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Reinforcement–concrete bond behavior: Experimentation in drying conditions and meso-scale modeling

A. Michou [a,b], A. Hilaire [a], F. Benboudjema [a,*], G. Nahas [a,c], P. Wyniecki [d], Y. Berthaud [e]

[a] LMT-Cachan, ENS Cachan, CNRS, Université Paris Saclay, Cachan, France
[b] Sorbonne Universités, UPMC Univ Paris 06, Paris, France
[c] Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France
[d] Nuvia Structure, Aix-en-Provence, France
[e] Sorbonne Universités, UPMC Univ Paris 06, CNRS, Institut Jean le Rond d'Alembert, Paris, France

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ABSTRACT

Reinforced concrete structures must fulfill serviceability functions in terms of durability and bearing capacities. Steel–concrete interface plays a crucial role in the cracking behavior (crack openings, spacing). Hence, its accurate description should be considered in a relevant way. In this paper, a meso-scale reinforcement–concrete bond model is proposed, based on an explicit mesh of the interface area. This area implicitly considers the presence of steel ribs and the progressive steel–concrete slip through two coupled plastic criteria. The model is calibrated on pull-out tests, validated on long reinforced concrete ties in tension and compared with experimental tests carried out for this study. In this experiment, local strain in reinforcement and surface cracking mapping have been measured. Special attention is also devoted to the effect of drying shrinkage and creep on the structural and cracking behavior. Their effects are significant, but greatly depend on the reinforcement ratio.

1. Introduction

Reinforced concrete structures are used for various applications in civil engineering. In some particular cases, in addition to the knowledge of their structural strength, the issue of the durability and the tightness is involved. Tightness and durability are closely related to the cracking behavior of the structure. A flow of liquid or gas across the structure significantly increases in the presence of cracks [1–3], leading to internal concrete degradation and corrosion of reinforcement for example. The cracking evolution in reinforced concrete structures mainly depends on the transfer of internal forces between concrete and reinforcement, and consequently on the evolutive steel–concrete bond. Considering the aforementioned feature in numerical simulations enables an accurate prediction of the cracking behavior [4].

The mechanisms of the steel–concrete bond and its progressive degradation have been intensively studied. The bond resistance can be decomposed in different stages [5]. For ribbed rebars, a relatively low physical and chemical cohesion links up steel with concrete. Inclined cracks then appear at steel ribs, leading to a first decrease of the bond stiffness. Concrete crushing and shear cracks progressively propagate from the ribs until their coalescence (maximum and loss of bond stress). For large relative displacements between steel and concrete, the residual bond resistance is provided by friction. These local degradation mechanisms have been experimentally studied on reinforced concrete ties [6], on pull-out tests [7], and also numerically studied [8]. In an overall approach, a lot of works on pull-out tests have been conducted in order to study the parameters influencing the bond resistance: concrete strength, diameter and geometry of the rebar, active and passive confinement [9,10].

Numerically, different approaches have been developed to model the behavior of the steel–concrete bond. The principle is to consider the non linear evolution between the bond stress τ and the steel–concrete relative displacement. Based on damage theory [11], or on plasticity theory [12], joint elements between steel and concrete were developed. They ensure the load transfer and an explicit relative displacement between concrete and reinforcement. These methods generally imply an important calculation cost for concrete structures. Moreover, convergence problems can be identified, because non-penetration conditions must be imposed between both materials. An other approach models the interface through a 2D and 3D explicit area [13–15], using the plasticity theory to model the relative slip between steel and concrete (Mohr–Coulomb or Drucker–Prager criterion). This

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* Corresponding author.
E-mail address: farid.benboudjema@ens-cachan.fr (F. Benboudjema).

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technique is numerically convenient, but has difficulties in capturing the progressive loss of bond stiffness during loading. We can also cite other interesting studies: (i) one is based on internal forces and kinematic relations between a truss-element rebar and plain concrete [16], (ii) an other one extends an explicit cracking model for concrete to the bond behavior, taking into account the progressive degradation in shear [17], (iii) embedded or extended finite element methods are also used on joints elements [18].

In this communication, a meso-scale bond model is proposed. Unlike other approaches, it implicitly considers the influence of the geometry of the steel rebar on the local bond degradation and bond slip. For sake of simplicity in the modeling and calibration process, the interface is considered as an explicit massive area around a truss-element rebar [14,15,19]. Compared to joint elements, this approach remains in a continuous problem, without contact resolution. It favors the numerical robustness and the convergence of the calculations. A procedure for the calibration and the validation of the bond model is proposed, and is based on experimental tests: standard pull-out tests and tension tests on reinforced concrete ties. The behavior of the specimens is locally analyzed by Digital Image Correlation for concrete cracking, and optic sensors for strain measurements of the embedded rebars. After calibration and validation, the meso-scale bond model can be used for structural analysis.

