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STEEL WIRE EFFICIENCY IN MECHANICAL TESTING OF CONCRETE

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ABSTRACT

In concrete technology steel wires are generally assumed being "randomly" distributed through the material. The efficiency in improving mechanical characteristics is therefore expressed in a constant reduction factor with respect to a material reinforced by an unidirectional system of similar wires. This holds for analytical approaches underlying design as well as for the experimental assessment of material parameters. Stereological notions have been employed for modelling partially oriented wire systems. Using this concept, the orientation distribution is studied of the sub-set of wires responsible for improvements in mechanical characteristics. Results are applied to interpret various pull-out test set-ups used in practice.

Keywords: Cracking, concrete, mechanical testing, pull-out, reinforcement efficiency, wire orientation.

INTRODUCTION

It has been demonstrated by quantitative image analysis approaches that segregation and anisometry in the reinforcement system will inevitably arise from placement and compaction of the fresh mix (Stroeven & Shah, 1978; Kasperkiewicz, Malmberg & Skarendahl, 1978; Stroeven & Babut, 1986; Granju & Ringot, 1989; and others). Global mechanical experiments on such specimens as a result revealed anisotropic behaviour in splitting tensile mode and disproportionally improved bending behaviour.

For correctly assessing mechanical behaviour in tests, as well as for properly estimating mechanical behaviour (such as for design purposes), models are developed simulating actual wire dispersions. A practical solution is provided by taking mixtures of portions of 1-D, 2-D and 3-D wire systems. Anisotropy is governed by the relative amounts of 1-D and 2-D wires. Gradients in the gravity field direction of volume density will reflect segregation.

Fluctuations in volume density along the specimen or element axis allow simulating features of the weakest chain link in the reinforcement system (Guo and Stroeven, 1989). Also the under-reinforcement of boundary layers can be modelled by applying a similar stereological concept (Stroeven, 1991).

The reinforcement efficiency of small volume fractions of short steel wires becomes significant only in *cracked* concrete. Hence, beyond the so called cracking strength or onset of major cracking at, say, three-quarters of the structural element's ultimate capacity, one should deal with the wires inhibiting cracks to open up under increasing loadings. *This wire sub-set is a weighted portion of the population*, a phenomenon generally ignored in concrete technology. Even when crudely approximating wires to be "randomly" distributed in bulk this sub-set contains wires with a prevailing orientation!

The *active part* of the cracks in concrete subjected to uniaxial tensile stresses presumably will form (approximately) a parallel array. As a result the morphology of the sub-set of wires can easily be derived from that of its population. Stereological estimates for wire efficiency under these conditions have been based on such notions (Stroeven, 1989; Stroeven and de Haan, 1992; and Stroeven, 1993). Global mechanical modelling requires insight into leading micro-mechanical mechanisms. The latter is pursued, among other things, by pull-out testing. 1-D, 2-D, respectively, 3-D wire pull-out tests, aiming the simulation of group behaviour of wires in a tensile stress field, will be evaluated in this paper on the basis of these stereological principles.

WIRE REINFORCEMENT EFFICIENCY

An arbitrarily selected short steel wire intersecting with a crack in a concrete element subjected to direct tension will tend to slip out of the matrix pocket. The same situation is met when a wire embedded in a concrete specimen is subjected to a pull out load, provided the angular mismatch is similar in both cases. This is sketched in Fig. 1. Brandt (1985) has shown along analytical lines that three mechanisms will predominantly contribute to energy dispersion under increasing loadings in the given set up, ie friction along the wire-matrix interface, shearing of the wire over the crack edge and plastic deformation of the wire at the crack surfaces. It was experimentally shown, however, that the completely pulled out wire ends more or less seem to maintain their original orientation after full separation of the specimen parts. This is probably due to local destruction of the crack edges. Contribution of plastic deformation to energy dispersion will therefore be significantly reduced.

