. This formulation, however, is very limited, since each concrete element cannot be crossed by more than one reinforcement segment. Many researchers employ this formulation when they need to investigate the bond-slip between steel and concrete, since this phenomenon can be introduced straightforwardly. Bond-links [1,2] and contact elements [13] are the most common finite elements used to represent this feature.

In the context of the finite element analysis of reinforced concrete structures, the embedded model seems to be the most appealing, since the discrete rebars can be positioned independently of the concrete mesh. Thus, the rebars can intersect the elements used to represent the concrete in any direction. The contribution of the reinforcement stiffness is superimposed to their parent elements. In the case of perfect bond, the stiffness matrix of the reinforcement (corresponding to its embedded length) is evaluated using the same strain displacement relation of the parent element. It is important to note that, in this case, the size of the stiffness matrix remains unchanged.

In the formulation developed independently by Phillips and Zienkiewicz [14] and Elwi and Murray [15], the embedded reinforcement needs to be aligned with the local isoparametric coordinate axes of the parent elements, bringing some restrictions regarding the reinforcement layout. Chang et al. [16] developed a formulation that allows the reinforcement layer to have an angle relatively to the local isoparametric element axes. However, the reinforcement layer must be straight, and the parent element mesh rectilinear. Elwi and Hrudey [17] published a formulation for curved embedded bars in two-dimensional parent elements that allows slip, whereas Al-Bayati and Fahed [18] developed a procedure to embedded reinforcement in shell elements. Cheng and Fan [19] extended the formulation proposed by Elwi and Hrudey [17] to general three-dimensional elements with improvement and corrections in the transformation process to take into account the reinforcement confinement. Barzegar and Maddipudi [20] developed an automatic procedure for three-dimensional analysis and inclusion of straight segments of embedded reinforcement in a mesh of solid-parametric elements representing concrete. With this procedure only the global coordinates of the nodes need to be provided. Then, an extension of this formulation for modeling of bond-slip in three-dimensional applications is presented by these authors [21]. Markou and Papadrakakis [22] developed an automatic procedure for the generation of embedded steel reinforcement inside hexahedral finite elements to decrease the computational cost in the generation of the input data for the embedded rebar elements.

It is important to consider that in all embedded formulations allowing slip between reinforcement and concrete, the number of degrees of freedom is increased, and consequently, also the size of the stiffness matrix and the computational cost. Another important aspect that should be considered is related to the algorithm necessary to obtain the intersection between the reinforcements and parent elements, and to properly account for the length of reinforcement within each parent element. An integration method or an iterative approach is usually employed to map from global to local the Gauss points coordinates of the reinforcement, and then, evaluate its contribution to the stiffness matrix.

Besides of the approaches mentioned above, nowadays some authors considered the effect of the rebars based on the use of the mixture theory. In this way, Manzoli et al. [23] accounted for the presence of the reinforcing bars oriented in different directions. According to these authors, bundles or layers of rebars, surrounded by concrete, are modeled as composite materials without the need for representing the mesoscopic scale at which the rebars geometrically belong.

In this paper an alternative approach based on the use of coupling finite elements for modeling rebars and their bond-slip relation against concrete are proposed. The model can be classified as a variation of the embedded approach, since both reinforcement layout and concrete are discretized initially in an entirely independent and non-conforming way. Coupling finite elements developed by Bitencourt Jr. et al. [24] are inserted in the mesh to describe the interaction between reinforcements and concrete. This alternative approach is very appealing since it avoids the need for implementing an algorithm to detect the length of the bar embedded in each “parent” element, as is usually the case in existing embedded approaches. Moreover, with the proposed formulation, a concrete element can be crossed by more than one reinforcement segment in any direction automatically. Finally, in order to simulate reinforced concrete structures using the proposed methodology, constitutive models based on the Continuum Damage Mechanics Theory (CDMT) are also formulated for the concrete behavior and rebar interaction.

This paper is organized in five main sections. In section 2, the strategy used to describe the interaction of the rebars on the concrete matrix based on coupling finite elements is presented. Both cases involving perfect and non-perfect bond conditions are detailed. Then, in section 3, continuum damage mechanics models are proposed for handling the bond-slip and concrete behavior under tension and compression. Finally, in section 4, several structural examples are presented as means to validate the proposed strategy. The concluding remarks are presented in section 5.

2. Discrete representation of rebars

To present the strategy for the discrete representation of rebars in reinforced concrete structures, let us consider the reinforced concrete corbel in Fig. 1. In such example, the reinforcement layout is quite complex, given that the rebars have different geometries, positioned in distinct directions and completely independent of the concrete mesh. The strategy proposed can be summarized as follows:

1. Concrete mesh discretization based on the geometry of the structural member (Fig. 1(a));
2. Definition of the rebars and corresponding mesh discretization (Fig. 1(b));
3. Definition of coupling finite elements (CFEs) to describe the interaction between concrete and rebars (Fig. 1(c)).

The main novelty of the proposed approach lies in the use of CFEs to couple the two independent and non-conforming meshes for concrete and reinforcement. According to Bitencourt Jr. et al. [24], each CFE has the same nodes of the matching concrete element plus an additional node – herein designated coupling node – represented by the *loose* node of the rebar that belongs to the domain of the referred concrete element.