BOND-BASED COMPUTATIONAL MECHANICS APPROACH TO PLAIN AND FIBRE REINFORCED CONCRETE

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The paper outlines the various steps towards simulating the process of structural loosening in plain concrete and SFRC. A major part of this process is governed by debonding of interfaces.
On the one hand, geometrical statistical features of material structures can be described by stereological methods. The mechanical characteristics, on the other hand, should be derived from bond experiments. These two subjects are covered. Bond testing has been accomplished by way of pull-out testing. The debonding has been visualized in a two-dimensional set-up by means of holographic interferometry.

INTRODUCTION

Mechanical behaviour of plain and steel fibre reinforced concrete (SFRC) heavily relies on bond. The process of structural loosening in such materials, either in tension or in compression, involves debonding of interfaces, since they form the weakest chain link. The resulting crack will not necessarily have to follow the interface, but will mostly be situated in a porous, coarse-textured interphase layer surrounding embedded bodies, such as particles and fibres. A computational mechanics (CM) approach to such problems would require modelling the relevant structural and micromechanical systems. Particularly,

a. a computer-simulation should be established of actual structural components by making use of sound geometrical-statistical (stereological) methods;
b. the appropriate details of debonding processes have to be determined.

This paper will present the main lines of such approaches, following a wide-ranging research program executed at the Civil Engineering Faculty of Delft University of Technology.

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UNIT VOLUME FOR STRUCTURAL LOOSENING

The general problem being tackled is concerned with a narrow zone through the material body comprising the fracture surface that will gradually develop under increasing loadings. This is called the unit volume of structural loosening (UVSL). It should be large enough to represent bulk properties of the material body. It may have different features when oriented in the respective orthogonal coordinate directions. In the case of stiffness in a certain direction, the location can be selected randomly. For strength simulation, the weakest chain link position would be the most appropriate one. A considerable amount of particles and fibres will be encompassed. In the weakest cross-section we will have relatively large amounts of particles and small numbers of fibres.

STEREOLOGICAL MODELLING

A fully developed system of isolated microcracks inside the UVSL characterizes an upper limit of stable crack development. The microcracks are predominantly located in the particle-matrix interfaces oriented (roughly) in-plane with the principal orientation plane of the UVSL. This limiting stage has also been defined as the lower limit of structural loosening, the (macro)crack initiation strength, or the discontinuity point (on the analogy of the elastic limit for steel). Figure 1 reveals the basic features of the model (Stroeven (1)).

Upon joining of roughly in-plane microcracks under increasing direct or secondary tensile stresses, a fully developed macrocrack will originate. It will separate the UVSL in two separate parts. Only fibres may still bridge the crack, transmitting in-plane and out of plane stresses as to the crack orientation (Fig. 2); It must be obvious from Figure 1, that the fibres have only minor influence on the process of microcracking below discontinuity. Simulations of these states of microcracking can therefore be limited to the particle structure. The underlying mechanisms of particle debonding have been described in Stroeven (1,2). The size distribution function of the cracks at the onset of macrocracking offers a stereological problem, the solution of which is readily available (Stroeven (3,4)). It is derived from a well-known theoretical concept stemming from the early twenties (Wicksell (5)).

The onset of macrocracking can be conceived in fracture mechanical (FM) terms. Either unit extension of the largest (circular) microcrack (its size being related to the particle size distribution), or unit extension of all in-plane microcracks can be presumed for a FM approach. The relevant 3-D model concerns a penny-shaped crack in the interior of an elastic body under tensile loadings. Due to fibre reinforcement, part of the crack surface will be stressed; at the crack tip region fibres may be assumed to inhibit crack opening as a result of interfacial shearing resistance, while behind this area a plateau value is obtained due to fibres being pulled-out from the matrix. The model, as sketched in Figure 3, has been successfully applied to asbestos fibre cement (Lenain and Bunsell (6)) and to SFRC (Stroeven (3)). In the latter case an orienting effect of the larger particles on the neighbouring fibres is incorporated. Anisometry of bulk fibre structure is accounted for as well.

For a continuum mechanical approach to SFRC one can interpret the onset of structural loosening as a fractional reduction in the load-bearing cross-section. Load is additionally transmitted by the fibre fraction that reinforces this reduced area. By assuming the fibres to be lineal elements in space (justified by their high aspect ratio) the stereological problem of an anisometric fibre reinforcement can be easily handled (Stroeven (7-9)).

