SEISMIC RETROFIT OF MASONRY-INFILLED NON-DUCTILE REINFORCED CONCRETE FRAMES USING SPRAYABLE DUCTILE FIBER-REINFORCED CEMENTITIOUS COMPOSITES

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ABSTRACT :

Understanding and assessing the seismic performance of masonry infilled reinforced concrete structures has been a significant area of research over the last several decades. There is both field and laboratory evidence that demonstrates the detrimental impact an unreinforced masonry infill imparts on a structure due to its interaction with the bounding frame. There is a current lack of reliable and effective retrofit techniques for this group of structures. A new retrofit technique specifically for unreinforced masonry infills in non-ductile reinforced concrete frames is under investigation and presented here. The technique uses a ductile fiber-reinforced mortar material referred to as Engineered Cementitious Composites, or ECC. A series of experiments have been performed in order to examine the impact of a thin layer of ECC applied on masonry alone as well as when it is applied on a masonry wall bounded by a non-ductile reinforced concrete frame. Results indicate that the ECC can help keep unreinforced masonry walls intact to large lateral drifts, adding significant ductility to the structural system under cyclic loading.

KEYWORDS: Non-ductile reinforced concrete frames, masonry infills, walls, engineered cementitious composites, sprayable, retrofit.

1. INTRODUCTION

Structures with unreinforced masonry infills can be found in many places around the world such as the western United States and in countries of the Mediterranean region. Masonry infills have been widely used because of their good thermal and acoustic insulation properties, for aesthetic reasons and for fire resistance. However, recent earthquakes (e.g. 1999 Kocaeli, 2003 Boumerdes, 2008 Sichuan) have demonstrated the vulnerability of masonry infilled structures.

In order to improve the performance of unreinforced masonry infilled structures, different retrofit techniques are being used, the most common being a single- or double-sided shotcrete jacket reinforced with welded wire steel mesh. With this method, substantial weight is added to the structure and when a double-sided jacket is provided there is a negative impact on the aesthetics of the structure (Triantafillou, 1998). Alternative retrofit techniques have been investigated by many researchers such as epoxy-bonded fiber-reinforced polymer (FRP) laminates (Hamid et al., 2005), ferrocement and plaster overlays (Mander et al., 1994). FRP laminates are very effective in enhancing substantially the strength of the masonry infill which can be desirable for certain structures (e.g. steel frames) but not for others (e.g. non-ductile reinforced concrete frames). Thick ferrocement overlays with two layers of wire reinforcement have been tested by Mander et al. 1994 and demonstrated rapid strength deterioration of the steel bounding frame under cyclic loading.

The new retrofit technique proposed by the authors specifically for unreinforced masonry infills in non-ductile reinforced concrete frames uses a sprayable, ductile fiber-reinforced mortar material referred to as Engineered Cementitious Composites, or ECC. The aim is to develop a cost-effective retrofit technique for such structures that will improve the seismic performance of the frame-infill system by enhancing its ductility and delaying its strength degradation. Compression and flexural tests of masonry specimens with various retrofits using sprayable ECC have been performed with promising results. Triplet tests using ECC have also been performed to study the bond between the brick surface and the ECC. Four small-scale infilled frame tests have been completed to date to validate the proposed retrofit technique. This project is a collaboration of three

Universities through the National Science Foundation's Network for Earthquake Engineering Simulation research (NEESR) program. As part of the collaboration, medium-scale infilled-frame tests will be conducted with the NEES Fast Hybrid Test facility at the University of Colorado, Boulder and the final proof-of-concept tests will be conducted on 2/3-scale three-story, two bay reinforced concrete infilled frames using the NEES Large High Performance Outdoor Shake Table at the University of California, San Diego (UCSD).

