Engineering Structures 49 (2013) 696–706

Contents lists available at SciVerse ScienceDirect

Engineering Structures

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

2D mesoscopic modelling of bar–concrete bond

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ARTICLE INFO

Article history:
Received 6 March 2012
Revised 27 September 2012
Accepted 19 November 2012
Available online 24 January 2013

Keywords:
Bond
Mesoscopic approach
Concrete damage
Bar roughness
Confinement stress

ABSTRACT

The degradation of the steel–concrete connection is a complex phenomenon depending on both the interface behaviour and the surrounding concrete damage. The purpose of this paper is to study bar/concrete interface behaviour by performing a numerical analysis at the mesoscopic scale. The interest of this approach is to provide local information unavailable from experimental investigations. The presented results concern the 2D modelling of LMT pull-out test (to identify bond and friction) with the assumption of perfect bond between the mesoscopic mortar and the steel bar. The influences of bar roughness and the lateral stresses were analysed.

1. Introduction

The bond between reinforcing bars and concrete has been acknowledged as a key factor to the proper performance of reinforced concrete structures for well over 100 years. Bond response may be modelled at three different scales: the dimensions of the structural element, the reinforcing bar and the lugs on the bar. Modelling bond behaviour at the structural scale implies the development of a model that characterises the effect of bond-zone response on beam, column or connection response.

At the bar scale, the bond zone is represented as a homogenous continuum. The state of the bond zone may be characterised by concrete and steel material properties [1,2] that are defined by standardised tests (pull-out test, beam test, etc.).

Bond response can also be considered at the scale of the lugs on the reinforcing bar. At this scale, the response is determined by the material properties of the concrete mortar and aggregate [3,4], the deformation pattern of the steel reinforcing bar [1,5,6], load transfer between concrete mortar and aggregate [7] and the rate of energy dissipation through fracture and crushing of the concrete mortar and aggregate. The numerical concrete (initially proposed by Wittman [8]) can be a good solution to represent concrete meso-structure numerically. Mesoscopic models have proven to be the most practicable and useful approach for studying the influence of the concrete composition on the macroscopic properties and also to gain insight into the origin and nature of the nonlinear behaviour of concrete [9].

To perform the mesoscopic representation of concrete material, both discrete element methods, such as truss model [10] and lattice model [11,12], and continuum finite element methods [13,14] have been adopted. In most of the mesoscopic models, the concrete is subdivided into three phases: the coarse aggregates, the mortar matrix with fine aggregate and the interfacial transition zone (ITZ) which affects the initiation and propagation of cracks. The mechanical behaviour of the concrete belonging to the ITZ is significantly different from that of the bulk concrete. However, it is very difficult to obtain the mechanical parameters of ITZ. Therefore including ITZ in the model introduces some uncertainties. Moreover, considering ITZ in the model increases the computational time and computer memory requirement. For these reasons, in some models the ITZs are not considered in the numerical simulations [9,13,16,15,14,30] and recently [34]. Different meshing techniques have been applied for the discretisation of the complex microstructure. Aligned meshing approaches have the advantage of explicitly representing the boundaries between particles and matrix. However, this method is rather tedious in 3D [13] developed a mesh generation method based on the advancing front approach in which the ITZ is modelled. Van Mier and Van Vliet [11] used a projection method of regular mesh onto the random aggregate structure. Zohdi and Wriggers [32] introduced an unaligned approach in which the number of integration points is increased in order to better capture the interfacial zone. A refined mesh close to the geometrical boundaries has been proposed by Lohnert [33]. Nguyen et al. [15] used a diffuse meshing technique which consists on the projection of the heterogeneous material properties on the shape functions of a finite element mesh. Each Gauss point takes the corresponding material properties. Although this method does

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http://dx.doi.org/10.1016/j.engstruct.2012.11.018

not represent explicitly the ITZ, it allows a good reproduction of damage localisation around the aggregates.

In a mesoscale model, the most important parameters, such as the shape, size and distribution of coarse aggregates within the mortar matrix, significantly influence the mechanical behaviour of concrete. The simplest aggregate shape is circular [11,15] (2D) and spherical [9] (3D) [13] developed a procedure to generate random aggregate polygons for rounded and angular aggregates based on the Monte Carlo random sampling principle. Garboczi et al. [17] developed an algorithm to generate realistic shapes of different aggregate particles.

On the other hand, various material models for the aggregate and the mortar have been employed to study the concrete behaviour, for example, 2D linear elastic analysis [18], nonlinear orthotropic fracture model [14] and isotropic damage model [9,19].

The mesoscale modelling of the connection between steel and concrete have been very little studied. A lattice approach has been used, by [20], to describe the mechanical interaction of a corroding reinforcement bar, the surrounding concrete and the interface between steel reinforcement and concrete. The effects of rib on surrounding concrete are taken into account with a cap-plasticity interface model. The rust expansion is modelled as an Eigenstrain. This approach is very interesting and capable of representing many of the important characteristics of corrosion-induced cracking and its influence on bond. Nevertheless, the post-peak response of the bond stress–slip curve is not in agreement with experimental results: the parameter controlling the volume of rust expansion is dependant of local phenomenon: crushing of the rust and penetration of rust in concrete.