It has been shown experimentally that a certain amount of anisometry (partial orientation) results from placing and compaction of the fresh concrete. Figure 4 shows data on fibre anisometry (expressed by the degree of orientation) and on the splitting tensile test executed perpendicularly to the gravity field. The degree of orientation, ω, was found to be proportional to V_f, the nominal value of the fibre volume fraction (Stroeven and Babut (10)). The actual reinforcement ratio of the fracture plane was also established to be proportional to the same design parameter, though being much lower than nominal. This is in accordance with theoretical predictions based on stereological reasoning. The design concept of the "characteristic strength" can therefore be applied to SFRC as well (Stroeven and Babut (11,12)).

In the case of plain concrete one may conceive the extension of the highly-stressed region in front of the bond cracks to govern strength. For a plane fracture surface (apart from the particle caps) we can directly relate the total length of this front, L, per unit of fracture surface (= cross-sectional area), A, to the specific surface area, S_V (=S/V), of the coarse particles in the UVSL (Stroeven (1)). Hence, $L/A=L_A=\pi S_V/4$. For mono-sized particles S_V is directly derived from its volume fraction, V_p. For a particle mixture we have $S_V=6M_2V_p/M_3$, with M_2 and M_3 being the second and third moment, respectively, of the designed particle size distribution (Stroeven (13)). This approach yields a CM concept in which strength would depend on the mix characteristics. At least, materials test data could be better interpreted in this way.

For shear loading the fracture mechanism is additionally governed by the roughness of the fracture plane. Roughness depends on the test conditions (a fast running crack yields a smoooth fracture surface) and on the particle size distribution. It has been demonstrated (Stroeven (13)), that the relevant stereological features can be expressed in moments of the particle size distribution function. A common measure to define surface roughness is the R(oot) M(ean) S(quare) value of the surface amplitude, i.e. the height, h, of the debonded caps of the one-sided embedded particles at the fracture plane. It is included in the stereological data set derived from the particle size distribution. The size distribution function of the circular sections of these caps in the fracture plane can easily be obtained upon substitution of the appropriate grain size distribution function in a well-known integral equation of Abel's type (Stroeven (1,4,13)). It has been demonstrated additionally that suitable approximations can be obtained by assuming the particles to be cubes or cylinders.

MICROMECHANICAL MODELLING

For FM as well as CM concepts it is required to model the pull-out behaviour of the fibres. Pull-out load-displacement curves have been determined experimentally for that reason on a large number of single fibres. Use was made of prismatic fibres (ARBED) and of fibres with anchoring facilities (THIBO and BEKAERT)(Stroeven and Shah et al (14)). In the latter case, a ploughing mechanism is added to the conventional stress transfer by interfacial shear and friction. As a consequence, the post-peak behaviour in a pull-out set-up is modified considerably.

Such typical differences are not reflected by SFRC specimens-containing the mentioned fibre types- subjected to direct tension (Shah and Stroeven et al (15)). This is due to the predominant oblique orientation of the fibres with respect to the fracture plane (Stroeven (3)). Hence, energy is consumed by additional mechanisms, that are similar for the various fibre types, provided their cross-sectional dimensions are equal (Aveston, Cooper et al (16), Brandt (17)). Finally, fibres will be pulled-out successively, as a result smoothing the sharp-peak characteristics of the single fibres.

Next the effect of the surface roughness on the pull-out behaviour was investigated (Stroeven and de Wind (18), Stroeven and Staveren et al (19)). It was found that upon increase of the surface roughness, the slip line moved from the interface between steel and mortar to a position inside a relatively porous, coarse-textured interphase layer surrounding the wire. In those cases, pull-out characteristics will be (predominantly) governed by matrix properties. The steel wires were pulled through a cubical specimen in a RILEM test set-up (Anonymus (20)). The location of the slip line was visualized under the microscope.

Progress was further achieved by recording the debonding front under load. To that end, in a 2-D configuration steel strips with different surface roughness profiles were embedded in mortar specimens. Pulling-out was observed by means of holographic interferometry. An example is shown in Figure 5. The pull-out load-displacement curves could be interpreted in terms of the debonded area at all stages of loading, as a result. Insight is obtained by doing so in the varying contributions of shearing and friction in the mixed-mode boundary situations over the load-displacement curve.