2. RETOFIT SYSTEM

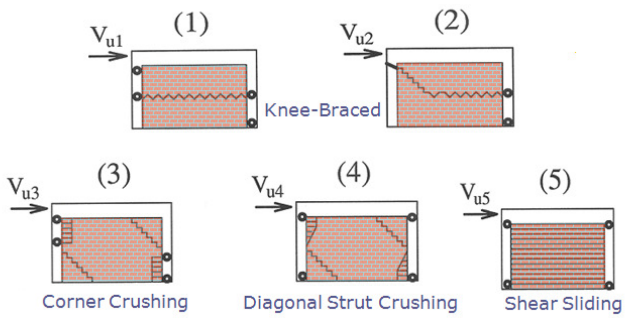


Figure 1 Common failure modes of unreinforced masonry infill walls in non-ductile reinforced concrete frames subjected to cyclic lateral load.

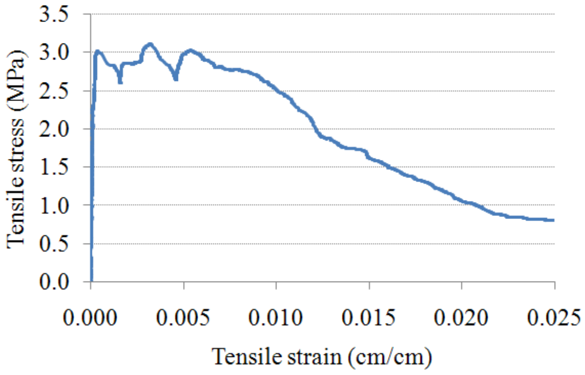


Figure 2 Tensile stress-strain response of sprayable ECC.

The ductile cement-based composite under investigation is a class of high performance fiber-reinforced cement-based composites referred to as Engineered Cementitious Composites (ECC). In particular, a sprayable version of this material was recently reported and was capable of being sprayed on to a concrete wall achieving a thickness of 45mm (Kim et al, 2003, Kim et al, 2004). The reported mix design is made up of Type I Portland Cement, Class F Fly Ash, Calcium Aluminate Cement, fine silica sand and 2% by volume of treated (with oil) polyvinyl alcohol (PVA) fibers.

The ultimate goal of the retrofit strategy is to achieve better ductility from the structural system as it undergoes cyclic lateral loading, where ductility is defined as maintaining 80% of the peak capacity at large deformations (e.g. 3-4% interstory drift). There are multiple failure modes of such structures where in general the masonry wall loses capacity (e.g. sliding failure, corner crushing) and a brittle shear failure and/or hinging occurs in the non-ductile reinforced concrete frame (Shing and Mehrabi 2002) (figure 1).

The use of a spray-on ECC layer is proposed to tie the masonry wall together as it is undergoing cyclic lateral loads. Furthermore, by tying the ECC to the reinforced concrete beams above and below the wall an alternate shear path is provided for the lateral load through the wall rather than having the load shed to the columns after the wall is damaged and cause a brittle failure. Spray-on ECC is a good candidate material for achieving improved ductility in that it can reach uniaxial tensile strains of up to 1% while maintaining its load-carrying capacity (figure 2) (i.e. final crack localization occurs after 1% strain).

3. EXPERIMENTAL INVESTIGATION OF ECC AS A RETROFIT

A series of small-scale component tests and small-scale infilled frame tests have been conducted to validate the performance of sprayable ECC as a retrofit technique for masonry infilled non-ductile reinforced concrete frames.

3.1. Small-scale component tests

Small-scale tests have been conducted on prisms and beam specimens using different retrofit schemes. The aim of these tests was to investigate the impact of a thin layer of ECC on plain masonry specimens in terms of changes in stiffness, strength and ductility.

3.1.1. Prism tests

Masonry prisms retrofitted with a 13mm layer of ECC have been tested in compression according to ASTM C1314-03b. These tests have shown that when a thin layer of ECC is applied to a plain masonry prism, the strength and stiffness are increased by ~45% and ~60% respectively compared to those of a plain specimen (figures 3a&b). Surface preparation was found to be important in order to improve the bond between the retrofit and the brick surface and avoid delamination.

