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TOUGHENING IN CEMENT BASED COMPOSITES

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ABSTRACT

This paper reviews the mechanisms of toughening in fiber reinforced cement based composites. Reference is made to frontal, crack tip and wake processes, and estimates of contributions to composite toughness of the individual mechanisms are included. It is emphasized that the wake processes, which dominate the inelastic energy absorption during fracture development in these materials, can be well characterized by tensile stress vs. crack opening relationships. The fiber/matrix interface debonding energy, not usually important in fiber reinforced concrete, is shown to play an important role in a new straining-hardening engineered cementitious composites as an additional frontal process with significant energy absorption capacity, thus giving rise to a cement based material with extremely high damage tolerance.

INTRODUCTION

Cement is a highly brittle material. Neat cement by itself can self-destruct by stresses created due to plastic shrinkage, without any external loads. The addition of fillers, in the form of sand or aggregates, reduces shrinkage stresses, and at the same time enhances the fracture toughness of the resulting mortar or concrete. Investigation of the fracture toughness of concrete has been on the rise in the last decade, due to the recognition that structural behavior is controlled not only by compressive strength of concrete, but also by the independent material parameter -- fracture toughness.

Fracture mechanics based numerical tools, mainly in the form of finite element codes, are now widely available to simulate structural response by explicitly accounting for crack development in the structure. The successful utilization of these tools require input information on fracture toughness of the material. One of the most important revelations of recent research on fracture mechanics of concrete structures is the placing of experimental evidence of structural size effect on solid theoretical grounds (see, e.g. [1]). These works have advanced so far that serious considerations are being given to code implementations [2].

A parallel development, and with equal significance, is the investigation of toughening mechanisms of cement based composites. These research are motivated by the need to engineer the toughness property of the material, especially in light of the advances in high strength concrete in the laboratory and in field applications, and the 'brittleness' associated with these newer materials [3]. Scientific curiosity also drives deeper exploration into the source of brittleness or toughening mechanisms. This is greatly aided by recent advances in various experimental tools, such as scanning electron microscopes, laser interferometry and long distance microscopes, to probe the material micro- and meso-structures in fracture specimens [4].

In recent years, it is becoming clear that the use of fibers in cement based composites leads to significant toughening effect, much more so than improvements in the strength properties for which the fibers were originally intended for in the early days of fiber reinforced concrete (FRC). Thus serious efforts are now underway in designing these brittle matrix composites with toughness that are orders of magnitude higher than that of regular cement or concrete (e.g. [5], [6]). To achieve this objective, tailoring of the fiber, matrix and interface requires knowledge of how these three phases interact in the composite such that large amount of energy is absorbed in the inelastic process. Attempts are being made at this moment to bring this knowledge to bear on the performance of structures built partially or fully with such composites (e.g. [7], [8]).

Perhaps one of most detail studied structural element is the steel headed anchor embedded in concrete [9]. It has been demonstrated, both numerically and experimentally, that the performance in the form of structural capacity, of the headed anchor is governed mainly by the fracture toughness of the concrete material, rather than its compressive strength [10]. This distinction is important because the use of fiber reinforcement leads to significant changes in the fracture toughness but typically minor changes in the compressive strength. Surprisingly, no research has yet been carried out with anchors embedded in FRC. Structural behavior affected by fracture toughness includes not only structural load carrying capacity, but also structural durability. For example, the phenomenon of concrete spalling around corroding steel reinforcement in concrete structures has been traced to crack extension in the concrete tension loaded by pressure generated by the corrosion debris [11]. It is therefore expected that the durability of R/C structures susceptible to spalling with subsequent strength reduction can be advantageously modified by cement based composites with higher fracture toughness.

From the above discussions, it can be seen that significant advances in concrete structural performance can be gained by our increasing ability to predict their behavior accurately via modern concrete fracture mechanics, and the emerging science and technology of systematically tailoring the concrete microstructure for enhanced fracture and cracking resistance.

In this paper, we shall limit our focus to the mechanisms of toughening in fiber reinforced cement based composites. We begin by providing a synopsis of the theoretical background on crack growth in brittle matrix composites. This synopsis will be helpful in laying the ground work for a rational discussion of the toughening mechanisms reported in the literature. A review of recent advances in the new toughening mechanisms in strain hardening cement based composites is also included.

Curiously, when very high toughening is achieved to the extent that notch sensitivity is eliminated, fracture mechanics is no longer useful in describing structural performance. But then again it is perhaps structural performance, rather than 'fracture mechanics performance', that we should be striving for.

The literature in toughening in cement based composites is expanding rapidly. Recent conferences proceedings with part or complete focus on this subject include Fiber Reinforced Cement and Concrete, Ed. Swamy and B. Barr, Pub; Elsevier Applied Science, 1989; Micromechanics of Failure of Quasi-Brittle Materials, Ed. S.P. Shah, S.E. Swartz and M.L. Ming, Pub. Elsevier Applied Science, 1990; Toughening Mechanisms in Quasi-Brittle Materials, Ed. S.P. Shah, Pub. Kluwer Academic, 1991; Fracture Processes in Concrete, Rock and Ceramics, Ed. J.G.M. van Mier, J.G. Rots and A. Bakker, Publ., E. and F.N. Spon Pub., London, 1991; Fracture Mechanics of Concrete Structures, Ed. Z.P. Bazant, Pub. by Elsevier Applied Science, 1992; High Performance Fiber Reinforced Cement Composites, Ed. H.W. Reinhardt and A.E. Naaman, Pub. E & FN Spon, 1992; Fiber Reinforced Cement and Concrete, Ed. R.N. Swamy, Pub. E & FN Spon, 1992; Micromechanics of Concrete and Cementitious Composites, Ed. C. Huet, 1993, and the proceedings of this Symposium on Brittle Matrix Composites, edited by A. Brandt and I. Marshall, 1985, 1988, 1991. Two recent text books provide particularly broad coverage on toughening mechanisms in FRC. They are Fibre Reinforced Cementitious Composites, by A. Bentur and S. Mindess, Pub. Elsevier Applied Science, 1990; and Fiber Reinforced Cement Composites, by P.N. Balaguru and S.P. Shah, Pub. McGraw Hill, 1992.

THEORETICAL CONCEPTS

The Cohesive Crack Model proposed by Barenblatt [12] and Dugdale [13] suggests that the crack tip singularity in Griffith [14] and Irwin [15] type ideal brittle material concept will be removed by the presence of a cohesive zone in which non-vanishing traction acts across the crack flanks. This cohesive crack concept has been widely adopted in the concrete fracture literature, subsequent to the enlightening research of Hillerborg et al [16]. The cohesive crack model is identified with the situation when the physical mechanisms of crack advance (or the damage process controlling the advance of the cohesive zone) is the same as that governing the cohesive traction and crack opening of the crack wake. In this cohesive model, the stress profile is assumed to rise to the tensile strength of the material at the physical crack tip (Figure 1a), and thereafter decay as the crack opens in the wake. The traction profile maintains continuity across the transition of the intact material and cohesion zone material. This implies a vanished stress intensity factor K_I at the tip of the cohesive zone.