CM MODEL FOR SINGLE FIBRES AND FOR SFRC

An approach is being elaborated in analogy to a method used in foundation engineering (Poulos and Davis (23)). It is based on Mindlin's strain nuclei technique, dealing with an elastic half space subjected internally to a concentrated load, F. By superimposing a large series of such loads, F_i, acting along a line- being the axis of the wire- the complete stress-strain state in a pull-out experiment can be simulated.

Sofar only preliminary data are available (Bień and Grady (24)) revealing an exponentially type of interfacial shear stress distribution (Figure 6). Once the shear strength is exceeded near the surface of the body, we have to deal with mixed boundary conditions; a constant value of the friction resistance might be accepted. Oscillations occur near the surface of the body (=crack surface), as expected. This points towards an optimum solution for the slenderness of the elements. On the other hand, the concentrated loads may be shifted to other positions along the line, however more in aacordance with the exponentially type of interfacial shear stress distribution. This would lead to a (fastly converging) iterative approach, which strongly suppresses the oscillations at the protruding end of the wire. Small modifications would allow for encompassing a wire being pulled-out obliquely with respect to the crack plane. By superposition also wire interferrence effects could be studied.

The finite element method (FEM) was also used to find the stress-strain distribution in pull-out specimens. Figure 7 presents a single result of the numerical analysis of the 2-D model. The FEM analysis will be developed to incorporate experimental data.

CONCLUSIONS

All necessary steps have been realized towards simulating structural loosening of plain concrete and of SFRC. The CM model is based on debonding as the leading mechanism for structural loosening during load transfer in these materials. Modelling of the geometrical-statistical features of the material body is accomplished with stereological methods. Mechanical characteristics have been determined experimentally in 2-D and 3-D pull-out set-ups. Mindlin's strain nuclei approach and models based on FEM sofar offered relevant information on the stress-strain state in pull-out testing. This would also render possible to evaluate the holographic interferometry data in terms of local bond versus local slip.

SYMBOLS USED

L_A = crack length (L) per unit area (A) (mm/mm^2)

S_V = crack surface area (S) per unit volume (V) (mm^2/mm^3)

REFERENCES

(1) Stroeven,P.,PhD thesis, Delft University of Technology, 1973.

(2) Stroeven, P.,"Mechanical behaviour of materials". Edited by K.J.Miller and R.F.Smith, Pergamon Press, Toronto, 1979.

(3) Stroeven, P.,Proceedings"Fracture mechanics of fibre reinforced cement-based composites". Edited by P.Stroeven, Delft University of Technology, 1970.

(4) Stroeven, P.,Proceedings of the "Third Conference on Safety of Bridge Structures".Technical University of Wroclaw, 1987.

(5) Wicksell,S.D., Biom., Vol.17, 1925, pp.84-96.

(6) Lenain,J.C., Bunsell,J.,J.Mater.Sci., Vol.14, 1979, pp.321-332.

(7) Stroeven,P.,Mater.Constr., Vol.12, No.67, 1979, pp. 9-20.

(8) Stroeven,P.,J.Microsc., Vol.111, Pt.3, 1977, pp.283-295.

(9) Stroeven,P.,Proceedings "Second European Conference on NDT". Austrian Soc.NDT, Vienna, 1981.

(10) Stroeven,P.,Babut,R.,Heron, Vol.31, No.2, 1986, pp.15-45.

(11) Stroeven,P.,Babut,R.,Proceedings "Fourth European Symposium for Stereology". Edited by R.Karlsson et al, Chalmers University, Göteborg, 1987.

(12) Stroeven,P.,Babut,R.,"Brittle Matrix composites". Edited by A.M.Brandt and I.H.Marshall, Elsevier, London, 1986.

(13) Stroeven, P.,Composites, Vol.13, No.4, 1982, pp.129-139.

(14) Stroeven,P. et al,Proceedings "RILEM Symposium Testing and Test Methods of Fibre Cement Composites". Construction Press, Lancaster, 1978.

