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Concrete splitting and bond in prestressed concrete beams with indented wires

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ABSTRACT: The bond between wires and concrete is fundamental to the transmission of stresses between the two materials in prestressed concrete. Indented wires are used to improve the bond. The radial component of the bearing force, increased by Poisson's effect, may split the surrounding concrete. This work presents a novel testing procedure to evaluate the bond-slip between steel and concrete, and its relation to the splitting action of the pretensioned indented wire. The geometry, failure mechanism and mechanical properties are studied. Specimens with three wire indentations and three concrete covers were tested. Also, a numerical procedure is developed to model the bond-slip, taking into account the concrete splitting. The model uses parameters with fully physical meaning, which can be measured experimentally. The numerical procedure accurately reproduces the experimental records

1 INTRODUCTION

In precast prestressed concrete elements the bond between the indented wire and the concrete is necessary to transmit the force from the prestressed steel to the concrete. The precast prestressed elements are usually cast in a pretensioned bed, where the wires are previously prestressed, and after an accelerated curing process, when the concrete reaches sufficient strength, the wires are released from the supports. In elements with a high prestressed reinforcement ratio a splitting of the concrete may occur, and can be dangerous if the splitting is not easy visible. The concrete splitting leads to a reduction or even to a complete loss of bond (Den Ujil 1992) and increases the steel-concrete slip.

As shown by Tepfers (1973), the compression force exerted by the indentation on the concrete is inclined at an angle α to the wire axis (Figure 1). The radial component of this force creates a ring tension in the concrete cover around the wire. This wedging action, generated by the wire indentations, is magnified by Poisson's ratio and brings in a radial increase of the sections, close to the wire extremities, on release of the wire prestressing force. This combined effect improves the bond but may be detrimental, since the tension ring may split the surrounding concrete (Gambarova & Rosati 1996). Consequently, the bond-slip behaviour of the prestressed concrete elements should be studied in connection with a possible splitting of the concrete.

Considerable effort has been devoted in recent years to the gathering of experimental data on the bond-slip in reinforced concrete (Gambarova & Rosati 1996, Tepfers & Olson 1992, Abrishami & Mitchell 1992a, Cairns & Jones 1995, Kankam 1997, Yeih et al. 1997, Plizzari et al. 1996, Malvar 1993). Less experimental attention has been devoted to bond-slip in prestressed concrete elements (Den Ujil 1992, Abrishami & Mitchell 1992b, Tassios & Bonataki, 1992) and there is not yet enough reliable experimental data to study the bond-slip related to splitting of the surrounding concrete during the release of the prestress force of the wire. Complementary tests will be welcome for a better understanding of the combined mechanisms of bond and splitting. This paper describes a test to evaluate the bond-slip behavior of prestressed concrete, related to a splitting of the concrete, during release of the pretensioning force of the wire. 27 prismatic pretensioned specimens were tested, combining 3 concrete covers and 3 indentation depths.

In the analytical and numerical field, the Tepfer's model (Tepfers 1973), and its improvements (Rosati & Schumm 1992, Reindhardt & van der Veen 1992) are based on the equilibrium of forces in the transversal section, and serve to study the splitting under constant stress along the wire. The model of Cox & Hermann (1994, 1998) is better for the study of splitting along the element under non constant stresses along the wire. This model shows conceptual advantages and is attractive from the numerical point of view, but it also presents practical a)

b)

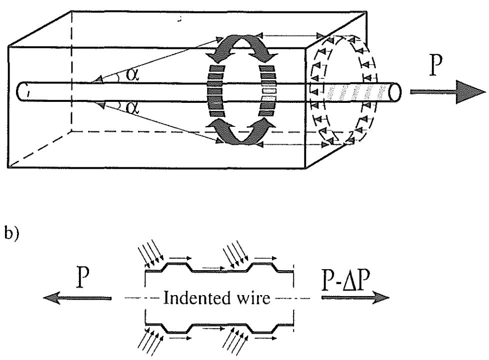

Figure 1. a) Schematic representation of the bond splitting forces generated by the indentation wire (Tepfers, 1973). b) Stresses around the prestressed indented wire.

difficulties: it uses parameters very difficult to measure or estimate experimentally. Based on the ideas of Cox (1994), a numerical procedure for bond slip in relation to splitting is presented. It includes the fracture mechanics theory and uses parameters with fully physical meaning, experimentally measurable. The procedure accurately predicts the experimental records.

