Engineered Cementitious Composites for Structural Applications*

Victor C. Li
The ACE-MRL
Department of Civil and Environmental Engineering
University of Michigan, Ann Arbor, MI 48109-2125

Tetsushi Kanda
Kajima Technical Research Institute
Kajima Corporation, Tokyo, Japan

Introduction

In the last several decades, concrete with increasingly high compressive strength have been used for structural applications. However, most of these materials remain brittle. In some cases, the brittleness as measured by the brittleness number (Hillerborg, 1983) actually increases as the compressive strength goes up. This poses potential danger and limitations of high strength concrete in structural applications. In certain locations, such as where steel and concrete come into contact (e.g. steel anchors in concrete at column base) or in connections of steel/concrete hybrid structures, the high stress concentration created can lead to fracture failure of the concrete. In seismic elements, high ductility in the concrete can make a significant difference in the seismic response of the overall structure. These and other examples discussed below point to the need to develop cost-effective high ductility cementitious materials suitable for structural applications. In the last several years, the University of Michigan has been investigating a composite material known as Engineered Cementitious Composites, or ECC for short. In many respects, this material has characteristics similar to medium to high strength concrete. However, the

* Published in ASCE J. Materials in Civil Engineering, Vol. 10, No. 2, pp. 66-69, 1998.

tensile strain capacity generally exceeds 1% with the most ductile composite in the 6-8% range. This article briefly reviews these emerging materials, and also reports on some ongoing developmental application studies.

What is ECC?

In terms of material constituents, ECC utilizes similar ingredients as fiber reinforced concrete (FRC). It contains water, cement, sand, fiber, and some common chemical additives. Coarse aggregates are not used as they tend to adversely affect the unique ductile behavior of the composite. A typical composition employs w/c ratio and sand/cement ratio of 0.5 or lower. Unlike some high performance FRC, ECC does not utilize large amounts of fiber. In general 2% or less by volume of discontinuous fiber is adequate, even though the composite is designed for structural applications. Because of the relatively small amount of fibers, and its chopped nature, the mixing process of ECC is similar to those employed in mixing normal concrete. Also by deliberately limiting the amount of fibers, a number of proprietary studies have concluded economic feasibility of ECC in specific structural applications. Various fiber types can be used in ECC, but the detail composition must obey certain rules imposed by micromechanics considerations (Li, 1998; Kanda and Li, 1998). This means that the fiber, cementitious matrix, and the interface (mechanical and geometric) properties must be of a correct combination in order to attain the unique behavior of ECCs. Thus ECC designs are guided by micromechanical principles. Most data so far has been collected on PVA-ECC (reinforced with PolyVinyl Alcohol fibers) and PE-ECC (reinforced with high modulus polyethylene fibers).

The most fundamental mechanical property difference between ECC and FRC is that ECC strain-hardens rather than tension-softens after first cracking (Fig.1). In FRC or fiber reinforced high strength concrete, the first crack continues to open up as fibers are pulled out or ruptured and the stress-carrying capacity decreases. This post-peak tension-softening deformation is typically represented by a softening stress-crack opening relationship. In ECC, first cracking is followed by a rising stress accompanied by increasing strain. This strain-hardening response gives way to the common FRC tension-softening response only after several percent of straining has been attained, thus achieving a stress-strain curve with shape similar to that of a ductile metal. Closely associated with the strain-hardening behavior are the high fracture toughness of ECC, reaching around 30 kJ/m^2, similar to those of aluminum alloys (Maalej et al, 1995). In addition, the material is extremely damage tolerant (Li, 1997), and remains ductile even in severe shear loading conditions (Li et al, 1994). To illustrate the ductility of ECC, Fig. 2 shows the deformed shape of a ECC plate subjected to flexural load. These behaviors appear to be scale invariant, confirmed by specimens with sizes ranging from cm to meters (maximum 1.5 m longest dimension) scale. The compressive strength of ECC varies from 30 to 70 MPa, depending on the matrix composition. Compressive strain capacity is approximately double those of FRC's (0.4 – 0.65%) (Li, 1998).