(15) Shah,S.P. et al,Proceedings "RILEM Symposium Testing and Test Methods of Fibre Cement Composites". Construction Press, Lancaster, 1978.

(16) Aveston,J. et al,Proceedings "Conference National Physical Laboratory". IPC Science and Technology Press, 1971.

(17) Brandt,A.M., Report Stevin Laboratory, D.U.T., 1985.

(18) Stroeven,P., de Wind,G.,"Bond in Concrete". Edited by G. Bartos, Applied Science Publishers, London, 1982.

(19) Stroeven,P. et al,Proceedings"Internationalen Kolloquium über das Festigkeits- und Verformungsverhalten von Beton", Technische Universität Dresden, Dresden, 1979.

(20) Anonymus, Recommandations for approval, supply and acceptance of steels for prestressing tendons, RILEM/FIP/CEB,1974,

(21) Bień,J., Report 1-86-9, Stevin Laboratory, D.U.T., 1986.

(22) Stroeven,P.,Bień,J.,Proceedings"International Conference Measurement of Static and Dynamic Parameters of Structures and Materials", IMEKO, Plzen, 1987.

(23) Poulos,H.G.,Davis,E.H., "Pile Foundation Analysis and Design", Wiley, New York, 1980.

(24) Bień,J.,Grady,S., Report 1-86-12, Stevin Laboratory, D.U.T., 1986.

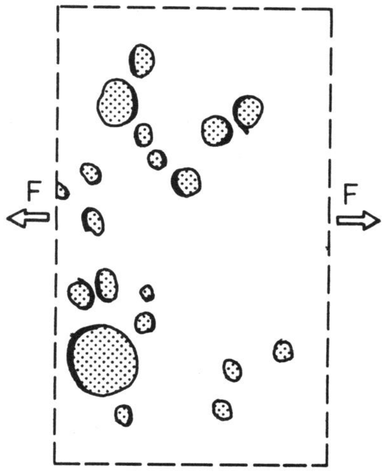

Figure 1 Cracking at lower limit of structural loosening.

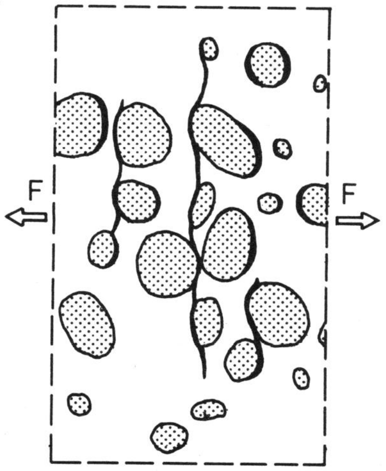

Figure 2 Formation of macrocracks due to crack coalescence.

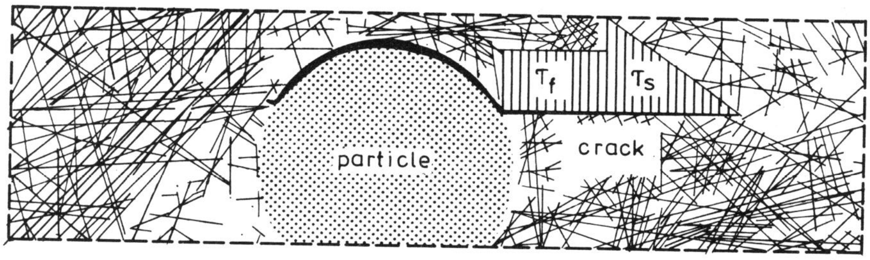

Figure 3 (Macro)crack initiation in SFRC; crack opening is inhibited by shear τ_s and friction τ_f at steel-matrix interfaces.

