Fracture Mechanics of Concrete Structures, de Borst et al (eds) © 2001 Swets & Zeitlinger, Lisse, ISBN 90 2651 825 0

Investigation of ductile cementbased composites for seismic strengthening and retrofit

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ABSTRACT: Traditional civil engineering materials such as reinforced concrete are continually being engineered with more specific performance characteristics. Engineered cementitious composite (ECC) materials, which consist of a cement-based matrix reinforced with a low volume fraction of polymeric fibers, represent an example of materials with specific performance characteristics. ECC materials exhibit steady-state cracking and pseudo-strain hardening in tension. The use of ECC materials as an infill wall system for seismic retrofit of critical facilities is being investigated. Preliminary numerical results indicate that ECC infill panels can increase the strength, stiffness and energy dissipation in steel frames. An improved material model is needed for further analysis of infill panel systems. Therefore laboratory tests on ECC materials under cyclic load are conducted. Results of cyclic testing are presented and key aspects of the response are discussed.

1 INRODUCTION

1.1 *Background*

Engineered cementitious composite (ECC) materials represent an innovative fiber reinforced cement-based composite. The materials are comprised of a Portland cement matrix with a low volume fraction of fibers such as ultra high molecular weight polyethylene (UHMWPE) fibers. ECC materials are developed from micro-mechanical analysis of the interaction between the matrix and fibers. (Li, 1998)

The use of ECC materials in the development of seismic repair and strengthening applications is being evaluated. The development of these applications has highlighted the need for a rigorous material model for use in finite-element based simulation of ECC in structural applications.

To develop a material model, laboratory tests are being conducted to evaluate the response of ECC materials to cyclic load. Results obtained from the cyclic testing are presented here, and key aspects of the response are discussed. Material model development is ongoing and will be used to further analyze the infill-panel system as well as investigate potential test set-ups for experimental verification of the system.

1.2 *Literature review*

Previous research on the development of ECC materials has resulted in significant theoretical development of the materials from micro-mechanical principles (Li and Leung, 1992). ECC materials differ from conventional concrete materials in that they exhibit pseudo-strain hardening and steady-state cracking in tension. This is in contrast to the largely brittle or quasi-brittle nature of traditional concrete and fiber reinforced concrete materials. The development of ECC materials is based on evaluating the pullout behavior of the fibers from the Portland cement matrix. The majority of the development of ECC materials has been by Li. (Li, 1998).

In ECC materials, fibers are used as a traction force bridging cracks, with the load carried by the fibers increasing with crack extension. Due to the lack of chemical bond between the polyethylene fibers and the Portland cement matrix (the fibers are inert), the stress-crack opening relationship is based solely upon frictional debonding of the fibers. The toughening effect due to fiber bridging leads to an increase in the composite's first crack strength.

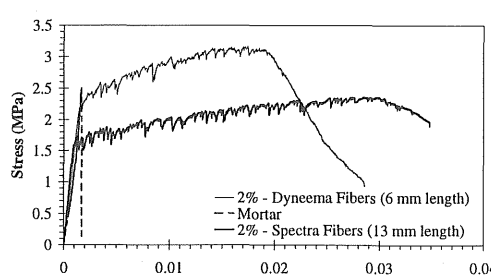

Figure 1. Tensile response of mortar and of ECC made with Dyneema (10 μm dia.) and Spectra (38 μm dia.) fibers.

Steady-state cracking arises as a result of the balance between the composite toughness increase and the increase in the stress-intensity factor at crack tips during loading and crack extension. Figure 1 shows an example of the pseudo-strain hardening behavior of ECC materials made with different fiber types compared to an unreinforced mortar.

2 PROPOSED APPLICATIONS

2.1 *Application development*

The development of portable retrofit strategies for critical facilities (e.g. hospitals) is a primary goal of the research program. For critical facilities, the retrofitted structure must be operational after seismic events. This necessitates retrofit strategies that both protect the structure and prevent damage to non-structural components (NEHRP, 1997). In the current research the use of ECC in retrofit strategies for critical facilities is being investigated. The following sections describe one of the applications being considered.