A most common question asked of ECC is how it achieves its unique ductile properties, but uses ingredients similar to those for FRC or HPFRC, and at the same time contains such small amount (typically less than 2% by volume) of discontinuous fibers. The answer lies in the composite constituent tailoring. A fiber has several attributes - length, diameter, strength, elastic modulus, etc. Interface has chemical and frictional bonds, as well as other characteristics such as slip-hardening behavior. And a cementitious matrix has fracture toughness, elastic modulus and flaw size which can be controlled within a certain range. The tailoring process selects or otherwise modifies these “micromechanical” parameters so that their combination gives rise to the ECC composite with its attendant properties. Tailoring is guided by micromechanical analyses (Li and Leung, 1992; Li, 1993; Kanda and Li, 1998), which quantitatively accounts for the mechanical interactions between the fiber, matrix and interface when the composite is loaded. Note that unlike the even smaller amount of fibers used in shrinkage control in some FRCs, fibers in ECC are used to create composite properties suitable for structural applications.

Application Studies

A number of investigations have been conducted on the applications of ECC in structural applications at the University of Michigan in the US, and the Univ. of Tokyo, Kajima Corporation, and the Building Research Institute, Tsukuba City in Japan. These studies include the use of ECC in shear elements subjected to cyclic loading, in mechanical fuse elements in beam-column connections, in shear wall retrofitting of R/C buildings, in R/C beams as durable cover for re-bar corrosion control, and in general concrete structural repair. Highlights of some of these studies are included here to illustrate the potential practical uses of ECC. Other investigations on ECC and its applications are being planned in Denmark and Australia.

To investigate the structural strength and ductility of reinforced beams under cyclic loads, PVA-ECC (with V_f = 2%) beams with conventional steel reinforcements (R/ECC) have recently been tested with four point off-set loading, with the mid-span subjected to fully reversed uniform shear load (Kanda et al, 1998). Varied parameters in the tests include the span/depth ratio and amount of shear reinforcement. Control specimens with ordinary concrete (R/C) of similar compressive strength (30 MPa) as the ECC were also tested.

Figure 3 shows the double set of diagonal crack patterns in the shear span of the failed specimens. The R/ECC specimens reveal a much higher crack density, about four times that of the R/C specimens. Almost all cracks have opening less than 0.1 mm in the R/ECC compared with mm-size cracks in the R/C specimens.

The load-deformation envelope curves for the test specimens are summarized in Fig. 4. It is concluded that by replacing plain concrete with ECC in the shear beam,

1. load capacity increased by 50% and ultimate deformation by 200% under shear tension failure mode (comparing ECC-1-0 to RC-1-0), and
2. load capacity increased by 50% and ultimate deformation remains the same under shear compression failure mode (comparing ECC-1-1 to RC-1-1).

These observations and Fig. 4 suggest that R/ECC out-performs R/C in shear performance (load capacity, ductility and crack control). R/ECC beams behave in a ductile manner even without transverse reinforcement (but is further enhanced by combining ECC with transverse reinforcement), and remain ductile even for short span shear elements which are known to fail in a brittle manner with normal concrete. This investigation establishes confidence in the application of ECCs in structural shear elements.

The use of ECC in the hinging zone of a beam-column connection was investigated by Mishra (1995). Using normal detailing, it was found that the hysteretic loops were more full in the PE-ECC connection with many more load cycles sustained, resulting in a total energy absorption 2.8 times that of the R/C specimen (Fig. 5). The cracking behavior was similar to those described above for the shear beam specimens. Because of the lower first crack strength of this ECC, the damage initiates inside the hinge zone as designed. This investigation suggests the potential of ECC to serve as a mechanical fuse in critical structural systems which may be subjected to severe earthquake loads.

The use of a PVA-ECC in precast shear panels for building wall retrofits is being investigated numerically (Kabele et al, 1997) and experimentally (Kanda et al, 1998). Using a FEM simulation of rigidly jointed shear panels and a material constitutive model which captures the strain-hardening behavior of ECC, it is found that the PVA-ECC panel sustained much higher seismic load and deformation capacity in comparison with similar panels made with plain concrete (Fig. 6). The ability of the ECC to relax the stress and redistribute the damage at the joints to the interior of the shear panel is responsible for the improved structural strength and ductility observed in the ECC panels. The prevention of localized fracture at the joint was also demonstrated in a shear test of a dry joint using steel bolt (Fig. 7, Kanda et al, 1998).

