# EFFECT OF FIBER-MATRIX BOND STRENGTH ON THE CRACK RESISTANCE OF SYNTHETIC FIBER REINFORCED CEMENTITIOUS COMPOSITES

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## ABSTRACT

Fiber matrix bond characteristics can be changed by treatments of the fiber surface. The effect of such treatments on the fiber reinforced concrete (FRC) tension-softening behavior and crack resistance is studied in this paper. Various R-curve behaviors are predicted based on a simple double cantilevered beam (DCB) model using the experimentally derived tension-softening curves. The result suggests that fiber surface treatments can substantially alter the composite fracture resistance as measured by the R-curve.

## INTRODUCTION

It is well known that the ability to absorb energy and the resistance to crack growth during fracture of cementitious materials can be significantly improved by fiber reinforcement. Such crack resistance is strongly influenced by the fiber-matrix bond strength. Since the bond strength varies over a wide range for different fibers, we expect different fracture behavior of FRC containing these fibers. Even for the same type of fiber, its bond strength with the cement matrix can be changed by surface coating, mechanical crimping, or even abrasion during fiber pull-out from the matrix [1].

Most of the synthetic fibers used in FRC have relatively low bond strength compared with steel and glass fibers [2,3]. To obtain effective reinforcement, a high aspect ratio (length/diameter) for synthetic fibers is generally used. However their slenderness and low bending stiffness often cause difficulties in FRC fabrication process and affect the FRC properties, as the fibers tend to become entangled and thus unevenly distributed, particularly for high volume fractions. These problems, as suggested by the results of this study, could be reduced by using lower fiber aspect ratio while modifying the fiber-matrix bond characteristics so as to retain essentially the same crack resistance at a possibly lower fiber volume fraction.

It has been shown [e.g. 4] that the tensile stress ($\sigma$) vs. crack opening width ($\delta$) relation, the so called "tension softening ($\sigma$–$\delta$) curve", is a material characteristic measurement of the crack resistance of FRC. However, this tensile relation does not directly describe the crack growth process. In FRC, the crack growth process is usually accompanied by the growth of a process zone, in which energy dissipation is associated with fiber pull-out. Increase of fracture resistance with crack growth may be expressed by means of an R-curve (resistance curve), which is given by a resistance parameter, usually the apparent fracture toughness $K_R$, or the strain energy release rate $G_R$, as a function of the crack extension for stable crack growth. In general, the R-curve is not a material property, but depends on the specimen size and geometry, and the loading configuration [5,6]. Nevertheless, for specified specimen size, geometry and loading configuration, the FRC R-curve could be uniquely determined from the tension-softening curve, and used to study its fracture process.

In this paper, a theoretical model to compute the R-curve for double cantilever beam (DCB) specimens from the $\sigma$–$\delta$ curve is first developed. Based on the pull-out tests of nylon fibers with different surface characteristics, the tension-softening curves are deduced. The effect of fiber-matrix bond strength on the resistance to crack growth for FRC is then studied by comparing the theoretical R-curves for a typical-sized DCB. Emphasis is placed on the influence of fiber surface treatment on composite toughness development.

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## A DCB FRACTURE MODEL

In experimental determination of R-curve for FRC, DCB specimens are often used [7,8,9,10]. Visalvanich and Naaman [7] proposed a model to calculate the R-curve for FRC DCB. In their analysis, it is assumed that the crack face has a straight profile and that the crack opening angle remains constant once the crack starts to grow. From the $\sigma$-$\delta$ curve and the energy balance criterion, the R-curve is then calculated. However, the requirement to measure the crack opening angle, a quantity depending on material properties and specimen geometry, limits the use of this model. Cotterell and Mai [6] calculated the R-curve for FRC based on Linear Elastic Fracture Mechanics (LEFM) crack growth condition, also assuming a straight crack profile. In both models by Visalvanich and Naaman and by Cotterell and Mai, the $\sigma$–$\delta$ curve is expressed in simple analytical forms for ease of computation.