2.2 *Infill panel system*

Installation of infill walls is a common method to increase the lateral load capacity of both concrete and steel frames (NEHRP, 1997). Many infill walls are constructed of brick or concrete masonry units or reinforced concrete. In the current research, the use of ECC panels for infill wall construction is being investigated. For steel frames, the use of bolted tab connections is being studied. The use of bolted connections between the ECC infill panels builds upon the work of Kanda et al. (1998). Kabele, et al. (1998) investigated such a system numerically and found that compressive failure of the ECC at the connections controlled the system capacity. The concept of bolted panel connections is shown schematically in Figure 2. In Figure 3 a schematic representation of a connection type being considered in the current investigation is shown. Kahn and Hanson (1979) have also investigated the behavior of precast infill panels as a retrofit for concrete frames. They found significant variations in the effectiveness of the infill depending upon the type of panel, and connections details to the frame. Frosch et al. (1996) researched the use of precast concrete infill panels grouted together and strengthened with vertical post-tensioning to retrofit concrete frames.

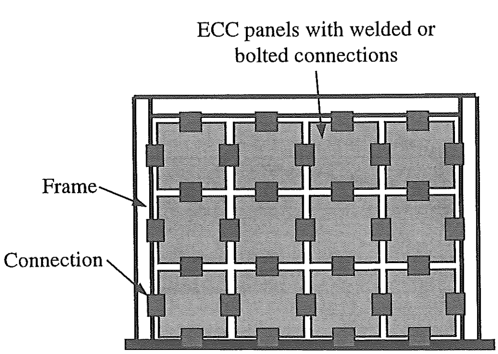

Figure 2. Schematic representation of ECC infill panels installed in steel frame.

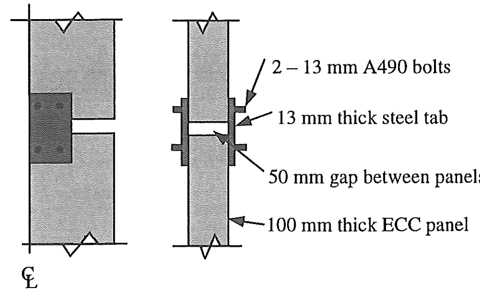

Figure 3. Schematic representation of connection between infill panels using tab connections.

For a preliminary evaluation of the infill panel system, a typical frame geometry is selected from a hospital structure located in the northeastern United States. The frame member properties are summarized in Table 1. The connections between the frame members are assumed to be rigid. The geometry of the infill wall panels is selected to minimize the number of panels in the frame, while maintaining the portability and flexible use of the system. A preliminary selection of 1220 mm by 1220 mm by 100 mm thick panels is chosen. This size yields an approximate panel weight of 273 kg.

As shown in Figure 4, two different connection geometries are evaluated in the preliminary analysis. Two different connection tab widths (w = 150 mm and 300 mm) are considered in the evaluation of the center tab system. Only one corner tab width (w = 150 mm) is evaluated. Alternatively, a single tab

Table 1 – Frame member properties.

Member	Moment of Inertia	Area	Depth
	mm^4	mm^2	mm
Top Beam	508,219,000	25,200	327
Columns	185,639,000	6800	403

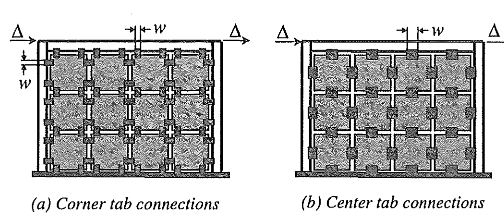

Figure 4. Infill panel connection geometries.

could be used to connect two thinner panels, similar to the work of Kanda et al. (1998). The thickness of the connection tabs is 13 mm.

2.3 *Preliminary analysis model*

To evaluate the effect of the infill wall addition, a finite element model is created. The frame members are modeled using 2-noded beam elements. The infill panels and the steel connections are modeled with 4-noded plane stress elements.

