FRACTURE ENERGY OPTIMIZATION IN SYNTHETIC FIBER REINFORCED CEMENTITIOUS COMPOSITES

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ABSTRACT

A study has been carried out on cementitious composites reinforced with various synthetic fibers, focusing on their tensile behavior, toughness, and fracture mechanisms. A model is formulated to predict the tensile behavior and fracture energy of fiber reinforced cementitious composites (FRC) with short, randomly distributed fibers. The model accounts for the pull-out of fibers oblique to the fracture surfaces (including snubbing friction effect), and the variation of the fiber/matrix interfacial shear stress during pull-out. Experimental and analytical results are shown to be in close agreement for the one class of fiber reinforcement which best satisfies the assumptions of the model. Systems which violate the assumptions exhibited different failure mechanisms and were observed to show less satisfactory reinforcement performance, especially the composite fracture energy. The model is used to examine the effect of fiber properties on composite post-cracking behavior and is useful in design of such material systems with optimum performance and cost effectiveness.

INTRODUCTION

Synthetic fibers can provide effective, inexpensive reinforcements for concrete as alternatives and replacement of asbestos, steel and glass fibers. However, most fibers are not effectively used in FRC because the fiber mechanical/geometrical properties are not properly tuned to give the best reinforcement results. In other words, if the fibers were optimized, the same FRC property improvement could be achieved at lower expenses, or better improvements could be obtained without increasing the reinforcement cost. An illustrative example is given as follows.

Consider an FRC with short fibers in 3-D random distribution for which it is observed that all fibers bridging a matrix crack are pulled out from the matrix when failed. Since there is no fiber rupture, the fiber rupture strength plays no role in the FRC. Because the cost of a fiber generally increases with its strength, we can reduce the FRC cost by using fibers with lower strength but still high enough to prevent fiber rupture while other quantities being fixed. Alternatively, we could increase the fiber/matrix bond strength until fiber rupture starts to occur. Better FRC properties are expected due to this change if the fiber volume is kept constant. Or reduced cost can be achieved for the original property improvement since the fiber volume required is lower.

Mat. Res. Soc. Symp. Proc. Vol. 211. ©1991 Materials Research Society

The optimization of fiber reinforcement of concrete requires both a theoretical study to predict FRC behavior from the properties and dimensions of the fibers, matrix, and the fiber/matrix interface; and an experimental study to develop practical methods to control those reinforcement parameters. Studies on this subject have not been widely carried out. In this study on synthetic fiber reinforced cementitious composites, commercial synthetic fibers were used, including aramid, nylon, acrylic, polyethylene, and polypropylene. Some of the results have been summarized in previous papers [1-7].

UNIFORMITY OF FIBER DISTRIBUTION IN FRC

A uniform fiber distribution is essential for effective fiber reinforcement because fiber bundling and clumping in FRC not only reduce the efficiency of fibers, but also introduce weak spots in the composite. The uniformity of fiber distribution in FRC depends strongly on the fiber surface finish applied by the fiber manufacturers [1,2,4]. It has been observed that the finishes on Spectra 900 (polyethylene) and Herculon PP (polypropylene) fibers made the fibers readily dispersible in aqueous media, and the fiber distribution in FRC was fairly uniform at low fiber volume fractions. However, aramid fibers (Kevlar 49, Technora), coated with other types of finishes, did not disperse well in cement slurry and they appeared in large bundles in FRC. As a result, most aramid FRCs exhibited relatively low fracture energy. A comparison of fiber distribution in FRC is provided in Figure 1. Clearly, suitable fiber finishes promoting good fiber dispersion in cement slurry should be developed and be used with fibers for optimal reinforcement.

The uniformity of fiber distribution also depends on the workability of the freshly mixed concrete. The use of superplasticizers in concrete mix to improve the workability is now a common practice. The effect of superplasticizer on the fiber/matrix interfacial properties, especially over long periods of time, still remains to be determined.

CONSTITUTIVE THEORY FOR FRC TENSILE BEHAVIOR

In general, the properties of FRC depend on the fiber properties (tensile, bending) and size (length, diameter), the matrix properties, the fiber/matrix interfacial properties (bond strength, frictional characteristics), the fiber volume fraction, and the distribution of fibers in the composite matrix.