The damage tolerant property of ECC prompted its application in the above mentioned dry joint. A critical test of this concept was conducted with indentation tests of steel plates on PVA-ECC slabs. The test was conducted for the assessment of maximum allowable bolt force used in the joint between panels for rapid on-site retrofit installations. Figure 8 shows the test results. The maximum bolt force for the ECC slab was about double that of the control mortar slab, while the deformation capacity was almost one order of magnitude higher. The mortar failed by a brittle fracture mode (Fig. 9) while a ‘plastic’ indent was observed for the ECC specimen. The superior damage tolerance of ECC further increases allowable bolt force due to high material reliability compared with mortar, thus enabling one to achieve high performance panel joint with simple details.

Other potential applications

Apart from structural application studies briefly described above, ECC has also been investigated as a protective layer for enhancing the corrosion durability of R/C structures (Maalej and Li, 1995). The fine cracks and anti-spall properties of the PE-ECC demonstrates the potential of this material in achieving the durability function. In addition, PE-ECC reveals a novel kink-crack trapping behavior when used as a repair material in concrete structures (Lim and Li, 1997). This behavior eliminates the deterioration mechanisms of delamination and spalling in the repair material commonly observed in repaired concrete structures.

Some additional potential applications of ECC are in high energy absorption structures/devices, including short columns, dampers, joints for steel elements, and connections for hybrid steel/RC structures. Structures subjected to impact or 3-D loading may also take advantage of the isotropic energy absorption behavior of ECC, such as highway pavements, bridge decks, and blast-resistant building core elements. In addition, structures subjected to large deformations, such as underground structures which need to conform to soil deformation and requires leak prevention, are also potential targets for ECC applications. Other applications of ECC being considered are in permanent formwork, extruded elements with structural properties, FRP reinforced concrete structures, and as a binder for radio-active waste treatment (Wu et al, 1996) for leaching control.

Conclusions

The theoretical background and design methodology of ECC has been established. Application studies of this material are emerging at the present time. Development work is international, inter-disciplinary involving materials and structural engineers, and with inter-sector cooperation between governments, industry and academia. The relatively small amount of fibers (less than or equal to 2%) utilized ensures economic feasibility in practical applications, whether in precast elements or on-site constructions. The results of some application studies highlighted in this forum article provides confidence in the widening use of ECC in a broad range of new and retrofitted concrete structures.

Acknowledgments

Many people have been involved in the development of ECCs and their applications, both in and outside of the ACE-MRL at the University of Michigan. We would like to thank each and everyone of them for their significant contributions over the years. The research associated with ECC and its applications have been supported by a number of government agencies and industrial concerns. The continued support of the National Science Foundation deserves special mention. We also wish to express our appreciation to two anonymous reviewers who provided helpful comments.

References

Hillerborg, A., Analysis of One Single Crack, in Fracture Mechanics of Concrete, edited by F.H. Wittmann, Elsevier Science Publishers B.V., Amsterdam, pp. 223-249, 1983.

Kabele, P., Li, V.C., Horii, H., Kanda, T. and Takeuchi, S. "Use of BMC for Ductile Structural Members," in Proc. of 5th International Symposium on Brittle Matrix Composites (BMC-5), Warsaw, Poland, pp. 579-588, Oct., 1997.

Kanda, T. and Li, V.C. "A New Micromechanics Design Theory for Pseudo Strain Hardening Cementitious Composite," Submitted to *ASCE J. of Engineering Mechanics*, 1998.

Kanda, T. Watanabe, S. and Li, V.C. "Application of Pseudo Strain-Hardening Cementitious Composites to Shear Resistant Structural Elements," to appear in Proc. Fracture Mechanics of Concrete Structures - 3, AEDIFICATIO Publishers, Freiburg, Germany, Oct., 1998.

Li, V.C. and Leung, C.K.Y., Steady State And Multiple Cracking Of Short Random Fiber Composites, ASCE J. of Engineering Mechanics, 118(11) 1992, pp. 2246-2264.

Li, V.C., From Micromechanics To Structural Engineering -- The Design Of Cementitious Composites For Civil Engineering Applications, JSCE J. of Struc. Mechanics and Earthquake Engineering, 10(2) 1993, pp. 37-48.

Li, V.C., Mishra, D.K., Naaman, A.E., Wight, J.K., LaFave, J.M., Wu, H.C. and Inada, Y., On the Shear Behavior Of Engineered Cementitious Composites, J. of Advanced Cement Based Materials, 1(3) 1994, pp. 142-149.

Li, V.C. "Damage Tolerance Of Engineered Cementitious Composites," in Advances in Fracture Research, Proc. 9th ICF Conference on Fracture, Sydney, Australia, Ed. B.L.Karihaloo, Y.W. Mai, M.I. Ripley and R.O. Ritchie, Pub. Pergamon, UK, pp. 619-630, 1997.