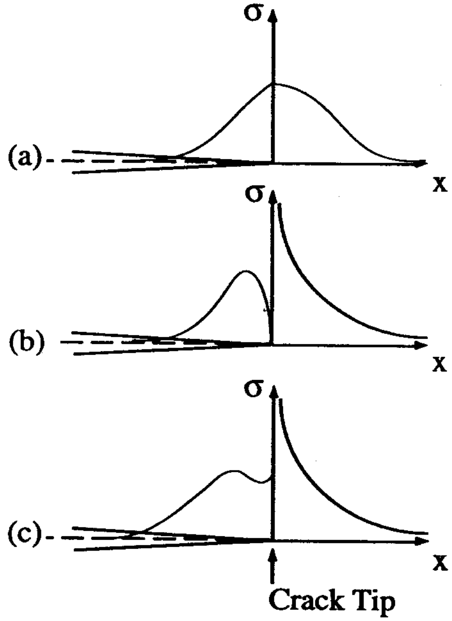
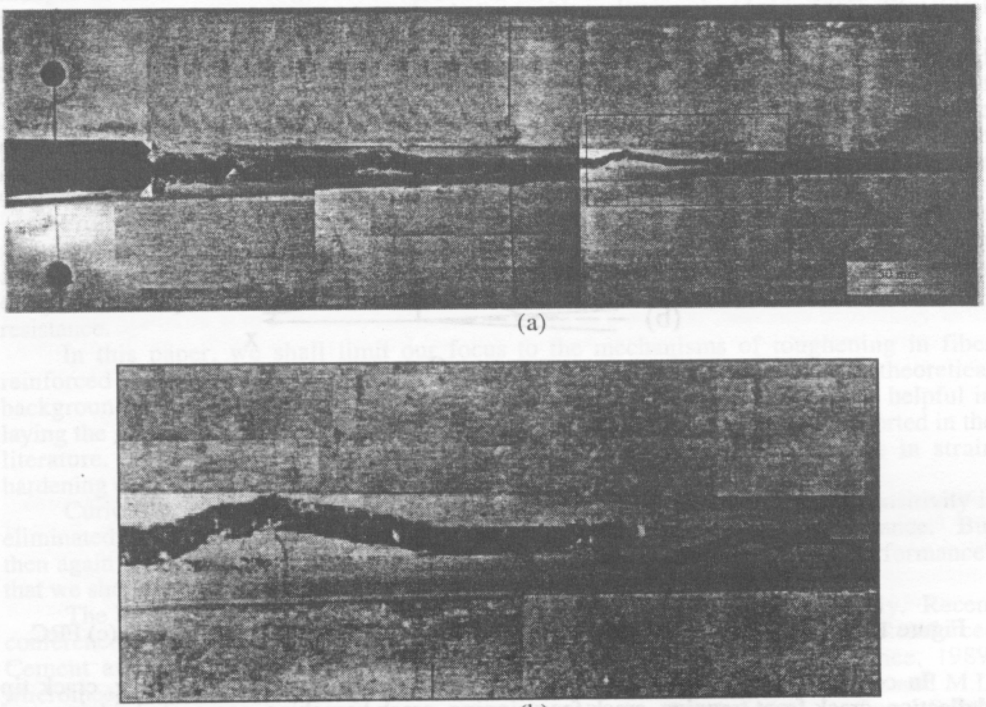


Figure 1: Stress Profile of (a) Cohesive Crack Model; (b) Bridged Crack Model; (c) FRC.

In concrete, crack advance may include processes such as microcracking, crack tip deflection, crack front trapping, crack face pinning, crack branching, aggregate bridging, and aggregate rupture [17,18,19,20]. Some of these processes are also responsible for the presence of the cohesive traction in the crack wake. These cohesive tractions are expected to decrease with effective 'opening' of the crack. Hence the Cohesive Crack Model is indeed suitable for describing crack growth in concrete. The microcracking process ahead of the physical crack tip is usually ignored, or lumped into a generalized 'fracture process zone' (FPZ).

Recently, Cox and Marshall [21] clarified the Bridged Crack Model as being distinct from the Cohesive Crack Model. Thus in the Bridged Crack Model, the bridging mechanisms acting on the crack flanks are assumed to derive from a different source from that responsible for crack advance. This is certainly the case in fiber reinforced cement. In this material, crack advance is associated with the damage localization in the cement matrix. This process is different from the mechanisms of fiber bridging, which includes fiber/matrix interface debonding, friction sliding, and other fiber/matrix interaction mechanisms which will be discussed in more detail later. For this reason, development of the bridging zone does not necessitate the cancellation of the crack tip singularity. Further, the stress profile on the crack line (Figure 1b) does not need to maintain continuity across the physical crack tip. Indeed, the bridging stress acting on the crack flanks can be a rising function of the crack opening, corresponding to processes dominated by fiber/matrix debonding. Only after a certain amount of crack growth, if steady state [22] is not reached will the bridging stress descend, corresponding to processes dominated by frictional sliding of fibers.

It may be surmised that the cement paste has its own innate toughness against crack growth. Even though this may incur only a small fraction of the total energy absorption in concrete or especially in FRC, it may be useful, for the sake of completeness, to account for this toughness explicitly. If the inelastic process (e.g. microcracking) associated with this toughness takes place in a small (in the 'small scale yielding' sense of linear elastic fracture mechanics) zone, it will be suitable to allow a crack tip singularity with singularity strength reflecting the toughness of the cement.


(a)

(b)

Figure 2: Crack Wake of an FRC Showing Extensive Fiber Bridging. Area Enclosed in Box in (a) Shown Magnified in (b).

Thus, the stress profile on the crack line in a FRC, due to the presence of aggregates and fibers, may combine the effects of crack tip singularity, aggregate tension softening and fiber bridging, as shown in Figure 1c. Some experimental evidence of this combined behavior is available [23]. The Cohesive Crack Model and the Bridged Crack Model provide a clear theoretical definition of the crack tip location, which is usually not easily identifiable in experimental investigations. This definition is useful for discerning two families of energy absorption processes associated with crack growth. The family of physical processes acting generally ahead of this crack tip are referred to as frontal processes, and those generally behind it are referred to as wake processes. Frontal processes involves inelastic deformation occurring over a volume of material, whereas wake processes involve inelastic deformation which are effectively occurring on the crack plane.