In this study, a similar model is developed using LEFM and beam theory for a DCB with arbitrary $\sigma$–$\delta$ relation. It is then used to study the effect of fiber-matrix bond strength on the crack resistance of FRC.

Consider a DCB shown in Figure 1. If we neglect the shear deformation and beam rotation at the crack tip plane, the crack mouth opening w, and the crack face displacement $\delta(x)$ are given as [11]

$$w = 2\,P\,a^3 / 3\,E\,I \qquad (1)$$

$$\delta(x) / w = 3/2\ (1-x/a)^2 - 1/2\ \ (1-x/a)^3 \equiv u(x) \qquad (2)$$

where P is the applied load, a is the crack length, E is the Young's modulus, and I is the moment of inertia of the beam cross sectional area. From LEFM, the strain energy release rate can be expressed in terms of the change of compliance with crack length:

$$G = \frac{P^2}{2b}\frac{\partial}{\partial a}\left(\frac{w}{P}\right) = \frac{P^2 a^2}{bEI} \qquad (3)$$

and, for plane strain condition, the stress intensity factor at the crack tip, $K_a$, due to applied load P is

$$K_a\ =\ [EG / (1-\nu^2)]^{1/2}\ =\ P\,a\,[b\,I\,(1-\nu^2)]^{-1/2} \qquad (4)$$

where b is the crack plane width, (w/P) is the specimen compliance, and $\nu$ is the Poisson's ratio.

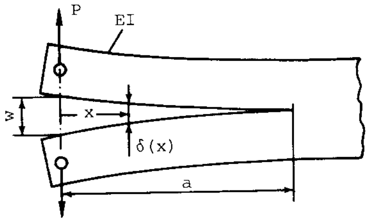

Figure 1. A DCB under loading

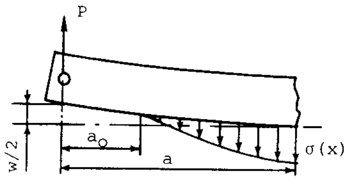

Figure 2. Replacement of Forces due to Bridging Fibers across the Crack by a Distributed Stress $\sigma(x)$

When there are fibers bridging the crack, we may replace the force acting against crack opening due to the bridging fibers by an equivalent distributed stress $\sigma(x)$, as shown in Figure 2. The stress intensity factor, $K_b$, at the matrix crack tip due to $\sigma(x)$ acting as a closing pressure is found to be

$$K_b = -\int_{a_0}^{a} \sigma(x) b (a-x) \left[bI\left(1-\nu^2\right)\right]^{-1/2} dx \qquad (5)$$

where $a_0$ is the traction-free crack length. The crack mouth opening w is obtained by superposition

$$w = 2Pa^3 / 3EI - \int_{a_0}^{a} \left[2\sigma(x)\,ba^3 / 3EI\right] u(x)dx \qquad (6)$$

In these two equations, we assume the stress $\sigma(x)$ to be related to the local crack opening $\delta(x)$ by a known tension softening curve, i.e. $\sigma(x) = \sigma[\delta(x)]$. Assuming that the crack profile for FRC DCB can still be described by u(x), as defined in Eq (2), $\sigma(x)$ and $\delta(x)$ can be evaluated for any given w and a, for any imposed crack growth condition.

For equilibrium crack growth in the matrix, the total stress intensity factor, $K_a + K_b$, can be considered to be equal to the matrix toughness, $K_{IC}$:

$$K_a + K_b\ = K_{IC}. \qquad (7)$$

For a given w, solving Eq(7) requires an iterative process to find the crack length, a. Once a is found, the corresponding composite fracture energy, G, can be calculated from

$$G = \int_{a_0}^{a} \sigma(x) \frac{\partial \delta(x)}{\partial x} dx + \frac{1-\upsilon^2}{E} K_{IC}^2 \qquad (8)$$

and the crack resistance, $K_R$, from $K_R = [EG/(1-\nu^2)]^{1/2}$. Note that when the process zone becomes fully developed, $K_R$ will reach its steady state value, and the corresponding G is given by

$$G = \int_0^{\delta_c} \sigma(\delta) d\delta + \frac{1-\upsilon^2}{E} K_{IC}^2 \qquad (9)$$

where the integral part is simply the area under the $\sigma$–$\delta$ curve and $\delta_c$ is the maximum $\delta$ when $\sigma(\delta)=0$. In constructing the R-curve, $K_R$ is plotted as a fuction of the "crack growth" $\Delta a=a-a_0$.

