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Effects of Residual Strength of Cracked Concrete on Bond

Effets sur l'adhérence des contraintes résiduelles du béton éclaté

Einfluss der Restzugfestigkeit gerissenen Betons auf den Verbund

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SUMMARY

The local bond-slip law of an anchored ribbed bar after the complete cracking of the surrounding concrete is studied. The theoretical approach is based on the confining effects due both to the transverse reinforcement and the residual tensile strength of cracked concrete. Experimental confirmations and theoretical results are presented. In particular the confining effects produced by the residual strength of cracked concrete are investigated and discussed.

RÉSUMÉ

On étudie ici la loi localisée d'«adhérence-glissement» apparaissant dans le cas d'une barre nervurée ancrée après éclatement complet du béton d'enrobage. L'approche théorique se base sur des effets confinants dûs conjointement à l'armature transversale ainsi qu'aux contraintes de traction résiduelles du béton éclaté. Des confirmations expérimentales et des résultats théoriques sont présentés; les effets confinants provoqués par la contrainte résiduelle du béton éclaté sont examinés et discutés en détail.

ZUSAMMENFASSUNG

Das örtliche Verbundgesetz für die Verankerung eines gerippten Bewehrungsstabs in vollständig gerissenem Beton wird untersucht. Grundlage für die theoretische Untersuchung sind die Umschnürungseffekte infolge der Querbewehrung und der Restzugfestigkeit des gerissenen Betons. Theoretische Ergebnisse und experimentelle Bestätigungen werden vorgestellt. Insbesondere werden die Einflüsse einer Umschnürung infolge der Restfestigkeit des Betons untersucht und diskutiert.

1. INTRODUCTION

The importance of the tensile strength of concrete on bond was underlined in [1]. In the same paper this phenomenon was theoretically modelled and the bond strength was evaluated taking into consideration the tensile strength of solid concrete that surrounds the split core. Experimental tests [2] showed that the bond stress-slip relationship is influenced both by the amount of stirrups and by the thickness of the concrete cover. A theoretical interpretation and modelling of the phenomena involved around an anchored bar were proposed in [3,4], where the relevance of the confining action produced by the residual tensile strength of the split concrete was underlined. At the beginning, the splitting crack opens near the anchored bar (Fig.1a,b) and propagates both transversally and along the bar. When it is completely propagated throughout the cross-section, bond strength is still locally possible owing to the confining actions produced by the transverse reinforcement and the residual stress transmitted by the crack faces [5,6]. For light or no transverse reinforcement, bond stress decreases as slip increases, so that an unstable local behaviour occurs. When the split zone is limited as in Fig.1, bond stress redistribution along the bar can occur and a ductile global behaviour of the anchorage is still possible. The bigger the concrete cover and bar spacing become, the more relevant the confining contribution of cracked concrete is. This is because a small residual stress acting on a large split surface can produce a considerable confining action. Since the splitting crack opening is variable both across the transverse section and along the anchored bar, the local response of the cracked concrete is also variable. The cracked concrete confining contribution should be evaluated by means of the tensile stress-crack opening law. The well known specific fracture energy $\mathcal{G}_F$, which is the integral of this law, is not sufficient to express the cracked concrete confining capacity, at least in the present theory on bond.

2. ANALYTICAL FUNDAMENTALS

In anchorages with completely propagated splitting cracks, bond is still possible when an adequate transversal confining action is assured. This confinement can be produced both by the transverse reinforcement (secondary bars or stirrups) and by the residual strength of cracked concrete.

The modelling of the local bond behaviour in anchorages when splitting occurs is developed on the basis of the following assumptions:
1. The splitting crack is completely propagated along the bar spacing and cover in influence zone Δz of one transverse bar (Fig.1c).
2. Δz is small and has the same value of stirrup spacing, so that average crack opening w and bond stress τ can be assumed as the local values.
3. All the principal bars have the same diameter ϕ_p and all the transverse bars have the same diameter ϕ_{st}.

