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Introduction of Strain-Hardening Engineered Cementitious Composites in Design of Reinforced Concrete Flexural Members for Improved Durability


by Mohamed Maalej and Victor C. Li

This paper proposes a new design for reinforced concrete flexural members to improve durability. The design makes use of the unique properties of a strain-hardening cementitious composite to limit crack width. The composite is used as a replacement for the concrete material that surrounds the main reinforcement in a regular reinforced concrete member. With this design, it was shown that crack widths under service load conditions can be limited to values never before achieved using conventional steel reinforcement and concrete. Under these conditions, it was concluded that it would be possible to prevent migration of aggressive substances into the concrete or reinforcement. Furthermore, accelerated corrosion due to longitudinal cracking or spalling can be reduced, if not eliminated, and spalling and delamination problems common to many of today's reinforced concrete structures can be prevented.

Keywords: **concretes**; corrosion; cracking (fracturing); **crack width and spacing**; **durability**; fibers; permeability; spalling; strains.

Concrete is a brittle material effective in resisting compressive forces but weak in resisting tensile forces. Cracks exist in concrete materials due to processing, shrinkage, and thermal effects. In reinforced concrete (RC), the presence of a load-induced tensile stress field causes existing internal cracks to propagate and reach the exposed surface of concrete, and existing external cracks to penetrate deeper. The width of exposed cracks increases as applied load (or reinforcfement stress) is increased.[1] Large surface cracks are undesirable from an esthetic as well as a durability point of view. Wider cracks increase migration of aggressive agents into concrete and make the concrete cover more permeable to moisture, oxygen, and carbon dioxide (essential to corrosion). Consequently, reinforced concrete can experience reinforcement corrosion, spalling, strength loss, or progressive disintegration. Wider cracks can also lead to increased deterioration due to freeze-thaw action in certain environments. With more frequent use of high-strength steel [yield strength of 60 ksi (414 MPa) and higher] and the increasing trend toward use of limit state design, flexural cracking becomes inherent in RC flexural members.[2] Therefore, control of cracking becomes very important.

Table 1—Tolerable crack widths as a function of exposure condition*

Exposure condition	Tolerable crack width, in. (mm)
Dry air or protective membrane	0.016 (0.406)
Humidity, moist air, or soil	0.012 (0.305)
Deicing chemicals	0.007 (0.178)
Seawater and seawater spray under wetting and drying	0.006 (0.152)
Water-retaining structures	0.004 (0.102)

*Adapted from ACI Committee 224 report.[4]

Although cracking in RC flexural members cannot be prevented, it can be controlled. The current ACI 318 Building Code[3] specifies limits for maximum crack width in RC flexural members as a function of exposure conditions. The specified limits (based on corrosion protection) are 0.016 in. (0.406 mm) for interior exposure and 0.013 in. (0.330 mm) for exterior exposure. ACI Committee 224[4] provides more specific recommendations for allowable crack widths at the tensile face of reinforced concrete structures as a function of exposure conditions. These limits are shown in Table 1. The CEB (Euro-International Committee for Concrete) Code[5] limits crack width at the concrete surface according to exposure conditions, sensitivity of reinforcement to corrosion, and loading conditions. For instance, under "severe exposure" (e.g., corrosive industrial or maritime atmospheric conditions), the CEB Code recommends limiting crack width at the concrete surface to 0.0039 in. (0.10 mm) for reinforcement that is highly sensitive to corrosion under any loading condition. Crack width limits for an aggressive environment are so low that they are nearly impossible or at least

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impractical to achieve in practice using conventional steel reinforcement and concrete, in particular if a large cover is also required.[6] In addition, when these limits are used in conjunction with recommended equations for controlling crack widths, it is expected that a portion of the cracks in a structure will exceed these values significantly.[4]

In this paper, we propose to replace part of the concrete surrounding the main flexural reinforcement in an RC flexural member with a cementitious composite that can exhibit strain-hardening behavior. This strain-hardening engineered cementitious composite (ECC) can be designed with a low volume fraction of discontinuous short fibers. The design principles are based on micromechanics of defect growth in a brittle matrix composite, whereby crack bridging is provided by fibers. ECC is expected to improve cracking behavior and durability of an RC member. If, with this process, better cracking behavior were achieved, a contribution to the solution of a major infrastructure problem, namely, spalling and deterioration in concrete bridges and parking garages, could be made. When ECC is introduced into an RC member, additional but thinner cracks are expected to form on the beam tensile face rather than fewer but wider cracks. According to ACI 318,[3] many fine cracks are preferable to a few, wider cracks for reinforcement protection against corrosion.

Stang and Aarre[7] suggested use of fiber reinforcement (e.g., steel and polypropylene fibers with volume concentration ranging from 1 to 3 percent) in conventional RC structures to reduce and control crack width in the serviceability limit state, in particular, structures exposed to aggressive environments and those where watertightness is critical (e.g., reservoirs and containers). This allows reduction in the conventional steel reinforcement used for crack width control. In their research, steel reinforcement was used as the main crack width control element, while fibers were added to supplement crack width restraint. In the present study, ECC was used as the main crack width control element. This was made possible by the strain- hardening behavior of ECC, uniquely different from most fiber reinforced concrete. Utilization of ECC as the main crack width control element creates the possibility of completely eliminating steel reinforcement placed for the sole purpose of crack width control.

In the first part of this paper, we present a brief review of the effect of crack width on reinforcement corrosion in RC members, migration of aggressive substances into RC members, and possible deterioration of concrete by these substances. Then we present results of an experimental program where a control regular RC beam and an RC beam with an ECC layer were tested in third-point bending. The test allowed evaluation of the performance of the latter in terms of strength, ductility, and cracking behavior. The approach followed in design of the RC member with an ECC layer is also presented.