To guide the optimization of FRC behavior by proper selection of type and form of the material components, and to predict the response of FRC in direct tension, a theoretical model has been developed for the tensile behavior of FRC containing fibers in 3-dimensional random distribution [3]. The model predicts the tensile stress vs. crack opening width (σ-δ) curve of FRC based on the properties and dimensions of the fibers, matrix, and the fiber/matrix interface. Its modeling procedure is shown in Figure 2. The model is based on: (1) the theoretical model for two-sided fiber pull-out which takes into consideration possible fiber/matrix bond strength variation with slippage distance due to fiber surface abrasion or matrix break-down during pull-out [1,6]; (2) the snubbing friction effect due to fiber pull-out at angles which characterizes the increase of fiber pull-out load with the increase of fiber inclining angle observed in experiments [1,5]; (3) the probability density functions of fiber embedded lengths and orientations relative to the matrix crack for fibers bridging the crack, and (4) the equilibrium and geometric compatibility conditions. The

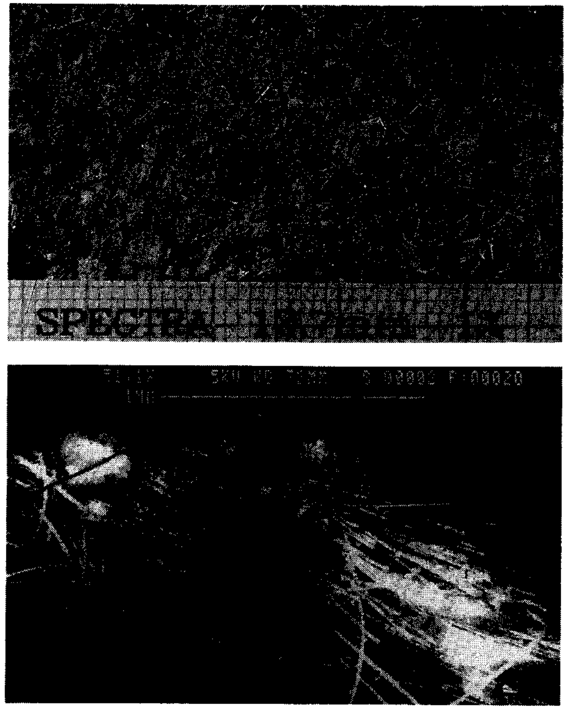
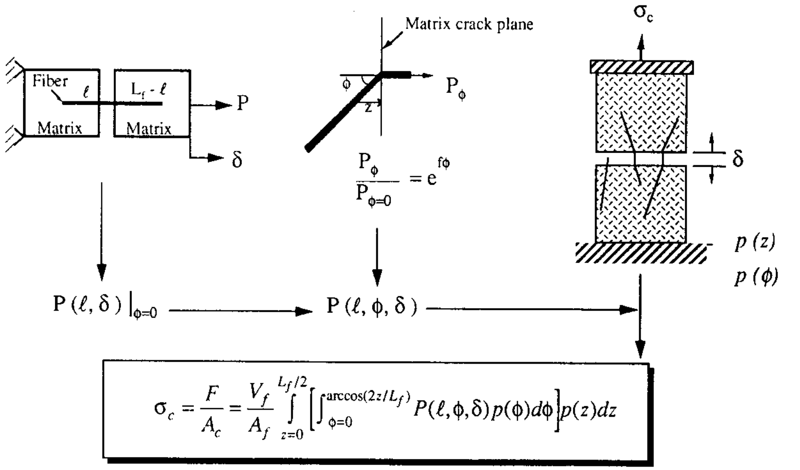


Figure 1: Photographs of Fracture Surface of FRC Specimens tested in Direct Tension. *TOP:* FRC containing 1% by volume of 12.7 mm-long SPECTRA fibers. Spacing of grids is 1 mm/grid. Uniform fiber distribution can be seen. *BOTTOM:* FRC containing 1% by volume of 6.35 mm-long TECHNORA fibers. Almost all the fibers were in bundles or clumps.



$$\sigma_c = \frac{F}{A_c} = \frac{V_f}{A_f}\int_{z=0}^{L_f/2}\left[\int_{\phi=0}^{\arccos(2z/L_f)} P(\ell,\phi,\delta)p(\phi)d\phi\right]p(z)dz$$

Figure 2: Modelling procedure for predicting the stress-crack separation curve of FRC

model is applicable to FRC that has uniform fiber distribution (rather than in bundle forms) and exhibits fiber pull-out as its major failure mechanism. Comparison between theory and experimental measurement of Spectra FRC with low fiber volume fractions indicates that the model gives good prediction of the FRC tensile behavior, as shown by Figure 3.