According to these assumptions, the following equations were proposed in [3,4]. For bond:

$$\tau = \tau_{m,o}\,(1 - \gamma_1\, w/\phi_p)\,(1-e^{-(\beta_1+\beta_2 w/\phi_p)(s/\phi_p-\gamma_2 w/\phi_p)}) \tag{1}$$

$$\tau = \tau_0(1/(1+K_1 w/\phi_p)) + \tau_1\sigma_n(1/(\,1+K_2 w/\phi_p)) \tag{2}$$

where $\tau_{m,o}$ = maximum bond stress for w=0; γ_1, γ_2, β_1, β_2, K_1 and K_2= coefficients experimentally determined on the basis of the curves plotted in Fig.2a,b and obtained in [7]; s = principal bar slip and σ_n = radial stress produced by the principal bar. The limitation $\tau = \tau_{m,o}$ when $\tau > \tau_{m,o}$ was adopted. For stirrup stress (1st confining action) equation:

$$\sigma_{st} = E_s\sqrt{a_2(w/(\alpha\,\phi_{st}))^2 + a_1(w/(\alpha\,\phi_{st})) + a_0} \tag{3}$$

plotted in Fig.2c, was assumed according to [8] where E_s = Young's modulus for steel; a_0, a_1 and a_2 = coefficients of the ideal trilateral local bond stress-slip law of the transverse bars and α = factor characterizing the position of the splitting crack (Fig.4d). For tensile stress transmitted by the splitting crack faces (2nd confining action) equation:

$$\sigma_{rc} = f_{ct0}/(\kappa\ w/\phi_a + 1) \tag{4}$$

plotted in Fig.2d, was adopted according to [6] where f_{ct0} and κ = coefficients experimentally determined and ϕ_a = maximum aggregate size.

Eq.1 is based on the following similitude criterion: both crack opening w and slip s are proportional to bar diameter ϕ_p. In this way, for the same value of ratios s/ϕ_p and w/ϕ_p all the coefficients γ_1, γ_2, β_1 and β_2 should be independent of ϕ_p. Even coefficients τ_0, τ_1, K_1 and K_2 in Eq.2 should be independent of ϕ_p, having adopted ratio w/ϕ_p in the place of w. The first confining action produced by the stirrup legs increases with the splitting crack opening (Eq.3) and this phenomenon is governed by the progressive unsticking of the bar studied in [8]. For the second confining action due to the tensile strength of cracked concrete (Eq.4), a similitude criterion for the relationship between w and the maximum aggregate size ϕ_a was also proposed in [6], so that coefficient κ turned out to be be independent of ϕ_a.

For equilibrium, the global confining action in zone Δz, given by Eqs.3 and 4, is equal to the global radial force produced by the anchored bars, so that:

$$\sigma_n = \Omega\ \sigma_{st} + B\ \sigma_{rc} \tag{5}$$

where Ω = stirrup index of confinement, defined as the ratio between global cross section area A^*_{st} of the stirrup legs and area A^*_p of the principal bar in the split plane (Fig.4f), B = concrete index of confinement, defined as the ratio between the net area $(b-n_p\phi_p)\Delta z$ of concrete in the split plane and the afore mentioned area A^*_p.

From Eqs.2 and 5, bond stress τ as a function of σ_{st}, σ_{rc} and w can be obtained:

$$\tau = \tau_0(1/(1+ K_1\ w/\phi_p)) + \tau_1(\ \Omega\ \sigma_{st} + B\ \sigma_{rc}\ )\ (1/(1 + K_2\ w/\phi_p))$$

Owing to the nonlinear equations involved, the relationship of bond stress τ as a function of slip s is obtained for the principal bar by means of a numerical approach which is based on the following procedure. Attributing a value w to crack opening, Eqs.3 and 4 give σ_{st} and σ_{rc}. Then bond stress τ can be calculated by means of Eq.6 and finally slip s is obtained from Eq.1.

3.RESULTS

In Fig.3 curves τ-s obtained by the present theory fit the experimental results well. Curves 1-4 (Fig.3a) concern the cases examined in [2] with different transverse reinforcement diameters ϕ_{st}. Fig.3b, referring to a specific test studied carefully in [3] to check this theory, shows a very good agreement also for crack opening and stirrup stress.This agreement still emphasizes the importance of the confining contribution due to the residual tensile strength of split concrete.