For the steel frame and connection members an elastoplastic material model with isotropic hardening is used. For ECC, an equivalent uniaxial strain model is used for tension and compression. In tension, a multilinear stress-strain curve is used wherein the transition points on the stress strain diagram are obtained from uniaxial tension tests. The tension model used in the current analysis is based on a total strain model (Feenstra et al., 1998) with fixed-cracks. There is no steel reinforcement in the panels. The material models used in the analysis are shown in Figure 5. Material properties are summarized in Table 2. A compressive strength of 70 MPa was used for the ECC.

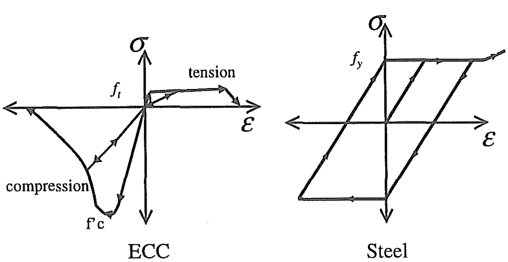

Figure 5. Material models used in preliminary analysis.

For cyclic behavior, secant unloading and reloading is used in both tension and compression. The accuracy of the secant-unloading scheme is an ongoing area of research in the current study. Material testing (Section 3) is being used to develop an improved model for the unloading and reloading of the ECC materials.

Table 2 – Material properties.

Material	Modulus of Elasticity	Yield/ Cracking Strain	Yield/ Cracking Stress	Ultimate Strain
	GPa	%	MPa	%
Steel	200	0.12	248 (f_y)	10
ECC	13.8	0.015	2.0 (f_t)	3

2.4 *Preliminary analysis results*

A cyclic displacement of the frame to two different drift levels is simulated. The frames are cycled to +/-0.25%, and +/-0.50% drift. Figure 6 shows the load vs. displacement response. The results show a significant increase in load capacity and energy dissipation in the frame with the infill panels. The type and width of connection between panels affects the magnitude of lateral load capacity increase. The load in the frame columns remains below the plastic moment capacity of the columns at the peak drifts. Yielding of the tabs does occur in the corner tab system (Fig. 4a), and the center tab system (Fig. 4b) with the 300 mm tab width.

The largest increase in lateral load capacity, compared to the bare frame, occurred with the 300 mm center tab connections. The capacity, at +0.50% drift with the 300 mm center tabs is approximately 490 kN higher than the frame with the 6" corner tab connections which had the same total steel area (2 – 150 mm wide connections), and 1100 kN higher than the frame with the 150 mm center tab connection. This difference in capacity between connection types indicates that both the connection location and width will need to be further evaluated to develop optimal retrofit solutions.

The strains in the majority of the panels are above the cracking strain (150 μstrain). However, the load-displacement response, as seen in Figure 6, does not indicate a decrease in load carrying capacity at this drift level. Due to the pseudo-strain hardening behavior of the ECC materials, the capacity of the system does not appear to have decreased at this drift level. Compressive failure of the ECC was not observed in the results.

2.5 *Discussion of results*

Preliminary analysis indicates that the ECC infill panel system can be used as a seismic retrofit strategy for a steel frame. Connection details (width and location) between the panels, and to the frame are important variables in determining the response of the retrofitted system and in particular how well the system protects secondary, nonstructural systems.

In the current study the size of the infill panels and connections are kept constant. With further investigation of panel size and connection details, a variety of infill wall systems should be able to prevent yielding of the frame, increase lateral load ca-

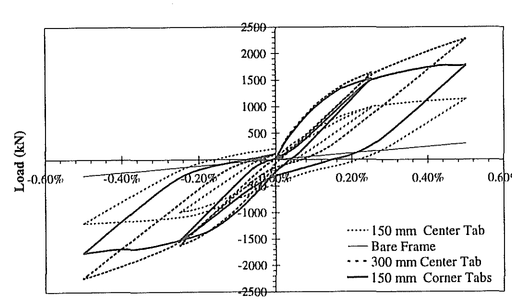

Figure 6. Summary of preliminary analysis results.

pacity and stiffness of the frame and increase energy dissipation in the structural system.

In the preliminary analysis, a simple secant-unloading scheme is used for the unloading and reloading of the ECC. To more accurately evaluate the behavior of the ECC in retrofit applications, an improved material model is required. The development of the model will be an essential step in performing large-scale simulations of ECC in retrofit applications. The following sections describe some of the ongoing laboratory testing being used to develop the material model.