PARAMETRIC STUDY AND DISCUSSION

An example of parametric study based on this model is shown in Figure 4. When the snubbing friction effect is neglected ($f = 0$), the theory shows that the FRC fracture energy G increases with the fiber length L_f, until it reaches $2L_c$, where L_c is the critical length of fiber pull-out defined as the maximum fiber embedded length for a fiber to be pulled out without rupture from the matrix, related to fiber diameter (d_f), fiber rupture stress (σ_f^u), and fiber/matrix bond strength (τ) by:

$$L_c = \frac{d_f\,\sigma_f^u}{4\,\tau} \tag{1}$$

After reaching $L_f = 2L_c$, G decreases with L_f due to fiber rupture.

When the snubbing friction is considered ($f > 0$), the fiber rupture occurs at shorter fiber length (i.e. $L_f < 2L_c$) because the stresses in the inclined fibers are higher than those in the aligned fibers for the same embedded length. At the same time, the maximum G achievable is lower in comparison with G_{max} for $f = 0$. However, for relatively short fiber length (i.e. $L_f < L_c$), G increases with f.

The experimentally measured values of the snubbing friction coefficient f for polypropylene and nylon fibers were in the range of 0.7—1.0 [1,5]. As seen from Figure 4 for f in this range, the highest toughness G is achieved when

$$L_f = L_f^{\text{optimal}} \approx \frac{2.6}{g} L_c = \frac{2.6}{g}\,\frac{d_f\,\sigma_f^u}{4\,\tau} \tag{2}$$

where g is defined in term of the snubbing friction coefficient f:

$$g \equiv \frac{2}{4+f^2}(1+e^{\pi f/2}) \tag{3}$$

For FRC with 3-D random fiber distribution, such condition ensures that almost all the fibers bridging a crack will be pulled out rather than rupture, and that the fiber strength can be reached in some fibers. It should also be borne in mind that maintaining acceptable workability of fresh FRC may impose an upper limit on L_f which is typically 25 mm.

For the special case when the fiber elasticity can be neglected, Li [8] showed that

$$G_c = \frac{1}{12}\,g\,\tau\,V_f\,d_f\,(\frac{L_f}{d_f})^2 \tag{4}$$

Using Equations (1)–(3), the optimal fracture energy is then

$$G^{\text{optimal}} \approx \frac{0.035\,V_f\,(\sigma_f^u)^2}{g}\,\frac{d_f}{\tau} \tag{5}$$

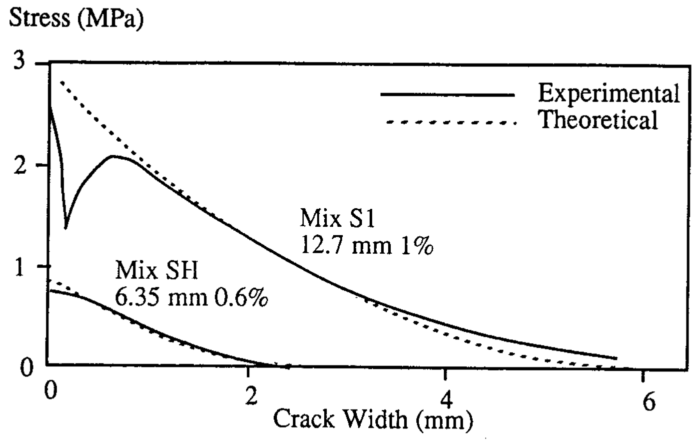


Figure 3: Comparisons of model predicted Stress vs. crack separation curves for two mixes of SPECTRA fiber reinforced mortar. Initial load drop in experimental curve for Mix S1 was due to matrix spalling, a factor not accounted for in the model. Method of direct tensile test is described in Ref. [7]. ($d_f = 38\mu$m, $E_f = 117$ GPa, $\tau = 1.02$ MPa, $L_c = 24.22$ mm, $f = 0.7$)

