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REPAIR AND RETROFIT WITH ENGINEERED CEMENTITIOUS COMPOSITES

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Abstract

This article presents the novel use of a super ductile fiber reinforced cementitious composite for repair and retrofit of concrete structures. Research in repair and retrofit demands immediate attention because of rapidly deteriorating and heightened safety requirements of civil infrastructures worldwide. The strain-hardening Engineered Cementitious Composites (ECC) has been engineered with the aid of fracture mechanics and micromechanics. It is emphasized that *material* ductility, not strength, can translate into strong and ductile *structural* performance.
Key words: infrastructure, repair, retrofit, composites, fracture

1. Introduction

Infrastructures in many industrialized countries are aging. In the US, the interstate highway system is in disrepair. Almost 40% of US bridges are in some state of serious deterioration. Put in economic terms, the magnitude of our infrastructure need is enormous. Worldwide, about 10% of GDP derives from infrastructure construction. In the US alone, infrastructure construction is a $400 B industry involving six million jobs. We have approximately $17 trillion of infrastructures in place. Obviously we cannot replace them frequently. Instead the solution must lie in repair, retrofit and rehabilitation technology. The materials which go into these technologies have to be long lasting, but must also produce a durable infrastructure system. In other words, advanced construction materials must support the organic growth of our new infrastructures, and at the same time, contribute to maintaining the health of our inventory of existing infrastructures. The impact of advanced civil engineering materials in the world economy is significant.

Concrete as a structural material has undergone several important phases of development. In the early 1900 and around 1940's, steel reinforced concrete and prestressed concrete established themselves as viable alternative to steel as major construction materials. Around 1970, high strength concrete became commercialized with the arrival of silica fume and superplasticizer as chemical additives, and continued to the present in impacting taller, longer and bigger infrastructures. Fiber reinforced concrete began its broader acceptance by the practice community in the 1980's, although mostly limited to non-structural use. At the moment we are undergoing a phase of structural FRCs being applied in infrastructures in which the fibers are expected to carry loads.

2. ECC Design

The design and properties of ECCs have been discussed at length in Li (1998). Here we provide a brief synopsis, focusing on those properties most relevant to the repair and retrofit example applications to follow. There are four performance targets for ECC: (1) high performance, (2) flexible processing, (3) short fibers at moderate volume fraction, and (4) isotropic properties. By high performance, we mean tensile ductility here, because this property appears to provide the greatest enhancement to infrastructural needs, and also appears to be the bottle neck property when viewed in light of the great strides made in high strength concrete in recent years. However, ductility is not exclusive to other desirable features such as durability, high strength or self-compacting rheological behavior. High ductility in the form of strain-hardening has been achieved with some fiber reinforced concretes (FRCs) which utilize large amount and/or continuous fibers (and therefore violates economic constraints), or requires highly specialized processes not easily implementable in a construction site. Ordinary FRC satisfies the later three targets but do not in general possess high tensile ductility especially when measured in uniaxial tension or fracture toughness test.

Our goal is to design ECCs which meet all four targets. The underlying technique is to tailor the microstructure of the composite based on mechanics understanding of the interaction between fiber, interface and matrix in the composite under load. Fracture mechanics is prominently utilized at the meso level of cement matrix crack propagation behavior, and at the micro level in the fracture debonding process of the fiber/matrix interface. Micromechanics deals with the mechanical crack bridging action of the fibers, in the form of a stress-crack opening relationship. Statistics is introduced to describe the random nature of pre-existing microcracks, and the random location and orientation of fibers. These analytic tools together generate a ECC model which can be inverted to serve as a composite tailoring guide.

To appreciate the power of this tailoring procedure, it is useful to recognize that each of the three composite phases fiber, matrix and interface has its own set of parameters. For example, the fiber is characterized in terms of its elastic modulus, tensile strength, length, diameter, and volume fraction. The matrix is characterized in terms of its toughness, elastic modulus and initial flaw size. The interface, or more generally the fiber/matrix interaction parameters, include the friction and chemical bond properties and the snubbing coefficients. For some fibers, strength reduction factors are also needed to describe the reduction of fiber strength when pulled at an inclined angle. These parameters together govern the composite behavior. In particular, it would be desirable to determine the combination of these parameters which gives rise to composite strain hardening as opposed to tension softening typical of regular FRC. Empirical means to find the right combination is practically impossible. Micromechanics allows a systematic means to determine the transition from quasi-brittle behavior to strain-hardening behavior, with the smallest amount of fiber. This amount, known as the critical fiber volume fraction V_f^{crit}, is strongly dependent on the matrix toughness, the interface bond property and the fiber aspect ratio. By tailoring these properties, it is possible to determine a V_f^{crit} small enough for regular processing and at the same time satisfy economic constraints. Simultaneously, high ductility is achieved.