The localized nature of wake processes usually imply that such processes govern the softening branch of a well controlled uniaxial tension test. Hence much information concerning energy consuming inelastic processes have been obtained from such uniaxial tension test in cement based composite materials. Indeed, if these processes can be characterized by a tensile stress vs. crack opening (σ–δ) relationship, then the fracture energy consumed G is given by

$$G = \int_0^l \sigma(x) \frac{\partial \delta(x)}{\partial x} dx = \int_0^{\delta_c} \sigma(\delta) d\delta \tag{1}$$

The first integral is a result of wrapping a contour around the crack wake based on a J-integral analysis [24], with the x-axis origin located at the crack tip, and l is the length of the crack wake along which traction is transferred across the crack flanks. The second integral is just the area under the σ–δ curve from a uniaxial tension test. Equation (1) connects the energy consumed in the wake processes of a crack to the energy consumed in the softening process of a uniaxially failed specimen. In concrete and FRC materials, increasing amount of experimental data on σ–δ curves have been obtained in the last decade (e.g. [23, 25, 26, 27, 28, 29, and 30]).

TOUGHENING MECHANISMS IN FIBER REINFORCED CEMENT BASED COMPOSITES

In this section, we review a variety of fiber/matrix interactions which contribute to composite toughening, and the σ–δ curve of fiber bridging with and without aggregates. The discussion will focus on randomly oriented discontinuous fibers typically used in FRCs.

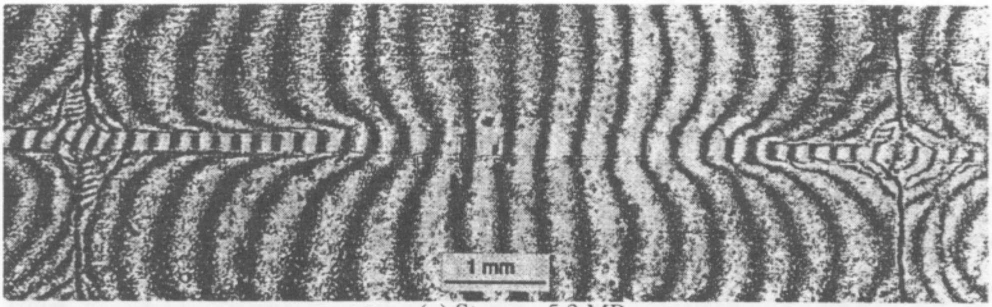
Fiber/Matrix Interactions

There are several types of fiber/matrix interactions which lead to energy absorption in the fiber bridging zone of an FRC. These include interface debonding, frictional sliding, and inclined angle effects associated with random fiber orientations (e.g. [31, 32]). Although the amount of energy associated with each mechanism for a single fiber may not be significant, the large amount of fibers, bridging over an extended length can contribute enormous toughening effect to the composite. Figure 2 shows the large bridging zone of such an FRC. The end of the bridging zone is associated with fibers being pulled out of the matrix. This is typical of steel and polymer fiber reinforced concrete. For composites with brittle fibers such as carbon, the end of the bridging zone is associated with the rupturing of fibers.

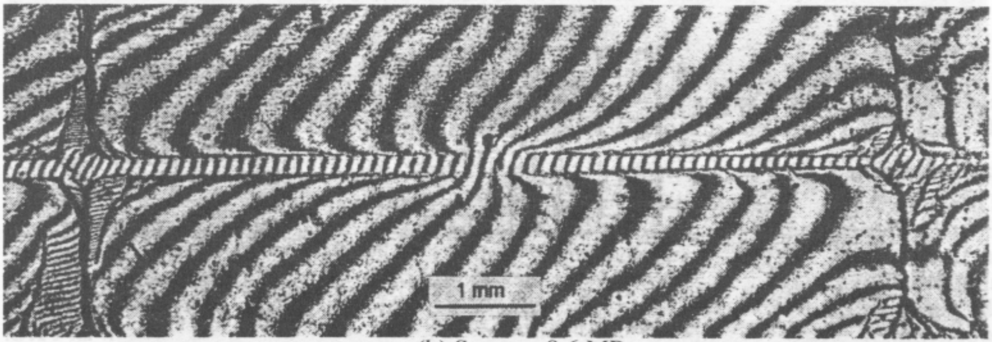
Fiber debonding involves the breakdown of the material in the interfacial zone due to interfacial shear resulting from the pulling of a fiber bridging a matrix crack. Figure 3 shows an image of an interface being debonded, with the debonded zone indicated by the distorted pattern of the Moiré fringes [33]. The debonding process can be strength or fracture controlled depending on the physical nature of the fiber/matrix interface [34]. In a composite, the discontinuous random fibers can be expected to have different embedment lengths. However, when the crack opening is small, most of the fibers can be assumed to be undergoing debonding. The resulting σ–δ will then be ascending. Measurement of this part of the curve in a uniaxial tension test is not usually conducted, since the load would have exceeded the maximum bridging stress when the matrix cracks in a typical FRC, resulting in a sudden load drop and a crack opening largely in the descending branch of the σ–δ curve. Parts of this curve, however, can be obtained by tracking the load-crack opening on one of the multiple cracks in a uniaxial tension test of a pseudo strain-hardening FRC. This is possible since in such a composite, the material can continue to carry higher load after matrix first crack. Figure 4 shows some experimental data points of the σ–δ curve of a strain-hardening Nylon fiber reinforced cement. The corresponding theoretical curve is from Li [35]:

$$\sigma_f(\tilde{\delta}) = \sigma_o \left[2\left(\frac{\tilde{\delta}}{\tilde{\delta}^*}\right)^{1/2} - \frac{\tilde{\delta}}{\tilde{\delta}^*} \right] \qquad for \quad 0 \le \tilde{\delta} \le \tilde{\delta}^* \tag{2}$$

where $\sigma_o \equiv g\tau V_f(L_f/d_f)/2$, $\tilde{\delta} \equiv \delta/(L_f/2)$, and where $\tilde{\delta}^* \equiv (2\tau/E_f)(L_f/d_f)/(1+\eta)$ corresponds to the maximum attainable value of δ_o (normalized by the half fiber length $L_f/2$) for the fiber with the longest possible embedment length of $L_f/2$. In the above,



(a) Stress = 5.3 MPa



(b) Stress = 8.6 MPa

Figure 3: Fiber Debonding as Imaged by Moire Interferometry [33].

