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Modelling of Interface Problems in Reinforced Concrete

Modélisation des problèmes d'interface dans le béton armé

Mathematische Modelle für Oberflächenprobleme im Stahlbeton

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SUMMARY

Some recent advances in mathematical models are presented for the most important interface problems, which regard plain concrete as well as concrete interacting with the reinforcement. Emphasis is placed on basic phenomena such as aggregate interlock and cracked concrete shear stiffness, steel-to-concrete bond with or without longitudinal splitting, dowel action with or without axial force, transmission of tensile forces across open cracks. Whenever the phenomenological aspects of a problem are clear, constitutive laws are presented and illustrative examples are shown.

RÉSUMÉ

L'article présente les progrès les plus récents dans la modélisation mathématique des phénomènes d'interface dans le béton armé et non-armé. L'attention est concentrée sur les problèmes de caractère général, comme l'interaction des agrégats dans la transmission du cisaillement, l'adhérence entre l'armature et le béton (avec ou sans le fendage du béton), l'effet de goujons des barres (avec ou sans force axiale), la transmission des forces de traction à travers les fissures ouvertes. Chaque fois que la phénoménologie des problèmes est bien connue, on présente des lois constitutives, ainsi que des exemples.

ZUSAMMENFASSUNG

Es werden hier die letzten Fortschritte im Bereich der mathematischen Modelle für Oberflächenprobleme im bewehrten und nicht bewehrten Beton vorgestellt. Besondere Aufmerksamkeit wird allgemeinen Fragen geschenkt, unter anderen der Rissuferverzahnung, der Schubsteifigkeit im gerissenen Beton, dem Stahl-Beton-Verbund mit oder ohne Spaltrissen, der Dübelwirkung mit oder ohne Achsialkraft, der Zugkraftübertragung durch offene Risse. Jedesmal, wenn die Phenomenologie der Probleme wohlbekannt ist, werden Grundgesetze und Beispiele zur Erläuterung vorgestellt.

1. INTRODUCTION

The Colloquium Delft 87 on Computational Mechanics of Reinforced Concrete comes six years after the Colloquium Delft 81 on Advanced Mechanics of Reinforced Concrete, and though this length of time is relatively short compared to the nearly centennial history of modern concrete, yet the remarkable amount of work done in the past six years makes it possible to draw useful suggestions on future developments of both basic research and applications in the field of concrete and reinforced concrete structures.

As a matter of fact, six years are quite a long period if one thinks of the remarkable growth in the number of scientists investigating the basic aspects of concrete, improving the analysis, developing or refining computational techniques, updating the codes in order to make them more sound and more exhaustive. All this is undeniably favoured by the rapid dissemination of the information through the many magazines, journals and special publications regarding the materials and the structures.

Nevertheless, six years are quite a short period, as already emphasized: as a consequence, fundamental novelties can hardly be expected, since new ideas arise, ripen and develop more slowly than the evolution of computational and investigation techniques, though - of course - the evolution of the latter is a great spur to new ideas.

Before getting to the heart of the problems mentioned in the heading of this paper, it seems useful to remember briefly what has been done so far in the eighties, and even to go back to the inheritance of the previous twenty years.

We have to recognize that in a certain way the inheritance of the sixties lies in the astonishing amount of experimental research work, regarding both the basic behavior of concrete as a structural material (for example, uni-, bi- and triaxial behavior) and the behavior of the structural elements, either in the working load stage or at collapse. At the same time, some scientists seized the opportunity to examine closely several basic but rather involved aspects of concrete and r.c. structures such as bond, strain softening, microcracking.

The inheritance of the seventies lies in the really remarkable effort to develop and to formulate suitable constitutive laws for describing concrete multiaxial behavior: these laws were devised primarily to be introduced into finite element programs aimed at the analysis of structural elements. As a consequence, often the scientists directed their attention more to the development of semiempirical, computer-oriented constitutive laws, than to the understanding of such basic phenomena as bond, strain softening, cracked concrete shear stiffness, crack formation and propagation. Anyhow, the test results obtained in the sixties and early seventies proved to be an invaluable landmark.

Finally, with regard to the eighties, it is too early to speak of an inheritance, but some indications can be drawn by re-examining briefly the most recurrent topics in the literature. It is easy to recognize that a renewed interest in basic problems has developed, with the twofold purpose of improving our understanding of the phenomena, and of formulating more rational, more realistic and (if possible) simpler constitutive laws.

An examination of the papers published since 1981 in six of the most respected magazines and journals (ASCE Journal of the Mechanical Engineering Division, ASCE Journal of Structural Engineering, Magazine of Concrete Research, ACI Journal, Materials and Structures, Cement and Concrete Research) shows that 77% (Fig. 1a) of the nearly 200 papers on concrete and r.c. structures deal with basic problems, and that 23% deal with the behavior of structural elements (beams, columns, frames, panels, slabs, shells). Furthermore, 1 out of 3 papers dealing with basic problems (Fig. 1b) are aimed at the constitutive laws for solid concrete (multiaxial behavior, failure criteria, impact and fatigue loads, damage theory, endochronic theory, orthotropic models, effects of passive confinement), 1 out of 3 papers are on the so-called interface problems (steel-to-concrete bond, dowel action, aggregate interlock, cracked concrete behavior), 1 out of 4 papers deal with crack formation and propagation (concrete fracture mechanics, continuum damage mechanics, size effect, concrete tensile behavior, strain-softening included). Finally, 1 out of 8 papers are on the rheological behavior of concrete.

The widespread interest in basic problems and constitutive laws is confirmed by the many specialised conferences and symposia, held in the last few years, which have offered many opportunities for the circulation of early results and of not yet fully developed theories. Among others, the following conferences or symposia can be quoted: Bond in Concrete (1982 [1]); Constitutive Laws for Engineering Materials (1983 and 1987 [2,7]); Mechanics of Geomaterials: Rocks, Concretes, Soils (1983 [3]); Application of Fracture Mechanics to Cementitious Composites (1984 [4]); Partial Prestressing: from Theory to Practice (1984 [5]); Creep and Shrinkage of Concrete: Mathematical Modelling (1986 [6]).

At the end of this very rapid and certainly not exhaustive review of the topics investigated over the last six years, one has to admit that - in spite of the remarkable increase of the total number of papers published in the last three years (Fig. 1c) - relatively little attention has been devoted to the behavior of concrete and r.c. structures under severe or even extremum temperature conditions. High temperatures may, for instance, occur in the secondary containment shells of nuclear reactors; on the other hand, very low temperatures are to be expected in the reinforced concrete walls of the cells which are being considered for the storage of electric energy, taking advantage of the superconductivity of huge metallic coils kept at very low temperature (this application of reinforced concrete is however for the years to come!).

Another problem, which is still regarded by many as "non structural", is the problem of durability: nevertheless, since many r.c. or prestressed structures are attaining their design life, structural durability can no longer be underevaluated and should be taken in due consideration in the formulation of constitutive laws.