2 EXPERIMENTAL PROGRAM

2.1 *Materials and specimens*

The specimens were manufactured from normal strength concrete, composed of Portland cement, siliceous sand as fine aggregates, and siliceous crushed coarse aggregates of 6 mm maximum size. Single indented wires were used, with a nominal diameter of 4 mm and with three different indentation depths: shallow (0.01-0.02 mm), medium (0.04-0.06 mm) and deep (0.10-0.11 mm). Table 1 shows the mechanical properties of the concrete and steel.

Twenty-seven prismatic specimens were cast with a wire embedded longitudinally in the specimen. The dimensions of the prismatic specimens were 400 mm in length, 60 mm in width and with three different concrete covers (5, 9 and 13 mm). Figure 2 shows the geometry and dimensions of the wire and the specimens, respectively. The transversal section was oblong to obtain only two splitting cracks.

Before casting the concrete, the wires were tensioned to 17 kN in vertical stiff steel frames. Once the wires were pretensioned, the specimens were cast horizontally in one layer in ground steel moulds, jointed to the pretensioning frames by screws. This screw device guaranteed the alignment of the wire with the longitudinal axis of the specimen and the horizontality during casting and vibrating

The specimens were left in the moulds for 24 hours, covered with saturated sacking at room temperature, and then covered with three coats of waterproof paint to maintain humidity during the curing process. The specimens were tested 28 days after casting. For detailed information on specimen preparation see Tork (1999) and Tork et al. (2000).

Table 1: Mechanical properties of the materials

Concrete	Steel wire
E = 21 GPa	E = 226 GPa
f_{ck} = 24 MPa	$\sigma_{0.2}$=1755 MPa
f_{ct} = 2.4 MPa	σ_u =1935 MPa
G_F = 100 N/m	ε_u = 5.25 %

2.2 *Experimental procedure*

The tests were performed in two stages: first, the force was transmitted from the pretensioning frame to the testing machine, and then the pretensioning force from the testing machine to the concrete prism by the controlled release of the pretensioning wire.

At the beginning of the first stage, the wire was tensioned, the pretensioning frame was compressed and the concrete prism had no stresses. The pretensioning frame was coupled to the testing frame machine. Figure 3 shows a sketch of the pretensioning frame and the specimen coupled to the testing machine. A tensile load was applied by moving the testing machine actuator downward at the rate of 0.1 mm/min till the pretensioning force (17 kN) was reached. Once the force was completely transmitted to the testing machine, the pretensioning frame and the concrete prism were unloaded.

As the second stage, the pretensioning force of the wire was transferred, under control, to the concrete prism, by moving the actuator upward at the rate of 0.3 mm/min, the gradual release of the wire transmitting the force to the concrete prism. The test was finished when the free ends of the wire were completely unloaded. During the tests the following parameters were recorded:

- Released load supplied by the testing machine.
- Displacement of the piston of the testing machine.
- Longitudinal shortening of the concrete prism, measured with a base of 387. 5 mm. Measurements were taken on opposite faces and the mean value was recorded.
- Wire-concrete slip was measured on the upper and lower faces of the prismatic specimens.
- Crack opening displacement of the longitudinal cracks. Measurements were taken on opposite faces to those with the thinnest cover.

Detailed information about testing equipment and measure devices are given in Tork (1999) and Tork et al (2000).