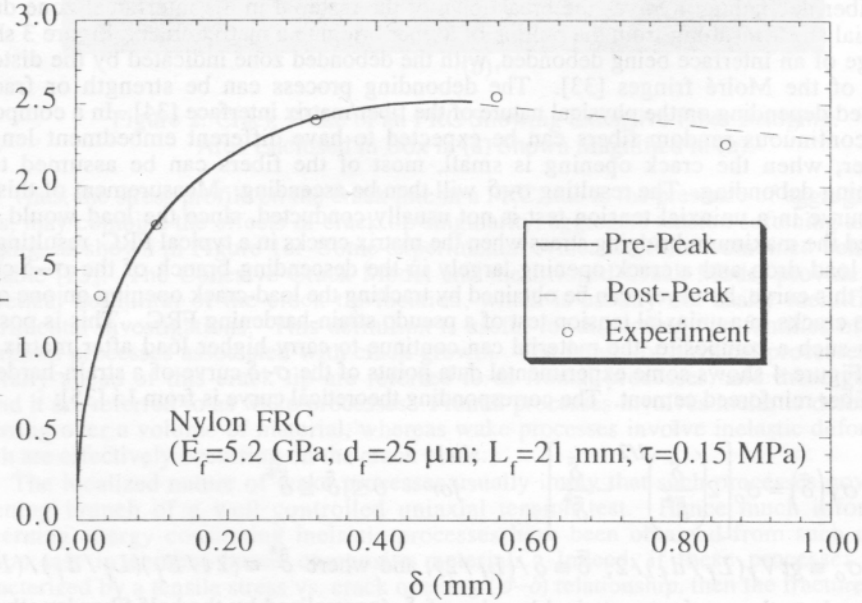


Figure 4: Ascending Branch of σ−δ data for Nylon FRC.Theoretical Curve is from Eqn. (2).

$\eta \equiv (V_f E_f)/(V_m E_m)$, E_m and V_m stands for the Young's modulus and volume fraction of the matrix material which contains the fibers. E_f, d_f and τ are the Young's modulus, diameter and interface bond strength of the fiber. The snubbing factor g is defined in terms of the snubbing coefficient f:

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

More on the snubbing factor and coefficient will be given later. In (2), it has been assumed that the interface debond process is governed by a single level interfacial strength τ. Corresponding equation can be obtained when the debond is governed by interface fracture process with the corresponding fracture energy Γ.

The fiber debonding energy can be estimated (using (1) and (2)) if the interface property is known. Li [35] showed that for the case of strength control interface, this energy is given by

$$G_r = \frac{5}{12} g \tau V_f d_f \left(\frac{L_f}{d_f}\right)^2 \tilde{\delta}^* \tag{4}$$

When the crack opening is large, most fibers would be fully debonded, and frictional sliding or pull-out of these fibers would occur towards the end of the crack wake. This corresponds to the descending branch of the σ–δ curve for FRCs in a uniaxial tension test. Experimental determination of this branch of the σ–δ curve for a variety of FRCs has been extensively reported. This softening branch has been very well modeled, both empirically [36, 37] and theoretically [35]. The analytic expression for the σ–δ curve based on constant frictional pull-out is given by

$$\sigma_f(\tilde{\delta}) = \sigma_o\left[1-\left(\tilde{\delta}-\tilde{\delta}^*\right)\right]^2 \quad for\ \tilde{\delta}^* < \tilde{\delta} \leq 1 \tag{5}$$

Equation (5) has been found to compare favorably with a wide variety of experimental data for both steel and polymeric FRC materials, as shown in Figure 5. This suggests that the frictional pull-out concept of fibers bridging a matrix crack is reasonably accurate. Refinement of the friction concept have been offered by Wang et al [38] with regard to slip-hardening or weakening behavior of fiber/matrix interfaces which suffer damage due to the sliding process. The process of slip-hardening has the potential of further toughening the FRC. Unfortunately, in most cases, the fiber abrasion damage process requires extensive sliding (several mm) to reach a significant level.

The fracture energy contribution based on constant friction sliding can be determined from (1) and (5). This energy component is given by

$$G_c = \frac{1}{12} g \tau V_f d_f \left(\frac{L_f}{d_f}\right)^2 \tag{6}$$

In both (4) and (6), a 3-D orientation has been assumed. Further, all fibers are assumed to pull-out rather than fracture. For a typical FRC, the pull-out energy would be on the order of several kJ/m^2. This is at least one order of magnitude larger than the fracture energy of cement or concrete. However, it should be noted that to access this high level of fracture energy, it is necessary to pull the fibers out completely, implying a large bridging zone and large crack opening on the order of mm to cm scale. Such large crack opening is not acceptable for normal serviceability in most practical structures.

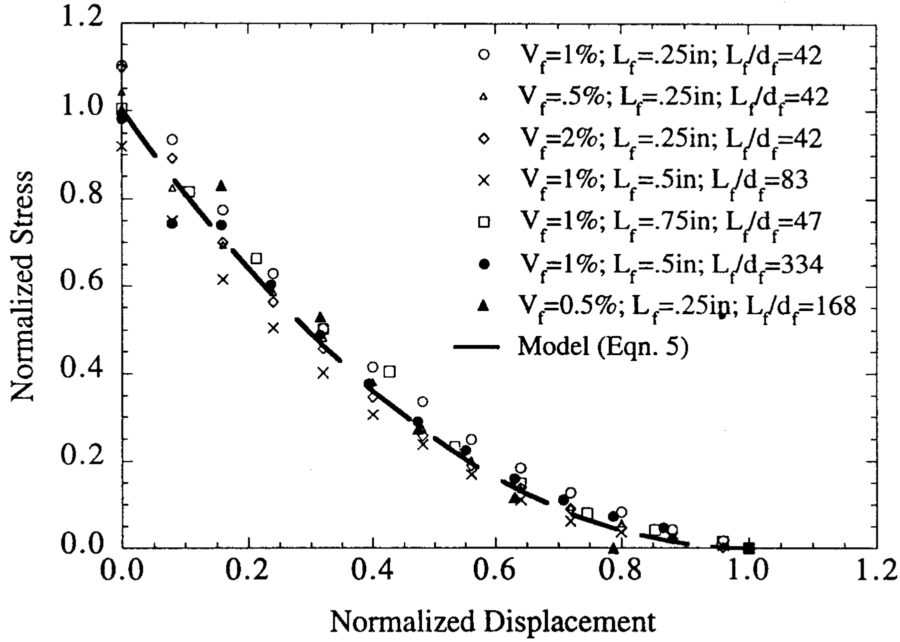


Figure 5: Softening Branch of σ–δ Data for a Variety of FRCs. Data From [29, 36] Theoretical Curve is from Eqn. (5).