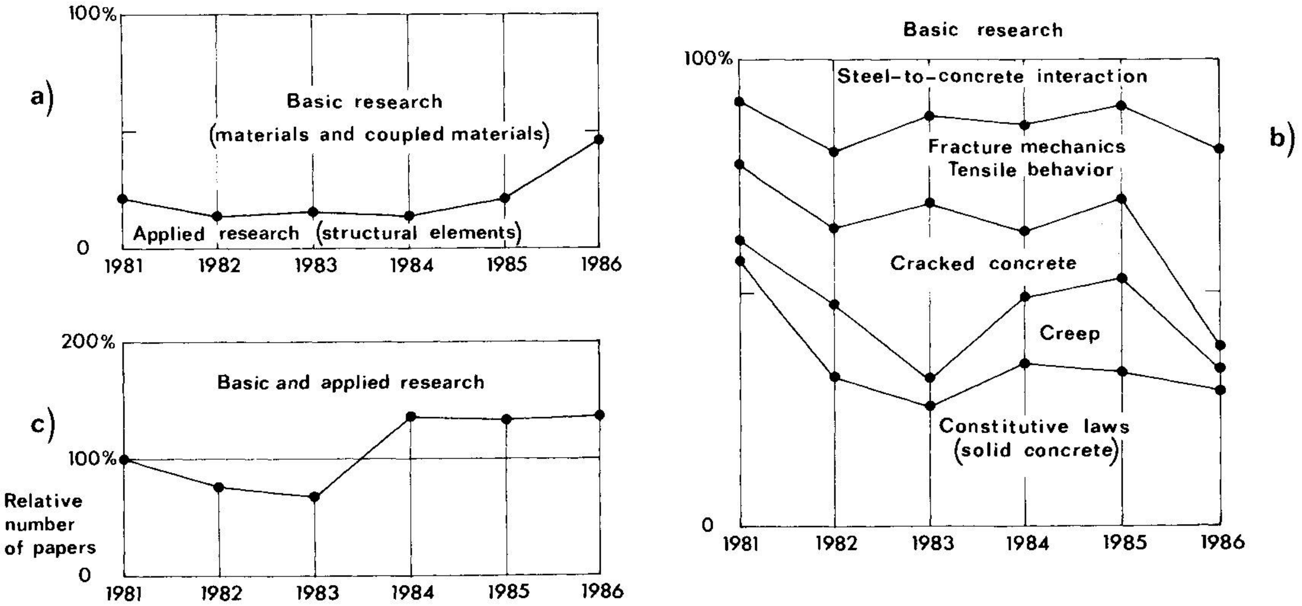


Fig.1 - Statistics regarding the papers published in 6 top journals and magazines (1981-1986) : (a) basic and applied research ; (b) distribution among different topics ; (c) number of published papers with respect to 1981.

2. INTERFACE PROBLEMS IN REINFORCED CONCRETE ELEMENTS

As shown in Fig. 1b much effort has also been devoted recently to the so-called interface problems, which are really typical of reinforced concrete. As emphasized by Vintzeleou and Tassios in [8], interface problems are characterized by a variety of aspects which are partly basic and partly structural. Four fundamental lines have been pursued in the study of steel-to-concrete and concrete-to-concrete interfaces.

Steel-to-Concrete Interfaces: Bond. Bond embraces all the phenomena of a chemical and physical nature, which allow the transmission of shear forces between the reinforcement and the concrete: consequently, bond is the very essence of r.c. elements.

As to chemical adhesion and bearing action (this latter characterized by the local crushing of the concrete keys in contact with the bar lugs), bond is essentially a basic problem limited to the two "coupled" materials (concrete and reinforcement, Fig. 2a); as to the mechanical interaction after cover and interspace cracking (due to longitudinal splitting), bond is essentially a structural problem (Fig. 2b), since concrete cover, bar free interspace and stirrup arrangement play a leading role.

Because of the fundamental role of bond, in the working load stage as well as at collapse, the formulation of realistic and reliable constitutive relationships between the bond stress and the bar slip, with or without concrete splitting, is still an important goal to be achieved.

Dowel Action. Dowel action embraces all the mechanical phenomena which permit considerable amounts of shear to be transferred across a crack, because of the local bending and shear stiffness of the bars at the crack interface, and also because of the remarkable stiffness and strength of the concrete, which is highly confined locally, close to the reinforcement. Whenever the shear transfer involves two contiguous structural elements (Fig. 2c) or two different parts of the same element, cast at different times (Fig. 2d), the dowel action is already active in the working load stage; whenever a single element, cast at the same time, is subjected to shear, the resisting contribution of dowel action becomes relevant only in a very advanced stage of the loading process, after the development of tensile or shear cracks (Fig. 2e). The dowel action is essentially a structural problem, but it may be reduced to a material problem once the constitutive laws of the reinforcement are formulated in such a way that concrete cover, bar free interspace and transverse reinforcement are properly introduced, together with the still largely unknown effects of the axial force in the main reinforcement.

Concrete-to-Concrete Interfaces: Aggregate Interlock. Aggregate interlock embraces all the mechanical phenomena which allow the transmission of considerable amounts of shear across a rough, generally open and continuous crack. Of course, in order to have aggregate interlock activated, a suitable confinement action must be provided either by the reinforcement crossing the crack, or by the structural restraints. Should cracking be regular, with parallel and closely spaced cracks (Fig. 2f), aggregate interlock could be considered as a material problem and its constitutive laws could be regarded as a property of (cracked) concrete.

Though the phenomenological aspects of aggregate interlock are well known, either at constant confinement or at constant crack opening, or even at constant restraining stiffness (transverse stiffness), more work has still to be done on spatial cracks, cyclic loads, dynamic behavior of cracked concrete.

Transfer of Tensile Forces across a Crack. As shown in Fig. 1b, a great deal of attention has recently been devoted to concrete fracture mechanics and - more generally - to the tensile behavior of concrete, strain softening included. As emphasized by Bazant in [9], concrete cracking starts as a process distributed over a crack band, because of the discontinuities of the concrete at the microlevel, and only in an advanced stage does cracking become localized, as a consequence of the release of the energy accumulated within the crack band. The specific fracture energy, as well as the width of the crack band can be regarded as material properties, the latter being a few times (1 to 3) as large as the maximum aggregate size.

Once cracking coalesces into blunt, continuous cracks, new interfaces are formed and the role of these interfaces in transferring tensile forces is a challenging problem. To this end, the analysis of the tensile response of cracked concrete must be extended to localized, continuous and open cracks (a few tenths of a millimeter, Fig. 2h), well beyond the crack width values that are generally investigated with regard to the process zone at the tip of a developing crack (a few thousandths of a millimeter, Fig. 2g).

The formulation of suitable constitutive laws for relatively large values of the crack width may be of great interest in certain problems such as the analysis of the flexural behavior of r.c. beams, since the moment-curvature diagrams are greatly influenced by the transfer of tensile forces in a section during the transition from the 1st uncracked to the 2nd cracked stage.

In the following Sections the different interface problems will be examined and the available constitutive laws will be discussed, as well as the developments in progress and the advances to be expected.