Theoretical diagrams of Fig.4 show the role of some significant parameters. Curves τ-s, w-s, σ_{st}-s refer to the following governing parameter values:

- Eq.1: $\tau_{m,0}$ = 18 MPa β_1 = 75 β_2 = 0 γ_1 = 42 γ_2 = 0.8;
- Eq.2: τ_0 = 1.8 MPa τ_1 = 0.8 k_1 = 115 k_2 = 35;
- Eq.3: τ_{02} = 2.5 MPa $\tau_{12}\phi_{st}$ = 500 MPa τ_{12}/τ_{11} = 0.3;
- Eq.4: f_{ct0} = 1.0 MPa κ = 250;
- geometrical and mechanical characteristics:

n_p=2 ϕ_p=20 mm α=2 E_s=206000 MPa Δz=100 mm ϕ_a=15 mm b=200 mm

Different values of the geometrical or mechanical characteristics adopted for each curve are indicated in Tab.1. Figs.4a,b,c show the role of the transversal extension of the concrete split-area dependent on section width b. Three different amounts of confining reinforcement are adopted and expressed through stirrup index of confinement Ω. Figs.4g,h,i show the influence of fracture energy $\mathcal{G}_F$ obtained by integrating the σ_{rc}-w curve (Eq.4) from w=0 to w=w_u. High values of $\mathcal{G}_F$, correspondent to an appreciable residual strength of cracked concrete, and large values of width b both increase the value of bond stress τ.

Note that fracture energy $\mathcal{G}_F$ could be assumed as one of the governing parameters of the present bond stress-slip relationship, but some specifications and remarks are necessary. In reality, the bond stress-slip relationship obtained in [4] showed the importance of the parameters f_{ct0}, κ and ϕ_a, characterizing the σ_{rc}-w relationship. These results were independent of the ultimate crack opening w_u (correspondent to stress-free crack surface). In fact, the maximum value of the splitting crack opening involved was 0.2-0.3mm, which was remarkably less than values w_u=0.4-0.7 mm indicated by experiments [6]. Fracture energy $\mathcal{G}_F$ depends on the same governing parameters f_{cto}, κ and ϕ_a, but also on w_u. This ultimate crack opening seems to be only variable with maximum aggregate size ϕ_a, according to both the similitude criterion introduced in Eq.4 and to some experiments in progress, so that the ratio w_u/ϕ_a could be assumed as a constant for every type of concrete, as well as coefficient κ. In this way $\mathcal{G}_F$ and ϕ_a can become the only governing parameters involved in σ_{rc}-w relationship. Diagrams of Fig.4g,h,i refer to an aggregate size ϕ_a=15mm (w_u/ϕ_a=0.05) and three values of $\mathcal{G}_F$ (50,100,150 J/m^2) correspondent to low, medium and high residual strength.

4. CONCLUDING REMARKS

The analytical model here proposed for the local bond stress-slip relationship after concrete splitting gives results which have a good agreement with the experimental tests (Figs.3a,b). The theoretical curves considerably depend on the residual tensile strength of cracked concrete especially when light or no transverse reinforcement is present. This residual tensile strength of split concrete is here introduced by means of two governing parameters which are fracture energy $\mathcal{G}_F$ and maximum aggregate size ϕ_a. In the present theory the single parameter $\mathcal{G}_F$ is not sufficient to describe this confining action due to the split concrete.

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Diag.	ϕ_{st} [mm]	n_{st}	f_{ct0} [MPa]	G_F [J/m²]
4,a	0	0	1.00	150
4,b	6	1	1.00	150
4,c	8	2	1.00	150
4,g	0	0	1.00 0.66 0.33	150 100 50
4,h	6	1	1.00 0.66 0.33	150 100 50
4,i	8	2	1.00 0.66 0.33	150 100 50