As a consequence, the wire load transferred perpendicular to the crack surfaces will be given by

$$P_f'(\alpha) = \pi d l_i \tau_f (\cos\alpha + f \sin\alpha) \tag{1}$$

in which α is the angular mismatch of a wire with diameter d and length l. This wire is embedded over a length l_i. The presumably uniform friction resistance excercised along the embedded part is τ_f, and the coefficient of friction at the crack edge f. It must be obvious that in a single fibre pull-out test $f = 0$, so no information is obtained on this mechanism of load transfer. When more wires are simultaneously pulled-out they will be arranged in a symmetric way with respect to the loading direction. Hence, a two-wire pull-out test would be the bare minimum when aiming for incorporation of the "shearing over the crack edge" mechanism in the test programme.

For comparison reasons the average wire load component can be determined which is

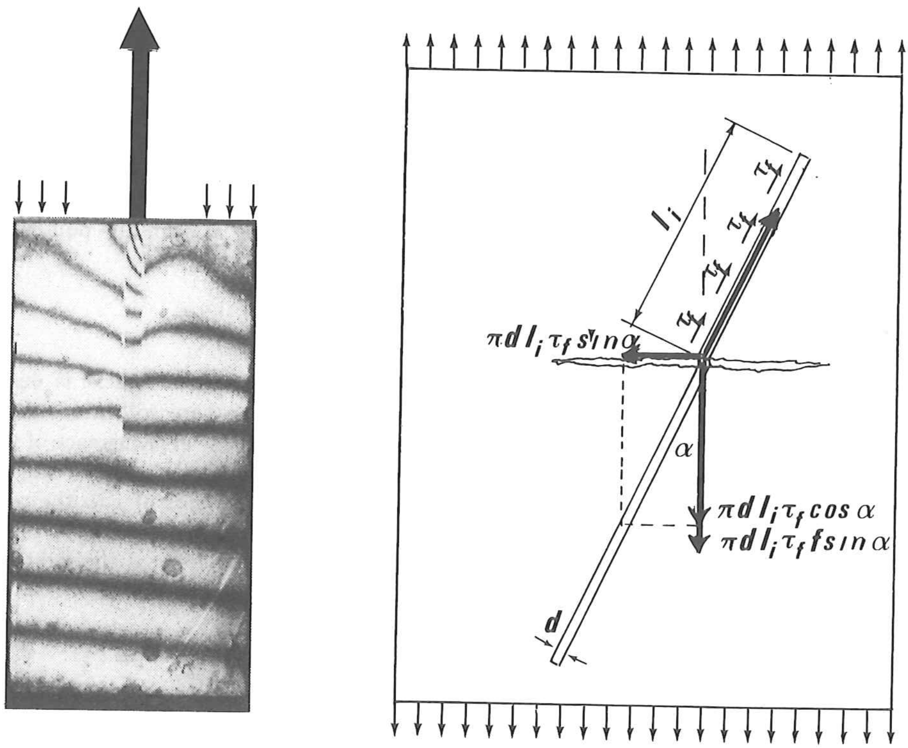

Fig. 1. Single wire pull-out test observed with holographic interferometry, revealing debonded interface by discontinuities in fringes (left) and wire subjected to pull-out loading at crack in tensile test (right)

transferred perpendicular to the crack surfaces in a tensile test. This is obviously given by

$$\overline{P_f'}(tension) = \pi d \frac{l}{4} \tau_f \overline{(\cos\alpha + f \sin\alpha)} \tag{2}$$

in which the average values of the trigonometric functions exclusively deal with the aforementioned sub-set of wires. The average value of the pull-out load perpendicular to the "crack" is obtained by averaging eq (1) with respect to α. Hence,

$$\overline{P_f'}(pullout) = \pi d \frac{l}{2} \tau_f \overline{\cos\alpha + f \sin\alpha} \tag{3}$$

in which it is assumed that the wires are embedded over half their length. The average values of the trigonometric functions concern the angular orientation distribution of the wires as arranged by the researcher.

When a large number of wires is involved in pull-out testing it is also possible to determine as a reference the stress component transferred perpendicular to the crack plane.