3 CYCLIC TESING OF ECC MATERIALS

3.1 *Background*

The cyclic behavior of concrete materials has been extensively studied in previous research, and summarized in CEB (1997). This research has led to the development of numerous material models describing the response of concrete to cyclic compressive and tensile loads. In ECC, the pseudo-strain hardening behavior of the materials in tension is significantly different than the behavior of conventional cementitious materials. This precludes the direct application of many previously developed models to evaluate the response of ECC to cyclic loading.

The cyclic response of ECC has not been extensively studied to date. Kabele et al. (1998) proposed a model for the opening cracks and sliding displacement (shear) of ECC. This model was used to simulate the cyclic response of ECC infill panels.

In the following sections ongoing work aimed at developing a cyclic material model for ECC is presented. The results shown in the figures are representative results that clearly show salient features of the response.

3.2 *Testing program*

To evaluate the cyclic response of ECC materials, both cylindrical (50 mm in diameter by 100 mm in height) and prismatic (300 mm long by 75 mm wide by 25 mm thick) specimens are studied in cyclic tension, cyclic compression and cyclic tension/compression. Different specimen geometries are tested to examine possible geometry effects in the testing, and to allow for comparisons with other ongoing testing. The mix design used in the testing program is shown in Table 3, with the pertinent fiber characteristics shown in Table 4.

Table 3 –Mix designs used in the cyclic testing.[1]

Fiber	w/cm	Silica fume[2]	Fiber volume
Spectra	0.35	10%	2%
Dyneema	0.30	15%	2%

1. *Superplastizer added to improve workability of the mixes.*
2. *Silica fume percentages by weight of cement*

Table 4 – Summary of pertinent fiber characteristics.

Fiber	Shape	Length	Aspect ratio	Modulus
		mm	L_f/d_f[1]	GPa
Spectra	Round/Oblate	12.7	335	73
Dyneema	Round	6.4	800	88

1. L_f : length of fiber; d_f : diameter of fiber.

All of the specimens in the testing program are cured in a saturated limewater bath for 28 days, and then allowed to dry at 50% relative humidity prior to testing. The drying time, prior to testing, mitigates the effects of drying shrinkage. During the drying period the weight of the specimens is monitored, and sufficient drying time is allowed for the specimens to reach an equilibrium weight prior to testing (Billington and Kesner, 2001).

3.3 *Cyclic tension results*

The behavior of ECC materials in cyclic tension was evaluated as a part of a larger investigation of the effect of curing and drying conditions on the tensile behavior of ECC materials (Billington and Kesner, 2001). These tests were conducted in a displacement controlled uniaxial testing frame with a strain rate of 0.2% per minute. Swivel connections were used at both ends of the specimen to minimize bending stresses in the specimens.

Figure 7 shows a typical test result from a prismatic specimen made with Spectra fibers. In Figure 8, a photograph showing the multi-cracking of the ECC in tension is shown. To evaluate the cyclic tensile behavior, the loading regime was paused, and the testing machine crosshead moved to unload the specimen. The unloading and reloading occurred on both the initial strain-hardening portion of the curve and on the softening branch. The use of the double swivels in the test configuration prevented complete closure (returning to zero displacement) of the cracks during the unloading.

Prior to the onset of softening, the reloading of the specimen follows the initial elastic modulus.

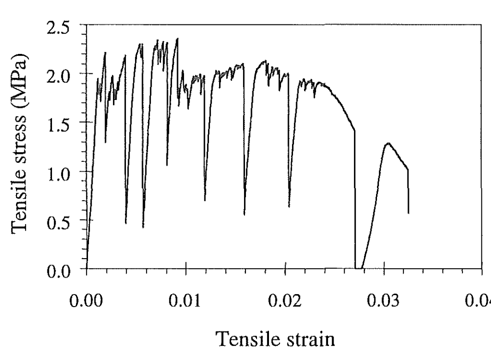

Figure 7. Cyclic tension test result.