RESEARCH SIGNIFICANCE

The design proposed in this paper for RC flexural members is aimed at improving durability of these members when exposed to an aggressive environment. With the proposed design, the width of cracks that develop in these members can be limited to low values that could never be achieved using conventional reinforcement and regular concrete materials under similar loading conditions. The research should provide a new direction for addressing the common durability problems of RC structures. This new direction involves strategic use of emerging engineered cementitious composite materials with a high strain capacity and fracture resistance. The overall objective of the proposed design is to extend the life cycle of RC structures while maintaining the minimum associated increase in material cost.

EFFECT OF CRACK WIDTH ON REINFORCEMENT CORROSION

Given the type of materials and designs currently used, even if crack widths in an RC flexural member were limited to 0.004 in. (0.102 mm) under service load conditions, a possible overload of such structures could widen these cracks significantly. Moreover, justifications for provisions limiting crack width at the concrete surface to reduce corrosion are not well established. Some researchers have suggested that, in most structures, it is unnecessary to limit surface crack width for the sake of corrosion protection.[6,8] To better understand and evaluate these claims, we shall review the corrosion process in reinforced concrete members and how it is affected by developing cracks.

A bar embedded in concrete is normally protected from corrosion by concrete alkalinity. In an alkaline environment, reinforcement is protected against corrosion by a very thin layer of oxide forming on its surface. In this state, the reinforcement is described as being passivated. Carbonation or chlorides can break down this passivity and permit the corrosion process. The existence of a crack allows the migration of either chlorides or carbon dioxide and moisture from the air into the concrete, and this causes the depassivation of a small area of bar in the region of the crack. Corrosion is an electrolytic process and, therefore, when corrosion starts at a crack, the depassivated zone near the crack becomes the anode of a corrosion cell as portions of the bar still protected by intact alkaline concrete become the cathode. At the anode, metal ions are liberated. At the cathode, oxygen mixes with water to produce hydroxyl ions, which travel through the electrolyte to the anode, where they react with metal ions to form iron hydroxide. In a secondary reaction, hydroxide combines with additional oxygen to form rust. Therefore, availability of oxygen and water away from the crack and passing through the concrete cover is necessary to maintain the corrosion process.[8]

From this description, it can be concluded that crack width may affect initiation of corrosion, but does not affect the subsequent corrosion process. However, studies have shown that initiation of corrosion is not significantly affected by the width of transverse cracks, as long as they are not very wide [less than 0.016 in. (0.406 mm)].[6] This may explain why ACI 318 has restricted crack width to a maximum of 0.016 in. (0.406 mm). Although most design codes recognize the fact that crack width limits are not always a reliable indication of the corrosion and deterioration to be expected, they still recommend limiting crack widths in conjunction with the use of proper cover and good quality concrete (e.g., low permeability).[3-6] Moreover, it should be noted that, in particularly aggressive environments, it may be necessary to limit crack width to protect the concrete material itself from being attacked by aggressive substances.[9]

EFFECT OF CRACK WIDTH ON FLOW OF AGGRESSIVE SUBSTANCES INTO RC MEMBERS

Aggressive substances can migrate into RC members through water. Tsukamoto[10] studied the tightness of plain concrete and polymer and steel fiber reinforced concrete (FRC) against the flow of water. The tightness of each material was determined by measuring the flow through a crack for various predetermined crack widths. The study indicated that flow rate scales with the third power of crack width, and under a certain crack width (critical crack width), no further flow occurs. Moreover, the study concluded that fibers in concrete reduce flow rate at a given crack width and increase critical crack width. The measured critical crack widths were 0.0039 in. (0.1 mm) for plain concrete, 0.0047 in. (0.12 mm) for 1.7 percent polyacrylonitril FRC, 0.0055 in. (0.14 mm) for 1 percent steel FRC, and 0.0061 in. (0.155 mm) for 0.8 percent polyvinylalcohol FRC under a pressure gradient of 7 ftWS/ft (7 mWS/m) and temperature of 68 F (20 C). Results of this study suggest that the flow of aggressive agents into concrete and through cracks can be significantly reduced by decreasing crack width.

ATTACK OF CONCRETE BY AGGRESSIVE SUBSTANCES

One weakness of concrete is its rather poor resistance to virtually all acids, both organic and inorganic. Acids attack concrete by dissolving the cement, thereby causing concrete disintegration (especially near crack openings), or internal damage if they can penetrate the concrete through cracks.[9] Limestone and dolomite aggregates are susceptible to acid attack and may also cause concrete disintegration. Acids that attack concrete may come from acid-containing or acid-producing substances such as coal-tar distillates, acidic industrial wastes, silage, fruit juices, sour milk and buttermilk, salts of weak bases, and some natural waters. Near coastal areas, seawater can also be destructive to concrete, largely because of its sulfate content.[11] Therefore, in such environments, permeability of concrete to aggressive substances becomes very critical to its durability.

PROPOSED DESIGN FOR RC MEMBERS EXPOSED TO AGGRESSIVE ENVIRONMENT

In this section, we propose a design for RC flexural members that can significantly reduce crack widths that inevitably develop in these members. The design makes use of an ECC characterized by its ability to sustain higher levels of

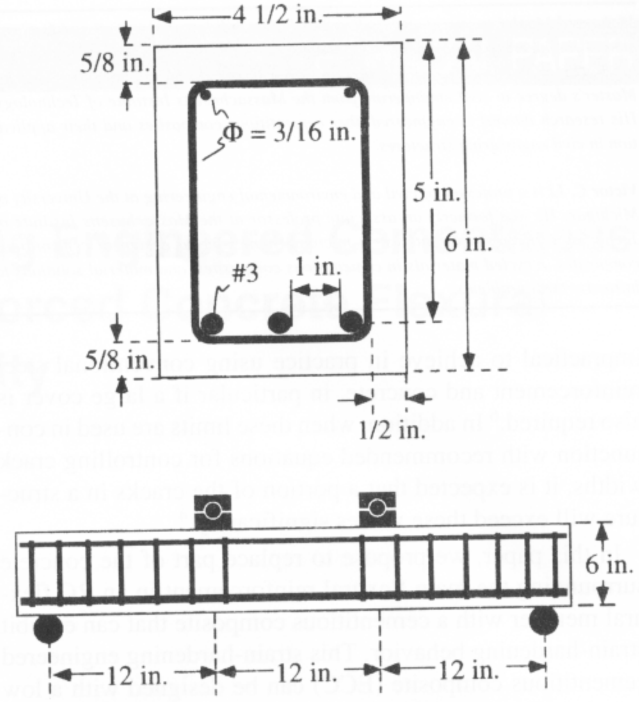


Fig. 1—Geometry of control RC beam and reinforcement details (1 in. = 25.4 mm)