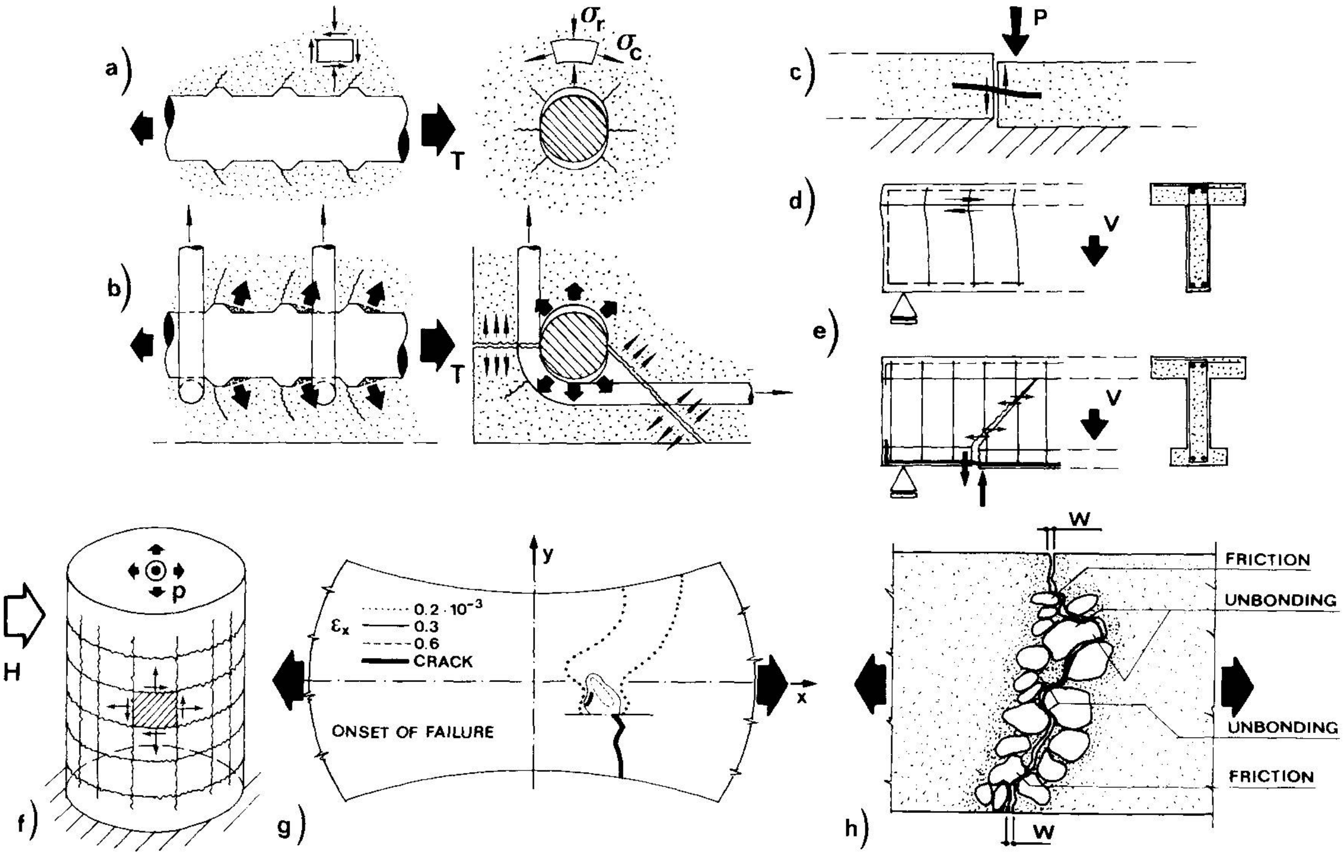


Fig.2 - Various types of interfaces : (a,b) steel-to-concrete bond ; (c,d,e) dowel action ; (f) aggregate interlock ; (g,h) tensile fracture : developing crack (g) [34] and through crack (h) [35].

3. BOND

In spite of the great amount of research work done in this area, bond is still a topical subject for different reasons. Primarily this is because of the many parameters involved, but also because of the ongoing improvements in the mechanical properties of both concrete and steel, as often required by special structures or unusual environmental situations (f_{sy} = 500 - 600 MPa , f'_c > 100 MPa) . Because of the problems which are still open, the formulation of suitable constitutive relationships is far from definite. As a matter of fact, beside a few well defined main parameters (such as bond stress, confinement stress, shear strain in the concrete and bar slip, interface dilatancy accompanied by longitudinal splitting), many other parameters are involved, either geometrical (concrete cover, bar interspace) or mechanical (transverse reinforcement, loading rate, cyclic loading), physical (temperature of the structure) and technological (casting modalities and type of formwork).

Apart from the technological aspects (which are often very critical, see for instance Schmidt-Thrö, Stöckl, Kluge and Kupfer "Tests on the Bond Behavior of Bars in Slipform Concrete Structures", DAfSt, Heft 378, Berlin, 1986), the basic problems being investigated nowadays are: local bond-slip law (Yankelevsky [13] ; Jiang, Shah and Andonian [14]; Lahnert, Houde and Gerstle [36]), bond behavior with transverse and splitting cracks (Tepfers [10]; Gambarova, Rosati and Zasso [11]; Giuriani and Plizzari [12]), effects of lateral pressure (Robins and Standish, MCR, Vol.36, No.129, Dec.1984), temperature (Morley and Royles, MCR, Vol. 35, No.123, June 1983), loading rate (Vos and Reinhardt, Mat. and Structures, Vol. 15, No.85, 1982) and fatigue (Johnston and Zia, Mat. and Struc., Vol.17,No.97, 1984).

Great attention has been lately devoted also to the analysis of bond at the local level, considering the local effects of bar lugs pushing against the concrete, and the individual microcracks originating at bar-to-concrete interface. Generally, complex F.E. programs have been used. Two papers are particularly relevant in the author's opinion, because of the different approaches used in bond analysis. In the first paper (Reinhardt, Blaauwendraad and Vos [15]) the concrete layer (slip layer, Fig. 4) close to a bar is modeled by means of axisymmetric,torus-like elements with nonlinear behavior, whilst the surrounding mass is considered as linearly elastic: transverse microcracking is introduced through a suitable law in tension with a softening branch; a Mohr - Coulomb's failure surface is adopted for compression. In the second paper (Ingraffea, Gerstle, Gergely and Saouma [16]) the transverse cracks are modeled by means of suitable interfaces (the mesh is refined at each loading step, Fig. 3) and a nonlinear fracture mechanics scheme is adopted to model mixed-mode concrete fracture. As an alternative, special tension softening elements are introduced at the interface between a bar and the concrete, wherever a transverse crack may originate.

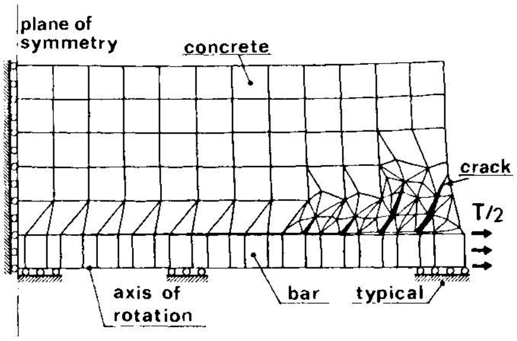
With regard to bond behavior after concrete splitting, we may observe that many tests and several models have been so far devoted to the evaluation of the ultimate force (cracking resistance) in the case of short embedments (i.e. with a limited bond length), with no transverse reinforcement (see for instance Tepfers [10], Fig. 5). On the other hand, much less effort has been made to investigate the effects of longitudinal splitting on bond, when adequate confinement is exerted by the transverse reinforcement.

The cracking resistance f_{bc} of a short anchorage with no transverse reinforcement lies between the following limits (Fig.5) :

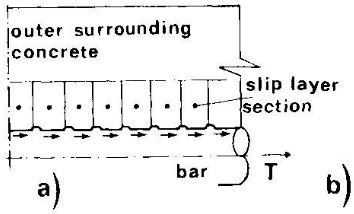
$$f'_{bc} = f_{ct} \frac{c + D_b/2}{1.664\, D_b \tan\alpha} \text{ (elasto-cracked model)}; \quad f''_{bc} = f_{ct} \frac{2c}{D_b \tan\alpha} \text{ (plastic model)}$$

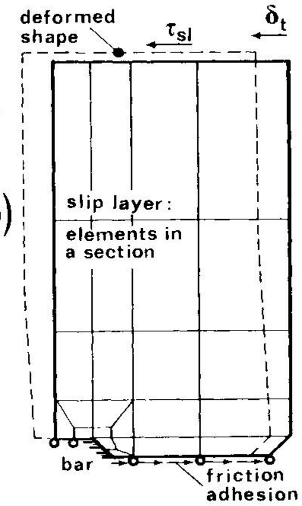
where α is the average angle between the transverse cracks in the concrete and the axis of the bar ($\alpha \simeq 45°$), and f_{ct} is the tensile strength of the concrete. As a matter of fact, the test results fall between f'_{bc} (lower bound) and f''_{bc} (upper bound) [10].

As soon as the bond stress reaches f_{bc} at any section of the bar, bond efficiency is guaranteed primarily by the transverse reinforcement (mostly by its bond properties) and by the interaction between bond and confinement stresses at the bar-to-concrete interface; secondly, by the tensile stresses transmitted across

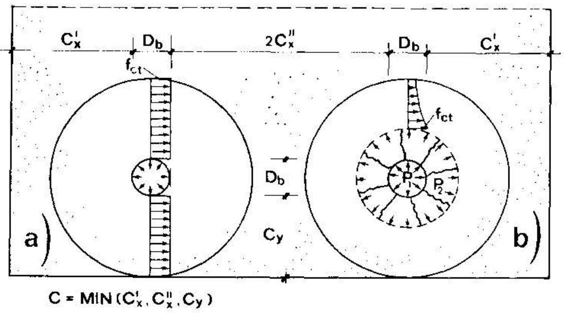


▲Fig.3 - Deformed mesh of portion of tension pull-out specimen with four secondary cracks [16].