Li, V.C., "Engineered Cementitious Composites – Tailored Composites Through Micromechanical Modeling," to appear in Fiber Reinforced Concrete: Present and the Future, Eds: N. Banthia, A. Bentur, and A. Mufti, Canadian Society of Civil Engineers, 1998.

Lim, Y.M. and Li, V.C. "Durable Repair of Aged Infrastructures Using Trapping Mechanism of Engineered Cementitious Composites" *J. Cement and Concrete Composites*, Vol. 19, No. 4, pp. 373-385, 1997.

Maalej, M., Hashida, T. and Li, V.C., Effect Of Fiber Volume Fraction On The Off-Crack-Plane Fracture Energy In Strain-Hardening Engineered Cementitious Composites", ," *J. Amer. Ceramics Soc.*, 78 (12) 1995, pp. 3369-3375.

Maalej, M., and Li, V.C. "Introduction of Strain Hardening Engineered Cementitious Composites in the Design of Reinforced Concrete Flexural Members for Improved Durability," *American Concrete Institute Structural J.*, Vol. 92, No. 2, March-April, pp. 167-176, 1995.

Mishra, D., Design of Pseudo Strain-Hardening Cementitious Composites for a Ductile Plastic Hinge, PhD Thesis, Univ. of Michigan, Ann Arbor, MI, 1995.

Wu, H.C., Li, V.C., Lim, Y.M., Hayes, K.F., and Chen, C.C. "Control of Cs Leachability in Cementitious Binders," *J. Mater. Sci. Lett*, 15 [19], 1736-1739, 1996.