Table 1

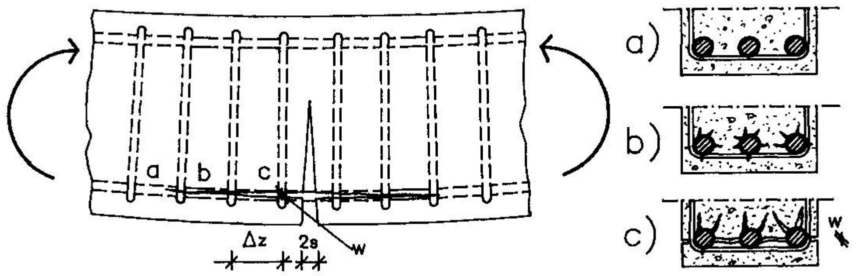
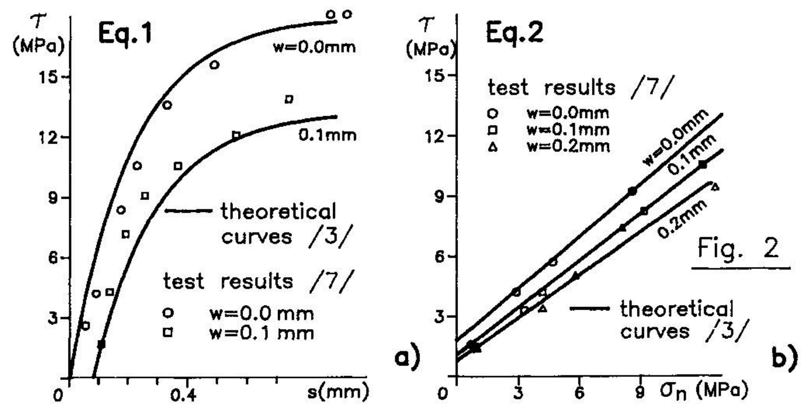
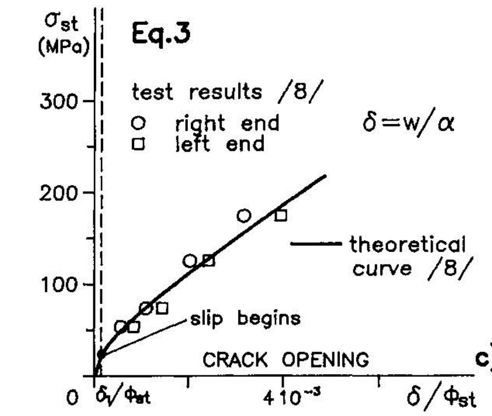


Fig. 1 – Splitting crack propagation in anchorages: a)no splitting crack; b)partially propagated splitting crack; c)completely propagated splitting crack.





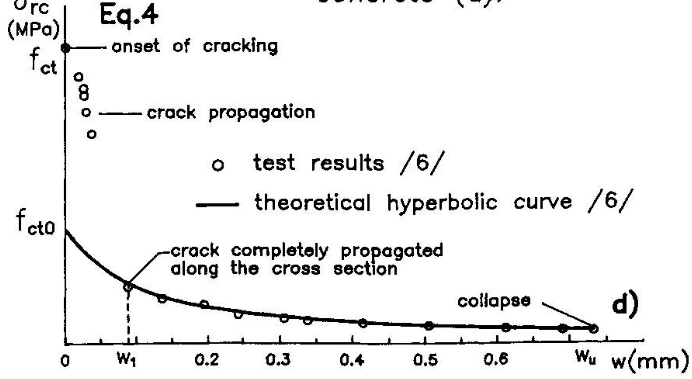
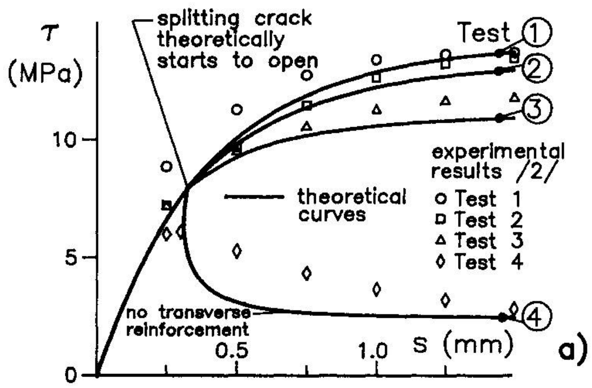


Fig. 2 – Analytical modelling of bond stress τ (a), radial stress σ_n (b), confining stress σ_{st} of stirrups (c) and of residual tensile stress σ_{rc} of cracked concrete (d).



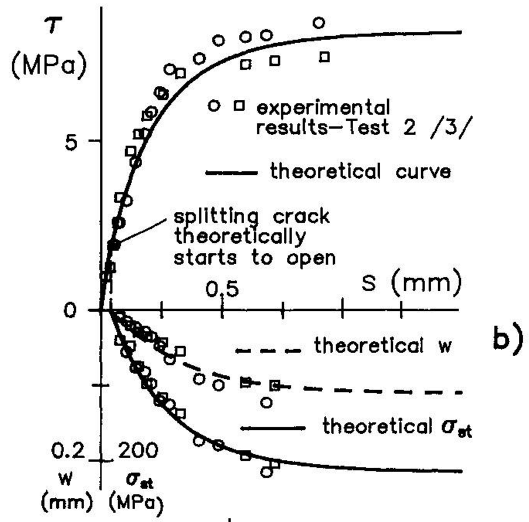


Fig. 3 – Comparison between theoretical and experimental results.