▲▶Fig.4 - Axisymmetric representation of slip layer (a) and F.E. mesh of a slip layer section (b) [15].



◀Fig.5 - Hoop stresses close to a bar according to the perfectly plastic model (a), and to the elasto-cracked model (b) by Tepfers [10].

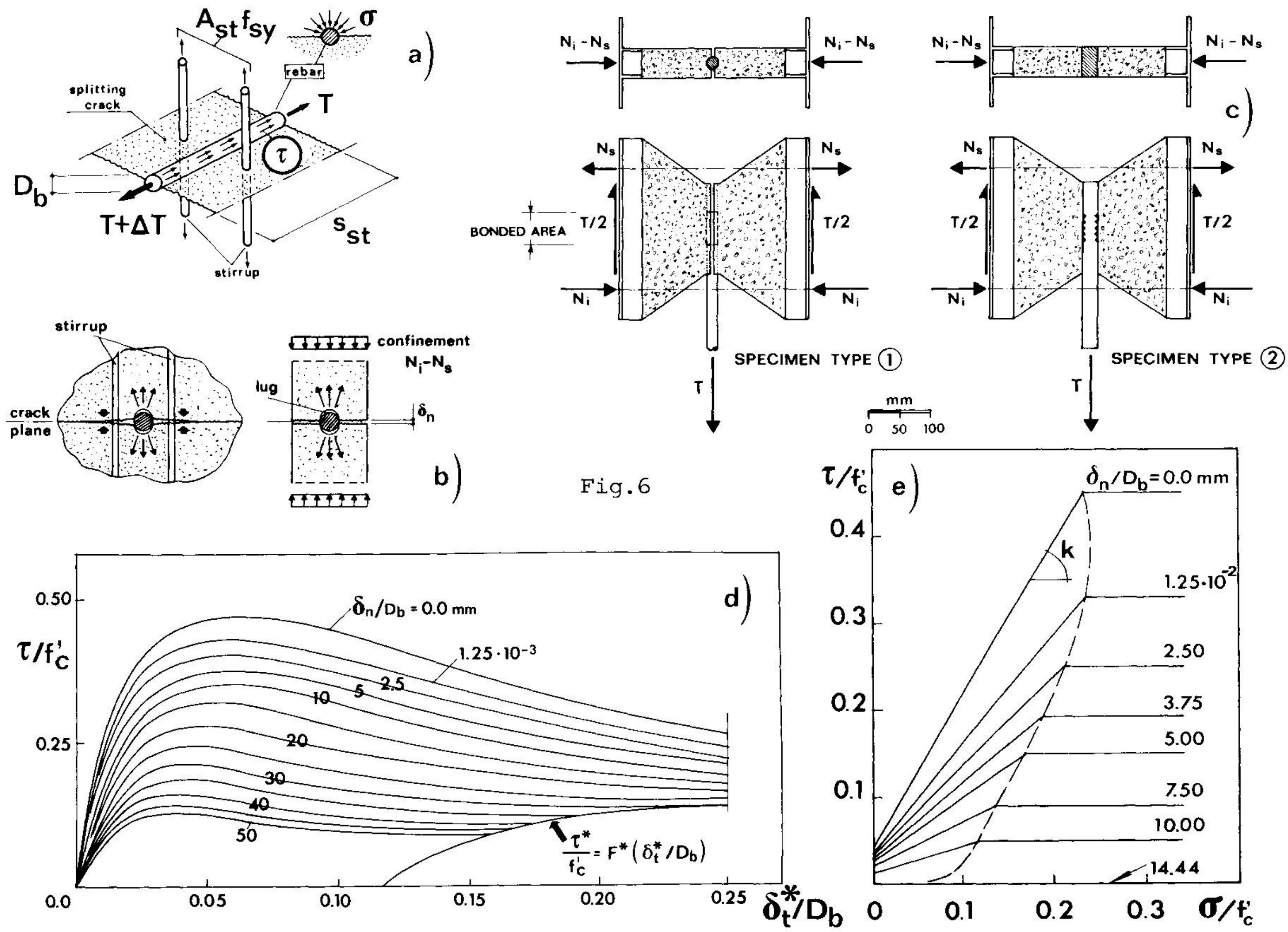


Fig.6 - (a) Interaction between a longitudinal bar and a two-leg stirrup; (b) Actual splitting crack and idealised splitting crack [11]; (c) Pre-splitted specimens tested in [11] (N_s,N_i confinement forces); (d) Shear-slip constitutive law; (e) Shear-confinement envelopes.

the plane of the splitting crack. In [11] three series of precracked specimens (Figs. 6b, c) reinforced with a single deformed bar (D_b = 18 mm), and characterised by a short bond length ($l_b/D_b \simeq 3$) were subjected to pull-out tests, the crack width being kept constant throughout each test. The local bond-slip relationship (Fig. 6d) was given the following empirical formulation:

$$\frac{\tau}{f'_c} = R(w)\frac{\Delta}{1 + a_1\Delta + a_2\Delta^2 + a_3\Delta^3} \quad , \text{ with } \Delta = \delta_t^*/D_b \text{ and } w = \delta_n/D_b \; ,$$

where $\delta_t^* = \delta_t - \delta_t^0$ is the net bar slip, δ_n is the crack opening and R, a_1, a_2, a_3, δ_t^0 are parameters related to δ_n/D_b. The bond-confinement curves at constant crack width (Fig. 6e) were idealised as trilateral envelopes:

$$(\tau/f'_c) = (\tau_0/f'_c) + k(\sigma/f'_c) \quad \text{with} \quad (\tau_0/f'_c) = a_4 - a_5 w \; , \quad k = a_6 - a_7\sqrt{w} \; ,$$

$\sigma/f'_c \leqslant 0.35$, where a_4, a_5, a_6, a_7 are constants.

Since in structural analysis with F.E. programs it is much more expedient to introduce a comprehensive bond-slip relationship (longitudinal splitting and confinement included) than to push the analysis to such details as local cracking at the bar-to-concrete interface and bar-to-stirrup interaction, further studies on the effects of splitting and on the efficiency of transverse reinforcement are needed (see for instance Giuriani [12]).

4. DOWEL ACTION

The transfer of membrane forces across cracks in r.c. containment vessels, as well as the transfer of shear forces in the partially cracked sections of a r.c. beam are largely based on the dowel action mechanism which accounts for 15 to 35% of the overall shear to be transmitted by the various shear mechanisms (Fig. 7). As a consequence, dowel action is an important interface mechanism, which has essentially structural aspects.

From both a phenomenological and a speculative point of view, the dowel action is characterised by several interesting aspects, which regard : bond, tensile strength of concrete and concrete fracture mechanics, bar-to-stirrup interaction with stirrup tension stiffening.