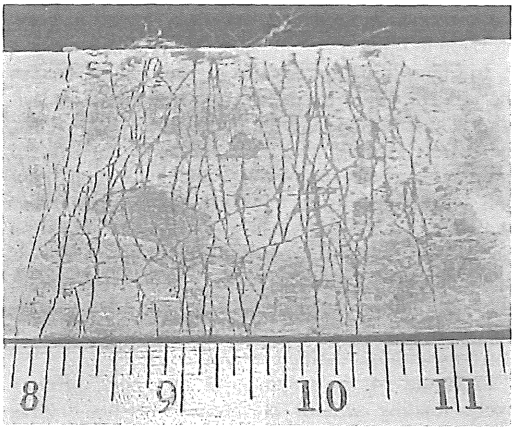

Figure 8. Multi-cracking in ECC tension specimen. (Scale in inches. 1 in. = 25.4 mm)

The reloading modulus decreases when the reloading occurs on the softening branch. The type of fiber (Spectra or Dyneema) did not affect the unloading/reloading behavior.

3.4 *Cyclic compression results*

To evaluate cyclic compression response of ECC, tests are performed on both cylindrical and prismatic specimens. The tests are conducted under displacement control in a 50-kip MTS testing frame. A strain rate of 0.1% per minute is used. LVDTs are used to monitor the displacement of the specimen during the test. As seen in Figure 9, a swivel joint is located at the top of the specimen to minimize bending stresses in the specimen during testing.

Figure 10 shows a typical cyclic compression test result for a cylindrical specimen made with Spectra fibers. The initial loading of the specimen consists of loading and unloading to progressively higher stress levels without exceeding the compressive strength of the material. After the peak compressive stress is reached, the specimen is cyclically loaded on the post-peak, softening branch, of the curve. Figure 11 shows the extensive lateral bulging and cracking that occurred during the testing. The boxed area in Figure 11 is shown in Figure 12, highlighting the vertical, lateral cracks that resulted from lateral expansion under compressive load.

The ECC behaves as a linear-elastic material at stresses below the peak compressive stress. The lack of aggregate in the material results in a lower elastic modulus (~14 GPa) in comparison to traditional concrete. On the post-peak curve, the unloading of the specimen is largely elastic. At low stress levels while unloading, the response deviates from elastic behavior. This deviation is consistent with the behavior of concrete (Yankelevsky and Reinhardt, 1987). The reloading modulus progressively decreases with increasing levels of compressive strain. This reduction in stiffness is attributed to the multi-cracking in the specimen.

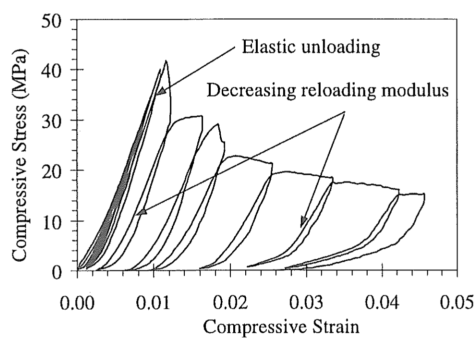

Figure 10. Cyclic compression test result.

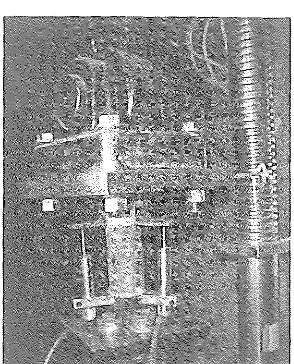

Figure 9. Experimental set up for cyclic compression testing of ECC materials.

Figure 11. Lateral bulging and cracking in ECC cyclic compression specimen. Close-up of boxed area shown in Figure 12. (mm scale in background.)

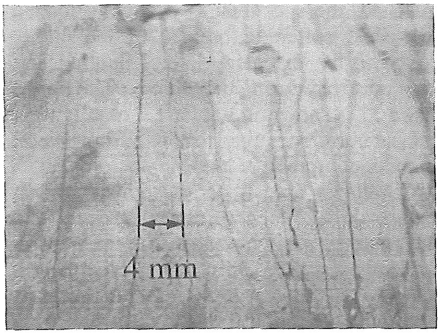

Figure 12. Vertical, lateral cracking in ECC compression specimen.