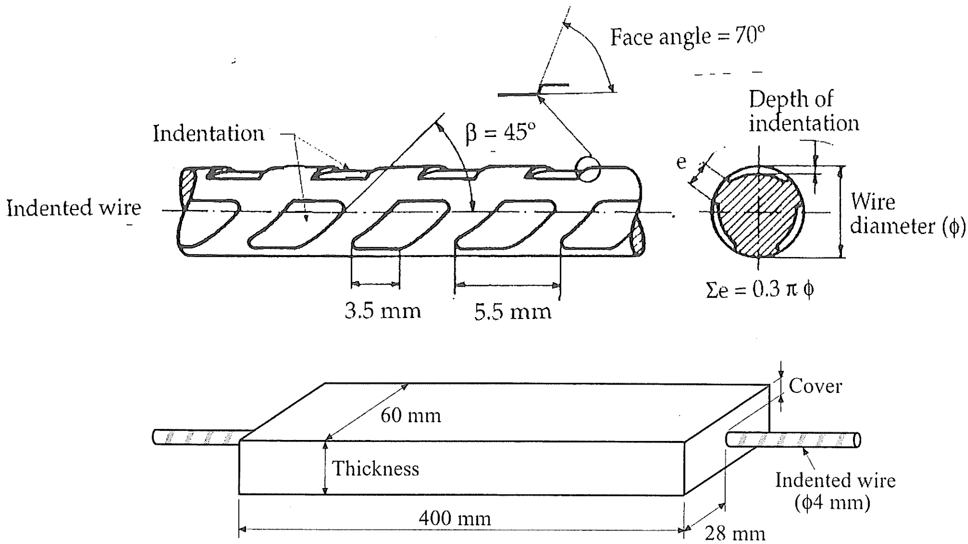

Figure 2. Geometry and dimensions of the: a) indented wire, and b) specimens

2.3 *Experimental results*

Figures 4a, 4b and 4c show the experimental records of released load versus longitudinal shortening of the concrete prism, for specimens with shallow, medium and deep wire indentations, and concrete covers of 5, 9 and 13 mm. Specimens with the thinnest concrete cover present a break point behind which the longitudinal shortening of the concrete prism diminishes while the testing machine releases the tension of the wire. This break point marks the beginning of the longitudinal splitting of the concrete prism. The splitting cracks reduce the friction between the steel and concrete due to the loss of the wire confinement, and consequently induce a release of part of the compressive force in the concrete, which diminishes the longitudinal shortening of the concrete prism, as seen in the experimental records Specimens with 9 and 13 mm concrete cover do not show this behavior.

Figure 4d compares the experimental records of released load versus longitudinal shortening of the specimens with the thinnest concrete cover and shallow, medium and deep wire indentations. The deepest indentation gave the smallest load of concrete splitting, which suggests that deeper indentation leads to a more intensive tension ring in the concrete, owing to the mechanical interlock between steel indentations and concrete. The average splitting loads were 15, 13, 12.5 kN, approximately, for specimens with wires of shallow, medium and deep indentations respectively. Before the concrete split, the deeper the indentation the greater the shortening of the concrete prism.

Figure 4e shows the experimental records of the released load versus crack opening displacement (COD) of the splitting crack of the prism of concrete, measured on the upper face of the specimen.

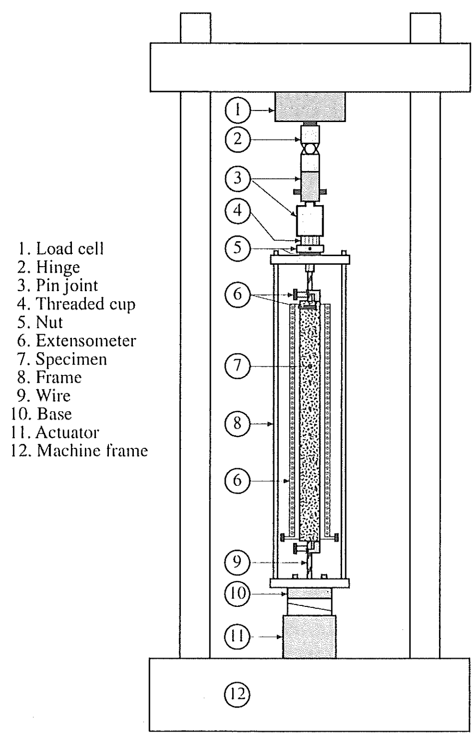

Figure 3. Sketch of the test setup.