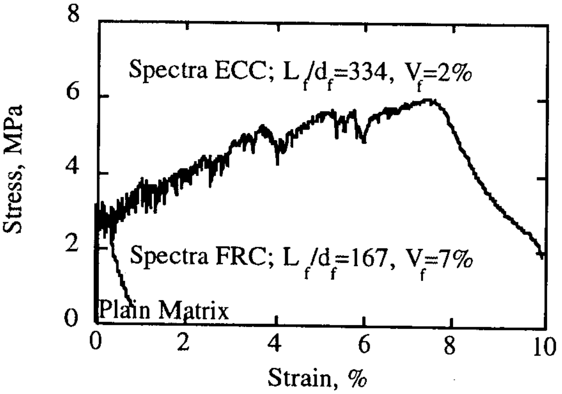
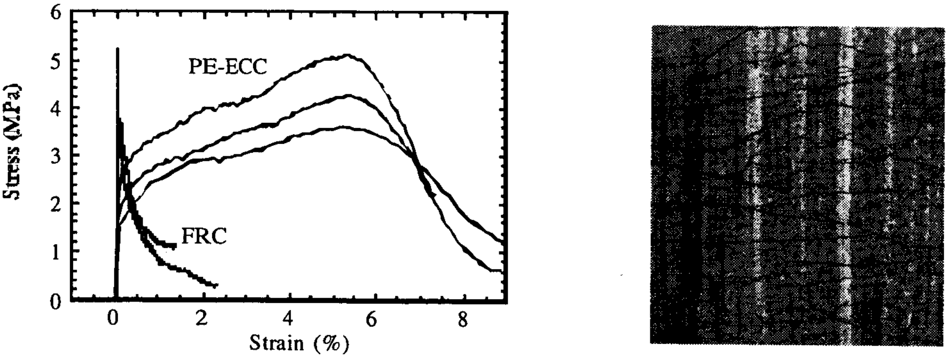


Fig. 1. Stress-strain curves demonstrating the importance of V_f^{crit}

To emphasize the importance of tailoring rather than forcing as much fiber into the composite as possible, Fig. 1 shows that an FRC with $V_f = 7\%$ has quasi-brittle behavior in contrast to the strain-hardening behavior of an ECC with only $V_f = 2\%$, under uniaxial tensile loading. In this ECC the fiber aspect ratio is twice that of the FRC, while everything else remains identical. This example reveals that with the lower aspect ratio ($L_f/d_f = 167$), the V_f^{crit} exceeds 7%, while for $L_f/d_f = 334$, the V_f^{crit} is lower than 2%. The ideally brittle behavior of a plain matrix specimen with no fiber is also shown.

3. ECC Tensile and Fracture Related Properties

In the following, we review the tensile and fracture properties of an PE-ECC. These properties are relevant to the application examples in repair and retrofit to be discussed in the following section. Details of testing technique, material composition and other mechanical properties tested can be found in Li (1998). Fig. 2 shows the uniaxial tensile behavior of the ECC. The first crack strength (at the bent over point) can be adjusted by the cement or mortar matrix composition. As shown, it is lower than that of a typical steel FRC. Often times, a lower first crack strength can be desirable if damage initiation is needed at limited load magnitude. After first cracking, the all important strain-hardening process begins, accompanied by inelastic deformation and load capacity increase. This continues until about 5.6% in tensile strain capacity for this example, when microcracking saturates and a localized fracture finally forms. Beyond this stage, tension softening as in the case of an FRC predominates.



(a) (b)

Fig. 2 (a) Uniaxial tensile behavior of ECC, and (b) microcracking with spacing of about 1mm on tension specimen.

The fracture behavior of an ECC compact tension specimen is shown in Fig. 3. Note the extensive damage development around the initial notch. The width of the inelastic zone is approximately 20 cm, resulting in a fracture toughness about 30 kJ/m^2. ECC is extremely damage tolerant. Fig. 4 shows the damage pattern of a double edge notched specimen loaded in tension. Diffusion of the microcrack damage away from the notches can be clearly observed. This strain redistribution renders the ECC notch insensitive, as can be seen in the failure load plot also shown in Fig. 4.