3.5 *Cyclic tension-compression results*

To fully develop a material model for ECC cyclic tension/compression tests are conducted to examine how ECC behaves in the transition from tension to compression. This transition behavior will commonly occur in the ECC applications for seismic loadings.

The tests were performed in a 50kip MTS test frame. Similar to the cyclic compression tests a strain rate of 0.1%/minute is used. To evaluate different cyclic loading situations, several loading schemes are used in these tests, as will be discussed.

Figure 13 shows one of the results from the cyclic tension compression testing program. The loading scheme approximates previous cyclic tension/compression tests used in the development of a cyclic tension model for concrete materials (Yankelevsky and Reinhardt, 1989). The specimen is loaded to predetermined tensile strain levels. After the predetermined strain level is reached the specimen is unloaded, and then loaded in compression. To ensure complete closure of cracks in the specimen the peak compressive stress in each test cycle is increased, without exceeding the compressive strength of the material. The upper tensile strain limit is reached when the ECC material begins to soften. After this tensile strain limit is reached

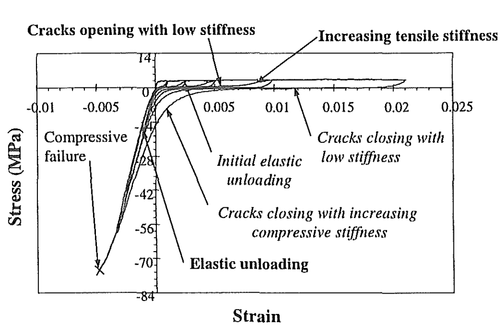

Figure 13. Cyclic tension compression test result from prismatic specimen with Dyneema fibers.

the specimen is unloaded, and then loaded in compression to failure.

In Figure 13, three distinct regions can be seen in the unloading portion of the curve (labeled in italics). These regions are the initial elastic unloading, the cracks closing with low compressive stiffness (similar to a slip region), and the increasing compressive stiffness as the cracks in the specimen close and bear compressive stress. The tensile reloading curve, similar to the unloading curve, has three distinct regions (labeled in bold). These regions include the initial elastic unloading, the cracks opening with low stiffness, and the increasing tensile stiffness with increasing crack opening.

In Figure 14, the response of ECC to a different cyclic loading scheme is shown. In this loading scheme, the specimen is loaded to 0.1% strain in tension, then to –0.1% strain in compression. In subsequent cycles the strain limit is increased to +/-0.25%, +/-0.5%, +/-1.0% until softening behavior was observed in compression. After compressive softening is observed, the specimen is loaded in cyclic compression to a strain of approximately –5.5%. In most of the tests in this series compressive softening occurs at strain levels above –0.5%, as the specimen is loaded to –1.0% strain. In a few cases softening occurred at strain levels less than –0.5%.

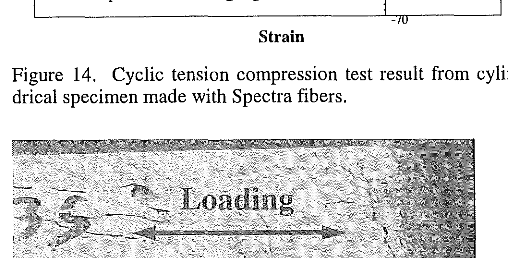

Figure 14. Cyclic tension compression test result from cylindrical specimen made with Spectra fibers.

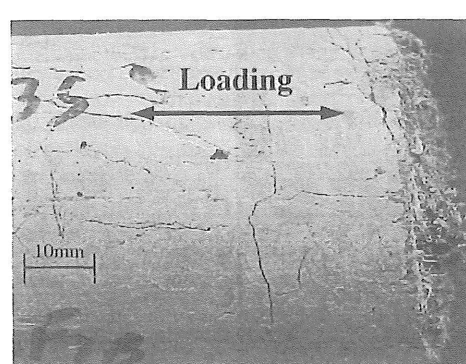

Figure 15. Cyclic tension compression specimen after completion of testing.

The tensile response shown in Figure 14 has the same features as that shown in Figure 13. The compression response shows a large softening region beyond the peak compressive stress. The shape of the compressive softening response is very similar to the result shown in Figure 10.

