Construction of Test Specimens for 
Retrofit of Non-Ductile RC Frames with Masonry Infill

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1.0 Abstract

Masonry infills are often used as interior partitions and exterior walls and treated as non structural elements of a building. Many of the structures with reinforced concrete (RC) frame with the masonry infill are located in seismic regions and must withstand earthquake loads. Although it is considered as a non structural element of a structure, the infill walls develop a strong interaction with the bounding frames under earthquake loads and contribute to the lateral stiffness and load resistance of the structure.

An ongoing research project conducted by the Network for Earthquake Engineering Simulation Research (NEESR) hopes to develop standardized methodologies to assess the seismic performance of the structure and effective retrofit methods for the infill wall. At Stanford University, a one-fifth scaled RC frame with masonry infill was constructed and will be placed under cyclic loading. The test results will supplement larger scale model testing at the University of Colorado, Boulder, and full scale testing at the University of California, San Diego. In terms of seismic retrofitting of the structure, Engineered Cementitious Composite (ECC) was selected as a possible candidate. Various brick specimens with an ECC appliqué were prepared and will be tested at Stanford.

2.0 Research Background

Many of the structures built with RC frames (Fig.1) with masonry infills (Fig. 2) were constructed prior to modern seismic codes and are often found in seismically active regions. Previously, the seismic performance of RC frames and of masonry walls were analyzed, and guidelines for each type of structure were established. Despite the several decades of research, the seismic performance of the combined structure remains a major controversy.

Some research found that masonry infill develops a strong interaction with the bounding frames when subject to certain level of earthquake loads and contributes significantly to the lateral stiffness and load resistance of the structure. In 1994, Mehrabi et al. tested single story
reinforce concrete frames with unreinforced masonry infill. Mehrabi et al. tested two types of frames and infills; one with non-ductile frame and the other was a ductile frame designed for Seismic Zone 4 according to the 1991 Uniform Building Code. The test results observed the beneficial influence of masonry infills in all cases and that shear failure of RC columns can be prohibited in a frame. The Construction Engineering Research Laboratory of the US Corps of Engineers recently conducted the research to study the behavior of masonry infilled non-ductile RC frames. At first, a half-scale, three-story, and three-bay infilled frame was tested. Later, carbon fiber reinforced polymer (CFRP) was added to the non-ductile RC frame members as reinforcement. The specimens were subjected to quasi-static load and cycles (Al-Chaar et al. 2001). The test results concluded that the application of CFRP only slightly improved the strength of an infilled frame but significantly enhanced the deformation capability.

At low lateral load level, RC frames with masonry infills behave as monolithic system. At a higher lateral load level, however, infill partially separate from the frame, and form a compression strut mechanism (Stafford et al. 1962). In most cases, a simple sum of the lateral resistance of an infill and the bare frame is not equal to the resistance of an infilled RC frame. Frame-infill interaction can alter the load resting mechanisms of the individual components. Therefore, the behavior of the infilled RC frame greatly depends on the interaction of the frame and infills.

The main seismic performance issues concerning the masonry infilled RC frame are the soft-story mechanism and brittle shear failure of columns. Strength degradation of infill and columns under the earthquake loads developed significant loss of wall resistance at a particular story. As a result, a pronounced soft story mechanism in the structure develops (Figs. 3,4).

![Figure 3: Soft story mechanism](http://infill.ucsd.edu/presentation.pdf)

![Figure 4: Kocaeli, Turkey Earthquake 1999, Mw 7.4](http://www.ngdc.noaa.gov/seg/hazard/icons/small_res/46/46_925.jpg)

If the infill is too strong, however, it will exert an unnecessarily high load on the bounding frame and induce brittle shear failure on the columns. Therefore, efficient retrofit methods need to be developed to increase the ductility of masonry infills without enhancing their strength too significantly (Shing et al. 2002).
3.0 Research Objective:

The main goal of this NEESR project is to develop rational and reliable methodologies for seismic performance assessment of the structure with RC frames and masonry infill and develop practical and cost-efficient techniques for the seismic retrofit of these structures using ECC. The reliable analysis tools range from advanced computational models to simple analytical methods. At Stanford University, the analysis methods and retrofit techniques will be tested with a one-fifth scale component of a three-story prototype structure (Fig. 5). Then two-thirds scale specimen tests (Fig. 6) will be conducted with the NEES Fast Hybrid Test facility at the University of Colorado, Boulder in October, 2007. Final proof-of-concept tests will be conducted on a full-scale two bay, three-story RC frame (Fig. 7) using the NEES Large High Performance Outdoor Shake Table at the University of California, San Diego, in summer of 2008. At each testing site, control specimens without retrofit and testing specimens with retrofit will be tested.
3.1 Assessment Methods

In this NEESR project, refined finite element models (Fig. 8) will be developed to predict the damage and failure of infilled RC frames under earthquake loads. These models will help to replace physical experiments with model based-simulation using high-performance computing capabilities. The predictive capabilities and limitations of the models will be evaluated and areas for further improvements will be identified.