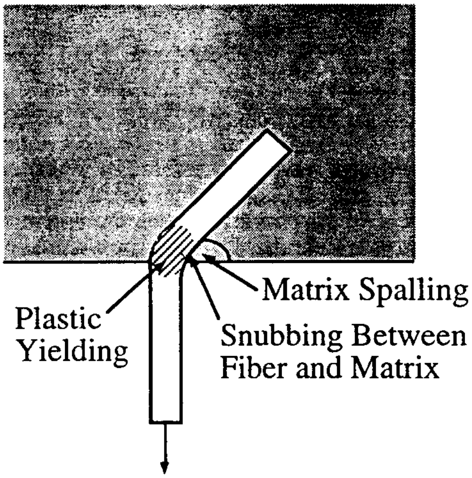


Figure 6: Inclined Fiber Bridging a Matrix Crack Showing Possible Mechanisms of Fiber Yielding at Bend, Snubbing, and Matrix Spalling.

Comparison between (4) and (6) indicates that the value of G_r/G_c is on the order of $\tilde{\delta}^*$. This is a very small value (on the order of 10^{-3}, for $\tau/E_f \sim 10^{-3}$ and $L_f/d_f \sim 10^2$), so that for most FRCs, this contribution to the composite toughness due to interface debonding can be ignored.

Apart from debonding and pull-out, additional interactions between fiber and matrix occur when the fibers are randomly oriented. When fibers cross a matrix crack at an incline angle (Figure 6), it is necessary for the fiber to bend so that the bridged segment of the fiber will be parallel to the tensile loading direction. The energy absorbed in the bending process necessarily depend on the type of fiber. For example, Morton [32] found that for steel fibers which plastically yield under bending, the amount of fracture energy consumption can be dominated by work due to the plastic bending process. The relative magnitude of this energy to the total fracture energy including that due to fiber pull-out (Eqn. (6)) will depend on the fiber and interface parameters. For low aspect ratio fibers and/or low bond strength fibers, G_c in (6) will be small, and the bending energy which depends only on the fiber yield strength will be important. The significance of flexural yielding will diminish for composites with fibers of large aspect ratio and high interfacial strength.

When fibers are brittle, such as in the case of carbon fibers, the effect of bending actually leads to fiber failure at lower bridging load in comparison to the aligned fiber case [39]. This cuts short the debonding and pull-out processes, and leads to lower energy consumed in the bridging zone. In the case of polymer fibers which yields at very low stress, the energy consumed due to fiber flexural yielding again can be expected to be small.

Another effect of inclining fibers is snubbing [40]. This effect is best visualized by considering a flexible fiber bearing on the matrix as it exits into the matrix crack as a rope passing over a friction pulley. This additional local friction effect is dependent on the fiber tension and therefore the fiber aspect ratio and interface bond strength, unlike that of flexural yielding described above. Indeed this coupling of tension and bending makes snubbing a multiplying effect, as opposed to the additive effect associated with plastic yielding and assumed by Morton [32]. That is, as the interface is strengthened or if the fiber aspect ratio is increased, the snubbing contribution also increases. This mechanism is quantified by the snubbing factor g in Eqn. (6). The value of g ranges from 1 to 2.3 [35, 40]. In the case of g =2, for example, the snubbing effect doubles the fracture energy of the case without snubbing effect.

It should be noted that while the energies associated with fiber flexural yielding and snubbing derives from fibers inclined to the matrix crack, random fiber orientation also reduces the number of fibers bridging across the matrix crack. This can result in a lower bridging energy level, as appears to be supported by experiments [31].

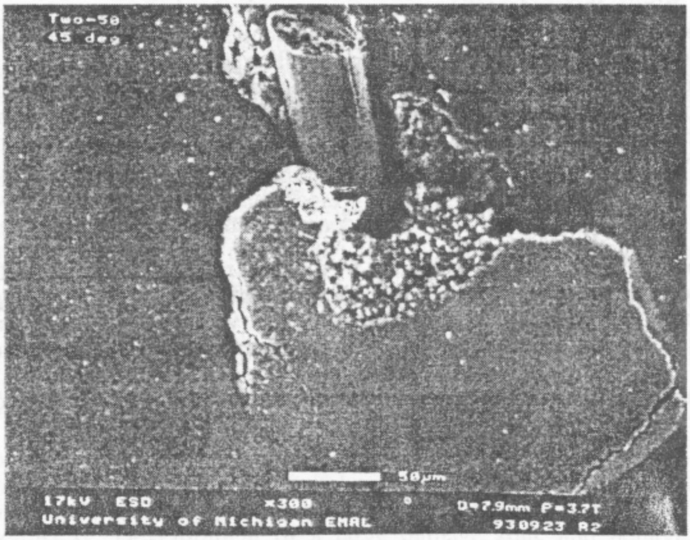


Figure 7: Spalling of Cementitious Matrix Under Indentation Loading of an Inclined Fiber.

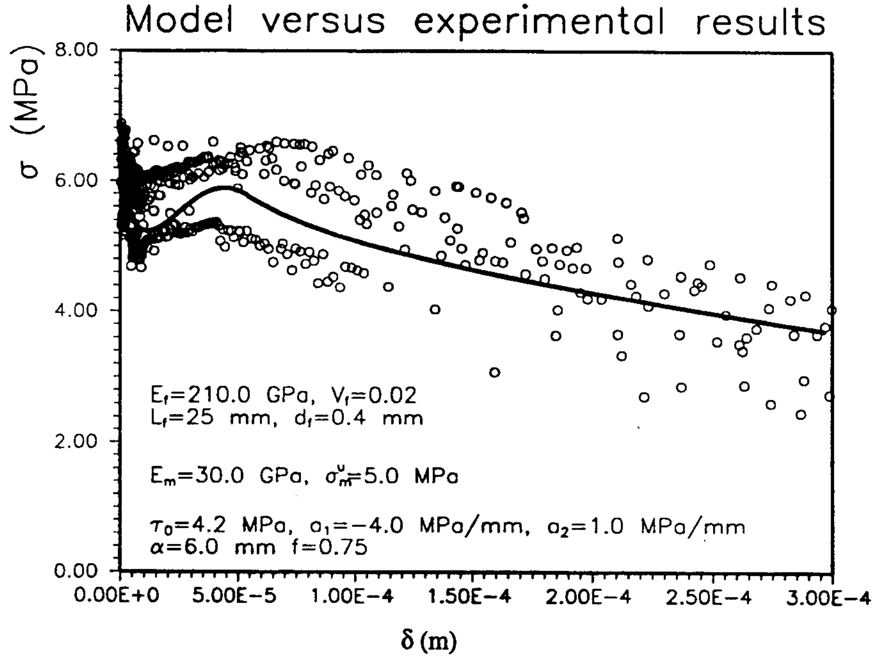


Figure 8: Combined σ–δ Data and Model of Aggregate and Fiber Bridging.