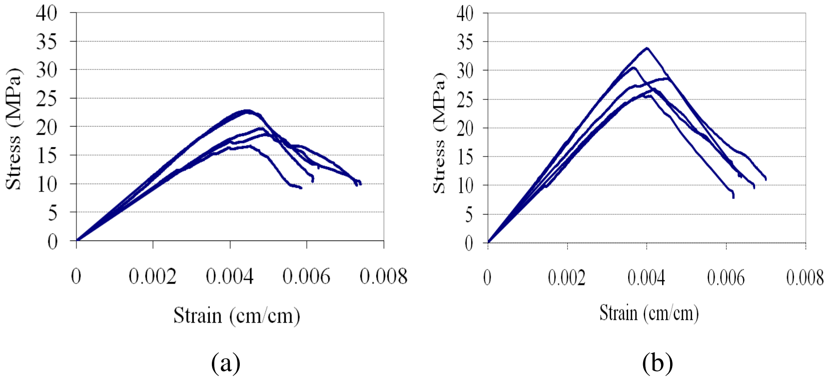
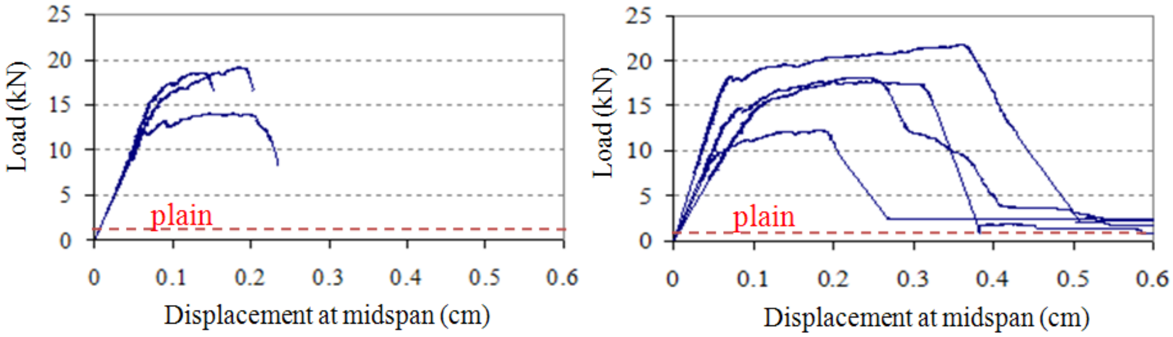


Figure 3 Stress-strain response of (a) plain masonry specimens and (b) masonry specimens retrofitted with ECC.

3.1.2. Flexural Tests

Four-point bending tests were conducted to assess the performance of the material in direct tension (approximate behavior of the tensile side of the constant moment region of the beams). The tests were conducted according to ASTM E518-03 but with quarter-point bending instead of third-point bending. These tests have indicated that the strength and more importantly the ductility of a retrofitted brick beam under four-point bending are increased by a factor of 20-25 times compared to the plain brick beams, which failed in a brittle manner (figure 4). Especially when the thin layer of ECC is lightly reinforced, more cracks are developed and propagate in the constant moment region leading to a more ductile response. The significant multiple cracking of the ECC was observed at the joints for unreinforced ECC and throughout the constant moment region (area of direct tension on the ECC) when the ECC was reinforced. Figure 5a shows the application of the load and figure 5b a view of the specimens from underneath at the ECC retrofit. It is noted that debonding between the ECC and the brick is advantageous for multiple cracking and therefore high ductility in direct tension but less so in compression where delamination buckling can occur.



(a) (b)

Figure 4 (a) Flexural response of masonry beams with a 13mm layer of ECC troweled to the brick surface and (b) specimens with both ECC and 0.1% by area steel reinforcement.