Figure 15 shows a photograph of a cylindrical test specimen after completion of cyclic tension compression testing. Both vertical cracks, in the direction of the loading and horizontal tension cracks orthogonal to the loading direction are visible. This orthogonal cracking is unique to ECC compared with traditional concrete.

3.6 *Discussion of cyclic test results*

The cyclic response seen in these experiments is more complicated than the simple secant unloading and reloading model used in the preliminary analysis of the infill panel retrofit (Section 2). The primary difference in ECC response compared to conventional concrete is the cyclic tension-compresion response. This unique response arises as a consequence of the fiber pullout behavior and steady-state cracking in ECC.

In ECC, fiber pullout from the matrix occurs with increasing levels of tensile strain (Li and Leung, 1992). When tensile specimens are unloaded, the initial elastic unloading behavior occurs as the elastic strain is removed from uncracked areas in the ECC. Only small elastic strains are present in the fibers after they are pulled out of the matrix. Once the elastic strain is removed the cracks (with fibers bridging them) can be closed. The low stiffness in the crack closing portion of the response occurs because the pulled out fibers that cross the cracks lack compressive stiffness without the lateral support of the matrix. The stiffness of the specimen increases as the cracks close and bear compressive stress. Similarly, when reloading in tension, the low initial stiffness is related to the stretching of the compressed fibers as the cracks are reopened. The increasing stiffness occurs as the fibers begin to carry load, in the case where they have not yet fully debonded.

In the testing program, no significant phenomenological differences have been found when comparing the response of ECC made with Spectra or Dyneema fibers. The difference in response between Spectra and Dyneema fibers can be predicted (such as the higher first crack strength with Dyneema fibers as shown in Figure 1) using the micro-mechanical principles (Li and Leung, 1992). Both the cylindrical and prismatic specimens yielded similar results. This suggests that the results from direct uniaxial tension and compression tests can be used to provide key parameters in the material model.

4 FUTURE WORK

The preliminary research into the use of ECC materials for seismic strengthening and retrofit applications has led to two primary areas for future work. These are the development of a material model that accurately reflects the response of ECC to cyclic loads, and the need to optimize the infill panel system in terms of panel size, shape, reinforcement, and connection details.

To develop a material model, the work of Kabele et al. (1999) and Yankelevsky and Reinhardt (1989) is being examined.

The development of the material model will require an evaluation of the effect of shearing stresses on the behavior of the materials. In the preliminary analysis, the shear strength of the ECC was not varied with increasing levels of tensile or compressive strain.

Completion of the material model will allow for accurate and efficient studies to further evaluate and develop ECC infill panels for seismic strengthening, stiffening and energy dissipation applications. Results from numerical studies will be used to identify promising systems for experimental investigations.

5 SUMMARY AND CONCLUSIONS

The results of preliminary studies of the behavior of ECC materials in seismic strengthening applications have been presented. Preliminary analysis indicates that infill panels made from ECC materials have potential for use as a seismic retrofit strategy for steel frames. The ECC infill panels are found to potentially increase the lateral load capacity, stiffness and energy dissipation in a steel frame subjected to cyclic lateral loads.

Material testing under cyclic loads indicates that the unique cyclic tensile behavior of ECC occurs as an outgrowth of the micro-mechanical principles used in the development of the material. In particular, the pullout of fibers from the matrix gives rise to the low stiffness areas observed in cyclic tension and compression. The cyclic compressive response of ECC is similar in shape to that of traditional cementitious materials. However, the modulus of ECC is lower. To simulate more accurately the cyclic response of ECC, a new material model is being developed.

6 ACKNOWLEDGEMENTS

This research is sponsored by the Multidisciplinary Center for Earthquake Engineering Research (MCEER) through an NSF Engineering Education Research Center. The opinions in this paper are those of the authors and not necessarily those of the sponsors. The authors gratefully acknowledge the support of material supplies from Synthetic Industries, Honeywell Corporation and DSM High Performance Fibers as well as discussions with Dr. Victor Li of the University of Michigan and Dr. Surendra Shah of the Center for Advanced Cement-based Materials. The finite element program DIANA was used for the calculations presented herein.

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