In summary ECC is an extremely ductile cementitious composite designed with mechanical science. Tensile strain-hardening with strain capacity exceeding 2% can be achieved with fiber volume fraction less than 2% by volume. The high ductility and damage tolerance has important implications in structural perforamnce, as will be described in the next section. The moderate amount of discontinuous fibers allow meeting cost and processing constraints and therefore is suitable for application in construction sites as well as in pre-cast plants.

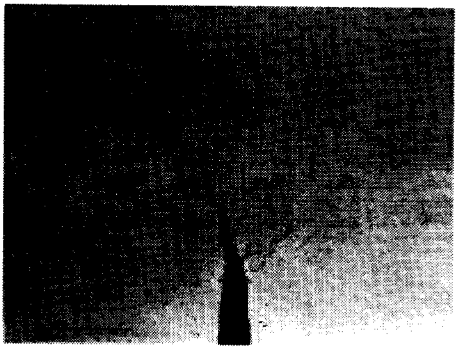


Fig. 3 Ductile fracture behavior of ECC. Scale marker is 50 mm.

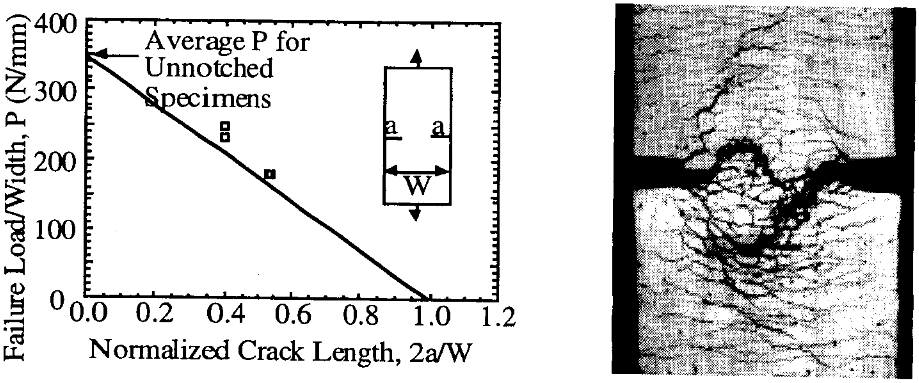


Fig. 4 Damage tolerance of ECC. Specimen width is 75 mm.

4. Applications of ECC in Repair and Retrofit

4.1 Repair

Designed for structural applications, ECCs have unique properties suitable for applications in repair and retrofit of existing structures as well as for new structural applications. Here we review highlights of studies in ECC repair and retrofit, emphasizing the translation of material ductility into structural system performance. Details of the ECC repair study can be found in Lim and Li (1997) (see also Lim and Li in this volume). Details of the retrofit study can be found in Kanda et al (1998) and Kabele et al (1997) (see also Horii et al in this volume).

The most urgent need in concrete repair system is durability. It is generally recognized that the bond between the repair material and the substrate material is most important. Failure can initiate from an interfacial defect causing delamination in the case of a weak "bond" and spalling in the case of an overly strong "bond". At the moment several types of bond tests are recommended to obtain a "bond strength" between the repair material and the substrate concrete. Unfortunately, there appears significant difficulty in tranforming what appears to be a strong bond in the laboratory to durable repair performance in the field. There are two issues here. (1) Mechanics: If failure of the repaired system (delamination or spalling) is governed by a fracture process, characterization of the interface by a bond strength becomes questionable and strong size effect of the measured bond strength can be expected. This may in fact be the reason why bond strength test does not produce field predictable results, as the laboratory specimen size and geometry, loading configuration, or flaw size can be expected to be quite different from those in the field. (2) Materials: Since elimination of delamination naturally give preference to spalling and vise versa, it becomes a dilemma that both material failure types cannot be eliminated simultaneously.