Since the dowel action is active after concrete cracking, the interaction between the tensile and dowel forces in the main reinforcement should always be taken into due account. As a matter of fact, any variation in the tensile force is accompanied by bond stresses, which produce a complex three-dimensional crack pattern (Fig. 8), consisting of transverse microcracks and longitudinal splitting cracks; cracking in turn modifies the stiffness properties of the concrete embedment of the main reinforcement and further cracking may occur. Nevertheless, should bond failure be due to concrete crushing (pull-out failure: short embedment length, high bond properties, large cover, large stirrup ratio), the local microcracking would not markedly affect the maximum dowel force, as long as the tensile force remains below 80 - 90% of the pull-out force (Fig. 9a). For long embedments, steel yielding preceedes bar pull-out and the tensile force should be better adimensionalized with the yield force (Fig.9b). The equation of the heavy full-line envelope is given by Soroushian and others in [17]:

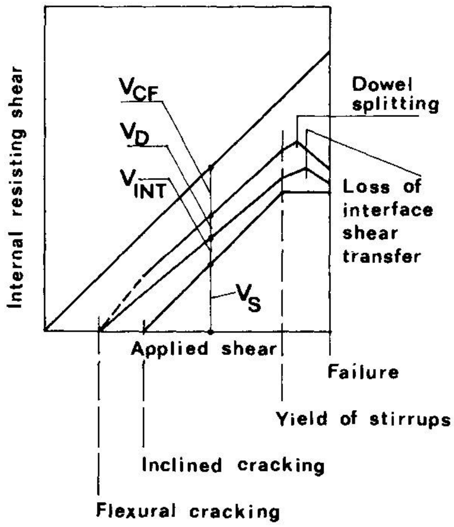
$$V_{Du} = 0.0685\,\gamma^2 d^2 f_b + 0.45 f_y d^2(1 - T^2/T_y^2)/\gamma$$

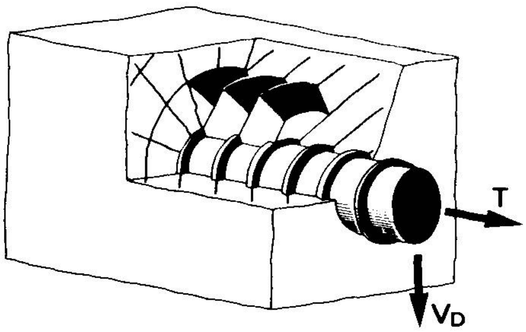
where : $\gamma = \sqrt[4]{E_s/K_f d}$, with K_f = 272 MPa/mm (foundation modulus)

d = dowel bar diameter (mm) ; E_s = dowel Young's modulus (MPa)

$f_b = 37.6\sqrt{f'_c}/\sqrt[3]{d}$ = concrete bearing strength (MPa) ; f_y = dowel yield stress (MPa)

T , T_y = axial force in the dowel, axial force at yielding.





▶ Fig.8 - Crack pattern close to a bar subjected to tension and dowel force.

◀ Fig.7 - Distribution of internal shears in a r.c. beam with web reinforcement.

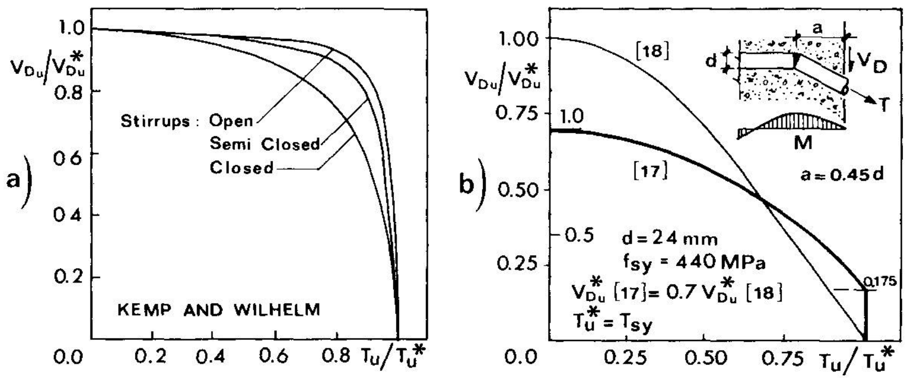
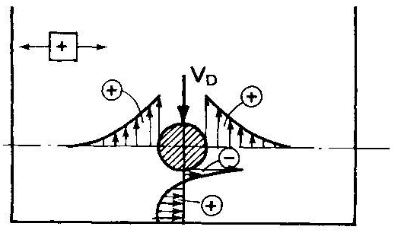
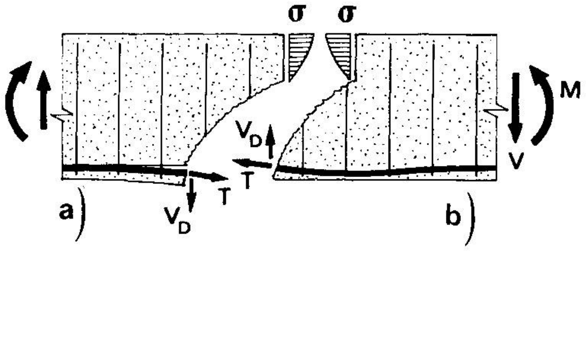


Fig.9 - Failure envelopes for short anchorage lengths (a) : pull-out failure , and for long anchorage lengths (b) : failure due to bar yielding , according to Soroushian et al. [17] , and to Vintzeleou and Tassios [18] .



▲ Fig.10 - Hoop stresses close to a bar subjected to a dowel force.

▼ Fig.11 - Bending of a bar subjected to dowel action : (a) against concrete cover and (b) against concrete core.



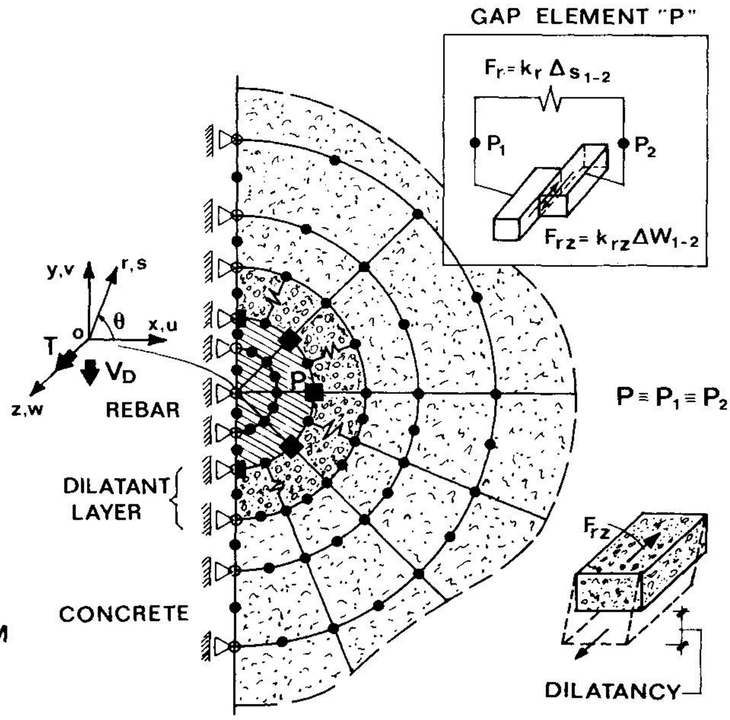


Fig.12 - Possible modelisation of the bar-to-concrete interface.

In Fig. 9b the thin envelope regards the section with the largest bending moment at the verge of plastic collapse (the section is plasticized either in tension or in compression): the dowel strength with no axial force is evaluated according to Vintzeleou and Tassios [18]. The difference between the two envelopes (Fig. 9b) is an indication of the further research work which is still needed in this area.

In case of no transverse reinforcement, with usual bar interspaces and concrete covers, dowel failure is due neither to concrete crushing nor to bar yielding, but to cover and interspace splitting, as shown in [18]. For this purpose, relevant confinement forces can be developed by the interface of the splitting crack (Fig. 10): this fact has been known for some time, but only recent results allow the evaluation of the tensile stresses which can be transferred across really open and continuous cracks (see Sect. 6), having width equal to several tenths of a millimeter.