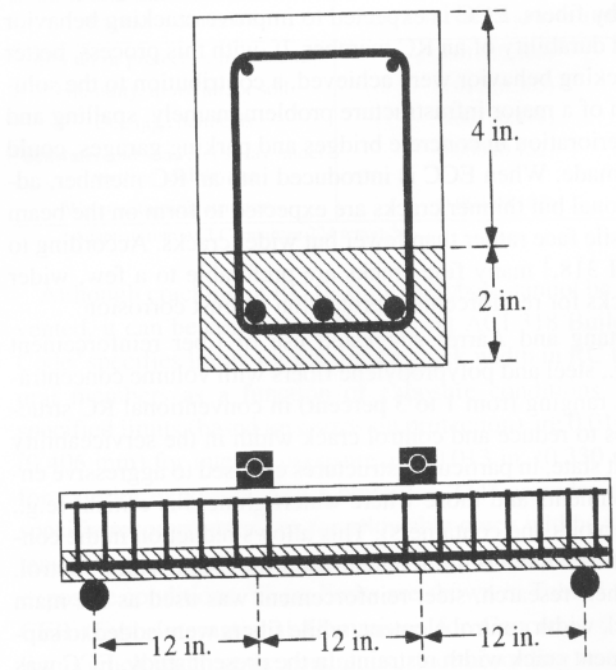


Fig. 2—Geometry of RC beam with ECC layer and reinforcement details (1 in. = 25.4 mm)

loading after first cracking while undergoing additional straining. This additional straining is associated with the development of multiple fine cracks. The strain capacity (at ultimate strength) of ECC can be one to two orders of magnitude higher than concrete or regular fiber reinforced concrete. Such a material is said to exhibit strain-hardening behavior. Strain-hardening behavior has been demonstrated in continuous aligned[12,13] and discontinuous randomly distributed[14,15] fiber reinforced cement materials. The conditions for strain hardening in the latter of these materials have

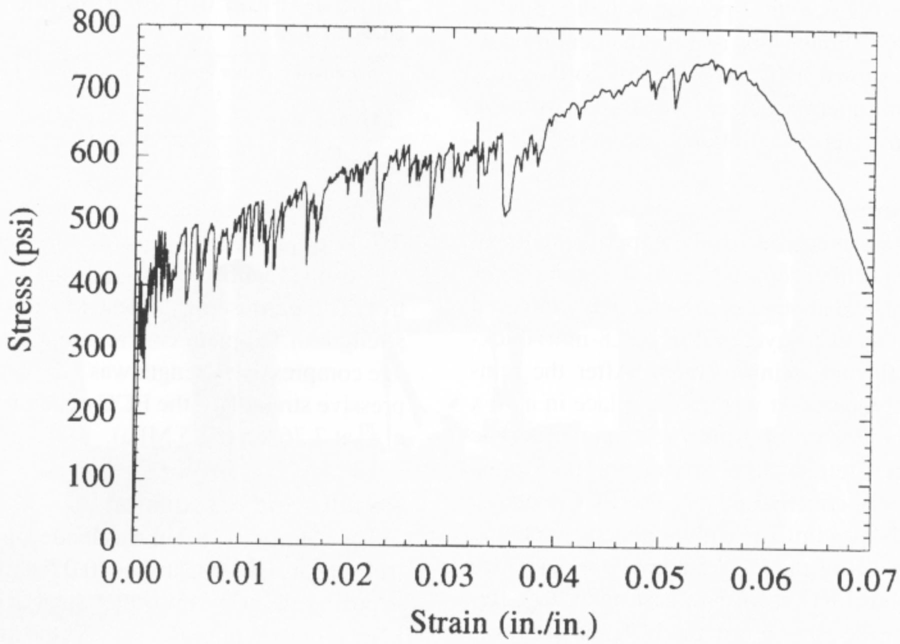


Fig. 3—Uniaxial tensile stress-strain curve of polyethylene ECC (V_f = 2 percent) (1 psi = 6.895 × 10^{-3} MPa, 1 in. = 25.4 mm)

Table 2—Material mix proportions

Material	Cement	Coarse/ fine aggregate	Silica fume	Superplasticizer	Water	V_f, percent
Plain concrete	1.00	1.72/1.72	0	0	0.45	0
ECC	1.00	None	0.10	0.01	0.27	2

recently been calculated[16-18] based on micromechanics principles.

Design of specimens

A control RC beam was designed with 6-ksi (41.4-MPa) compressive strength concrete and 60-ksi (414-MPa) yield strength steel. The beam, which had a 6 x 4.5-in. (152.4 x 114.3-mm) rectangular cross section and a 3-ft (914.4-mm) span length, was tested in third-point bending (Fig. 1). The main reinforcement consisted of three No. 3 bars, corresponding to a reinforcement ratio ρ equal to 0.0147. Shear reinforcement was provided to insure flexural failure of the beam. The shear reinforcement was made from small-diameter [3/16-in. (4.76-mm)] deformed bars. Two bars of similar size were used in the corners of the stirrups on the compression side of the beam to help anchor the stirrups and hold them in place in the mold.