It is proposed here that ECC may offer the possibility in resolving this dilemma. This is best explained by showing the test results of a simulated repaired system shown in Fig. 5. The base concrete is overlaid by a repair material (plain concrete, FRC and ECC). To simulate an interface defect, an initial notch is introduced at the interface. To deliberately simulate a severe loading situation, a joint is included in the base concrete below the interface notch. A four point loading then introduces a mixed mode load on the interface notch. For control specimens with concrete or FRC as the repair material, spalling of the repair material results with very small amount of delamination. The high phase angle (Lim and Li, 1997) gives preference to kinking of the interfacial crack into the repair material. For the concrete repair material, load drops occur immediately following the kink out and the specimen broke into two halves. For the FRC repair material, the spall crack is bridged by the steel fibers and gradual load drops occurs as the spall propagates to the surface. For the ECC repair specimen, a sequence of interface crack extension, kink out, arrest events occur, resulting in a pattern of microcracks in the ECC more or less following the interfacial crack tip. Fig. 6 shows a close-up view of the kink out cracks. Small load drops appear to accompany the kink outs in the load-deflection curve measured in this system. Fig. 7 compares the very different load-deflection curve of all three sets of specimens.

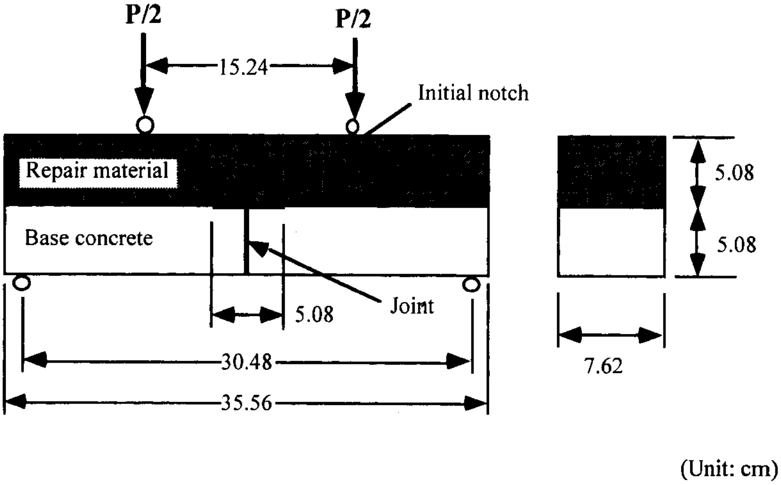


Fig. 5 Simulated repair system

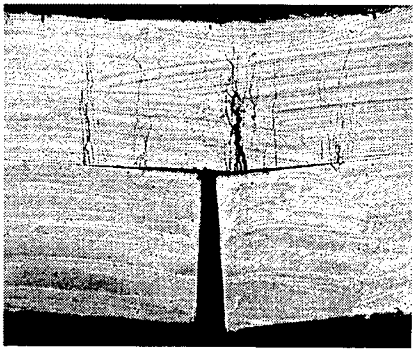


Fig. 6 Crack pattern in Conc./ECC

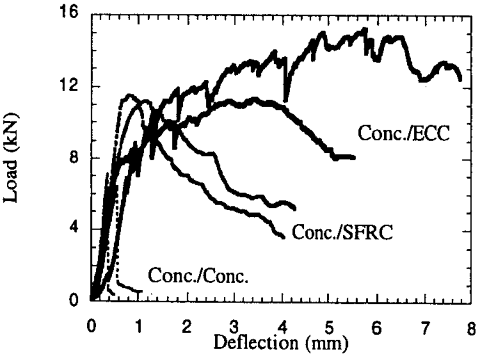


Fig. 7 Load-deflection curves

One interpretation of this unique behavior of ECC as a repair material is based on the concepts of interface crack kinking suggested by Hutchinson and Suo (1992):