Most of the research workers in the last 20 years have limited their attention to the maximum dowel force causing concrete splitting (Dulacska, 1972; Paulay, Park and Phillips, 1974; Taylor, 1974; Stanton, 1976), a few have recognized the importance of stirrup arrangement and concrete tensile strength (Baumann and Rüsch, 1970), of the axial force (Kemp and Wilhelm, 1977) and of the need for suitable mathematical models (Johnston and Zia, 1971). Recently, the many test results by Utescher and Herrmann (1983 [20]), and by Paschen and Schönhoff (1983 [21]) have shed further light on the failure of the bars and of the concrete, on the role of the cover, shape and arrangement of the stirrups. These results may hopefully foster the development of exhaustive mathematical models, which - in the writer's opinion - should reduce the complex structural problem to a material problem, through the formulation of suitable constitutive laws for the main reinforcement. To this end, further test results are needed with regard to the interaction between the dowel and the tensile forces, the deflection of a bar inside the concrete mass (Fig. 11), the interaction between the bars and the stirrups.

Numerical analysis may also give a decisive contribution, especially for the study of bar-to-concrete interaction: as an example (Fig. 12), the interface may be modeled by means of (I) a finite element layer with dilatant properties, in order to introduce bond dilatancy due to the wedging effects of the bar lugs; (II) gap-type elements, which transmit a frictional force and bring on a relative slip at the interface; (III) nonlinear, spring-like elements connecting the bar to the outer concrete elements, in order to reproduce the mechanical properties of the concrete embedment, as needed by the modelisation of the dowel action.

5. AGGREGATE INTERLOCK

The shear transfer mechanism based on aggregate interlock has been known for a long time in its behavioral aspects, owing to the many test results obtained in the sixties and early seventies. As a consequence of these tests, basic concepts such crack dilatancy (i.e. coupling between shear stress and crack opening, between normal stress and crack slip) and shear-confinement interaction were fully understood, the latter concept being still recently investigated for the purpose of developing new constitutive laws [27].

The remarkable experimental effort has not been matched by a comparable effort in the formulation of rational constitutive laws, because only recently have the properties of aggregate interlock been recognized as material properties. As a matter of fact, the formulation of suitable constitutive laws for cracked concrete became necessary after the concept of smearing the cracks over an entire element was shown to be highly suitable for F.E. analysis.

So far, most of the efforts have been devoted to planar cracks subjected to monotonic loading, in order to formulate the incremental stiffness matrices of a crack

[B], and of cracked concrete (for the symbols see Fig. 13) :

$$\begin{Bmatrix} d\sigma^c_{nn} \\ d\sigma^c_{nt} \end{Bmatrix} = \begin{bmatrix} B_{nn} & B_{nt} \\ B_{tn} & B_{tt} \end{bmatrix} \begin{Bmatrix} d\delta_n \\ d\delta_t \end{Bmatrix} \quad ; \quad \begin{Bmatrix} d\sigma^c_{nn} \\ d\sigma^c_{tt} \\ d\sigma^c_{nt} \end{Bmatrix} = s \begin{bmatrix} B_{nn} & 0 & B_{nt} \\ 0 & 0 & 0 \\ B_{tn} & 0 & B_{tt} \end{bmatrix} \begin{Bmatrix} d\varepsilon^{cr}_n \\ d\varepsilon^{cr}_t \\ d\gamma^{cr}_{nt} \end{Bmatrix}$$

where: $d\varepsilon^{cr}_n = d\delta_n/s$, $d\gamma^{cr}_{nt} = d\delta_t/s$, s = cracking spacing (to be considered as a state variable, i.e. a function of the strain field and of the reinforcement characteristics, in r.c. elements). Note that [B] is neither positive definite, nor symmetric.

Due to the complexity of the problem (which involves 4 parameters, δ_n , δ_t , σ^c_{nn}, σ^c_{nt}, in planar cracks), the tests have been mostly performed by decoupling either the interface displacements (tests at constant crack opening, Fig. 14c) or the stresses (tests at constant confinement, Fig. 14d); as a consequence, the constitutive laws proposed so far are mostly based on the total deformation theory, according to the following general formulations:

$$\sigma^c_{nn} = N(\delta_n , \delta_t) \quad , \quad \sigma^c_{nt} = T(\delta_n , \delta_t) \quad \text{or} \quad \sigma^c_{nt} = T(\sigma^c_{nn}, \delta_t) \quad , \quad \delta_n = \Delta(\sigma^c_{nn}, \delta_t)$$

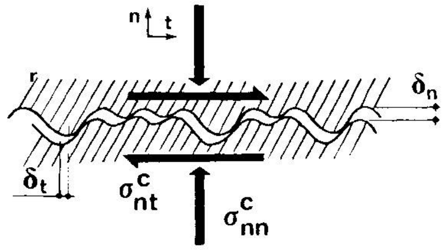
Of course path-independency hardly agrees with the very nature of interface phenomena, but there is little experimental evidence on the importance of aggregate interlock path-dependency.

As to research after Colloquium Delft 81 (for previous research see Bazant and Gambarova, "Rough Cracks in Reinforced Concrete", J. Struc. Div. ASCE, 106 - 1980, pp. 559-582), the following studies are to be cited: test results with constant or variable confinement stiffness (Fig. 14a, b) and Two-Phase Model (Walraven [22]), test results both at constant confinement and at constant crack opening (Fig. 14c, d, Daschner and Kupfer [23]), improvements of Rough Crack Model (Gambarova and Karakoç, see the References quoted in [24] and [25]), test results at constant or variable confinement stiffness (Fig. 14a, b, Millard and Johnson [26]), test results at constant confinement (Fig. 14d) and Dilatancy Factor Model (Divakar, Fafitis and Shah [27]). A further mathematical model which has been successfully applied to the description of aggregate interlock is the so-called Microplane Model (Bazant, Oh, Gambarova, see for instance [28]). Finally, a few engineering models for shear transfer (aggregate interlock and other mechanisms) have been lately proposed (see Perdikaris and White [29], and Yoshikawa and Tanabe [19]).

The 4 above-mentioned mathematical models have been thoroughly checked by fitting many of the available test results, and can be considered both realistic and reliable.

5.1 Rough Crack Model [24, 25]

The constitutive laws have a mostly empirical formulation, since they are based on Paulay and Loeber's test results. Nevertheless , the formulation introduces a few general properties to be expected for a crack, such as: (a) the wedging effects of interface asperities make the shear stress mostly dependent on the slip-to-opening ratio $r = \delta_t/\delta_n$ (this is certainly true for trapezoidal asperities); (b) for small crack openings, the confinement force is not needed (this is certainly true for spherical asperities); (c) for large values of the displacement ratio, r , the shear stress must exhibit an asymptote, because of microcracking and crushing in the mortar close to the aggregate particles; (d) for large values of the crack opening, the contact at the interface is lost ($\delta_n > d_a/2$ where d_a is the maximum aggregate size); (e) the grading of the aggregates matches Fuller's curve. The constitutive laws are as follows:



▲Fig.13 - Crack morphology.