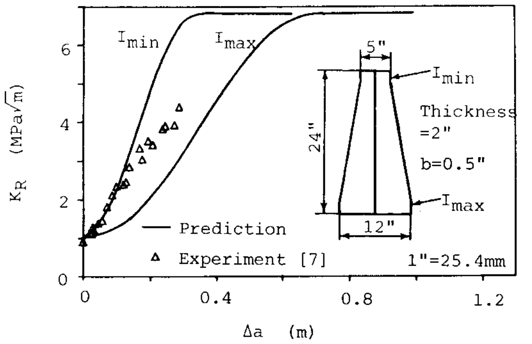

Figure 3. R-Curve Prediction

In this formulation, the beam shear deformation can also be included. However we have found that the shear effect on the overall solution is insignificant.

A calculation example is shown in Figure 3 for the DCB used by Visalvanich and Naaman [7, 8] for steel fiber reinforced mortar ($V_f$=1%, fiber length=6.4 mm, length/diameter=42). Typical values of E=21.5 GPa, ν=0.18, and $K_{IC}$=1 MPa $m^{1/2}$ for the matrix and experimentally determined σ–δ curve reported in [7] were used for the calculation. The experimental data for the R-curve in [7] were obtained from tests on tapered DCB. Depending on the choice of $I_{min}$ or $I_{max}$, which correspond to the smallest and largest cross-sections of the DCB respectively, in the calculation, different R-curves were obtained. Their experimental data fall essentially in between these two limiting curves. As expected, for small crack extension (Δa), the experimental data lie closer to the R-curve for $I_{min}$, and for large Δa, the data bend toward the curve for $I_{max}$.

## MONOFILAMENT PULL-OUT BEHAVIOR AND FRC TENSION SOFTENING CURVES

Fiber-matrix bond strength is usually measured by fiber pull-out tests. The bond strength can change during pull-out, or can be varied by certain treatment of the fiber surface. Figure 4 shows some pull-out test results in which each curve represents an average of six tests. The tests were all done on nylon monofilaments with a diameter of 0.508 mm. For these curves, the initial parts correspond to stretching of the fibers, inside and outside the matrix, causing gradual debonding of the elastic bond. When the fibers were fully debonded the whole fibers began to slide out, and this is indicated by the bend-overs in the curves. Curve 1 is for fibers washed in hot water at 75°C before they were put in the matrix. It was noted that as the fiber was pulled out, the load did not drop over a wide range of displacement, which was presumably due to the increased sliding resistance resulting from abrasion damages to the fiber surface [1]. For fibers coated with fluorocarbon mold release compound, represented by curve 2, the load decreased almost linearly as the fiber slid out, suggesting a constant bond strength after complete debonding. When the fiber was first crimped by running through a pair of loosely engaged gears and then coated with the same mold release compound, its pull-out relation was given by curve 3. Since lateral crushing of the fiber also took place during crimping, the maximum pull-out force was very high due to mechanical interlocking, after which there was a sharp load drop, and then the load gradually decreased with a periodic oscillation corresponding to the crimping period. It should also be mentioned that pull-out tests on crimped fibers without coating were also conducted. However, in these tests the fibers ruptured at a consistent load about 80 N at their exit points from the matrix, rather than being pulled out, indicating an even higher effective bond strength than that for the crimped fibers with coating.