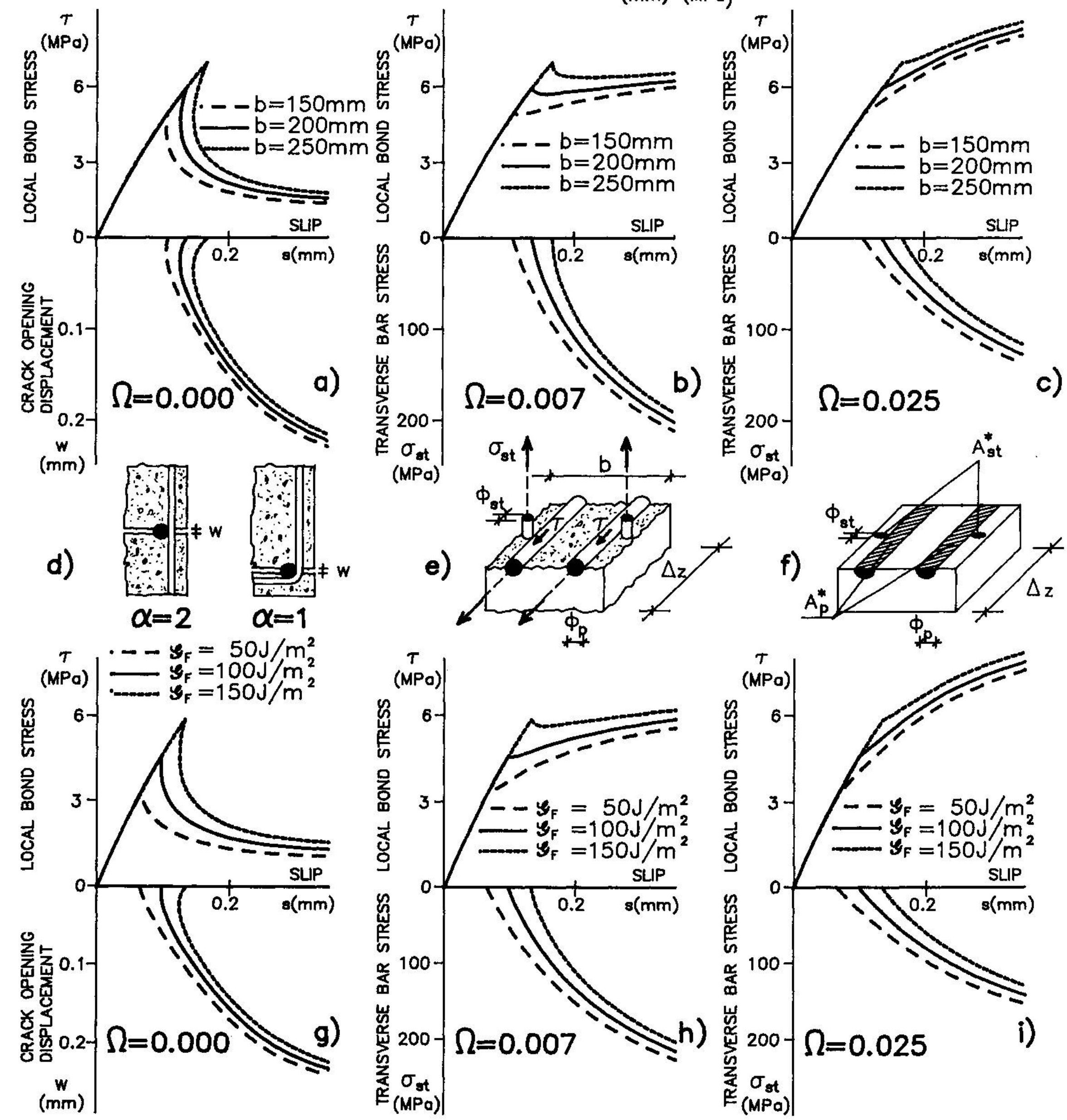


Fig. 4 – Influence of cross section width b and fracture energy $\mathcal{G}_F$ on bond after splitting.