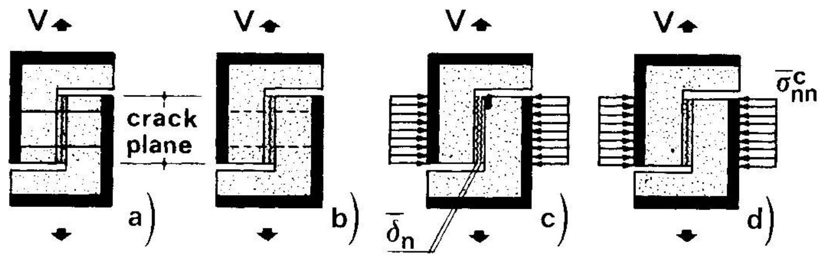
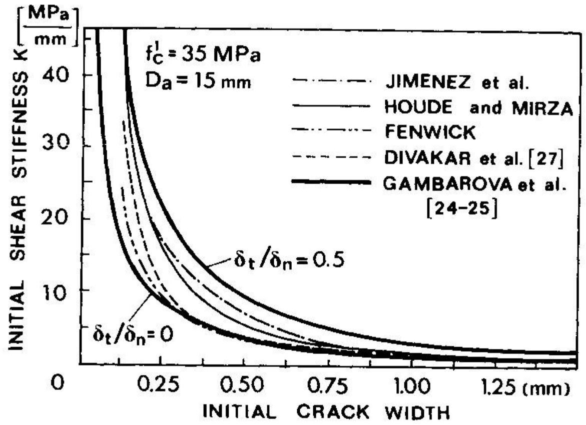
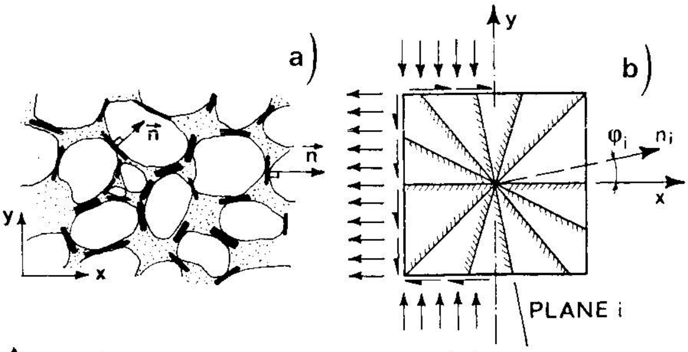
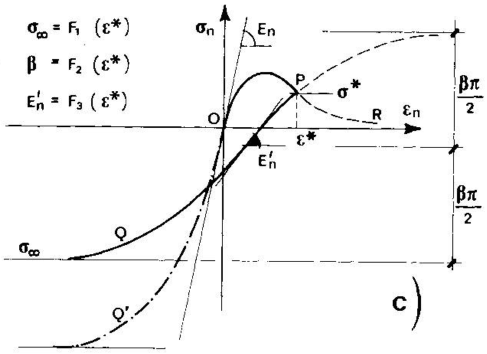


Fig.14 - Different specimens for the study of aggregate interlock.

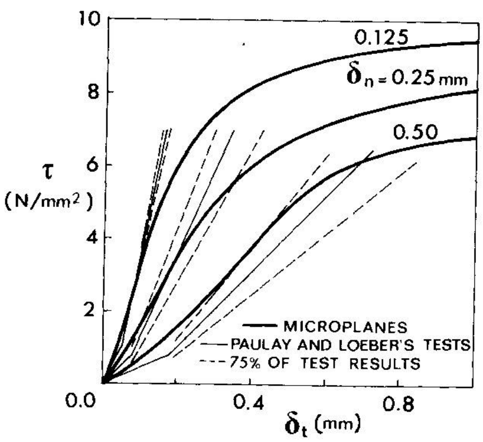


▲ Fig.16 - Initial shear stiffness according to various tests and analytical models.



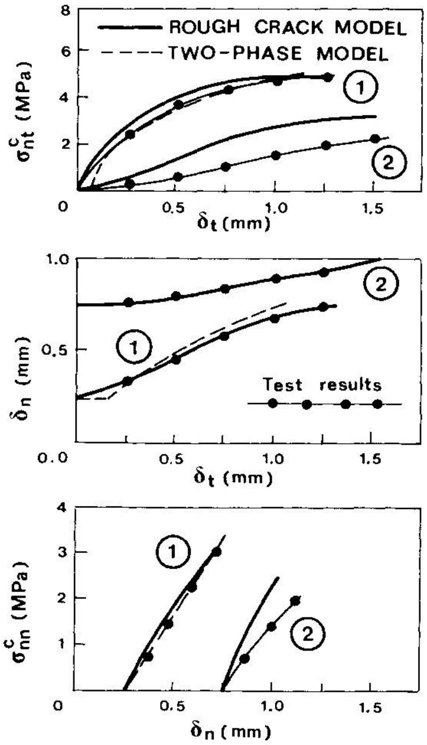


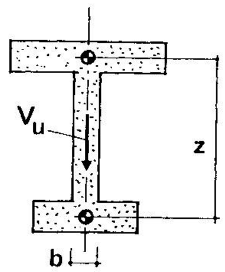
▲▼ Fig.15 - Microplane Model : (a) concrete microstructure; (b) microplanes; (c) constitutive law of a microplane [28].

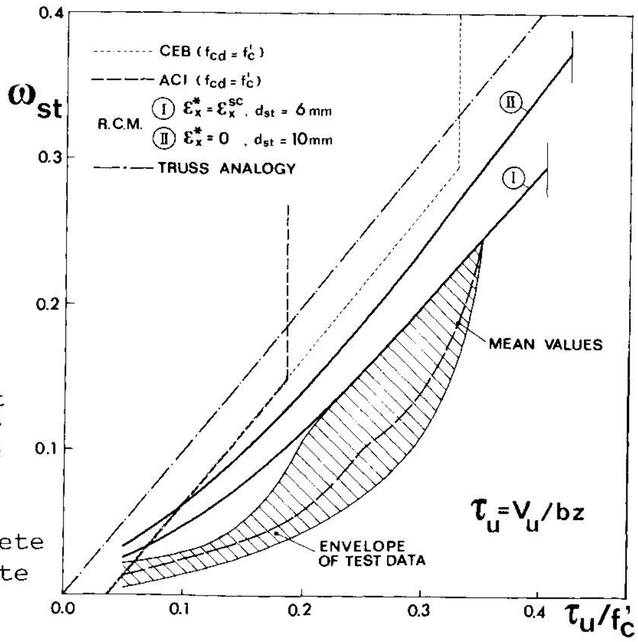


▶ Fig.18 - Fitting of Paulay and Loeber's test results [28].

▼ Fig.17 - Fitting of Millard and Johnson's test results [25 , 26].







▲▶ Fig.19 - Thin-webbed r.c. beams : curves of shear reinforcement degree ω_{st} and envelope of test data at collapse due to stirrup yielding [24].

I : prestressed concrete

II : reinforced concrete

$\omega_{st} = \rho_{st}\,(f_{sy}/f'_c)$

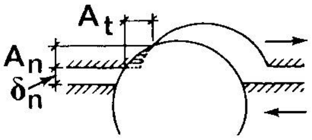
$$\sigma^c_{nt} = \tau_0(1 - \sqrt{2\delta_n/d_a}) \cdot r \frac{a_3 + a_4|r|^3}{1 + a_4 r^4}, \quad \sigma^c_{nn} = - a_1 a_2 \sqrt{\delta_n} \frac{r}{(1+r^2)^{0.25}} \sigma^c_{nt}$$, where

a_1, a_2, a_3 and a_4 are constants or parameters related to concrete strength f'_c.

5.2 Two-Phase Model [22]

The constitutive laws have a rational formulation based on a few apodictic assumptions: (a) concrete is regarded as a two-phase material, with perfectly stiff spherical inclusions (aggregate particles) and a perfectly plastic matrix (the cement paste); (b) the grading of the aggregates matches Fuller's curve; (c) the active contact areas between the inclusions and the matrix are related to interface displacements, via geometrical relations and taking into account the statistics of aggregate distribution; (d) the compressive contact strength of the matrix is related to concrete strength, while the shear contact strength is linearly related to the compressive contact strength via a constant friction coefficient. The constitutive laws are as follows:

$$\sigma^c_{nt} = \sigma_{pu}(A_n + \mu A_t), \quad \sigma^c_{nn} = \sigma_{pu}(A_t - \mu A_n)$$



where A_n and A_t are the averaged contact areas (in the direction n and t) between the inclusions and the matrix, σ_{pu} is the matrix compressive strength ($\sigma_{pu} = 6.39\, f'^{0.56}_c$) and μ is the inclusion-to-mortar friction coefficient ($\mu = 0.40$).

