Damage Mechanics of Engineered Cementitious Composites

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Introduction

In recent years, high performance fiber reinforced cement based composites (HPFRCC) have increasingly been demonstrated as a viable structural material. HPFRCC possesses tensile strain-hardening properties that can lead to substantial improvement in structural performance. There is converging opinion in the research community that such material can be achieved with a relatively small amount of fibers, a few percent in volume, and therefore are feasible for practical applications from both the economic viewpoint and from the processing viewpoint. It is anticipated that the use of HPFRCC in structural members and systems will eventually become commonplace.

Prior to practical adoption of HPFRCC in structural applications, several hurdles need to be removed. Amongst these are proper material characterization suitable for structural design, and material design for high performance to cost ratio. Both aspects require a good understanding of the damage mechanics of HPFRCC in the strain-hardening deformation stage.

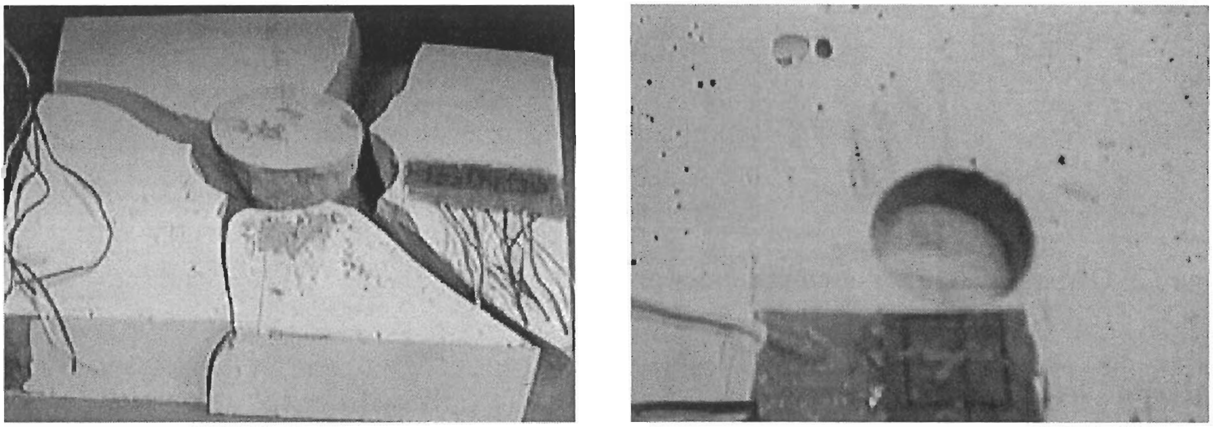

(a) (b)

Figure 1: Behavior of slabs under indentor loading for (a) mortar, and (b) ECC

Engineered Cementitious Composites (ECC)

ECC is a special family of HPFRCC that has been microstructurally tailored for high tensile ductility based on micromechanics principles (Li, 1998). The strength properties are similar to those of normal to high strength concrete, but the tensile ductility in terms of tensile strain capacity can reach 3-5%, several hundred times those of concrete and tension-softening fiber reinforced concrete. ECC is highly damage tolerate under severe loading, both in tension and in compression, and under monotonic or cyclic loading. Figure 1 shows the contrasting behavior of the failure mode of a mortar and an ECC under indentor load (Kanda et al, 1998). As expected, the mortar behaved in a elastic-brittle manner (Fig. 1a). The ECC slab deformed "elastic-plastically" under the indentor while microcracks developed around the edge of the indentor, but no radial fracture formed as in the case of a brittle mortar. Figure 2 shows the contrasting failure modes of a standard R/C column and that of a R/ECC column subjected to reversed cyclic loading (Fischer and Li, 2002). Shear fracture and subsequent spalling occurred in the R/C column (Fig 2a). For the R/ECC column, microcracks formed, but spalling of the cover was prevented even when the column experienced inter-story drift as high as 10%.