Another mechanism associated with incline bridging fibers is matrix spalling (Figure 6). The mechanics giving rise to the snubbing effect also causes a local indentation load acting on the matrix. As a result, the matrix may split under the indentation load and form a wedge spall. An SEM micrograph of such a spall obtained under an inclined pull-out test is shown in Figure 7. While this indentation process causes inelastic energy absorption, the energy contribution by this spalling mechanism is difficult to identify because of its interacting mechanisms with the bridging fiber. Matrix spalling is expected,to release fiber tension and therefore lower the bridging stress. This may in fact lower the energy consumption in the bridging zone. On the other hand, for brittle fibers, matrix spalling may allow survival of the brittle fiber by lowering the stress in the brittle fiber, and therefore lead to an extension of the σ–δ curve which would have otherwise been cut short by fiber rupture.

Combined Effect of Aggregate and Fibers

In concrete, the tension-softening σ–δ curve reflects a number of simultaneously operating toughnening mechanisms including aggregate and ligament bridging in the wake zone. Attempts at modeling the tension softening curve has been carried out by a number of researchers [17, 41, 42, 43, 44]. Stang [45] suggested an empirical approach which has the appeal that a wide range of experimental data can be fitted extremely well. In this model the aggregate bridging stress σ_a is expressed as a function of the crack opening δ:

$$\sigma_a = \frac{\sigma_m^u}{1+\left(\dfrac{\delta}{\delta_o}\right)^p} \tag{7}$$

where σ_m^u is the maximum bridging stress due to aggregate action at $\delta = 0$. The parameter p describes the shape of the softening process with increasing crack opening, and has been determined to be close to unity for most concrete tested to date. The parameter δ_o corresponds to the crack opening when the stress has dropped to half of σ_m^u.

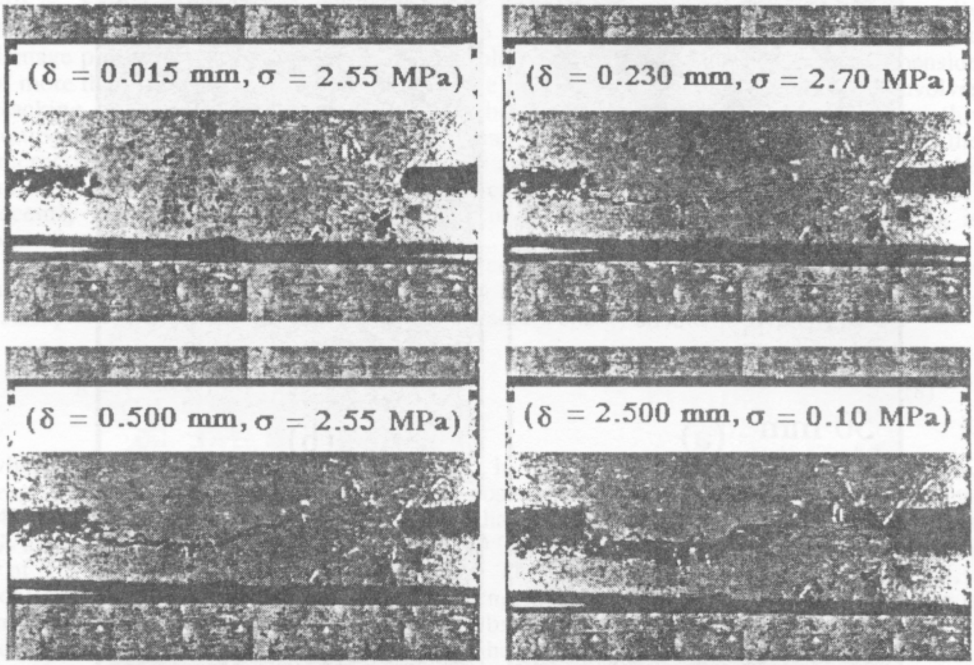


Figure 9: Photographs of Cracking Process at Different Stages of Uniaxial Tensile Loading in a FRC.

In FRC, it is interesting to consider the combined effect of aggregate and fibers acting simultaneously in the crack wake. This was carried out recently [23] in the form of σ–δ curves measurements and modeling for steel and pp-FRCs (Figure 8). The modeling combines in essence the concepts of aggregate tension-softening (Eqn. 2) and fiber bridging (Eqns. 3 and 6), with further additional refinements. Figure 9 shows a series of photographs at different stages of cracking in the uniaxial tension specimen. Although effects of interactions between the aggregates and fibers may be expected, especially for large size aggregates or high fiber volume fractions composites, Figure 8 appears to support a simple additive contribution of the aggregate and fibers to bridging toughening in the crack wake.

TOUGHENING IN STRAIN HARDENING CEMENT BASED COMPOSITES

In this section, we review recent observations of a new toughening mechanism in strain hardening cement based composites. The material has been designed based on micromechanical principles so that strain-hardening occurs despite a relatively low fiber volume fraction (typically less than 2%). We have called such a material an Engineered Cementitious Composite (ECC). Detail information on ECC can be found in [46] and in the references given below. The toughening mechanism leads to a high toughening level in cement based composites while at the same time reveals an R-curve behavior different from that of ordinary FRCs. Development of a large damage zone and behavior of notch insensitivity are discussed.