Each curve shows a break point corresponding to the opening of the crack, shown by a fast rise of the extensometer measurement. The break point load coincides with that in Figures 4a, b, c and d, and confirms the interpretation of these Figures.

Figure 4 f shows the experimental records of the released load versus penetration of the wire in the concrete, measured on the upper face of the specimens, for specimens with medium indentation wire, and concrete covers of 5, 9 and 13 mm. Specimens with a concrete cover of 5 mm show a sudden change in the slope of the curve. This point corresponds to the start of splitting and complements the above comments for these specimens. The splitting leads to a loss of confinement of the wire, increasing the slip between the concrete and steel, with a greater penetration of the wire in the concrete.

3 NUMERICAL PROCEDURE

3.1 *Problem posing*

Two processes have to be modeled: 1) the possible splitting of the concrete, and 2) the bond between concrete and steel. The two processes are coupled. In this work the model of splitting of the concrete is based on the cohesive crack approach (Hillerborg et al. 1976) and that of the bond on a plasticity formulation (Tork, 1999).

3.2 *The cohesive crack model*

The cohesive crack model, called *fictitious crack model* by Hillerborg and co-workers, has been successful in the analysis of the fracture of concrete, rock and cement based materials since its proposal (Hillerborg et al. 1976). Part of this success is due to its simplicity and physical meaning. A detailed review of this model is given in Bazant & Planas (1997). The softening function, $\sigma = f(w)$, is the main ingredient of the cohesive crack model. This function, a material property, relates the stress σ acting across the crack faces to the corresponding crack opening w (see Figure 1). For mode I opening (the mode acting during the whole process of these tests), the stress transferred, σ, is normal to the crack faces.

Two properties of the softening curve are most important: the tensile strength, f'_t, and the cohesive fracture energy, G_F. The tensile strength is the stress at which the crack is created and starts to open ($f(0)= f'_t$). The cohesive fracture energy, G_F, also called *specific fracture energy*, is the external energy supply required to create a full break unit surface