5.3 Dilatancy Factor Model [27]

The constitutive laws are empirical since they are based on test results obtained by the Authors, as well as on most of the test results published so far:

$$\sigma^c_{nt} = k_0\, \delta_t [1 + (k_0\, \delta_t)/(a_1\, \sigma_{tp})]\, \exp[-(2\, k_0\, \delta_t)/(a_1\, \sigma_{tp})]$$

$$\beta = \delta_n/\delta_t = a_2 \exp(- a_3 \delta_t - \sigma_n^{-a_4}) \qquad (\beta = \text{dilatancy factor}, \ \sigma_n = \sigma^c_{nn})$$

where: k_0 (initial shear stiffness) $= (\partial\sigma^c_{nt}/\partial\delta_t)_0 = a_5\, f'^{0.193}_c/\delta_n^{1.615}$

σ_{tp} (peak shear stress) $= 0.1\, f'_c \sqrt{\sum_{i=6,10} a_i (\sigma_n/f'_c)^{i-6}}$ with $a_6, \ldots, a_{10}$ = constants.

5.4 Microplane Model [28]

The concrete, either solid or cracked, is considered as a system of randomly oriented planes (microplanes: Fig. 15a, b) which are characterized by a uniaxial normal stress-normal strain law; the shear stiffness of the microplanes is disregarded. Although originally developed for the description of the nonlinear behavior and fracture of concrete and rocks (Bazant and Oh, "Microplane Model for Progressive Fracture of Concrete and Rock", J. Engrg. Mech. ASCE, 111 - 1985, pp.559-582; Gambarova and Floris, "Microplane Model for Concrete Subject to Plane Stresses", Nuclear Engrg. and Design, 97 - 1986, pp. 31-48), the Microplane Model has been applied also to describe shear transfer across blunt cracks, by modelling the cracks as "crack bands", with a width equal to maximum aggregate size [28]. Simple asymptotic or exponential laws have been adopted both for loading and unloading (Fig. 15c). The model can describe concrete path-dependency and reorientation of principal stresses with respect to principal strains, and allows easy evaluation of the coefficients of the incremental stiffness matrix.

In Figs. 16, 17 and 18 the curves obtained with the 4 different mathematical models show a very good agreement with test results. Fig. 19 regards the design of the stirrups in thin-webbed I beams failing in shear due to stirrup yielding [24]: a remarkable saving in reinforcement amount can be achieved, if aggregate interlock is correctly modeled.

6. TENSILE FORCES ACROSS AN OPEN CRACK

As already mentioned in Section 2, interest in the tensile properties of concrete has increased very much in recent years, in connection with further investigation on bond, size effect in structural shear strength, comprehensive material models, crack formation and propagation (fracture mechanics , see Reinhardt, Cornelissen and Hordijk [30]). As to this last topic, five parameters are important: Young's modulus at the origin, peak stress (i.e. tensile strength), stress-free crack opening and shape of the descending branch (or the area under the total stress-deformation curve, which is related to the fracture energy), cracking front width (only if the crack band approach is adopted, see Bazant [9, 31]). Within this framework, attention was focused on very small values of the crack opening (generally under 0.10 - 0.15 mm , see the tests by Petersson [32]; Gopalaratnam and Shah [33]; Cedolin, Dei Poli and Iori [34]).

In many important cases, however, the structural engineer has to deal with much wider cracks even under service loads. Very often, large cracked interfaces form due to concrete splitting as in lapped splices, short anchorages with limited transverse pressure, and around the dowels, or to tensile cracking, as in r.c. sections subjected to bending and shear.

In these cases, only the knowledge of the constitutive law $\sigma(w)$ for relatively large crack openings makes it possible to evaluate the contribution of cracked interfaces to the structural strength. For this purpose, a few very recent tests by Giuriani, Rosati and Tornello [35] may be quoted: as can be observed in Fig. 20 (4th test of a 4 test series), crack width values as large as 0.75 mm were investigated. At w = 0.1 mm (Point C) the tensile strength is close to 0.7 MPa ($\simeq$20% f_{ct}), while at w = 0.7 mm the tensile strength reduces to 0.1 MPa ($\simeq$ 2.5 - 3% f_{ct}). According to these test results, the constitutive law of the crack is tentatively formulated in [35] as follows: $\sigma = f_{ct}/(C_1 w + C_2)$, where C_1 and C_2 are constants.

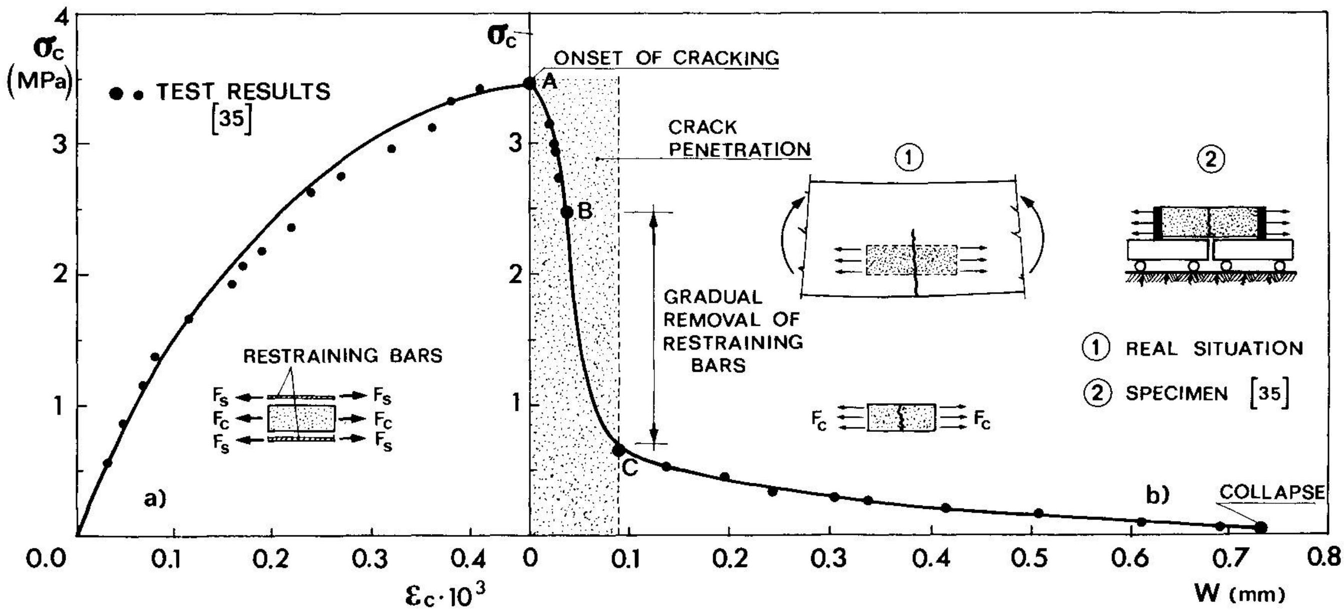


Fig.20 - (a) Stress-strain curve in tension and (b) stress versus crack opening curve for plain concrete [35]. Overall section of the restraining bars : A_s=161 mm^2 (steel); dimensions and area of the section of the concrete specimen : b=50 mm, h=60 mm , A_c= 3000 mm^2; f_c'= 42 MPa ; d_a (maximum aggregate size) = 15 mm.

Though the tensile strength of an open crack is certainly limited, still sizeable forces can be transferred across large cracked interfaces. Because of their contribution to the durability of concrete structures and to the control of concrete cracking, these forces should be taken into account and correctly evaluated.

7. CONCLUSION

Interface problems embrace so many different aspects of concrete mechanics that two risks are always involved, a lack of perspective if the research is devoted to one particular topic, and a lack of thoroughness if too many topics are investigated at the same time. Having this in mind, the different interface problems regarding either steel and concrete,or concrete and concrete are here analysed within the more general context of recent research on concrete mechanics.

As to bond behavior up to pull-out failure, to aggregate interlock and to concrete tensile behavior limited to small crack openings, suitable constitutive laws are already available though with lights and shades (particularly in the field of cyclic loads). On the other hand, bond behavior up to-and beyond concrete splitting, dowel action and transfer of tensile forces across open cracks require further research work in different directions (monotonic as well as repeated loads, for example). In the end, two goals will be achieved: a better understanding of the different phenomena and a more reliable and sound formulation of the constitutive laws.

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