In the proposed design of the RC member, a layer of ECC was substituted for the concrete surrounding the main flexural reinforcement (Fig. 2). Using the same cover thickness as for the control specimen, the thickness of the ECC layer was selected such that its cross section had the same centroid as the reinforcement. This was done to insure a uniform bond between the reinforcement and ECC layer. Two performance requirements were imposed on the ECC material to serve its intended purpose: 1) the ultimate tensile strain capacity of the ECC material had to be greater than the maximum strain that can be developed in the outermost fiber at the tensile face of the RC beam, and 2) the crack width at the ultimate strain capacity of the ECC material (hereafter referred to as ultimate crack width) had to be less than the maximum crack width allowed in a particular environment. The first condition insures that no strain localization will take place in the ECC layer, and the second insures that the crack opening in the ECC is maintained below the allowable value. Assuming that, at ultimate load, strain in the extreme compression fiber of the concrete is equal to 0.003, and that plane sections remain plane, the strain in the extreme tension fiber of the ECC was found to be equal to 0.013. Therefore, the ECC selected should have an ultimate strain capacity at least equal to 0.013. In addition, suppose that the member is to be exposed in an environment of seawater and seawater spray under wetting and drying. In this case, according to ACI Committee 224, the crack width should be limited to 0.006 in. (0.152 mm). Therefore, the ultimate crack width of ECC should be less than 0.006 in. (0.152 mm).

For the purpose of this study, a 2 percent (by volume) polyethylene fiber reinforced cement was selected as the material for the ECC layer. This composite exhibits a strain-hardening behavior characterized by the typical tensile stress-strain curve shown in Fig. 3.[18] As Fig. 3 indicates, the ultimate tensile strain capacity of this material is about 0.054. The average ultimate crack width for this material was measured at 0.0055 in. (0.140 mm). Therefore, this material is expected to satisfy the performance requirements established for the ECC layer.

Materials

The mix proportions of the plain concrete material and ECC material are shown in Table 2. All mix proportions are by dry weight of the ingredients. Mix constituents of the plain concrete included 3/8-in. (9.52-mm) maximum-size coarse aggregate and Type 2NS sand fine aggregate (each meeting the grading requirements of ASTM C33), Type I portland cement (meeting ASTM C 150), and water. Discontinuous polyethylene fibers with 2 percent volume fraction were used in the ECC. Dimensions and mechanical properties of the fibers are shown in Table 3. Type I portland cement, silica fume, and superplasticizer were used to form the cement matrix with a water-cementitious ratio of 0.27.

Specimen preparation

Two specimens were prepared for the experimental program: one control specimen consisting of a regular reinforced concrete beam, and another consisting of a reinforced concrete beam where an ECC layer of 2-in. (50.8-mm) thickness surrounds the flexural reinforcement. After the reinforcement cage was prepared, it was held in place in a 40 x 6 x 4.5-in. (1016 x 152.4 x 114.3-mm) rectangular acrylic plastic mold. Plain concrete material mixing was performed in a standard laboratory concrete mixer. The ECC material was mixed in a three-speed mixer with a planetary rotating blade. Processing details of the ECC material are described elsewhere.[19] The control RC beam was cast under low-frequency vibration. For the other beam, the ECC material was first poured under low-frequency vibration. After approximately 1 hr, the plain concrete was prepared and poured on top of the ECC layer under low-frequency vibration. The main reason for not pouring the plain concrete material immediately after pouring the ECC material was to prevent the aggregates (from concrete) from mixing with the ECC material. Three 3 x 6-in. (76.2 x 152.4-mm) compression cylinder specimens were also cast from each batch of concrete material. All specimens were moist-cured for 48 hr and then placed in water to cure for 4 weeks. Subsequently, they were removed from water and covered with polyethylene sheets until testing. A thin white coating of lime was applied on the beam specimens prior to testing to better monitor crack development. Age at testing of the specimens was 90 days.

Testing procedure

Beams were tested in a test system with a 110-kip- (489-kN)-capacity loading frame. The tests were run under displacement control, and total test time was approximately 15 min. Ram load and head displacement information were recorded on a personsal computer. Four linear variable differential transducers (LVDTs) were used to measure beam deflection and curvature during loading. The four LVDTs were connected to a signal conditioner, and data were recorded on the same personal computer. As shown in Fig. 4(b), a pair of LVDTs was attached on top and bottom surfaces of the specimen at the center span to measure the compressive and tensile deformation in a 6-in. (152.4-mm) gage. The other pair was used to measure deflection of two symmetric points located at a distance of 3 in. (76.2 mm) from the loading points. Loads were applied through rollers resting on 2.5-in. (63.5-mm) rectangular plates and the beam was supported on roller supports, as shown by Fig. 4(a). A video microscope equipped with a 50x lens and monitor/recorder was used to monitor variation of the first crack width that developed in the center span at the bottom of the beam during loading. An ordinary 8-mm video camera was also used to follow crack development along the beam span during loading.

Table 3—Fiber dimensions and mechanical properties

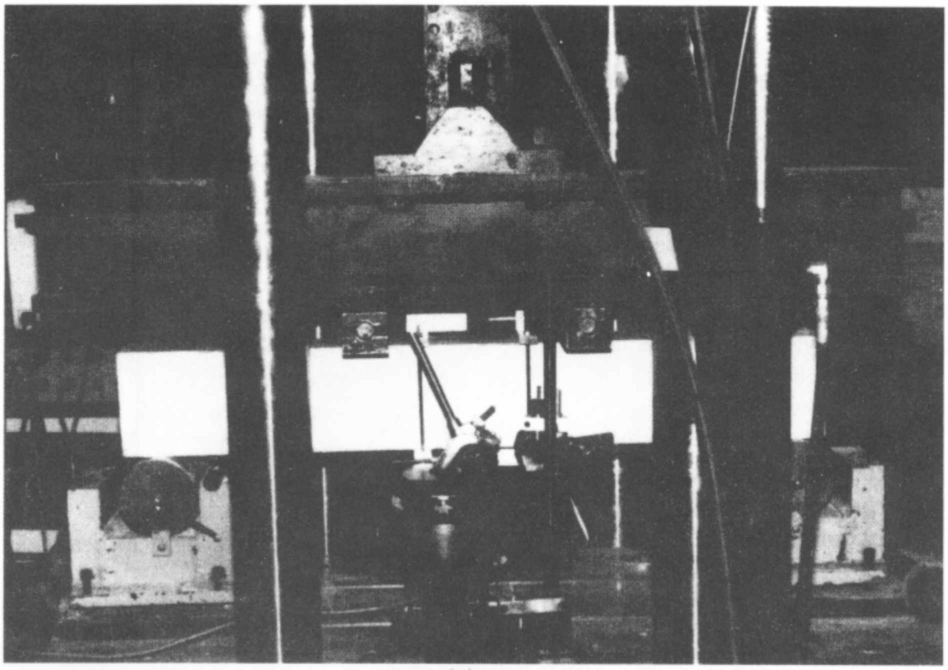
Fiber diameter, 10^{-3} in. (μm)	Fiber length, in. (mm)	Elastic modulus, 10^3 ksi (GPa)	Fiber strength, ksi (MPa)	Fiber density, lb/ft^3 (g/cm^3)
1.5 (38)	0.5 (12.7)	17.4 (120)	392 (2700)	61.2 (0.98)