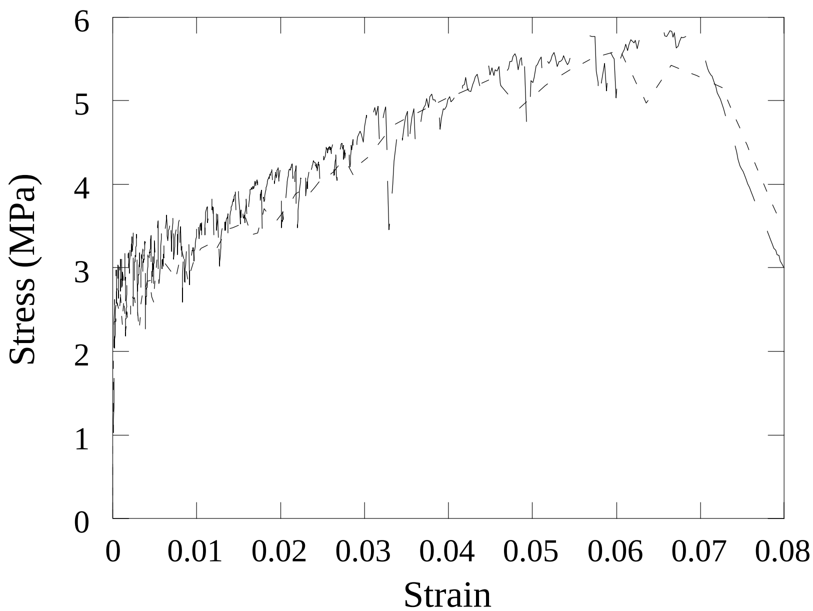

Figure 1: Tensile Strain-Hardening Behavior of a PE-ECC

Figure 2: Flexural Behavior of a PE-ECC

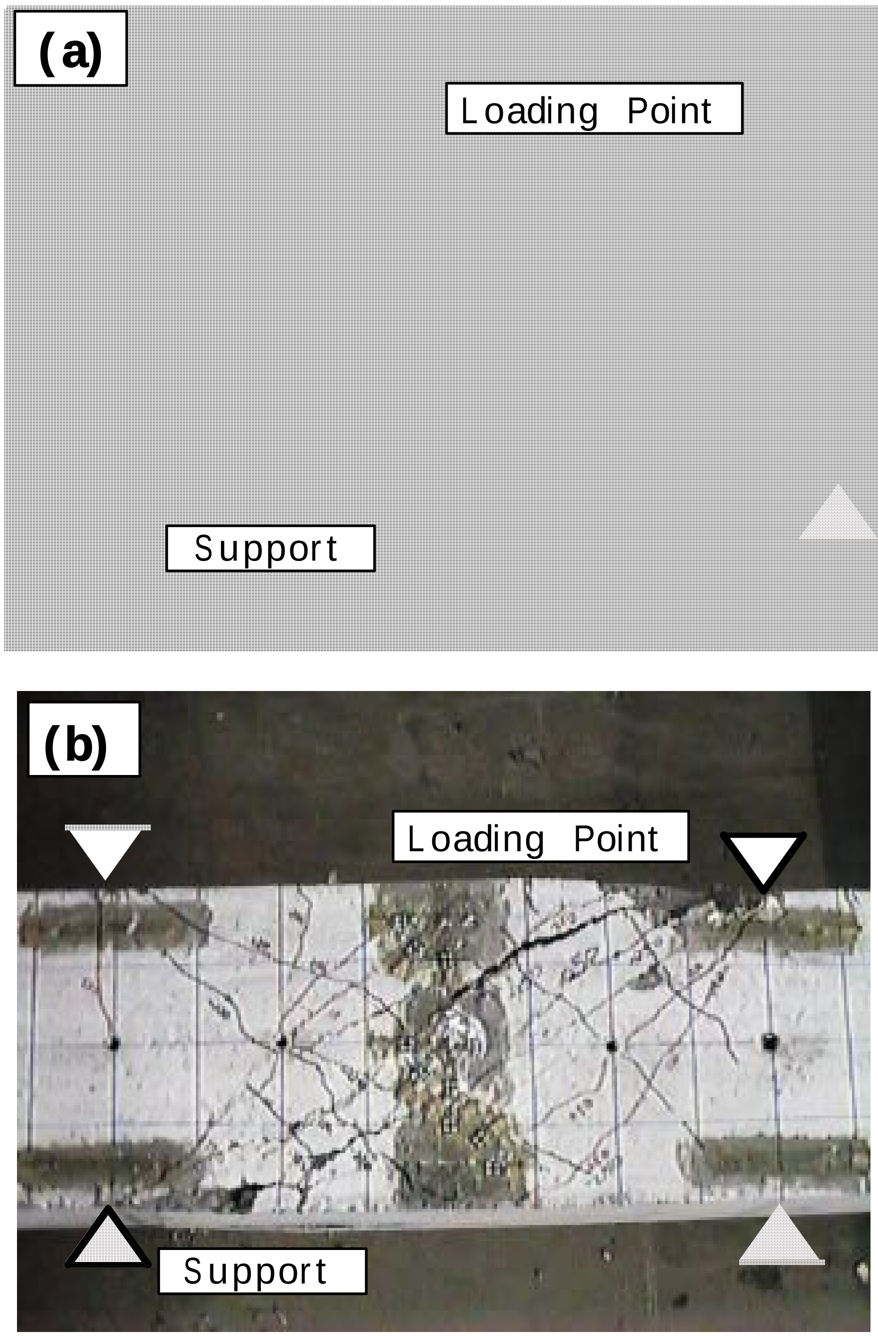

Figure 3: Damage pattern of Cyclic Loaded Shear Beams (a) R/ECC; (b) R/C.