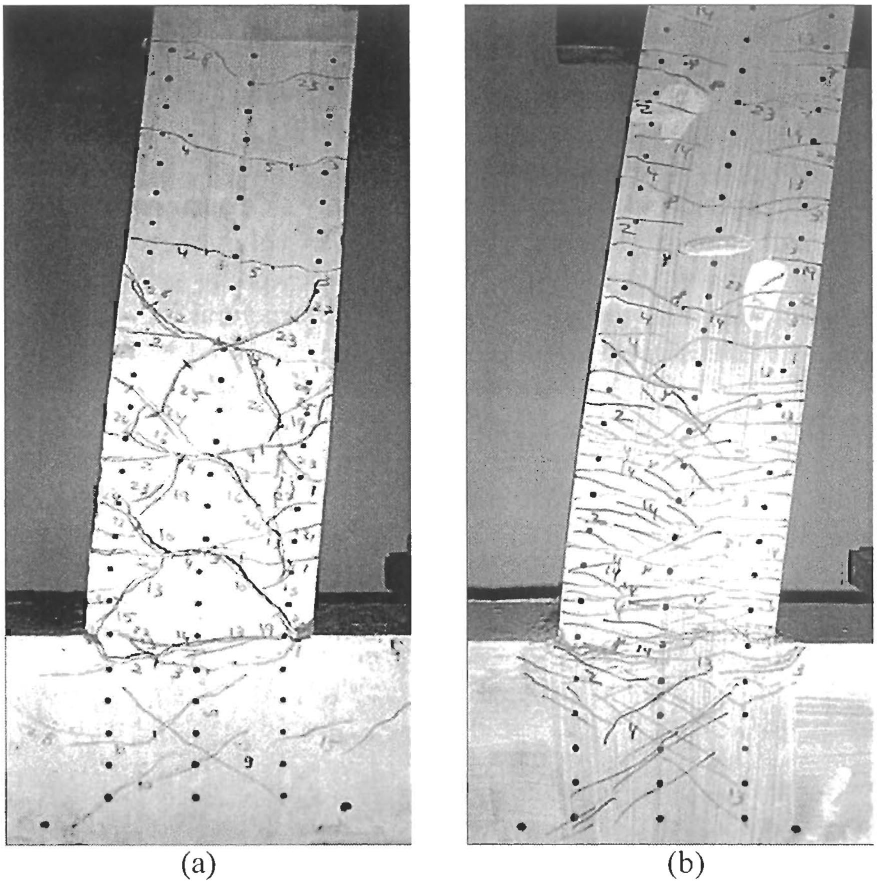

(a) (b)

Figure 2: Damage pattern of columns under reversed cycle loading for (a) R/C, and (b) R/ECC

Material Characterization of ECC

The tensile behavior of HPFRCC is characterized by its stress-strain curve under uniaxial tensile loading. In order to describe the tensile deformation as a "strain", it is necessary that the tensile elongation as measured by a gage attached on the specimen must cover a large number of cracks, so that this elongation over the gage length can be regarded as a true strain. If only a few cracks occur in the specimen and the gage happens to cover mainly the opening of a crack, the resulting "strain" could be artificially amplified. This observation implies that for proper material characterization of HPFRCC, it is necessary to document the crack pattern of the specimen. In addition, if the material is to be used in its micro-cracked state during service, then the crack opening should also be documented to assure durability requirements.

A typical stress-strain curve and associated crack width development curve is shown in Figure 3 for a ECC material reinforced with PVA fiber. This specimen shows a tensile first crack and ultimate strength of 4 MPa and 5 MPa, respectively. Of interest is the fact that the material reveals a steady state crack value of 60 μm, after an initial rise up to about 1% strain.

The crack pattern at the end of test (which terminates shortly after peak load is reached) is shown in Figure 4. It is seen that more than 76 cracks occur over the gage length of 90 mm, with final crack spacing of 1.18 mm.

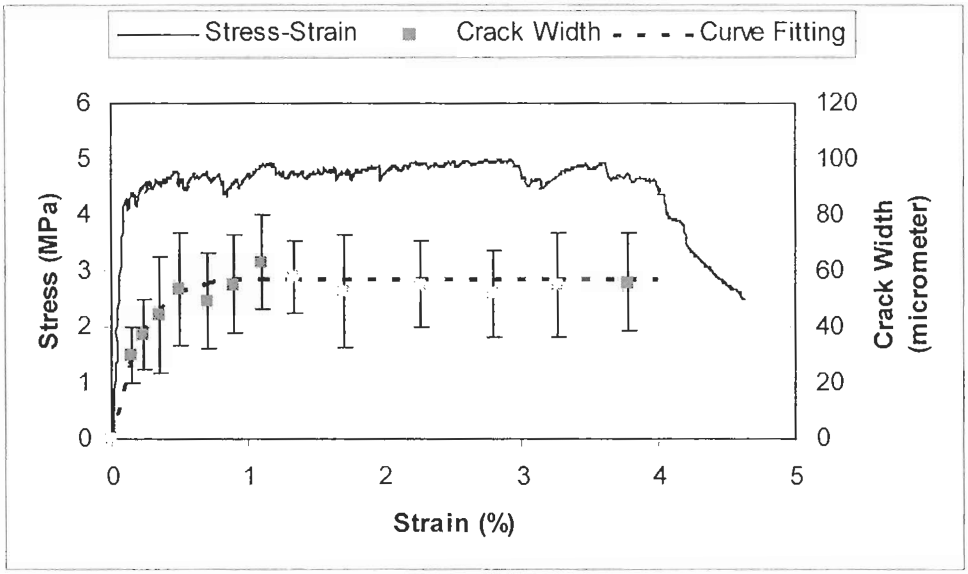


Figure 3: Typical stress-strain curve and associated crack width development curve of PVA-ECC

