Engineering Structures 86 (2015) 72–83

Contents lists available at ScienceDirect

Engineering Structures

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

New finite element to model bond–slip with steel strain effect for the analysis of reinforced concrete structures

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ARTICLE INFO

Article history:
Received 9 August 2014
Revised 6 December 2014
Accepted 17 December 2014
Available online 10 January 2015

Keywords:
Finite element
Cracking
Reinforced concrete
Bond–slip
Steel strain effect

ABSTRACT

The influence of steel strain in bond–slip relationship has been the subject of recent literature, especially steel strain after yielding. This paper presents a new bond element for finite element packages which performs the bond–slip relationship, including steel strain effect. The developed element consists of an orthotropic four-node plane stress element whose constitutive material laws were changed. In order to verify the accuracy of this element several 2D numerical results were compared with experimental data. The results obtained with this element showed the need for its use to achieve good results and the relevance of steel strain effect on bond–slip relationship, especially in tension elements.

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1. Introduction

The behaviour of reinforced concrete (RC) structures is considerably influenced by bond–slip relationship. On the one hand, bond stress should be high enough to minimise crack width and deformations in service, and, on the other hand, bond stress should be low enough to ensure large rotation capacity at plastic hinges near the failure.

For many years researchers have described bond stress mainly as a function of the slip between steel and concrete. The influence of other parameters was disregarded because numerical and experimental studies were mostly developed in service conditions, that is, before the yield of steel. Many studies are discussed in FIB Bulletin 10 [1]. The most well-known relationship between bond stress and slip is given by Eq. (1), which is used in many codes like Model Code 2010 (MC2010) [2]:

$$\tau_0(s) = \begin{cases} 2.5 \cdot \sqrt{f_c} \cdot s^{0.4}; & 0 \leqslant s \leqslant 1.0 \\ 2.5 \cdot \sqrt{f_c}; & 1.0 < s \leqslant 2.0 \\ \sqrt{f_c} \cdot \left(2.5 - 1.5 \cdot \frac{s-2.0}{c_{clear}-2.0}\right); & 2.0 < s \leqslant c_{clear} \\ \sqrt{f_c}; & s > c_{clear} \end{cases} \quad (1)$$

where f_c = compressive strength of concrete; c_{clear} = clear distance between ribs in the rebar.

More recently, because of the need to ensure ductile behaviour in reinforced concrete structures near the failure, several researchers have proposed extended formulations for bond–slip relationship, which take into account the post-yield tension stiffening effects. Parameters like steel strain, concrete strain, damage or confinement have been related to bond–slip relationship.

First, Shima et al. [3] formulated a constitutive model for bond behaviour which includes a relationship between bond stress, slip and steel strain. This model also includes the effects of bar diameter and concrete strength. By means of experimental data in the post-yield range of steel the model was validated. Eqs. (2–4) summarise this proposal:

$$\tau(f_c, s, \varepsilon_s, \varnothing) = \tau_0(f_c, s, \varnothing) \cdot g(\varepsilon_s) \quad (2)$$

$$\tau_0(f_c, s, \varnothing) = 0.73 \cdot f_c \cdot \left[\ln\left(1 + 5000 \cdot \frac{s}{\varnothing}\right)\right]^3 \quad (3)$$

$$g(\varepsilon_s) = \frac{1}{1 + \varepsilon_s \cdot 10^5} \quad (4)$$

where τ = bond stress, f_c = compressive strength of concrete, s = slip between steel and concrete, ε_s = steel strain, $\varnothing$ = diameter of rebars, τ_0 = reference value of bond stress and $g(\varepsilon_s)$ = reduction function.

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http://dx.doi.org/10.1016/j.engstruct.2014.12.036
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Marti et al. [4] presented the Tension Chord Model, which can be applied in problems of cracking, minimum reinforcement, tension stiffening and rotation capacity. This model assumes a rigid-perfectly plastic bond–slip relationship, but when the steel strain on rebar reaches the yield strain, the bond stress drops to half (Eq. (5)):

$$\tau(f_c, \varepsilon_s) = \begin{cases} 0.6 \cdot f_c^{2/3}; & \varepsilon_s \leqslant \varepsilon_y \\ 0.3 \cdot f_c^{2/3}; & \varepsilon_s > \varepsilon_y \end{cases} \tag{5}$$

where ε_y = yield steel strain.

With regard to experimental results Mayer and Eligehausen [5] recognised the need to model bond by taking into account the effect of steel yield and bar surface geometry.

Lundgren and Gylltoft [6] developed a three-dimensional interface element to connect concrete to the rebar. In this interface element the bond stress depends not only on the slip, but also on the radial deformation between the rebar and the concrete. By using this element in a finite element analysis is possible to predict reasonably splitting failures and loss of bond if the rebar is yielding.

Ožbolt et al. [7] presented a discrete two-node bond element which can be used in the 3D finite element analysis of concrete structures. The model response is controlled by a bond–slip relationship modified to include the loading–unloading–reloading, the concrete geometry, the concrete strain and the steel strain (Eq. (6)). This model applies non-local analysis from the vicinity of the rebar.

$$\Omega_s(\varepsilon_s) = \begin{cases} 1.0; & \varepsilon_s < \varepsilon_y \\ 1.0 - \alpha\frac{\varepsilon_s - \varepsilon_y}{\varepsilon_u - \varepsilon_y}; & \varepsilon_y < \varepsilon_s < \varepsilon_u \\ 1.0 - \alpha; & \varepsilon_u < \varepsilon_s \end{cases} \tag{6}$$

where $\Omega_s(\varepsilon_s)$ = reduction function and α = parameter which controls residual stress.