$$\frac{G}{G_{\max}^{t}} < \frac{\Gamma(\hat{\psi})}{\Gamma_c} \qquad (1)$$

Where G is the energy release rate for driving the delamination interface crack, G^{t}_{max} is the energy release rate (maximum at the most favorable angle) for driving the spall crack into the repair material, Γ (ψ)is the interfacial fracture toughness and Γ_c is the toughness of the repair material. A plausible scenario is as follows: Loading increases linearly until the kink condition (eqn. (1)) is satisfied. This means that the interfacial defect finds it energetically preferable to kink into the ECC because of the low cement toughness (a low G_c). However, as soon as the cement kink crack is formed, this "crack" is bridged by fibers with bridging stress so strong that opening of the crack is accompanied by rising traction across the crack. (Straightly speaking, this is not a real crack in the sense that traction is increasing with opening). Energetic consideration implies that eqn. (1) is no longer satisfied so that delamination is preferred, but only after a certain amount of load increase is imposed. As delamination reinitiates, once again the interfacial crack probes and finds it energetically preferable to kink into the ECC, once again because of the low cement toughness. This process can be repeated with load increase accompanied by small sudden drops whenever kinking occurs. On the specimen, we should expect a sequence of kink-out cement 'cracks.' (Fig. 6. Final failure for the specimen shown is due to a flexural crack). This concept of kink crack sequence is corroborated with another type of bimaterial specimen used to determine the interfacial toughness of ECC/concrete. At high phase angle ($\psi = 60°$), where the kinking tendency is strong, a serious of scale marks can be observed on the fracture surface on post-mortem examination (Fig. 8).

Fig. 8 Repeated kink crack scale marks left on specimen fracture surface

We conclude therefore that the peculiar low initial toughness (that of the cement paste or mortar) and the strong bridging action of ECC together induce a kink-crack trapping phenomenon not present in any other cementitious repair material. This kink-crack trapping mechanism may break the log-jam of the delamination/spalling dilemma, producing a very durable repair material which consumes significant amount of energy in the failure process. In the above discussion, we have depended on the concepts of interface fracture mechanics. If failure in repaired concrete system is governed by fracture, then the value of traditional bond test for bond 'strength' may be called into question. This area warrants further research in both the mechanics and material aspects.

4.2 Retrofit

Many R/C buildings in the US and Japan have open beam-column frames which may be filled with non-structural partitioning walls. For building safety during seismic loading, the need to retrofit such buildings with shear structural walls has been recognized. Performance requirement includes shear wall integrity maintained up to 1 to 2 % of shear deformation corresponding to relative floor shear, under full load reversal. To use the structural wall for energy absorption purpose, it is critical to initiate inelastic deformation of the wall at shear strain much less than 1%. In addition, the wall must be designed so that this inelastic deformation takes place prior to damage to the beam-column frame. For these reasons a lower first crack strength for the ECC is desirable (Fig. 2). Finally, for retrofitting an occupied building, it is necessary to install the shear wall rapidly.

One possibility being considered is to assemble pre-cast ECC panels on site. Kabele et al (1997) studied the failure process of a ECC panel using FEM combined with a constitutive model developed especially for ECC material (Kabele and Horii, 1997). The loading and boundary conditions are simplified as monotonic shear with rigid joints as shown in Fig. 9. For contrast, a quasi-brittle FRC panel is also studied. Results of the analyses are summarized in Fig. 10 which shows the much greater shear load carrying capacity of the ECC despite similar (first crack and compressive) strength compared with the FRC. The FRC panel failed by the joining of the shear cracks induced by the stress concentration at the joints. For the ECC panel, the stress concentration is relieved by the strain redistribution process of the ECC. Failure in the ECC panel was actually due to the compressive strain capacity being exceeded. At failure, three bands of tension microcracks have formed. However, the maximum tensile strain remains at less than the tensile capacity of the ECC (5%).

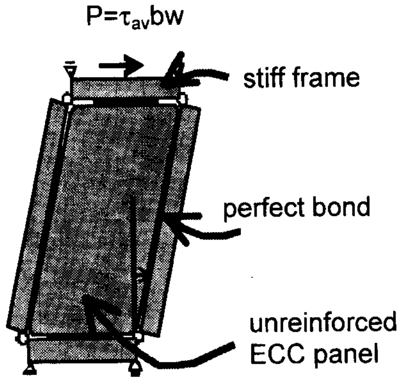


Fig. 9 Simplified Shear Panel

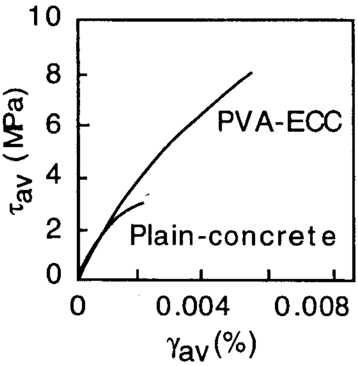


Fig. 10 Shear load capacity

Concrete elements generally are not suitable for dry jointing with high tension bolts. The unique strain-hardening and damage tolerant behavior of ECC, however, may make tension-bolt with connection plates (Fig. 11) suitable for joining ECC panels. To test this concept and to determine the maximum tension bolt force, indentation tests were conducted. The details of this test are summarized in Kanda et al (1998). For an indent area of 1% of the slab, the failure load (Fig. 12) for the ECC was twice (140 kN) that of the mortar (about 70 kN). Here we note the very ductile failure mode of the ECC slab in comparison with the brittle fracture failure of a mortar control specimen (Fig. 13).