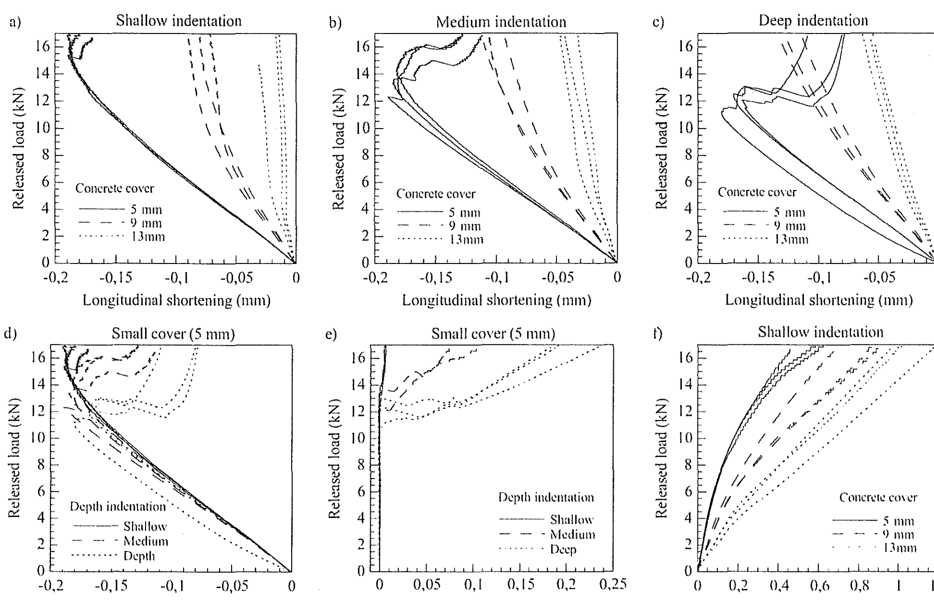

Figure 4. Experimental results: released load versus longitudinal shortening for specimens with 5, 9 and 13 mm concrete covers, and (a) shallow, (b) medium, (c) deep wire indentations; (d) released load versus longitudinal shortening for specimens with 5 mm concrete cover and shallow, medium and deep wire indentations; (e) released load versus crack opening displacement for specimens with small concrete cover and shallow, medium and deep wire indentations; (f) released load versus steel penetration in the concrete for specimens with 5, 9 and 13 mm concrete covers, and medium wire indentations. In the specimens with shallow indentation wire, the change in the curves is smoother than in the specimens of medium and deep indentation wire since the crack opening is smaller, as shown in Figure 4e.

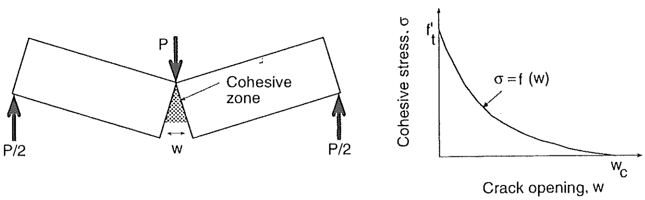

Figure 5. Cohesive crack and softening curve for mode I fracture of concrete.

area of a cohesive crack, and coincides with the area under the softening function. The tensile strength and the specific fracture energy are material properties and may be experimentally measured in accordance with ASTM C 496 and RILEM 50-FMC, respectively. Many softening curves have been developed to model the experimental fracture behavior of concrete in tension (Bazant & Planas 1997) The bilinear curves are accepted as reasonable approximations of the softening curve for concrete.

3.3 *Bond model*

The interface between concrete and steel transmits normal and tangential stresses and shows *dilatancy*. It is assumed that the bond strength of the interface is exhausted when the combination of the normal stress, σ, and the tangential stress, τ, reaches a cracking surface $F(\sigma,\tau) = 0$, like a yield surface in classical plasticity. In this work the following hyperbolic expression (Carol et al. 1997) is assumed:

$$F = \tau^2 - 2c\tan\phi_f\left(f_t - \sigma\right) - \tan^2\phi_f\left(\sigma^2 - f_t^2\right) \qquad (1)$$

where: c is the cohesion, ϕ_f the friction angle between concrete and steel, and f_t the tensile strength of the interface in the normal direction to the bar. The model assumes that the bond zone is approximately axisymmetric.

The cracking surface evolves with the concrete-wire slip. This effect is expressed by the *softening curves* of the cohesion and tensile strength of the interface in the normal direction to the wire, defined on the basis of the softening parameter u^{ieff}, which is the integral norm of the vector the inelastic relative displacements between the crack faces, $\dot{\mathbf{u}}^i$. The inelastic displacement vector is obtained by decomposition of the displacement vector, $\mathbf{u}$, into an elastic part, $\mathbf{u}^e$, and an inelastic part, $\mathbf{u}^i$. It is expressed: $\mathbf{u} = \mathbf{u}^e + \mathbf{u}^i$; $\dot{u}^{ieff} = \left\|\dot{\mathbf{u}}^i\right\| = \left(\dot{u}_x^{i\,2} + \dot{u}_y^{i\,2}\right)^{1/2}$, and the cracking surface $F = F(c, f_t)$, where $c = c(u^{ieff})$ y $\sigma_t = \sigma_t(u^{ieff})$. Figure 6 shows the cracking surface and its evolution.

The model has been included into a finite element code. The cohesive model for simulation of the radial cracks is included by means of non-linear springs. The bond model by an interface element. Details of the numerical implementation can be found in Bazant & Planas (1997). Figure 7 shows a sketch of the finite element model.