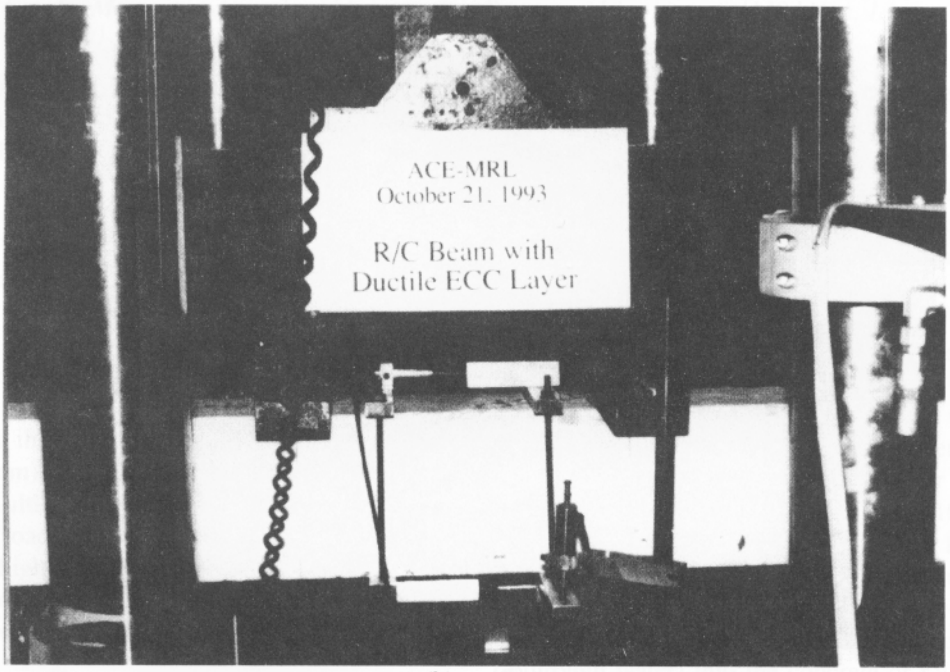
Compression cylinders were tested in a test system with a 550- kip- (2446-kN)-capacity loading frame. Each cylinder was capped with sulfur and tested under displacement control. The purpose of the test was to obtain the compressive strength of the plain concrete material. The measured average compressive strength was 7.27 ksi (50.1 MPa). The compressive strength of the ECC material was measured by Li et al.[20] at 7.76 ksi (53.5 MPa).

Results and discussion

The control RC beam was loaded under displacement control at a rate of 0.001 in./sec (0.0254 mm/sec). The first crack appeared in the beam center span at a load of 4 kips (17.8 kN) (about 1/6 of peak load). As the load increased, additional flexural cracks developed in the beam. During the stage of crack development, the load was increased at an approximately constant rate. After this stage, load increased at a much reduced rate. This was intended to correspond to the stage of steel yielding. As the test progressed, the video microscope indicated a continuously increasing crack width. At the peak load, we could see development of small areas of concrete crushing around the midspan. Initially, the crushing was limited to the extreme compression fiber and then progressed down. The test was terminated when the crushing reached the 3/16-in.- (4.76- mm)-diameter bars placed in the corner of the stirrups. A total number of four cracks developed in this beam inside the gage zone. Fig. 5(a) shows the cracking pattern in the RC beam at about the peak load.

The RC beam with the ECC layer was loaded under displacement control at the same loading rate of 0.001 in./sec (0.0254 mm/sec). The first crack appeared in the beam at approximately the same load as the control RC beam. The crack could be easily seen above the ECC layer, but was difficult to see in the ECC layer. As the load increased, further cracks developed in the concrete material as well as the ECC material. In the concrete material, a few wide cracks developed; however, in the ECC material, a large number of fine cracks developed. During the stage of slow load increase, no further cracking was observed in the concrete material, while cracks continued to develop in the ECC material. It is interesting to note that the large cracks that developed in the concrete material diffused into many fine cracks when they met the ECC material [Fig. 5(b)]. This phenomenon is similar to what has been observed in double cantilever beam (DCB) fracture specimens made of the same ECC material, where the concrete cracking can be compared to the prenotch in the DCB fracture specimen.[19] When a large crack develops in concrete, it is accompanied by strain concentration at the location where this crack meets the ECC material. Because of the stress transfer capability of the reinforcing fibers in ECC material, stress redistribution occurs, so that localized fracture is delayed. In fact, localized fracture may never develop in the ECC layer if the maximum strain in the layer is kept


(a)

