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Original Research Article

Crack opening estimate in reinforced concrete walls using a steel–concrete bond model

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ARTICLE INFO

Article history:
Received 28 September 2015
Accepted 7 February 2016
Available online 10 March 2016

Keywords:
Reinforced concrete
Crack spacing
Crack opening
Steel–concrete bond
Shear wall

ABSTRACT

This paper presents the application of a new steel–concrete bond model on a reinforced concrete shear wall, experimentally tested during the French National Project CEOS.FR. The proposed results include both global (evolution of the force as a function of the displacement for example) and local results (crack opening and spacing). A new post-processing method to compute these local properties even in a case of a complex crack pattern (oriented cracks for example) is proposed. It is based on the change in the sign of the bond slip between steel and concrete. The simulated results are in a good agreement with the experiment and validate the developments. Finally, the interest of including a specific steel–concrete bond model in the finite element simulation is highlighted, compared to classical ''no-slip'' relation.

1. Introduction

In particular cases, the estimation of the crack properties (spacing and opening especially) is a key point in the design and the evaluation of reinforced concrete structures [1,2]. Cracking may indeed question the safety and the durability (loss of confinement, corrosion of rebars or leakage issue for example). Development of cracks in reinforced concrete structures is a complex phenomenon. It includes crack initiation, propagation, change from microcracks to macro-cracks and interactions between concrete and reinforcement [3]. Among the different available approaches (discrete approach [4], cohesive zones [5], ...), damage models are widely used in literature to describe the initiation and propagation of cracks. Based on continuum mechanics, they include a reduction in the stiffness [6] and may be associated to irreversible strains [7,8], crack closure or to an isotropic or orthotropic description of the mechanical degradation [9,10].

In this context, when large reinforced concrete structures are considered, a no-slip (also called ''perfect'') relation is generally assumed to model the steel–concrete interface. But this hypothesis may have heavy consequences when the crack properties are studied, as the steel–concrete bond directly influences their evolutions. For example, in [1], an engineering law is provided which directly relates the crack spacing and the bond properties. In [11], bond effect is underlined and is responsible for a different cracking behavior, compared to

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http://dx.doi.org/10.1016/j.acme.2016.02.001

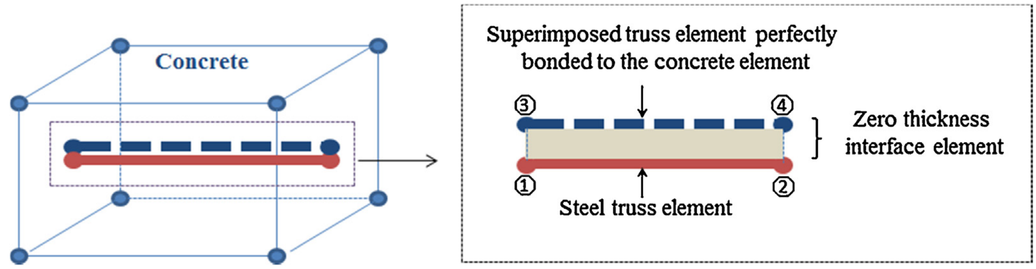

Fig. 1 – Principle of the interface element between steel and concrete [18].

classical perfect relation, especially in the active cracking phase (for bending reinforced concrete beams).

To solve this problem, numerical models have been developed to represent the steel–concrete bond more accurately. For example, Ngo and Scordelis [12] proposed a spring element to relate concrete and steel nodes, associated to a linear constitutive law. An interface element in 2D was then introduced by Brancherie and Ibrahimbegovic [13] or Dominguez et al. [14] which enables the use of a nonlinear law. Dominguez [15] and Ibrahimbegovic et al. [16] among others finally proposed an embedded element in which the bond behavior is described through an enrichment of the degrees of freedom. Even if these approaches lead to a correct description of the bond mechanisms between steel and concrete, they also have their own limits, especially in cases of real scale applications: meshing problems (explicit representation of 3D steel geometry) or increase in computation time (with enriched elements). That is why alternative solutions were proposed [17] to represent the effects of the steel–concrete bond in a context adapted to large scale applications: truss steel elements are used for reinforcement with no need to explicitly mesh the steel–concrete interface.