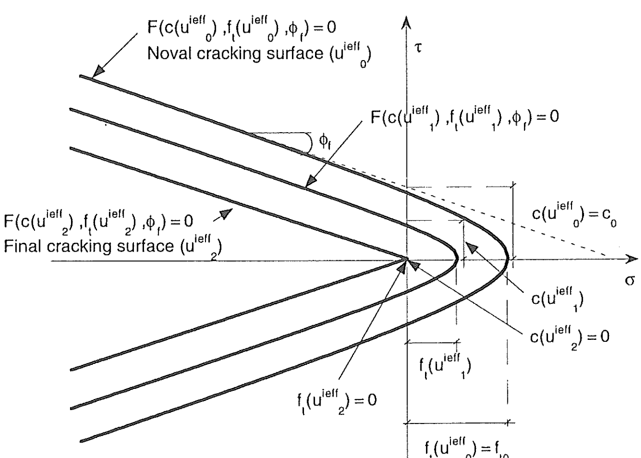

Figure 6. Failure surface for bond and its evolution

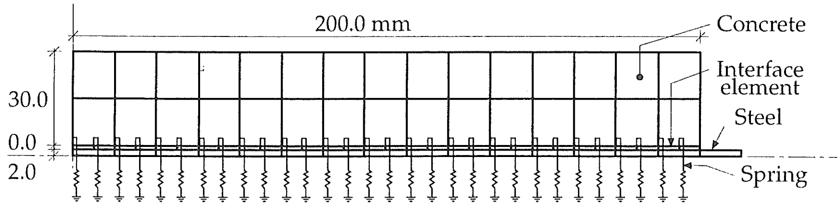

Figure 7. Finite element modelling

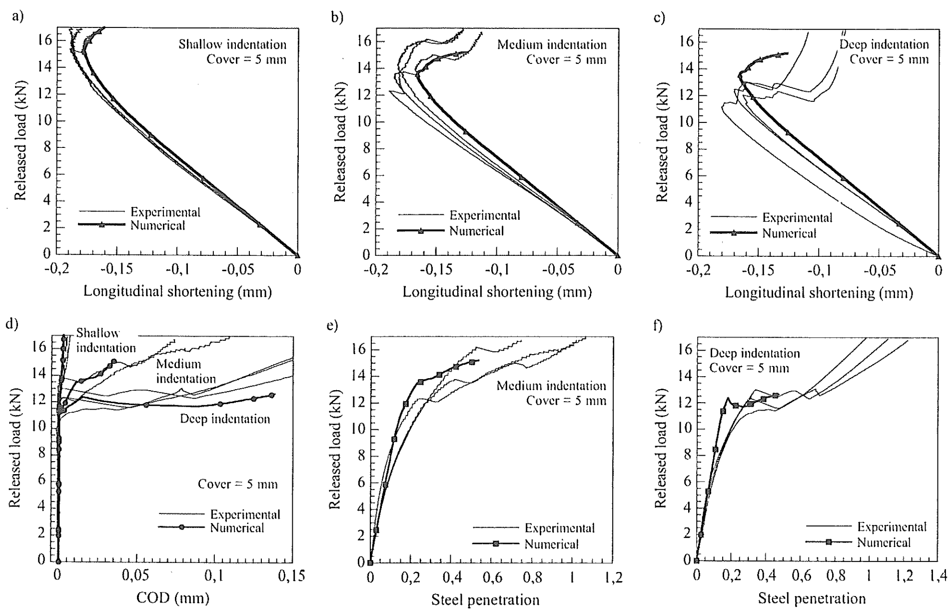

Figure 8. Numerical prediction and experimental results for specimens with 5 mm concrete cover: released load versus longitudinal shortening: a) shallow, (b) medium, (c) deep wire indentations; (d) released load versus crack opening displacement for specimens with shallow, medium and deep wire indentations; (e) released load versus steel penetration in the concrete for specimens with: (e) medium depth wire indentations, (f) deep depth wire indentations.

4 EXPERIMENTAL VERIFICATION

Figure 8 shows the numerical prediction and the experimental results. The numerical model is a good prediction of the experimental results. It is worth noting that the model predicts the experimental curves based on parameters measured independently, all with fully physical meaning.

5 ACKNOWLEDGEMENTS

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