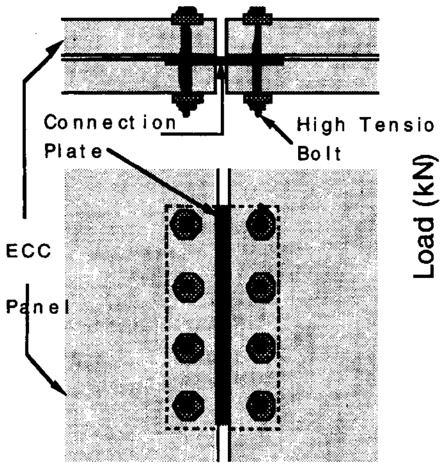


Fig. 11 Dry joint configuration

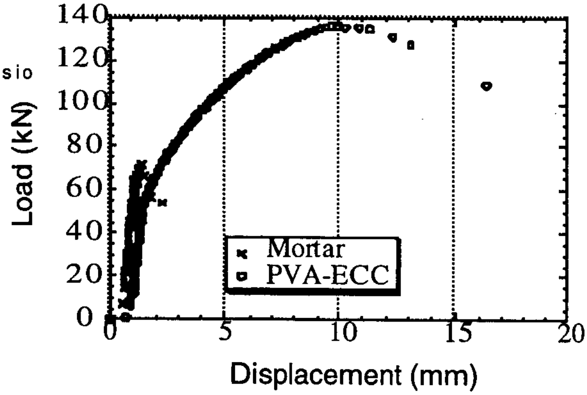


Fig. 12 Load-displacement curve of indent test


(a) (b) (c)

Fig. 13: Failed (a) Mortar (b) PVA-ECC Specimen (c) Close-Up of (b) near indentor

In summary, ECC may be a suitable material for energy absorbing structural shear wall for seismic retrofit of open frame R/C buildings. The damage tolerant behavior of ECC eliminates fracture failure at the joints. A low first crack strength of ECC is actually advantageous in this application as inelastic deformation and energy absorption begin at low building frame shear distortion. Also, the lower elastic modulus of the ECC in the strain-hardening stage lowers the possibility of damage on the frame due to the shear wall. Owing to the strain-hardening nature of ECC, wall integrity is expected even under full load reversal. The analyses also suggest that conventional steel reinforcement may not be necessary. These results will need to be confirmed by experiments of prototyped walls. The experimental indentation study confirms that dry jointing is applicable to ECC panels. Overall, therefore, the unique damage tolerant behavior of ECC makes it a suitable material for seismic retrofit applications.

5. Further Observations and Conclusions

Based on the above discussions, ECC has unique properties which can contribute to repair and retrofitting of structures. However, its applications are not limited to existing structures. New structures with performance requirements associated with large energy absorption, high impact resistance, large imposed deformation, crack width control, and large damage tolerance such as in hybrid (steel/concrete) structures can be potential targets of utilizing the unique properties of ECC.

Because of the strain-hardening behavior of ECC, this ductile material becomes more like steel than traditional concrete. As a result, the reliability of the material is greatly enhanced. Hence design of ECC structures will also need to take into account these different features of ECC in order to optimally translate the high performance of ECC into high performance of ECC structures. This means that traditional design methodology used in concrete or R/C structures may need to be modified.

Perhaps equally important, ECC can be utilized together with other high performance material such as FRP. Very little has been explored in such combinations so far, but the opportunity of innovation is very real.

Finally, it should be pointed out that in both examples of repair and retrofit discussed in this article, the revealation that the structural strength is not the same as material strength should be clear. Although the ECC has tensile or compressive strength not very different from the FRC or mortar used in comparison cases, structural strength and structural ductility for the simulated repair overlay system (Fig. 7), the shear panels (Fig. 10), and the simulated bolt jointing system (Fig. 12), are all much higher when ECC is used. This drives home the point that material ductility is critical for high structural performance.

6. Acknowledgments

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