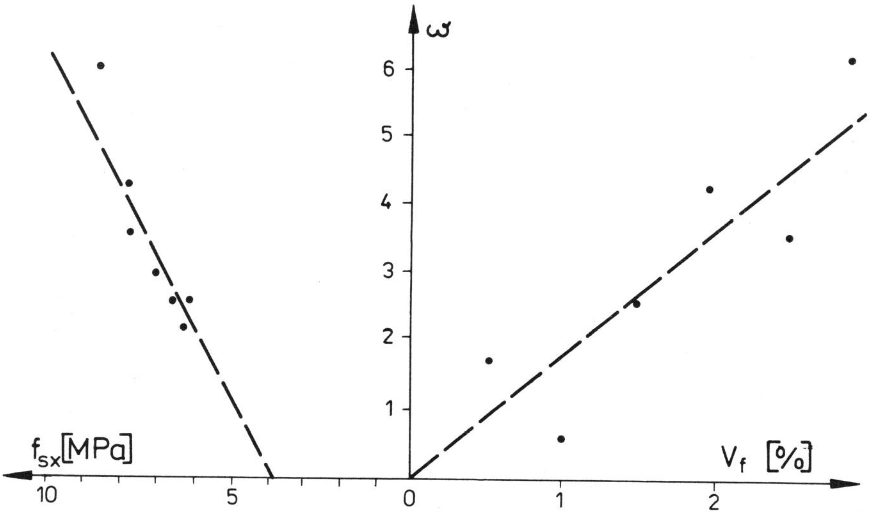

Figure 4 Splitting tensile strength f_{sx} as function of degree of orientation ω (left). ω is governed by fibre addition V_f (right).

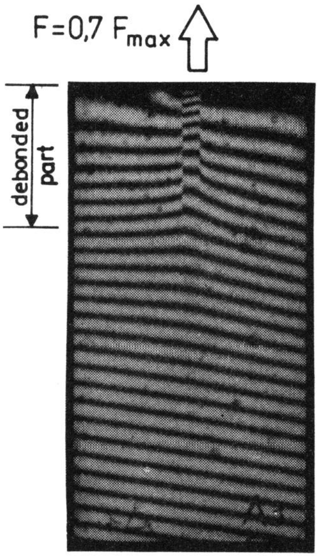

Figure 5 Interferogram reveals debonding in pull-out set-up.

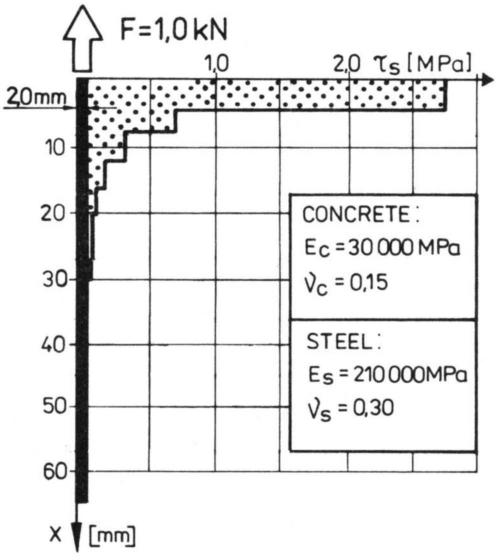

Figure 6 Interfacial shear stress distribution (Mindlin approach).

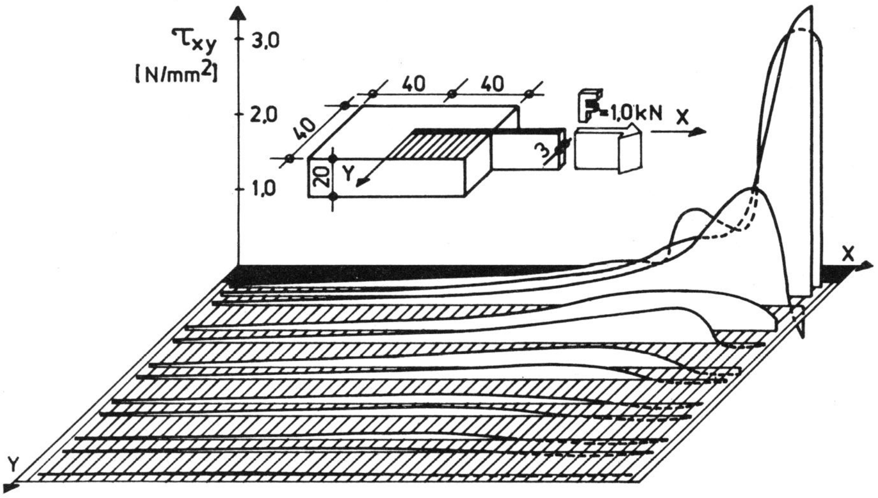

Figure 7 Shear stresses τ_{xy} in 2-D model of pull-out specimen obtained by finite element analysis (full bonded case).