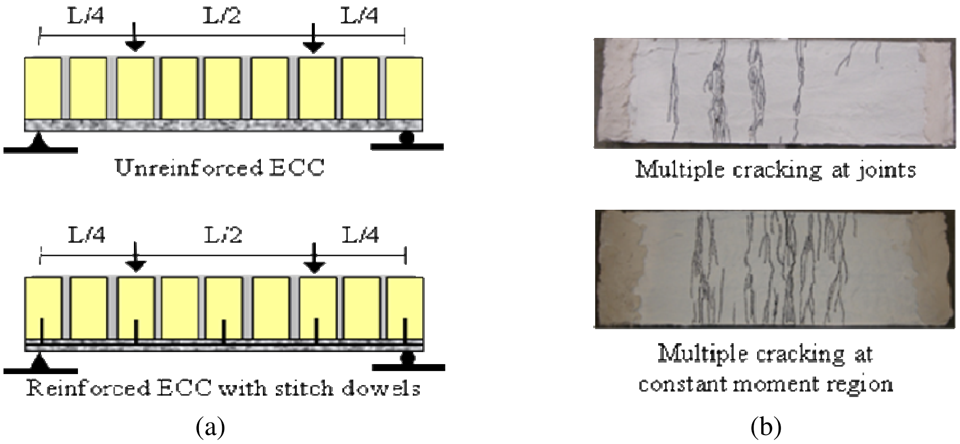


Figure 5 (a) Load application and (b) cracking response of 4-point bend specimens with unreinforced ECC (top) and with ECC reinforced with 0.1% steel (by area) and attached to screw anchors ("Stitch dowels") grouted into the masonry.

3.2. Small-scale infilled frame tests

A prototype building was selected that includes details typical of 1920s construction in the United States. This prototype was the basis for the small scale specimens being tested at Stanford University. It consists of non-ductile reinforced concrete frames with triple-wythe masonry infill walls on its perimeter. It is a three-story regular building with two bays in one direction and three bays in the other. The reinforced concrete members have been designed only for gravity loads that include the self-weight, the weight of the slabs, toppings, ceilings, masonry infills, and parapets, and the live loads. The specimens are a scaled down (~1/5th) version of one of the frames located on the first story of the two-bay frame.

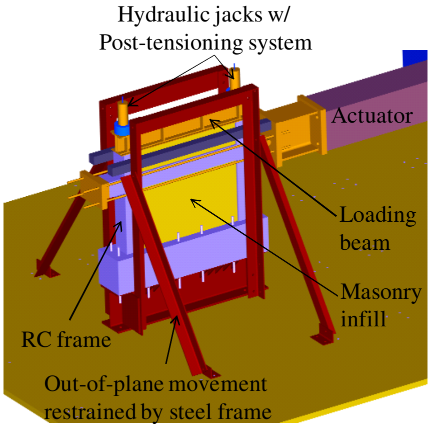


Figure 7 Test set-up for in-plane wall tests.

Four small-scale masonry infilled frames representing the first story frame within the 2-bay frame were fabricated to evaluate the proposed retrofit system; one unretrofitted and three retrofitted. The test set-up is shown in figure 7. The frames were fabricated at Stanford University in the John A. Blume Earthquake Engineering Research Center and the masonry infills were fabricated by local, professional masons. The specimens were tested under cyclic loading. The loading protocol consisted of a load control portion up to 10kips with 5kip load increments, followed by a displacement control portion with 0.125%, 0.25% and 0.5% drift increments up to 0.5%, 1.5% and 3.5% drifts respectively. Each load/drift level was applied for two cycles. Gravity load was applied to the specimens by center-hole hydraulic jacks with pretensioned rods passing through the center of the columns. The load was distributed to the columns and the wall through a loading beam. During the test the gravity load was controlled by the jacks and monitored by loadcells.

The four specimens tested have captured the anticipated target responses of (1) failure of the masonry infill leading to failure of the bounding frame (control specimen) (2) eliminating failure of the masonry infill and instead have failure of the bounding frame and (3) and (4) eliminating failure of the masonry infill and preventing shear failure of the bounding frame.

3.2.1. Specimen 1: Control specimen

The first specimen was an infilled frame with no retrofit and is referred to as the control specimen. The load vs. drift response is shown in bold in figures 8a and b. Different behavior was observed initially in each direction of loading with sliding along mortar joints in one direction and with sliding and diagonal cracking in the other direction. At 3% drift the specimen demonstrated a knee-braced mechanism in both directions with diagonal cracks. The final damage pattern is shown in figure 9a.