Lowes et al. [8] proposed a bond element whose constitutive model includes a typical bond–slip relationship, but also the effects of concrete confining pressure, concrete damage, steel strain (Eq. (7)) and others specific for cyclic loading. However, this formulation estimates some essential parameters by non-local techniques.

$$\Gamma_2(\varepsilon_s) = \begin{cases} 1.0; & \varepsilon_s < \varepsilon_y \\ 0.1 + 0.9e^{0.4}\left(1 - \frac{\varepsilon_s}{\varepsilon_y}\right); & \varepsilon_s > \varepsilon_y \end{cases} \tag{7}$$

where $\Gamma_2(\varepsilon_s)$ = reduction function.

Ruiz et al. [9] presented two models that describe the pre- and post-yield relationship of bond in reinforced concrete: the Square-Root Model (Eq. (8)) and the Rigid–Plastic Model (Eq. (9)). Besides the slip, the strain and stress of steel are used to calculate the bond stress:

$$k_b(\varepsilon_s) = \frac{\varepsilon_{bu} - \varepsilon_s}{\varepsilon_{bu} - \varepsilon_y} \cdot \sqrt{\frac{\varepsilon_y}{\varepsilon_s}} \quad 0 \leqslant k_b(\varepsilon_s) \leqslant 1 \tag{8}$$

$$k_b(\varepsilon_s) = e^{10\cdot(\varepsilon_y - \varepsilon_s)} \quad 0 \leqslant k_b(\varepsilon_s) \leqslant 1 \tag{9}$$

where $k_b(\varepsilon_s)$ = reduction function, $\varepsilon_{bu} = 4 \cdot a/\varnothing$ [generally between 0.07 and 0.12] and a = height of the ribs.

Wu and Gilbert [10] proposed a bond–slip relationship based on CEB-FIP Model Code 1990 (MC90) [11], suitably modified to include the effects of concrete damage, steel stress (Eq. (10)) and confinement. These authors implemented their formulation into an existing finite element code by using non-local analysis.

$$\lambda_2(\sigma_s) = \begin{cases} 1.0; & \sigma_s < 250\text{ MPa} \\ 2.0 - 0.004 \cdot \sigma_s; & 250\text{ MPa} \leqslant \sigma_s \leqslant 500\text{ MPa} \\ 0.0; & \sigma_s > 500\text{ MPa} \end{cases} \tag{10}$$

where $\lambda_2(\sigma_s)$ = reduction function and σ_s = steel stress.

According to MC2010 [2], the bond–slip curve is considerably influenced by reinforcement yielding and transverse pressure. Therefore, MC2010 defines two factors necessary to reduce the value of the bond defined in MC90: the first depends on the steel strain and the ductility of steel (Eq. (11)), and the second depends on the compressive stress (orthogonal to the rebar axis):

$$\Omega_y(\varepsilon_s) = \begin{cases} 1.0; & \varepsilon_s \leqslant \varepsilon_y \\ 1.0 - \left[0.85 \cdot \left(1.0 - e^{-5\cdot a^b}\right)\right]; & \varepsilon_y \leqslant \varepsilon_s \leqslant \varepsilon_u \end{cases} \tag{11}$$

$$a = \frac{\varepsilon_s - \varepsilon_y}{\varepsilon_u - \varepsilon_y}; \quad b = \left[2.0 - \frac{f_t}{f_y}\right]^2 \tag{12}$$

where $\Omega_y(\varepsilon_s)$ = reduction function, a and b are calculated by Eq. (12).

Lee et al. [12] presented a tension stiffening model which enables the calculation of average tensile stresses in concrete after yielding of steel. This model uses the factor proposed by Ruiz et al. [9] for the influence of steel strain on bond stress. The numerical results indicated good agreement with experimental values including after the yielding of steel.

All cited authors recognise the influence of steel strain on the bond–slip relationship after the yielding of steel. For this reason, its implementation in finite element (FE) models has considerable relevance. The classical models with non-linear springs cannot be applied because only the slip is used. Wu and Gilbert [10] successfully developed and implemented a bond element (including slip and steel strain), but used non-local analysis. To the best of our knowledge, in the literature there are no bond elements which include slip and steel strain in their formulation, without any non-local analysis.

The aim of this paper is to develop a bond element for connecting concrete to steel, which takes into account the steel strain in the bond–slip relationship, without changing the usual organisation of software code.

To achieve this aim: (i) a new bond element was formulated and (ii) several numerical examples were tested by comparing their results with experimental data for different situations regarding reinforced concrete: tension, compression and bending.

The results obtained from the performed analyses showed that the proposed new bond element is capable to simulate satisfactorily the experimental tests.

The results obtained in numerical simulations which use the developed bond element may be used to study many critical problems of reinforced concrete structures, like: crack spacing, minimum reinforcement, tension stiffening, rotation capacity, ductility and deflection. With the steady increase in processing power of computers is expected that modelling tend to more refined and detailed models where the proposed new bond element may be often applied.

2. Formulation of the bond element

The bond element was implemented in Diana software [13], which allows users to define and implement new formulations for materials. In the 'General User-supplied Material Model' only the subroutine USRMAT which computes the matrices respecting to the total stress (σ) and tangent stiffness (D) needs to be defined. The rest of the software code remains unchanged.

Besides the current data (materials and geometry), in each increment this subroutine has as input variables: total strain (ε), total stress (σ), stiffness (D), and incremental strains ($\Delta\varepsilon$), whereas the output variables are only: total stress (σ) and stiffness (D).

The bond element developed in this paper consists of an orthotropic four-node plane stress element, whose constitutive material laws were changed to perform the bond–slip relationship.

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