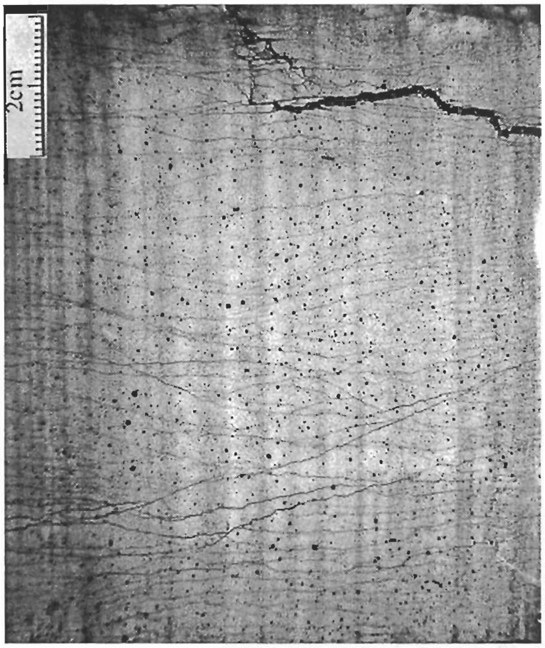


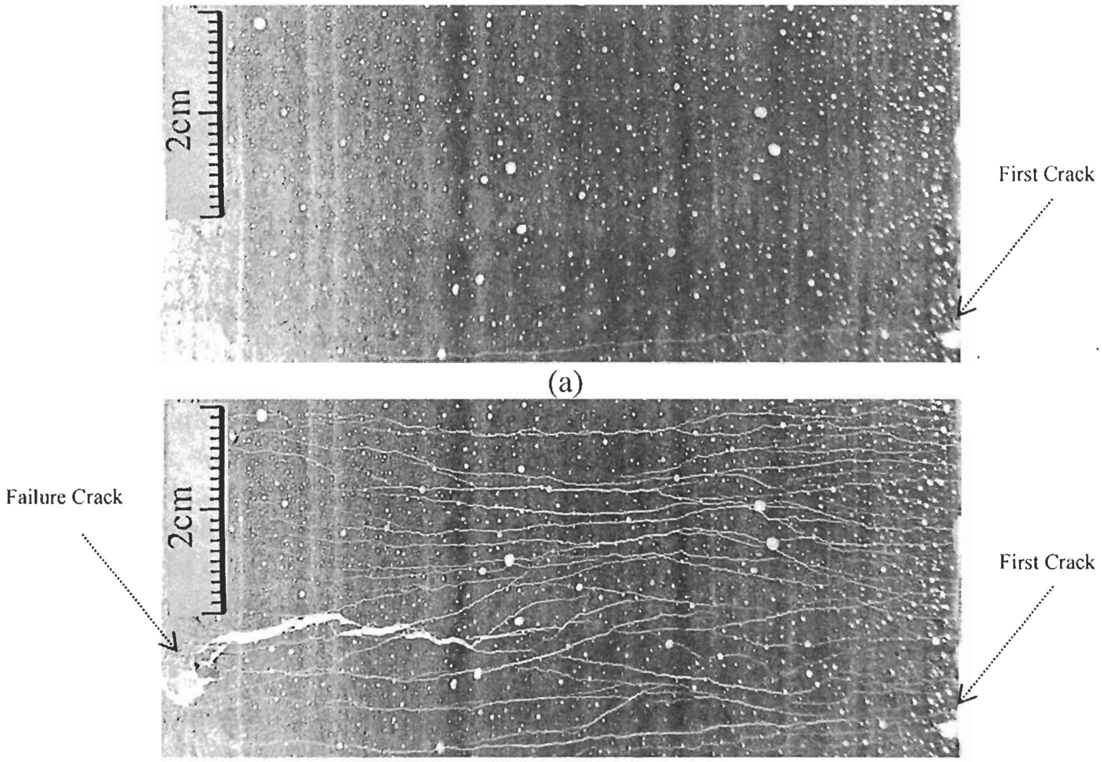
Figure 4: Crack pattern of PVA-ECC at the end of test

Damage Mechanics of ECC

Figure 5 shows the evolution of microcrack damage during tensile testing. It is clear that the first crack is not necessarily the final failure crack. This can be understood from the fact that the first crack is governed by the largest and most favorably oriented (to the tensile loading) defect and is therefore largely a property of the distribution of the random defect sizes in the specimen, and the fracture toughness of the mortar. In contrast, the final crack associated with the ultimate tensile strength results from exhaustion of the strength provided by the fiber bridges acting across a crack plane. The crack plane that hosts the weakest fiber bridges will undergo softening and localize into a fracture. Thus the final crack is mainly governed by the location where the fiber volume is lowest or poorly dispersed. Clearly the location where a large and favorably oriented defect resides does not need to coincide with the location where the fiber volume fraction is lowest or fiber dispersion the poorest.