3.2.2. Specimen 2: ECC retrofitted

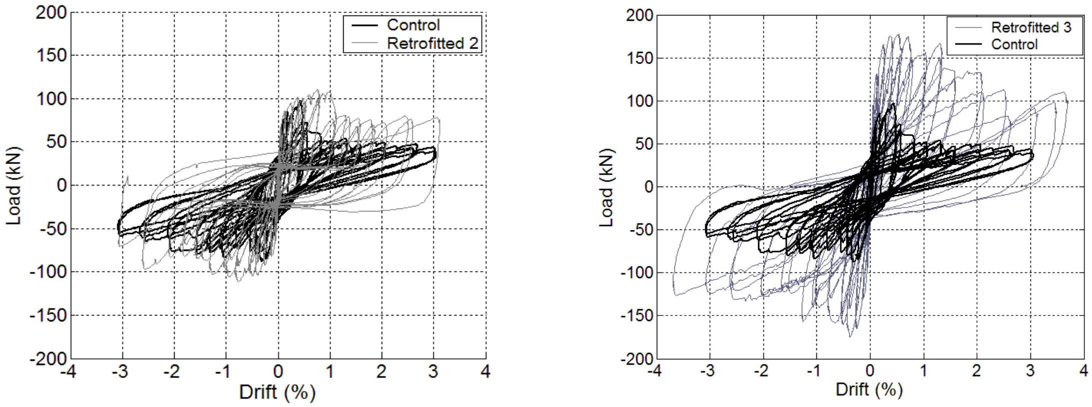
The second specimen was retrofitted with a 13mm ECC layer reinforced with welded wire steel mesh comprising 0.25% of the ECC area. Reinforcement was added based on the observation in the flexural tests that cracking was most well-distributed in the constant moment region when the ECC included welded wire reinforcement. In order to improve the bond between the ECC and the brick surface to limit delamination buckling in compression while at the same time facilitating multiple cracks to form in the ECC in tension, strips of bonding agent were painted on the masonry surface prior to application of the reinforcement and the ECC retrofit. With this retrofit scheme the aim was to eliminate the failure of the wall observed in the control specimen. It is noted that the ECC here has been troweled on. The load vs. drift response of the retrofitted specimen compared to the control specimen is shown in figure 8a. The specimen maintained its lateral strength up to 0.75% drift when minor mortar joint sliding occurred at the top brick course leading to shear failures at the top ends of both columns. After 1.0% drift, the specimen demonstrated a “pinching” behavior. The final damage pattern is shown in figure 9b.

3.2.3. Specimen 3: ECC retrofitted with shear dowels.

The retrofit scheme for the third specimen was similar to that of the second specimen in terms of ECC application. The differences in Specimen 3 were that shear dowels were used to connect the ECC layer with the top concrete beam and bottom concrete base and 0.4% welded wire steel mesh reinforcement was used instead of 0.25%. The shear dowels were added in order to transfer part of the lateral load into the retrofitted wall. Figure 8b compares the lateral load vs. drift response of the retrofitted wall with shear dowels and the corresponding response of the control specimen (the unretrofitted wall). The ECC exhibited multiple cracking along the diagonals and restrained the diagonal cracking and bed joint sliding that appeared in the masonry wall. No shear failure was observed in the columns. At 0.75% drift the dowels began pulling out of the base beam, causing a gradual load degradation leading to a rocking motion of the infilled frame. Up to 3.5% drift the capacity of the infilled frame maintained 60-68% of the peak load. The damage pattern of the specimen after testing is shown in figure 9c.

3.2.4. Specimen 4: ECC retrofitted with unbonded shear dowels at base.

Figure 10b compares the lateral load vs. drift response of the last retrofitted wall with the control specimen (the unretrofitted wall). For this last specimen unbonded shear dowels were used at the concrete base, thereby transferring shear but not tension between the wall and the base beam. The ECC exhibited similar performance with retrofitted specimen 3. Tensile cracks developed at the base of the concrete columns, initiated a rocking motion of the infilled frame. Up to 4% drift level the infilled frame was maintaining a lateral strength over 80% of the peak load. A monotonic load was applied after the 4% drift level in one direction, and the specimen maintained its lateral strength up to 5.35% drift where the limit of the test set-up was reached. The crack pattern of the specimen at the end of test as well as its deformed shape at 5.35% drift are shown in figures 9d and 10a respectively.



(a) (b)

Figure 8 Load vs Drift response of (a) control specimen and retrofitted specimen 2 (b) control specimen and retrofitted specimen 3.