It is obtained by multiplication of both sides of eqs (2) and (3) by the number of wires per unit of crack area, N_A. Hence

$$\sigma_{fn}(tension) = \frac{\pi}{4} d l \tau_f (N_A)_t \overline{(\cos\alpha + f\sin\alpha)} \tag{4}$$

$$\sigma_{fn}(pullout) = \frac{\pi}{2} d l \tau_f (N_A)_p \overline{(\cos\alpha + f\sin\alpha)} \tag{5}$$

The orientation distribution on which the averaging process should be based can be of a 2-D or 3-D character. This holds for the tensile test, but theoretically also for the pull-out set up. This morphological problem will be discussed in what follows.

WIRE ORIENTATION DISTRIBUTION

The orientation distribution function of the wire reinforcement at cracks is derived from that in bulk by accounting for the relative probability that a wire will intersect with the crack plane. This is obviously equal to $\cos\alpha$. Hence, the frequency of occurrence of wires reinforcing the crack increases with deminishing angle α. Or, loosely speaking: "the wires in the sub set are more favourably oriented for stress transfer perpendicular to the cracks than those in bulk".

With this in mind, the average values of the trigonometric functions at the right hand side of eq (2) are readily obtained. Hence, for a 2-D dispersion it is found that

$$\overline{\cos\alpha} = \frac{\int_0^{\frac{\pi}{2}} \cos^2\alpha d\alpha}{\int_0^{\frac{\pi}{2}} \cos\alpha d\alpha} = \frac{\pi}{4} \quad \text{and} \quad \overline{\sin\alpha} = \frac{\int_0^{\frac{\pi}{2}} \sin\alpha\cos\alpha d\alpha}{\int_0^{\frac{\pi}{2}} \cos\alpha d\alpha} = \frac{1}{2} \tag{6}$$

yielding for the in-plane load component in the 2-D case according to eq (2)

$$\overline{P'_{f2}}(tension) = \frac{\pi}{4} d l \tau_f (\frac{\pi}{4} + \frac{f}{2}) \tag{7}$$

When in case of a pull-out test the wire distribution would be artificially arranged as a 2-D "random" one, the average values of the trigonometric functions at the right hand side of eq (3) would be

$$\overline{\cos\alpha} = \frac{\int_0^{\frac{\pi}{2}} \cos\alpha d\alpha}{\int_0^{\frac{\pi}{2}} d\alpha} = \frac{2}{\pi} \quad \text{and} \quad \overline{\sin\alpha} = \frac{\int_0^{\frac{\pi}{2}} \sin\alpha d\alpha}{\int_0^{\frac{\pi}{2}} d\alpha} = \frac{2}{\pi} \tag{8}$$

so that eq (3) would yield

$$\overline{P'_{f2}}(pullout) = d l \tau_f (1 + f) \tag{9}$$

Obviously, the average transmitted wire load perpendicular to the crack plane in a pull-out set up is a biased estimator of the normal load component in a tensile test. Upon substitution of the average values of the trigonometric functions in eqs (4) and (5) a similar conclusion can be drawn as to the normal stress components in the different mechanical modes.

The average values of the trigoniometric functions in eqs (2) and (3) are for the 3-D case, respectively

$$\begin{aligned} \overline{\cos\alpha} &= \frac{\int_0^{\frac{\pi}{2}} \cos^2\alpha\sin\alpha d\alpha}{\int_0^{\frac{\pi}{2}} \cos\alpha\sin\alpha d\alpha} = \frac{2}{3} \quad \text{and} \quad \overline{\sin\alpha} = \frac{\int_0^{\frac{\pi}{2}} \sin^2\alpha\cos\alpha d\alpha}{\int_0^{\frac{\pi}{2}} \sin\alpha\cos\alpha d\alpha} = \frac{2}{3} \\ \overline{\cos\alpha} &= \frac{\int_0^{\frac{\pi}{2}} \sin\alpha\cos\alpha d\alpha}{\int_0^{\frac{\pi}{2}} \sin\alpha d\alpha} = \frac{1}{2} \quad \text{and} \quad \overline{\sin\alpha} = \frac{\int_0^{\frac{\pi}{2}} \sin^2\alpha d\alpha}{\int_0^{\frac{\pi}{2}} \sin\alpha d\alpha} = \frac{\pi}{4} \end{aligned} \tag{10}$$

so that the respective normal load components are given by

$$\overline{P'_{f3}}(tension) = \frac{\pi}{6} dl\tau_f(1+f) \tag{11}$$

$$\overline{P'_{f3}}(pullout) = \frac{\pi}{4} dl\tau_f(1+\frac{\pi}{2}f) \tag{12}$$