The latter was improved in [21] and applied on a reinforced concrete tie. Even if the results were promising (capacity of the model to reproduce the global and local experimental results), they were limited to simplified uniaxial loading. For more complex situations, especially in the case of more complex crack patterns, the results were questionable. This paper proposes to evaluate the performance of the model on a reinforced concrete shear wall. In the first part, the steel–concrete bond model is briefly recalled. In the second part, the test case is presented, associated to the results concerning the global behavior. Due to the use of a damage model for concrete, a new post-processing method, based on the slip between steel and concrete, is proposed to calculate the crack properties. This method is applied on the shear wall and a comparison with the experiment is performed. Finally, a discussion is proposed to evaluate the interest of the steel–concrete bond model compared to a ‘‘perfect’’ no-slip relation.

2. Description of the bond slip model

When reinforced concrete structures are considered, one of the most classical hypotheses is to model the steel reinforcement as truss (or membrane) elements and to consider a perfect relation between steel and concrete. This perfect relation is generally applied through kinematic relations between both models, using the shape functions of each element. But this hypothesis may have heavy consequences, especially when the crack properties (spacing and openings) are studied, as the steel–concrete bond directly influences their evolutions ([1,11] for example). To take into account this interfacial behavior between steel and concrete in a more appropriate manner, the new interface element developed in [18], based on the previous work from Casanova et al. [17], is used. It is a zero thickness four node element which relates each steel truss element with an associated superimposed segment, perfectly bonded to the surrounding concrete (Fig. 1).

Each node of the interface element has three degrees of freedom (nodal displacements) (Fig. 2). The relation between the generalized slip in the local direct frame $\{\delta(p)\}$ (Fig. 3) and the nodal displacements $\{u\}$ is written in the following form:

$$\{\delta(p)\} = \{\,\delta_t(p) \quad \delta_{n_1}(p) \quad \delta_{n_2}(p)\,\}^{T} = \overline{\overline{B}}(p)\{u\} \tag{1}$$

with

$$\overline{\overline{B}}(p) = \left[\overline{\overline{B_1}}(p) \quad \overline{\overline{B_2}}(p) \quad -\overline{\overline{B_1}}(p) \quad -\overline{\overline{B_2}}(p)\right] \tag{2}$$

and

$$\begin{aligned} \overline{\overline{B_1}}(p) &= 0.5(1-p)\overline{\overline{I_3}} \\ \overline{\overline{B_2}}(p) &= 0.5(1+p)\overline{\overline{I_3}} \end{aligned} \tag{3}$$

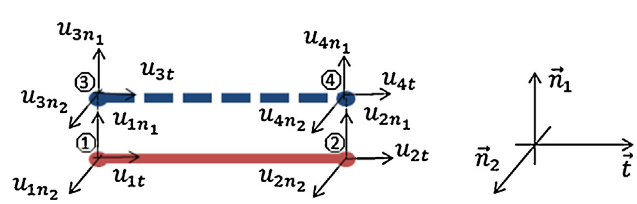

Fig. 2 – Degrees of freedom of the interface element [18].

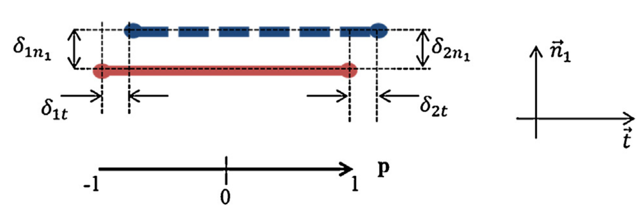

Fig. 3 – Definition of the slip between steel and concrete in the interface element in the ($t\rightarrow$, $n_1\rightarrow$) plane [18].