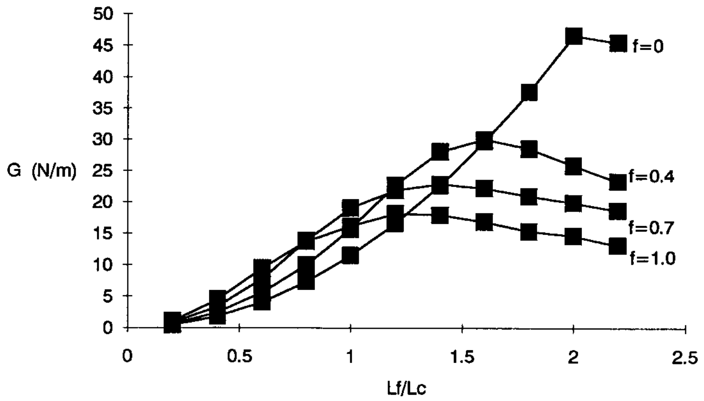


Figure 4: Model predicted fracture energy G as a function of fiber length L_f for different snubbing friction coefficients f ($d_f = 38\mu$m, $V_f = 1\%$, $E_f = 117$ GPa, $\tau = 1.02$ MPa, $L_c = 24.22$ mm).

Table 1: Predicted fracture energies for Spectra fiber reinforced mortar ($V_f = 1\%$, $\sigma_f^u = 2.6\text{GPa}$, $d_f = 38\mu\text{m}$, f=0.7)

Condition	L_f (mm)	τ (MPa)	G (kJ/m^2)
"As is"	12.7	1.02	6.4
optimal L_f, τ unchanged	≈35	1.02	≈49
optimal τ, L_f unchanged	12.7	≈2.83	≈18

It is interesting to note that the optimal fracture energy scales with d_f/τ. This implies that if the optimal fiber length L_f^{optimal} is always used, then large fiber diameter and low bond strength is preferred for maximizing fracture energy of the composite. In contrast, earlier work by Aveston *et al.* [9] for continuous fiber reinforced cement system, by Marshall *et al.* [10] for continuous fiber reinforced ceramic system, and by Li and Leung [11] for discontinuous random fiber reinforced brittle matrix system all suggest a preference for low d_f/τ for optimization of the first crack strength. It should be clear then, that composite optimization must be carried out with a clear view of the performance requirement in mind. In application where high energy is important, high fracture energy should be optimized. In applications where the structure members cannot tolerate a single crack, then high first crack strength should be given the first priority.

To have a better appreciation of practical constraint on fracture energy optimization, we use the Spectra fiber reinforced mortar as an example. In the "as is" condition, the fiber length is 12.7 mm and the (measured and predicted) fracture energy is 6.4 kJ/m^2 (Table 1). Using optimized L_f (35 mm) while keeping d_f and τ in the "as is" condition will increase the fracture energy by six times to 49 kJ/m^2. However, this long optimal fiber length may lead to unacceptable workability of the fresh FRC mix. An alternative may be to increase the interfacial bond strength while keeping the fiber length at 12.7 mm. The optimal bond strength, according to Equation (2), should be 2.83 MPa. This bond strength optimization would increase the fracture energy to 18 kJ/m^2, which is about 200% higher than that for the "as is" condition. Controlling the fiber/matrix bond strength may be achieved by, for example, (1) producing fibers with varying cross sections resulting in mechanical interlocking; (2) developing special fiber coating materials; (3) fiber crimping or texturing; and (4) plasma treatment of fiber surface.

SUMMARY

Fiber pull-out is the major mechanism contributing to the high toughness of FRC. Optimal utilization of the reinforcing fibers can be obtained when (1) fibers are uniformly distributed in the matrix and (2) the fiber/matrix bond property and fiber size (length, diameter) are properly selected. A micromechanical model developed for fracture energy optimization may be used for this purpose. Although designed for synthetic fiber composites, the model may be adapted for cementitious composites with other fiber types as well. In the case of synthetic fiber composites, the snubbing friction effect is shown to be important in determining the optimal fiber length and composite fracture energy. Since most fiber reinforced concrete presently used is not optimized, significant increase in fracture energy may be expected by optimization. It is pointed out, however, that fracture energy optimization may be constrained by processing considerations and by other performance requirements.

Acknowledgement

One of the authors (VCL) would like to acknowledge research grant supports to the University of Michigan from the Air Force Office of Sponsored Research (Program Manager: Dr. Spencer Wu), and from the National Science Foundation (Program Manager: Dr. Ken Chong).

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