This reveals the 2-D pull-out test to be the best estimator of 3-D wire reinforcement efficiency. In actual situations always partially oriented wire distributions are encountered, however. It can easily be demonstrated that the normal stress transferred at the crack by the wires of a *partially-planar* system, with the orientation plane perpendicular to the crack plane is by good approximation given by (Stroeven, 1989)

$$\sigma_{nf} = \frac{1}{3} a\tau_f V_f (1+f)(1+\frac{\omega}{2(1+f)}) \tag{13}$$

in which a and V_f are the aspect ratio and volume fraction of the wires, and ω is the degree of wire orientation. So even for the partially planar case the 2-D pull out test can provide reliable estimates for reinforcement efficiency!

RELEVANCE OF SIMPLE WIRE PULL OUT SET UPS

Pull-out testing of wires is complicated. Mostly, single wire tests are performed, as a consequence. But it was already demonstrated that only one of the two significant mechanisms for load transfer is reflected by such tests. A double wire pull-out test would be the best solution in terms of the economy of the experiment, provided an "appropriate" value is selected for the angular mismatch (ϕ_0).

To find solutions for this problem, the relative contribution to the normal load component of a set, $N(\phi)$, of similarly oriented reinforcing wires in cracked sections, is for 2-D and 3-D systems obtained from eq (2) by multiplication with the orientation frequency. Hence

$$\frac{N(\phi)}{N_T} P'_{f2}(\phi) = \frac{\pi}{4} dl\tau_f(\cos\phi + f\sin\phi)\cos\phi \tag{14}$$

$$\frac{N(\phi)}{N_T} P'_{f3}(\phi) = \frac{\pi}{4} dl\tau_f(\cos\phi + f\sin\phi)\cos\phi\sin\phi \tag{15}$$

in which N_T is the total number of wires intersecting with the crack. By taking $f = \tan\phi'$, eqs (14) and (15) can be transformed into

$$\frac{N(\phi)}{N_T} P'_{f2}(\phi) = \frac{\pi}{8} dl\tau_f(1+\frac{\cos(2\phi-\phi')}{\cos\phi'}) \tag{16}$$

$$\frac{N(\phi)}{N_T} P'_{f3}(\phi) = \frac{\pi}{8} dl\tau_f\frac{\cos(\phi-\phi')}{\cos\phi'}\sin 2\phi \tag{17}$$

It is easily seen that optimum contribution to load transfer in the 2-D case will be stemming from wires with an angular mismatch $\phi_0 = \phi'/2$. Taking f=0.36 yields $\phi' = 20^0$. Making the first derivative of eq (17) zero yields: $\cos(3\phi-\phi')/\cos(\phi+\phi') = -1/3$, which has a solution for $\phi_0 = 40^0$. Hence, particularly for the most general case of a partially planar wire system with a small to moderate degree of orientation the angular mismatch in a double wire pull-out test should be around, say, $\phi_0 = 35^0$.

CONCLUSIONS

Partially oriented wire reinforcement systems are modelled by using stereological notions. In concrete the employed steel wires become effective only after cracking of the matrix. Mechanical improvements are as a consequence only stemming from wires intersecting with the crack arrays developed under load. The global orientation distribution of the effective wire reinforcement is analysed. Since applied wires are relatively short, the major micromechanical mechanisms for energy dispersion under increasing global deformations are wire-matrix sliding (pull-out) and shearing of the wires over the crack edges. Tensile strength characteristics of wire reinforced concrete are derived from pull-out data on wires. Mostly, single wire pull-out tests are performed. The developed model allowed to analyse the possible pull-out concepts on relevance in estimating composite behaviour. It was demonstrated that a double wire symmetric pull-out set-up, with an angular mismatch of about 35^0 would offer optimum information.

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