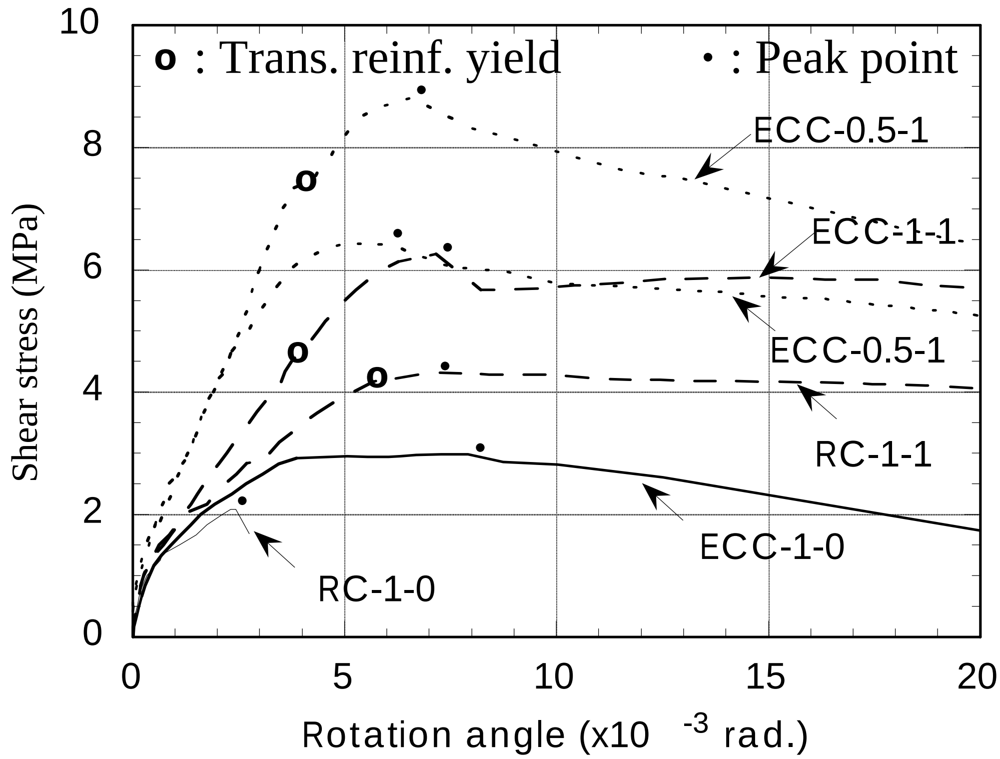

Figure 4: Shear Stress-Rotation Envelope Curves for the Various Specimens. Each Curve is labeled (Material - Span/Depth Ratio - Shear Reinforcement %).

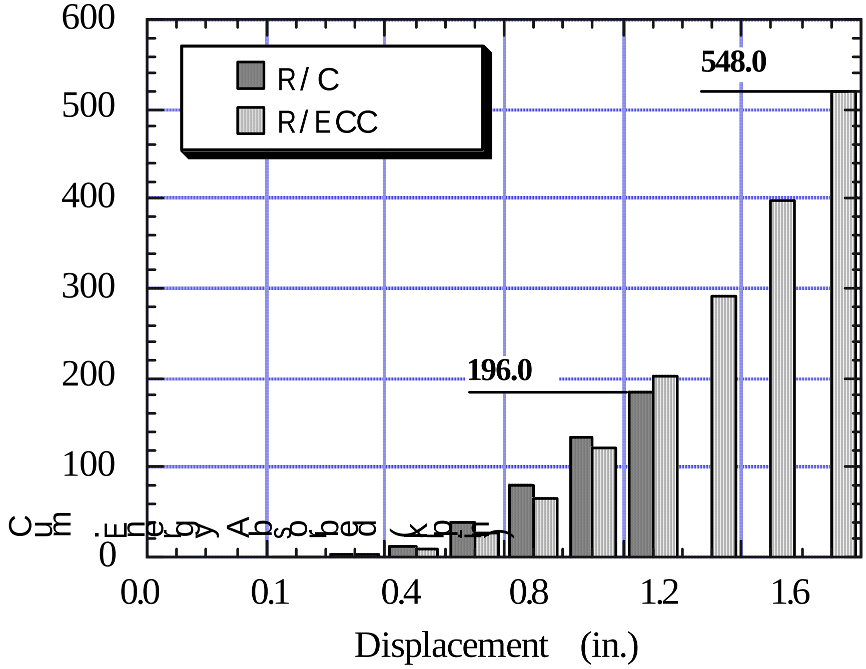

Figure 5: Energy Absorption Record in a Cyclically Loaded Beam-Column Connection

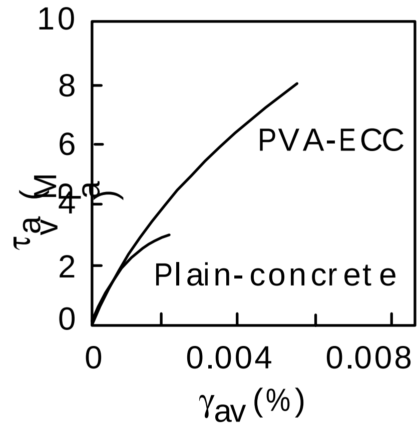

Figure 6: Computed Load-Deformation Capacity of a Shear Panel for Building Wall Retrofit.