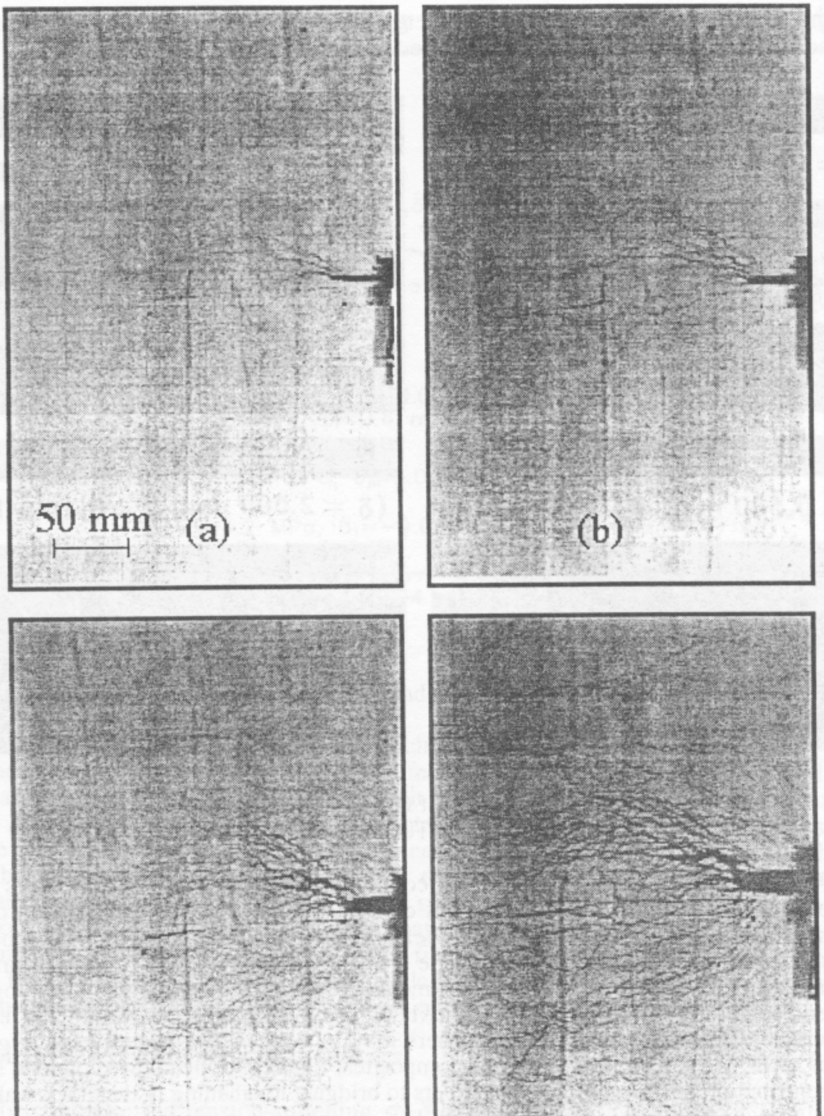


Figure 10: Damage Zone Development at Four Stages of Loading in a Double Cantiliver Beam Specimen.
(a) δ_L = 3.10 mm (b) δ_L = 7.32 mm (c) δ_L = 19.45 mm (d) δ_L = 23.16 mm.

Damage Tolerance

Figure 10 shows four stages of damage zone development on a large double cantilever beam fracture specimen [6, 47]. Advance of a main crack from the initial notch was significantly delayed and can only be observed (Figure 10d) after the an extensive damage zone off the main crack plane has been developed. It appears that the notch tip was rapidly blunted by the damage process, analogous to the process of dislocation blunting in a ductile metal. Notch tip blunting relaxes the strain-concentration, allowing further loading to be applied before real crack growth can begin. This crack growth process is very different from that of ordinary FRCs. Fracture energy as high as 27 kJ/m^2 has been measured. It was experimentally determined that a little more than 50% ($\approx$ 15 kJ/m^2) of this energy comes from inelastic damage process occurring over an extended volume of material, covering an area dimension of more than 1000 cm^2 on the specimen surface [47]. The inelastic damage process involves cracking of the matrix and the associated fiber bridging on these cracks. Because this composite shows strain-hardening behavior under uniaxial tension, it is expected that the microcracks observed in the damage zone are associated with the multiple cracking in the unaxial tensile specimens. Indeed, Horii and co-workers (personal communications, 1994) recently confirmed through a FEM-BEM simulation that material strain-hardening is occurring in the damage zone as it is developed.

Based on the above discussion, energy consumed in the damage zone should derive mostly from the debonding process of bridging fibers. If this were the case, the ratio of off-crack plane fracture energy to on-crack plane fracture energy should be given by

$$R = \frac{G_r A_d}{G_c A_m} \approx 1 \tag{8}$$

where A_d and A_m are the area of microcracks in the damage zone and area of main crack, respectively. G_r and G_c are the pre-peak and post-peak fiber bridging energies given by eqns. (4) and (6). Photographic evidence indicates that A_d = 5400 cm^2 and A_m = 87 cm^2, whereas G_r and G_c are estimated to be 0.17 kJ/m^2 and 9.9 kJ/m^2 based on an interfacial bond strength τ of 0.7 MPa and a snubbing factor g of 2.0. These numbers imply that the ratio $R \approx 1.1$, confirming the concept that the fiber debonding mechanism in the frontal process zone is indeed contributing as much as the familiar bridging mechanism in the wake process to composite toughness in this ECC. Thus, the interface debonding energy not usually significant in an FRC plays an important toughening role in an ECC. The blunting effect of the microcracking frontal process in ECC renders the material highly damage tolerant.

Notch Insensitivity

An implication of the large damage zone prior to fracture localization is that the ligament in a notched specimen must be at least as large as the dimension of this zone to observe fracture behavior (fracture dominated failure mode). Otherwise the material will show notch insensitivity, i.e. the strength of the specimen will become insensitive to the presence of the notch. Limited test results of a double edged notch specimen appear to support this idea. Figure 11 shows the damage effect on the ligament in the specimen. The microcrack pattern appears as a plastically yielded zone and extensive microcracking occurs over the whole length of the specimen. Figure 12 shows the net section strength line, confirming that this specimen did not suffer from brittle fracture failure.

A practical implication of this notch insensitivity behavior of this material could be in the enhancement of structural durability of R/C structures. In this type of structures, durability often suffers from large crack openings in the concrete cover, steel corrosion, and subsequent concrete spalling. Since concrete covers are typically of the dimension of several cms, which is smaller than the damage zone size of the strain-hardening material, a fracture can never be fully developed. Instead, it is expected that an expanding zone of microcrack damage will occur. In regular R/C structures, fracture will still be restrained by the reinforcing steel, but the R/C structure with an ECC layer will have microcrack width which is self-restrained. This concept is illustrated by Figure 13, which shows the crack pattern of a regular R/C beam and that of an ECC layered beam [48] loaded under flexure. Microcracks on the ECC cover shows a crack width an order of magnitude smaller than that on the regular concrete cover. Thus the damage tolerance of ECC can be advantageous in enhancing structural performance.

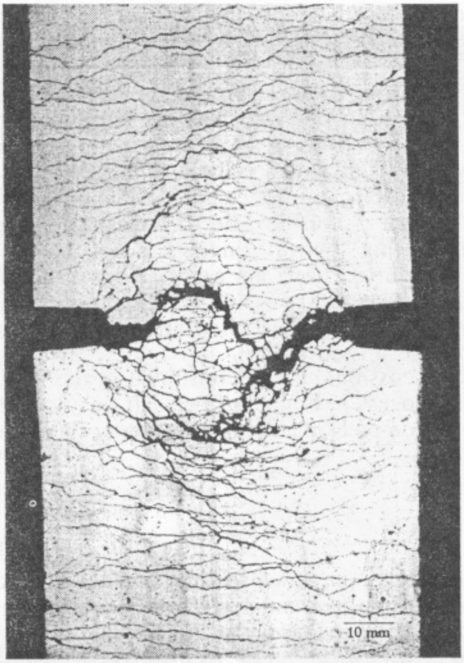


Figure 11: Damage Pattern of a Shallowly Double-Edged-Notched Specimen of an ECC Which Shows a Notch-Insensitive Failure Mode.