2. General approach

The presentation is decomposed into three main parts:

- The bond behavior is first studied by experimental tests. Standard pull-out tests are first carried out to quantify the local bond behavior. Tension tests on long reinforced concrete ties are then performed. They exhibit the coupled behavior between the steel–concrete interface and the concrete cracking. The bond resistance actually influences the number of cracks, the crack spacing and consequently the crack openings.
- A meso-scale bond model is proposed. The identification of the bond properties is performed on the experimental results of the pull-out tests. Characterization tests on steel and concrete serve to calibrate the numerical steel and concrete behaviors.
- Finally, the identified steel, concrete and bond properties are simultaneously used for numerical simulations of the tension test. The results of this structural analysis provide a validation of the proposed approach. They also guarantee its numerical relevance and efficiency to design reinforced concrete structures.

For that purpose, each specimen is fabricated with the same concrete mixture and the same steel rebar, in order to limit the variability of both the material and the bond properties. The samples are protected against desiccation up to 17 days and are tested after 110 days. They are therefore exposed to drying conditions during 90 days (average relative humidity of 40%). Concrete mixture presents a water–cement ratio equal to 0.48. Concrete properties are measured on cylindrical samples: Young's modulus, tensile strength (splitting test) and compressive strength E_c, f_t and f_c, respectively) and on notched concrete beams (fracture energy G_f) [20]. The results are presented in Table 1, as well as the mechanical properties of the steel rebar: Young's modulus E_s, yield strength f_y. The steel rebar and its idealized geometry are presented in Fig. 1. The distance between two consecutive ribs is equal to 8 mm. The length and height of the ribs are 4 mm and 0.5 mm, respectively.

Table 1
Main material properties.

Concrete	Mean value (min.–max.)	Steel rebar	
E_c	35 GPa (34.45–35.96)	E_s	200 GPa
f_t	2.9 MPa (2.78–3.04)	f_y	500 MPa
f_c	49.4 MPa (48.15–50.60)		
G_f	94.6 J/m^2 (81.5–104.5)		

Specific attention is also devoted to the "life" of the specimen before mechanical loading. Phenomena such as autogenous shrinkage, drying shrinkage, creep, induce a self-equilibrated stress field in the structure. Since the delayed strains are restrained by the steel rebars, tensile stresses are induced in concrete, which may lead to a debonding at the steel–concrete interface, the same way as the cracking and debonding at the aggregates–cement paste interface [21]. The influence of the delayed strains is numerically quantified on the studied specimens.

The numerical simulations are carried out with the help of the finite element code Cast3m [22].

3. Experimental bond tests

With the aim of calibrating the developed bond model, standard pull-out tests have been carried out. A single rebar of diameter $d = 12$ mm is embedded into a $15d$ concrete cube. The anchorage length is equal to $5d$ (Fig. 2b). This configuration provides a mechanism of pulling, instead of splitting. Teflon sheets are added on the loaded surface, as detailed in Fig. 2a, in order to avoid friction and spurious stresses in the specimen. The connection between the specimen and the fixed support is managed by a steel bearing (Fig. 2c). It corrects a possible lack of co-axiality between the fixed loading axis (hydraulic jack of 15 kN capacity) and the axis of the rebar. A displacement sensor is located at the unloading end of the rebar, measuring its relative slip with concrete. If the bond stress τ is supposed to be constant along the anchorage length l, it can be deduced from the applied load F:

$$\tau = \frac{F}{\pi d l} \tag{1}$$

Three samples are tested until large displacements, meaning until the residual friction between steel and concrete (Fig. 3). The results highlight a four-step bond behavior. A first increase of bond stress without slip is observed up to $\tau = 3$ MPa (point A). The bond stiffness progressively decreases until a maximum bond stress τ_{max} (about 13–14 MPa) (point B). This stage is followed by a loss of resistance with a larger slip (point C). It seems interesting to note the next increase of resistance for each test (point D). It can be explained by the "ribs by ribs" displacement of the rebar into concrete, involving friction and residual ribs resistance. Indeed, the distance between the point C and the point E is equal to the distance between two consecutive ribs on the rebar.

4. Experimental tension tests on reinforced concrete ties

Tests on long reinforced concrete ties are then carried out (Fig. 4). Three 1.15 m-long structures are tested in tension (Fig. 5). The concrete cross section is equal to 10×10 cm^2. The length of the specimens favors the localization of multiple transverse cracks during loading. A steel rebar (identical to the rebar in pull-out bond tests, diameter $d = 12$ mm) is embedded on 1 m. The test is performed up to yielding of reinforcement.

4.1. Concrete cracking

Digital Image Correlation [23], noted DIC, is performed during loading on each specimen. Two cameras are located in front of