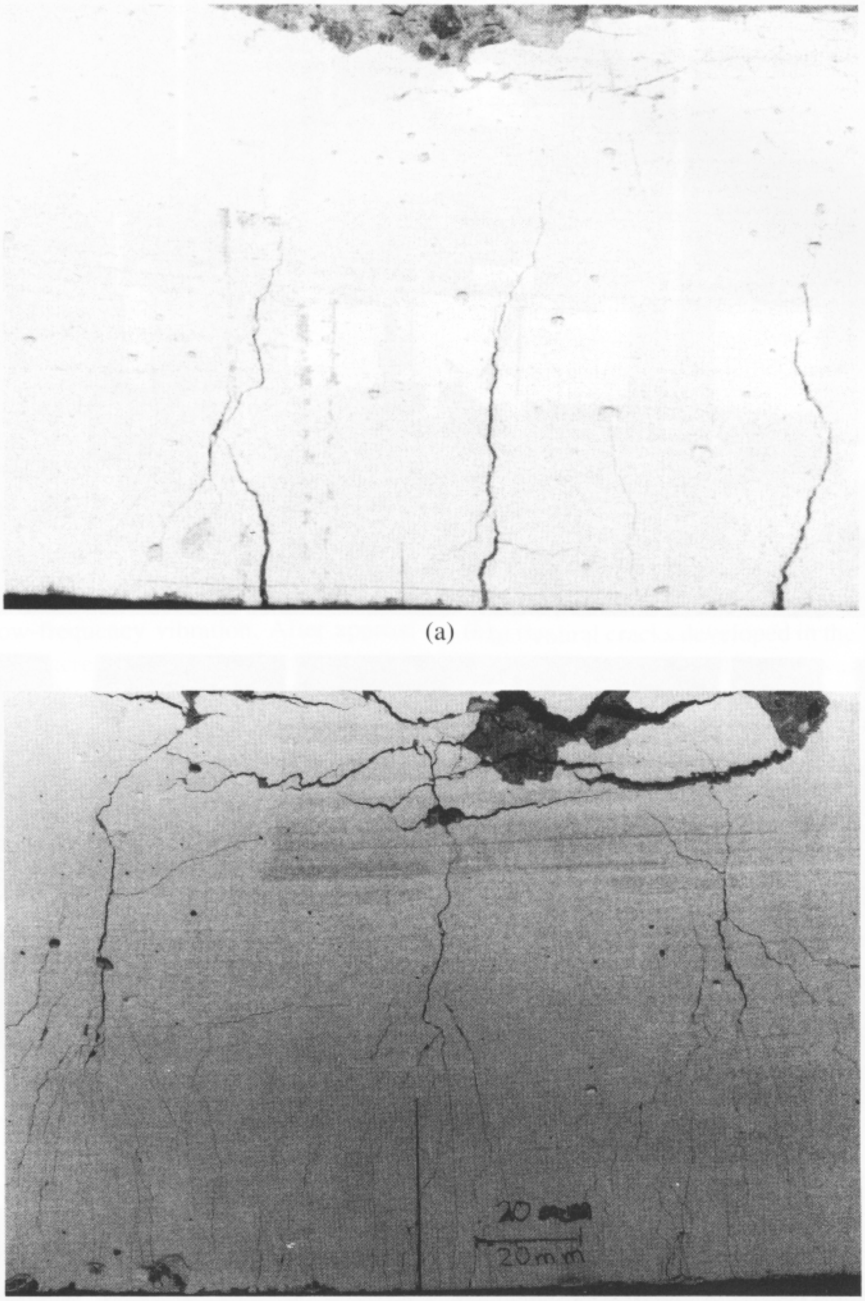


(b)

Fig. 4—Experimental setup

below the material ultimate strain capacity. Consequently, an expanded zone of matrix cracking must develop in the ECC layer prior to localized fracture. Such an extensive volumetric cracking process must involve considerable energy absorption, which can be related to the off-plane fracture energy recorded in a DCB fracture specimen.[19] As the specimen was being loaded, the video microscope indicated a slowly increasing crack width (compared to the control specimen) at the bottom of the ECC layer. The stage of slow load increase was accompanied by an even slower rate of crack width increase. At ultimate load, a total number of 40 cracks developed inside the gage zone. No sign of delamination between the concrete and ECC layer was observed. If the concrete had been poured on top of the ECC layer after it had hardened, delamination between the two materials might have been a problem.

Fig. 6 shows the moment curvature and crack width curvature diagrams for both beams. As this figure shows, there is no significant difference between the moment curvature response of the two beams. The beam with the ECC layer shows a 10 percent higher load and curvature at failure. The crack width-curvature response of the two beams is, however, significantly different. Fig. 6 shows that crack width in the control specimen increases almost linearly as a function of curvature. Before yielding of reinforcement [moment ≈ 95 in.-kip (10.7 kN-m)], crack width at the bottom of the beam



(a)

(b)

Fig. 5—Cracking pattern: (a) control RC beam; (b) RC beam with ECC layer

was maintained below 0.008 in. (0.203 mm). After yielding, the load started to increase at a much slower rate, while the crack width continued to increase at the same rate. At peak load, crack width was approximately equal to 0.06 in. (1.524 mm). When the beam was loaded 20 percent beyond yielding load, crack width reached the ACI crack width limit for interior exposure [0.016 in. (0.406 mm)]. Any crack widths larger than this limit may result in a high rate of reinforcement corrosion and possible deterioration of concrete if the beam is to be exposed in an aggressive environment.[6] From here, we can see that a possible overload of a properly designed member (satisfying crack width criteria under service load) can drive cracks significantly wider, resulting in eventual durability problems. Note that, for this particular (control) beam, the measured crack widths are relatively small because of the small cover (crack width scales with the square root of cover thickness measured from extreme tension fiber to the center of the closest reinforcing bar).[1]

Fig. 6 shows that, for a given curvature, the crack width measured on the beam with the ECC layer is much smaller than that measured on the control RC beam. For the former, the crack width begins to increase almost linearly as a function of curvature, and then continues to increase at a slower rate. Before reinforcement yielding [moment ≈ 95 in.-kip (10.7 kN-m)], crack width is maintained below 0.002 in. (0.051 mm). At ultimate load, the crack width reaches 0.0076 in. (0.193 mm). Also, the strain measured in the ECC material at the bottom of the beam was 0.026, smaller than