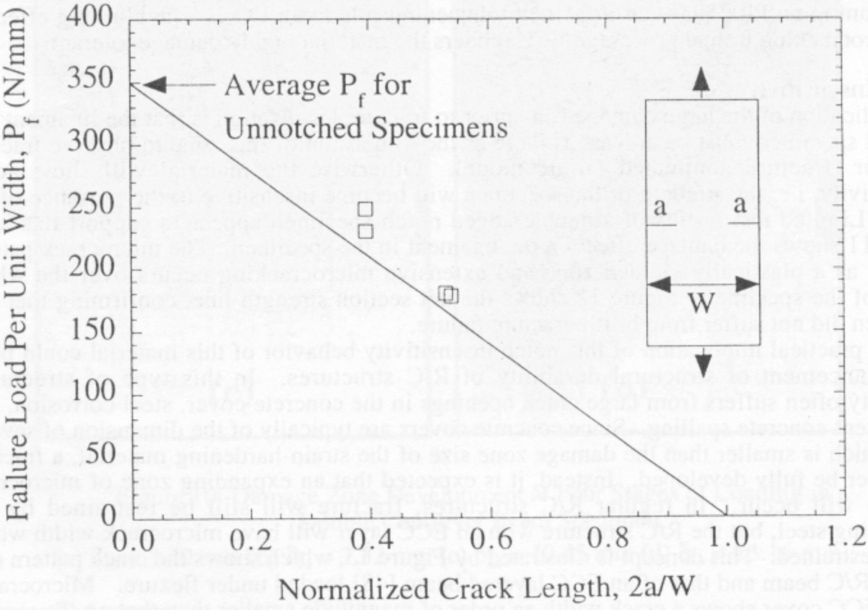
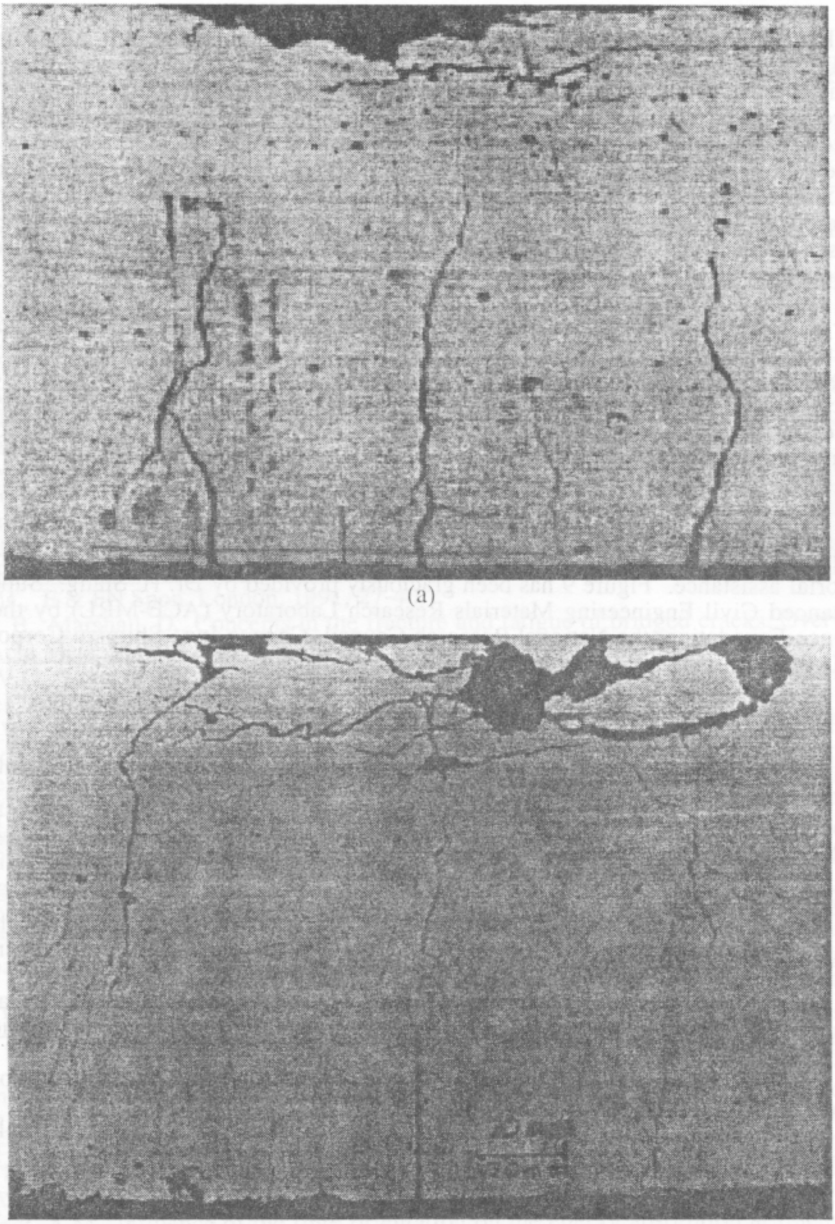


Figure 12: Failure Load vs Notch Depth Relation Confirming Notch-Insensitivity of ECC Materials.



(a)

(b)

Figure 13: Crack Pattern of R/C Beams Loaded to Failure [48]. Beam (a) has Regular Concrete Cover, and Beam (b) has an ECC Cover.

CONCLUSIONS

In this paper, the toughening mechanisms of cement based composites are reviewed. In concrete the major wake process appears to be associated with aggregate/ligament bridging.

In FRC, the major wake process appears to be associated with fiber pull-out against friction modified by inclined bridging effects. A Cohesive Crack Model is seen to describe the inelastic wake action of aggregates in concrete, whereas a Bridged Crack Model is seen to be appropriate to describe those of fibers in FRC. In either case, energy absorption in the wake processes generally dominate over those of the frontal processes. On a macroscopic level, wake processes can be characterized by stress vs. crack opening (σ–δ) curves obtained from uniaxial tensile test, and fracture toughness can be derived from the area under these curves. Normalized forms of σ–δ curves are available and appear general enough to describe broad classes of materials. Extensions to include specific mechanisms not accounted for in these models seem feasible.

In ECC material, an enlarged frontal process is responsible for significant amount of energy absorption, associated with fiber debonding over a large volume of material, in addition to the wake process available to all FRCs. The order of magnitude of fracture toughness is 0.01 kJ/m^2, 0.1 kJ/m^2, several kJ/m^2, and several tens of kJ/m^2 for cement, concrete, FRC and ECC, respectively. The toughness of the ECC material is competitive with some metallic materials such as aluminum alloys. Under suitable conditions, notch insensitivity can be achieved in ECC and utilized in structural applications.

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