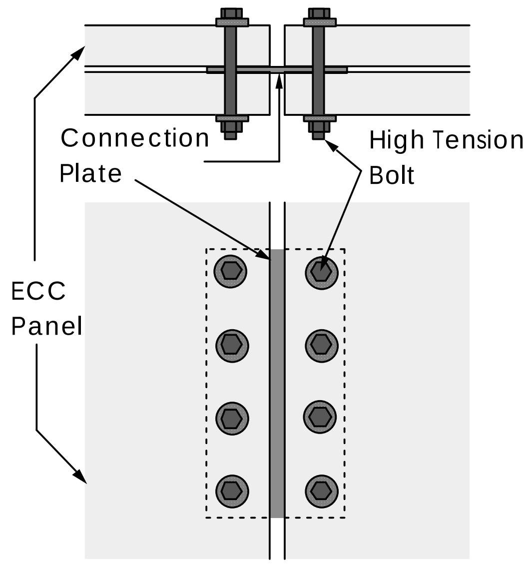

Figure 7: Dry Joint Configuration

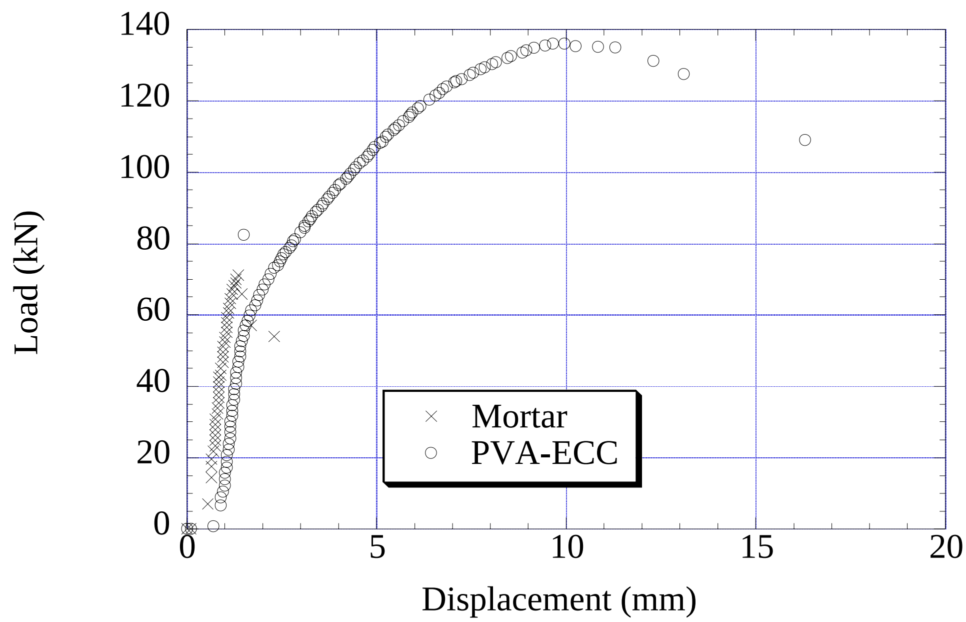

Figure 8: Load-Deformation Capacities of Indent Tests

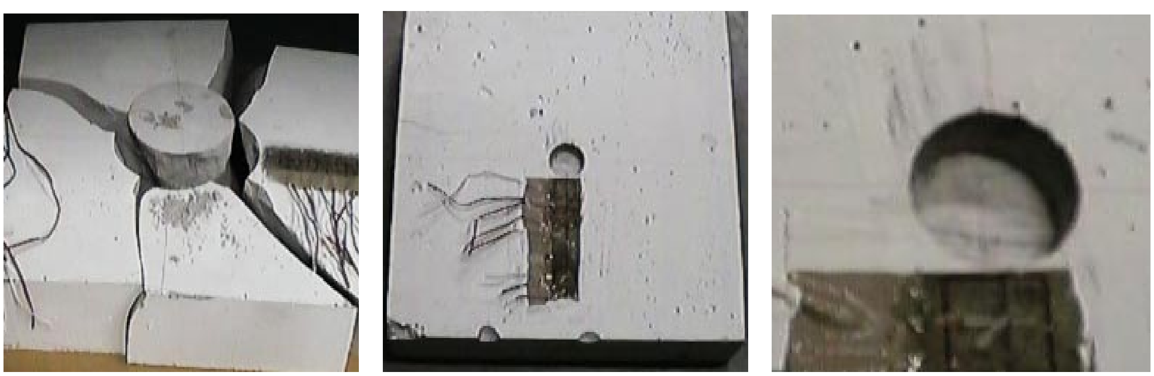

Figure 9: Failure Modes of (a) Mortar Slab, (b) PVA-ECC Slab and (c) Closeup View Near Indent