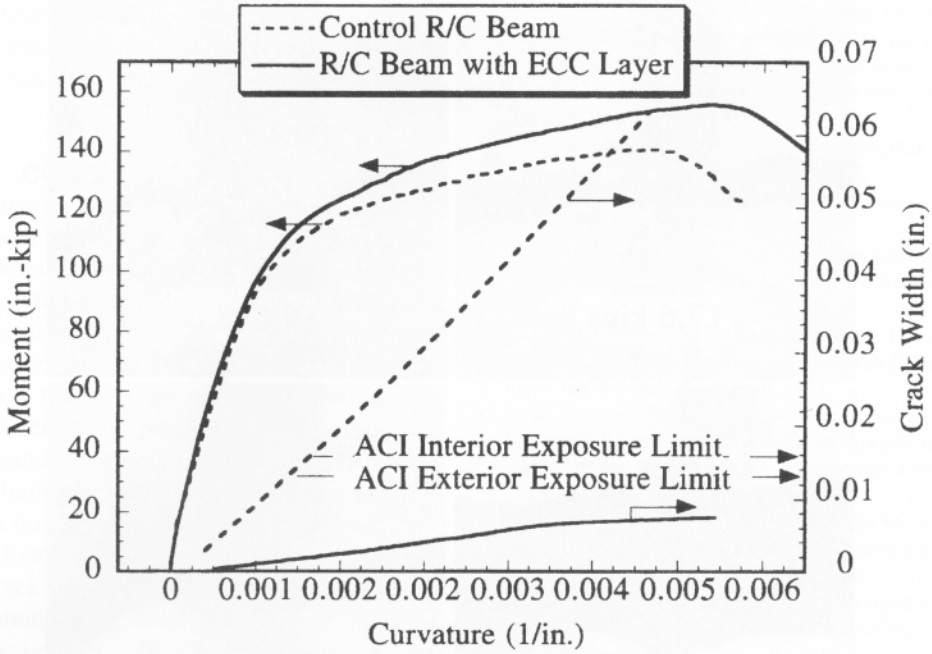


Fig. 6—Moment and crack width-curvature diagrams (1 in.-kip = 0.1130 kN-m, 1 in. = 25.4 mm)

the ultimate strain capacity of the material. Note that we have predicted a maximum tensile strain in the ECC layer of 0.013 at failure. This prediction was based on an assumed compression failure strain of 0.003. However, the measured compression strain at failure was 0.0052. Since the maximum tensile strain in the ECC layer is smaller than the ultimate tensile strain of material, we expect the average crack width in the ECC layer to be smaller than the average ultimate crack width. Using the measured strain value of 0.026 (the total number of cracks in the gage zone), and neglecting matrix deformation, we can estimate the average crack width in the ECC layer at the bottom of the beam, which measured 0.0039 in. (0.10 mm). This average value is indeed smaller than the average ultimate crack width [0.0055 in. (0.140 mm)]. At ultimate load, the crack width measured by the video microscope is higher than the latter. This is probably so because the microscope monitored the width of the first crack that developed in the center span, which appeared to be the largest of the cracks.

Fig. 7 shows two series of pictures illustrating the crack width increase as a function of load for both the control RC beam (Series a) and the RC beam with an ECC layer (Series b). These pictures were digitized from the video microscope tape. The vertical line in the middle of each picture is a reference line drawn at the bottom of the beam. The load level is indicated on the bottom of each picture. These series of pictures indicate a significant difference in the cracking behavior of the two beams. They illustrate that, for a given load level, the crack width in the RC beam with the ECC layer is always smaller than that in the control specimen, and that the rate of crack width increase as a function of load is much higher for the latter. The third picture of Series b shows the appearance of a new crack next to the existing crack. In this case, one can easily see that, if the new crack did not develop, width of the existing crack would have been larger. Therefore, it can be concluded that the crack width in the ECC layer is maintained at a low value because of the appearance of new cracks, which begin to accommodate further imposed deformation as soon as they form.

Based on the preceding results and referring back to Tsukamoto's study,[10] one could conclude that the flow of aggressive substance into an RC member might be significantly reduced, if not brought down to zero. This is achieved by selecting an ECC where the ultimate crack width (crack width at the ultimate strain capacity) is below the critical crack width (crack width under which no further flow occurs), and using that material to replace the concrete around the main reinforcement. One could infer from Tsukamoto's study that the critical crack width for this ECC material should be at least equal to 0.004 in. (0.102 mm). Under service load conditions, crack width in the RC beam with ECC material is limited to 0.002 in. (0.051 mm). Therefore, it can be concluded that, under service load conditions, the ECC layer will prevent migration of any aggressive substance (through water) into the concrete or reinforcement. Above the critical crack width, it is known that the flow rate scales with the third power of the crack width. Therefore, a small reduction in crack width translates into a significant reduction in flow rate. This is known to be true for a single crack; however, it is not known what effect cracking density in an ECC material would have on flow rate. This issue needs to be addressed in the future, in the context of durability studies of ECC materials, which consider not only crack width as a major variable but also crack density.

Corrosion of a reinforcing bar is accompanied by production of iron oxides and hydroxides, which occupy a larger volume than the original metal. As a result, considerable pressure is exerted on the surrounding concrete, resulting in local radial cracks. These cracks can propagate along the bar, producing longitudinal cracks.[4] Longitudinal cracks can also form due to structural (bond or dowel) action and/or transverse tension (such as along stirrups). Formation of longitu-