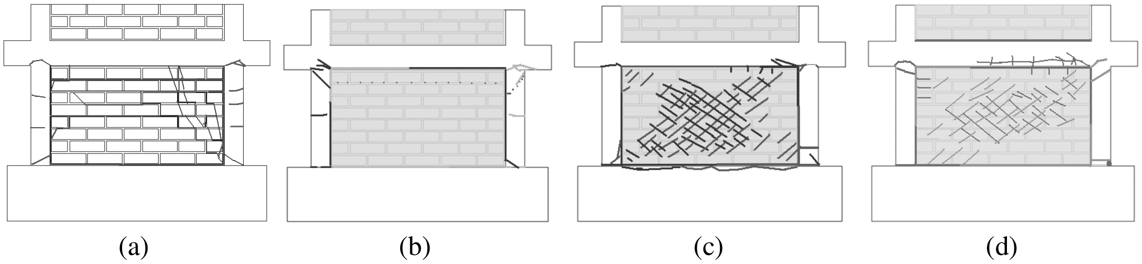
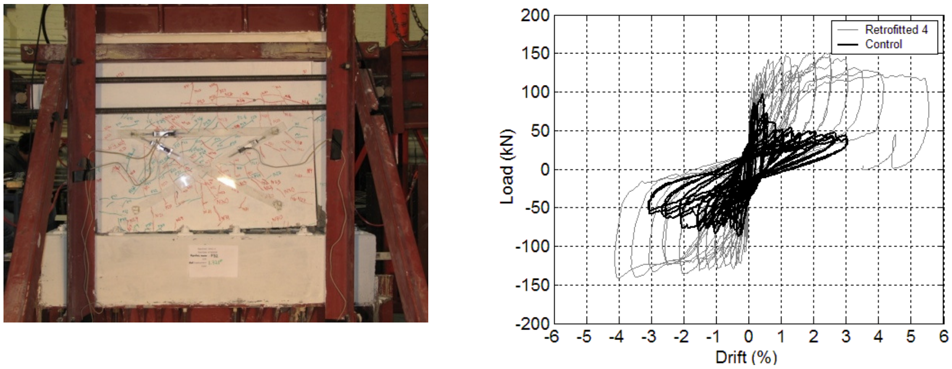


Figure 9 Final damage patterns in (a) the unretrofitted wall, (b) the wall retrofitted with reinforced ECC (view of ECC retrofitted side) (c) the wall retrofitted with reinforced ECC and shear dowels (view of ECC retrofitted side), (d) the wall retrofitted with reinforced ECC and unbonded shear dowels at the base (view of ECC retrofitted side).



(a) (b)

Figure 10 (a) Deformed shaped of specimen 4 at 5.35% drift and (b) response of control specimen and retrofitted specimen 4.

4. CONCLUSIONS & FUTURE WORK

Prism tests have shown that when a thin layer of ECC is applied on masonry, both strength and stiffness increase substantially. Flexural tests have demonstrated that ECC can add ductility to the system, especially when ECC is lightly reinforced.

The small-scale infilled frame tests have shown that a thin ECC layer with reinforcement can restrain the diagonal cracking and bed joint sliding in the masonry wall. When shear dowels are used between the ECC layer and the concrete beams, an alternate path of the load is developed and shear failure at the columns is avoided. A rocking motion is observed as tensile cracks develop in the columns and the shear dowels in the base beam pull out when bonded with the ECC. When using unbounded dowels at the base, a more ductile response with 80% lateral strength at high drifts (around 5.35%) is achieved compared to the retrofitted wall with the bonded dowels.

The retrofit technique developed at Stanford University will be evaluated in a 2/3 scale frame with a double-wythe infill at the University of Colorado at Boulder followed by the shake table test at UCSD. It is noted that the ECC at Stanford University was troweled on. For the specimens at the University of Colorado at Boulder and in UCSD, a sprayable version of ECC will be used. Finally, the research team will use the results of all experimental phases of the project to develop simplified analysis methods to predict the performance of retrofitted and unretrofitted unreinforced masonry infilled reinforced concrete frames.

5. ACKNOWLEDGEMENTS

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