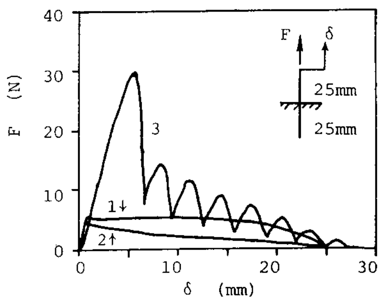

Figure 4. Pull-out Test of Nylon Fibers: 1-washed in hot water; 2-coated with fluorocarbon mold release; 3-crimped and coated with fluorocarbon mold release

Suppose that such fibers are aligned across a crack plane with an embedded length on one side of the matrix identical to those used in the pull-out tests (25 mm) and a much longer length on the other side, we can deduce the tension softening curve for this case based on the pull-out test curves in Figure 4. If we assume that the tension softening effect of the matrix has been included in the matrix toughness parameter $K_{IC}$, the composite stress, σ, is solely due to the fiber pulling forces,

$$\sigma = 4V_fF/\pi d_f^2 \qquad (10)$$

where $d_f$ is the fiber diameter, $V_f$ is the fiber volume fraction, and F is the load carried by each fiber corresponding to a given crack opening δ. Note that the initial part of the pull-out curves is due to the elastic elongation and uncrimping of the fiber, mostly for the fiber segment outside the matrix. Therefore the initial part should not contribute to the tension softening curve. The resulting tension softening curves corresponding to the pull-out results in Figure 4 are represented by linear or bilinear approximations as shown in Figure 5 for $V_f$=0.1.

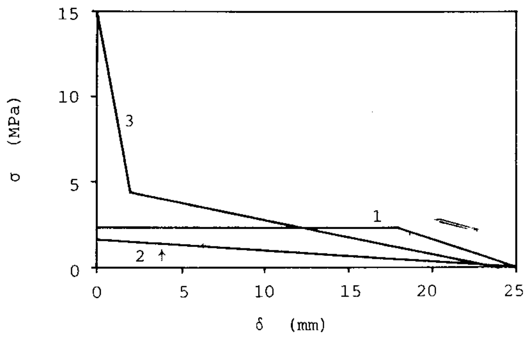

Figure 5. Approximate Tension Softening Curves from the Pull-out Test Results in Figure 3

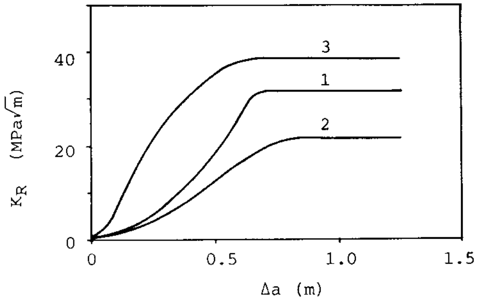

Figure 6. Calculated R-Curves for the Corresponding Tension Softening Curves in Figure 5 (DCB Cross-section: width=100 mm; total height=140 mm, b=25.4 mm)

## EFFECT OF BOND STRENGTH ON CRACK RESISTANCE

Figure 6 shows the computed R-curves for the DCB reinforced with the Nylon fibers treated in the three different manners described above. Comparison between curve 1 (fiber washed in hot water) and curve 2 (fiber coated with mold release compound) indicates that the improved fracture resistance derives from the effect of fiber abrasion, see also [1], with steady state $K_R$ improvement of about 40%. Crimping the fibers causes an early rapid rise in the R-curve (curve 3, figure 6), with steady state $K_R$ improvement of almost 100% over straight fibers with the same coating (curve 2). These R-curve results reveal that fiber surface treatment, either by crimping or that which induces abrasion, can be beneficial to the composite crack growth resistance. It is possible to exploit these effects to achieve high toughness composites with lower volume fraction of fibers or with fibers with low aspect ratios, thus obtaining favorable processing conditions while maintaining high effective composite toughness.

## CONCLUSIONS

Effects of fiber surface treatment on fiber pull out behavior directly influences the tension softening behavior of FRC, which in turn influences the crack growth resistance of the composite. Specifically this paper investigates the effect of crimping and fiber surface abrasion on the composite toughness, and shows that the R-curve of FRC DCB can be substantially improved by fiber surface treatment. These results may have important implications in optimal design of FRC. For example, by improving the fiber-matrix bond, it is possible to use lower fiber aspect ratio or volume fraction in FRC while retaining essentially the same crack resistance. This could significantly reduce the workability problems often encountered in FRC fabrication process.

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