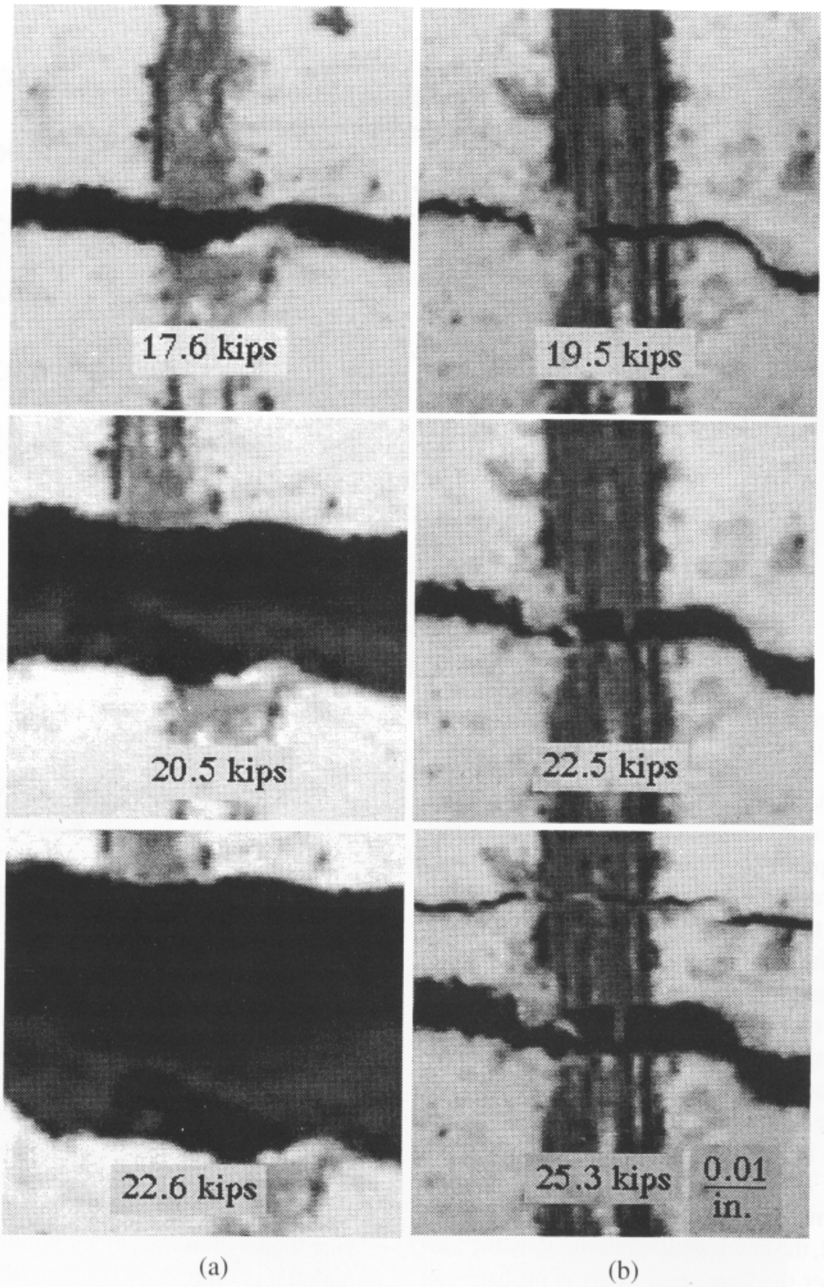


Fig. 7—Variation of crack width as function of load: (a) control RC beam; (b) RC beam with ECC layer (1 kip = 4.448 kN, 1 in. = 25.4 mm)

dinal cracks can lead to severe corrosion problems. This is because the electrolytic reaction can develop and continue along the bar, producing general corrosion. Consequently, a significant bursting pressure is created by corrosion products, resulting in further cracking and, in extreme cases, spalling of the concrete, especially at corner bars.[6] When spalling of concrete cover occurs, the corrosion process accelerates (corrosion of exposed bars may occur at about 10 times the rate at which it occurs at a crack),[21] and the member is likely to experience strength loss.

In addition, a large crack may form parallel to the concrete surface at a plane of bars, resulting in delamination of the surface, a serious problem in bridge decks.[4] When the concrete surrounding reinforcement is replaced with ECC material, longitudinal cracks are likely to be arrested before reaching the exposed surface, or otherwise be limited in width. In this case, control of the width of longitudinal cracks can be very effective in reducing reinforcement corrosion. Moreover, by using an ECC, spalling and delamination of concrete will be eliminated. This is due to the high fracture resistance of the ECC material[19] associated with a rapid-rising R-curve.[22]

The high strain capacity and fracture resistance observed in the polyethylene fiber composite can be obtained with other types of fibers, provided that conditions for strain hardening are satisfied.[16-18] Li et al.[15] showed that strain-hardening behavior can be obtained in steel fiber cementitious composites with a fiber volume fraction as low as 1.3 percent. This is achieved by controlling fiber length and enhancing the interfacial bond strength by using a coupling agent and/or high frequency vibration. In addition, recent research shows that strain- hardening behavior can be achieved in carbon and polypropylene fiber cementitious composites.[23,24] These composites have been designed by tailoring the micromechanical parameters (fiber, matrix, and fiber/matrix interfacial properties) such that strain-hardening conditions are satisfied.

CONCLUSIONS

With increasing use of high-strength steels and the strong trend toward ultimate strength design, control of cracking becomes very important in reinforced concrete structures. Cracks should be limited to protect reinforced concrete structures from aggressive environmental conditions and for esthetic reasons. The crack width limits for an aggressive environment are so low that they are nearly impossible or at least impractical to achieve in practice using conventional steel reinforcement and commonly used concrete. In critical structures, high-volume steel reinforcement usage requires expensive labor. In this paper, a design for reinforced concrete members, utilizing the unique properties of an ECC material to limit crack width, was presented. With this design, it was demonstrated that crack width under service load conditions could be limited to 0.002 in. (0.051 mm), and, even if the member is overloaded, crack width can still be limited to 0.0076 in. (0.193 mm). Under service load conditions, it was concluded that the ECC layer can prevent migration of aggressive substances into the concrete or reinforcement. In addition, with the proposed design, accelerated corrosion due to longitudinal cracking or spalling can be reduced, if not eliminated. Furthermore, spalling and delamination problems common to many of today's RC structures can be prevented.

These findings warrant future studies of the durability of RC members with the proposed design.

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