The above observation that the first crack is not necessarily the final crack implies that the first crack strength and the ultimate tensile strength are independent phenomena governed by different mechanisms. Since the difference between these two strengths defines a margin of safety for tensile strain-hardening and saturated multiple cracking (Kanda and Li, 1998), it is desirable to tailor them to different levels. The understanding of the governing mechanisms makes it possible to do so. As example, the first crack strength can be controlled without compromising the ultimate strength by the use of artificial defects of controlled size range.

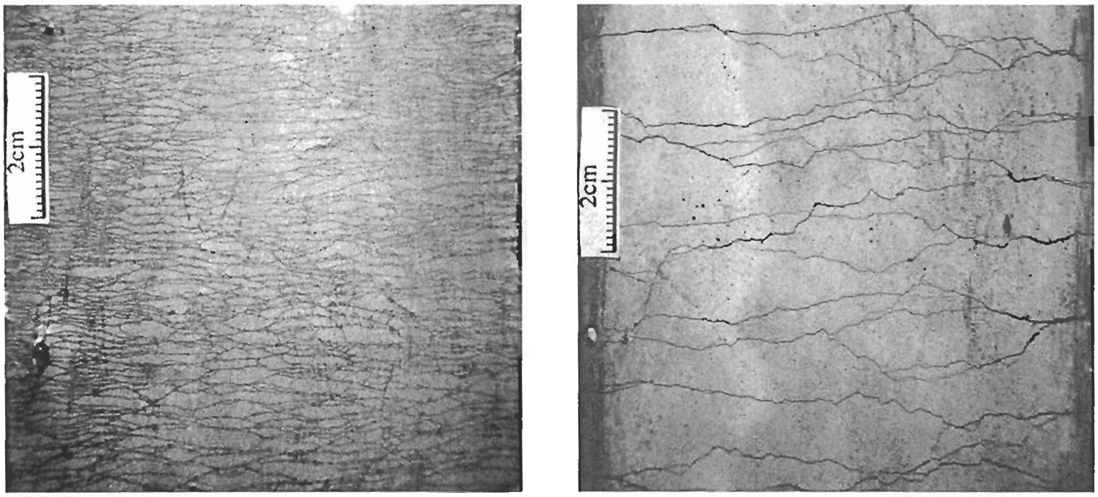
The steady state width of the microcracks is governed by the stiffness of the fiber bridges, which in turn is a function of the fiber volume fraction and elastic modulus, as well as the interface bond properties. High interface chemical and frictional bonds limit the segment of fibers undergoing stretching at a given load, and therefore increase the stiffness of the bridges. This results in tight crack width. Further, high interfacial bond allows more rapid transfer of stress from the cracked site back into the matrix and therefore limits the crack spacing. This explains why PVA-ECC has tighter crack width and small crack spacing compared with PE-ECC, despite the fact that the PE fiber has a much high elastic modulus, as is shown in Figure 6.



(a)

(b)

Figure 5: Evolution of microcrack damage of PVA-ECC during tensile testing for (a) first crack, and (b) failure crack



(a) (b)

Figure 6: Damage pattern (crack width and crack spacing) of (a) PVA-ECC, and (b) PE-ECC

Research Needs

If HPFRCC is to be used beyond the elastic stage, proper characterization and effective materials engineering methodologies must be developed. A deeper level of understanding of the micromechanics behind the damage evolution during tensile strain-hardening is necessary.

HPFRCC is often considered a high energy absorption material of particular value for structures subjected to impact loading. The mechanics of tensile deformation of HPFRCC at high strain rate is in its infancy. It may be expected that the macroscopic properties such as the first crack and ultimate strength, as well as the tensile strain capacity, could be significantly altered as a result of loading at higher strain rates. There will be a need to understand the fundamental governing mechanisms behind the modified damage evolution of HPFRCC under high rate loading. Rate dependencies of fiber, matrix and interface properties must be clarified in order to design HPFRCC suitable for high impact resistant structures.

References

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