1.1. Research significance

The present paper aims to analyse the bond force transfer, the damage evolution, crack pattern and displacement fields on the surrounding concrete by using a mesoscale modelling.

The bond test used in this study is the LMT pull-out test [21,22]. This geometry does not induce lateral stresses due to confining actions at the support of the testing machine. It enables local information (deformation and displacement fields) to be obtained on the steel/concrete interface not available with the standardised tests. Based on the geometry particularity of the LMT test, a plane stress 2D model has been adopted to limit time computation and to simplify the modelling. A heterogeneous mesoscale model is constructed for mortar material. The effect of bar roughness and lateral pressure are analysed to study the influence of aggregate distribution on the crack pattern around the reinforcing bar and the force transfer between steel and concrete.

2. Bond test

Various tests have been proposed to assess bond characteristics in reinforced concrete structures. Most of the classical bond test (pull-out test) does not allow a local measure but only global and make impossible to distinguish bond phenomena at the interface steel/concrete due to the confining actions at the support of the testing machine introducing a lateral stresses, which artificially increase the bond strength.

In order to improve the classical bond tests, a modified pullout test (called the LMT test: Laboratory of Mechanics and Technology, Cachan, France) has been proposed and designed by Ouglova et al. [21,22,35]. The aim of this test is to identify bond and friction at the interface. It consists of a mortar plate with three squared embedded bars (cross section 2 cm $*$ 2 cm) (steel A56 usually used in the civil engineering structure). The plate has a thickness of 4 cm. The mortar has the following characteristics: maximum aggregate size 4 mm, water to cement ratio equal to 0.46. The specimen have been cured during more than 1 week in a plastic vials then moved to the storage piece.

The geometry of the specimen and the experimental setup have been designed in order to eliminate the lateral stresses manifesting in the concentric pullout test (Fig. 1b). This test assesses the evaluation of displacement and deformation fields during the test by using a digital image correlation technique (Fig. 1c).

As a Teflon has been put around the central bar outside the zone corresponding to the window, the bond length is only 12 cm. The pullout load was applied at the free end of the central bar of the specimen (Fig. 1a). The two other bars were loaded in the opposite direction with respect to two bearings able to roll on a fixed beam, perpendicular to the loading direction, in order to avoid any lateral stress and parasite flexural actions. The central bar is in contact with mortar on only two sides (Fig. 1a coupe A–A).

This test has been created to characterise the behaviour of steel–concrete interface particularly when the steel is corroded. To model the behaviour of corroded reinforced concrete structures, it is necessary to identify the behaviour of corroded steel, the behaviour of concrete, the properties of rust and finally the behaviour of steel–concrete interface. In a classical pull out test, there is a longitudinal displacement between steel and concrete (slip) due to applied force. A triaxial state of stress is observed around the bar. The pull-out capacity is mainly characterised by a mean value of resistance. In the development of the new LMT test, the main idea is to eliminate the complex triaxial state of stress and to have a more simple state of stress due to lateral stresses imposed on two faces of concrete specimen. The stress state is almost homogenous. It prevents from an increase of confining forces during both classical pull out and tied tests. This new test that eliminates the lateral confinement also allows to impose very simply a known lateral pressure on the interface. This simplicity allows to determine very easily the friction angle and cohesion of interface from the shearing stress-confining stress curves. The interface behaviour can be then easily modelled.

3. Mechanical behaviour model for concrete components

Macroscopic models generally have many parameters to describe the complex mechanical behaviour of concrete. The main part of this complexity is due to geometry, so we choose for paste or aggregate a mechanical behaviour model as simple as possible, based on Mazars's model [23]. The contact between paste and aggregate is considered as perfect. The model used is Fichant's model [24] which controls fracture energy G_f. The plasticity could be activated if necessary. Damage effects in compression at the mesoscopic level are decreased with respect to macroscopic behaviour. Since, it has been demonstrated that the behaviour in compression of concrete is partially due to the aggregate spatial distribution. This simple model represents unilateral effects and provides objective results whatever the mesh size as shown by [19]. In its original version, the model couples damage and plasticity; here, we present only the isotropic damage part of the model.

The effective stress $\tilde{\sigma}$ is obtained from strain ε and initial characteristics of materials E and υ:

$$\tilde{\sigma}_{ij} = \frac{E}{(1+\upsilon)}\varepsilon_{ij} + \frac{E\upsilon}{(1+\upsilon)(1-2\upsilon)}\varepsilon_{kk}\delta_{ij} \quad (1)$$

Then the stresses σ_{ij} are calculated from the damage variable D:

$$\sigma_{ij} = (1-D)\langle\tilde{\sigma}\rangle^{+}_{ij} + (1-D)^{\alpha_1}\langle\tilde{\sigma}\rangle^{-}_{ij} \quad (2)$$

where $\langle X\rangle^{+}$ and $\langle X\rangle^{-}$ design the positive and negative parts of tensor X defined by [25]. Damage is calculated from equivalent strain $\tilde{\varepsilon}$ defined by [23].