Figure 8: Finite element analysis – deformed mesh

In addition, review of the existing finite element program (DIANA) with smeared and discrete crack modeling capabilities will be conducted.

3.2 Development and Evaluation of Retrofit Methods

In order to contain the soft-story mechanism and minimize falling hazards, infill retrofit techniques, which enhance the ductility and delay the strength degradation of the infill, need to be developed. The previous research shows that fiber reinforced polymer (FRP) enhanced the shear and tensile strength of masonry infill (Hamid et al. 2005) However, it is rather costly, and over strengthening the infill may not be desirable for a non-ductile RC frame. Mander et al. (1994) concluded that the use of a sufficiently thick ferrocement overlay with two layers of wire mesh will considerably increase the strength of a masonry infilled steel frame. The retrofitted frame, however, exhibited a rapid deterioration of resistance under cyclic loads.

In this research, cost-effective retrofit techniques that can prohibit the shear failure of non-ductile RC columns and contain the soft-story mechanism of an infilled frame will be developed. For this purpose, the use of sprayable, high performance fiber-reinforced cement based composites (HPFRCC) as an infill retrofit method was selected. In particular, appreciation of Engineered Cementitious Composites (ECC) will be extensively researched at Stanford University.

3.2.1 ECC: Brief Description of the Material

ECC is an ultra ductile fiber reinforced cementitious composite developed for applications in the large material volume usage and cost sensitive construction industry. The most significant characteristic of ECC is its tensile strain-hardening behavior with strain capacity
in the range of 3-7%, yet the fiber content is typically less than 2% by volume. The material is micromechanically designed with synthetic poly-vinyl-alcohol (PVA) fiber, cement, fly ash, fine sand, super plasticizer and water. During strain-hardening, multiple microcracks limited to about 60 μm in crack-width form along the length of the tensile specimen. The formation of the microcracks allows the ECC to exhibit strain hardening similar to many ductile metals (Li 2003).

The ECC Technology Network developed the following table showing the comparison among Fiber Reinforced Concrete (FRC), HPFRC, and ECC (Table 1)

<table>
<thead>
<tr>
<th></th>
<th>FRC</th>
<th>Common HPFRC</th>
<th>ECC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Methodology</strong></td>
<td>N.A.</td>
<td>Use high V&lt;sub&gt;f&lt;/sub&gt;</td>
<td>Micromechanics based, minimize V&lt;sub&gt;f&lt;/sub&gt; for cost and processability</td>
</tr>
<tr>
<td><strong>Fiber</strong></td>
<td>Any type, V&lt;sub&gt;f&lt;/sub&gt; usually less than 2%; d&lt;sub&gt;f&lt;/sub&gt; for steel ~ 500 μm</td>
<td>Mostly steel, V&lt;sub&gt;f&lt;/sub&gt; usually &gt; 5%; d&lt;sub&gt;f&lt;/sub&gt; ~ 150 μm</td>
<td>Tailored, currently polymer fibers most suitable, V&lt;sub&gt;f&lt;/sub&gt; usually less than 2%; d&lt;sub&gt;f&lt;/sub&gt; &lt; 50 μm</td>
</tr>
<tr>
<td><strong>Matrix</strong></td>
<td>Coarse aggregates used</td>
<td>Fine aggregates used</td>
<td>Controlled for matrix toughness and initial flaw size; fine sand used</td>
</tr>
<tr>
<td><strong>Interface</strong></td>
<td>Not controlled</td>
<td>Not controlled</td>
<td>Chemical and frictional bonds controlled for bridging properties</td>
</tr>
<tr>
<td><strong>Mechanical Properties</strong></td>
<td>Strain-softening:</td>
<td>Strain-hardening:</td>
<td>Strain-hardening:</td>
</tr>
<tr>
<td><strong>Tensile strain</strong></td>
<td>0.10%</td>
<td>&lt; 1.5%</td>
<td>&gt;3%; 8% demonstrated</td>
</tr>
<tr>
<td><strong>Crack width</strong></td>
<td>Unlimited</td>
<td>Typically several hundred μm, unlimited beyond 1.5% strain</td>
<td>Typically &lt; 100 μm during strain-hardening</td>
</tr>
</tbody>
</table>
4.0 Internship Assignments

The project at Stanford University was guided by Professor Sarah Billington and assigned to graduate research assistant, Marios Kyriakides. Marios has been working on this project since May 2006. My internship partner, Nancy Lee from San Francisco State University, and I joined the project when the construction of the test specimens with RC frame and masonry infill was just beginning. The entire design and construction planning, as well as some of the fabrication were completed before Nancy and I joined the project as summer interns.

My main role was to work with Nancy to build four one-fifth scale component of a three-story prototype RC frame with masonry infill structure for cyclic testing. The total height of the test specimen is 5 feet and the width is 7.5 feet (Fig. 9). The first specimen is the control specimen without ECC retrofit and the other three will be retrofitted with ECC, ECC with meshed wire, and ECC with shear connectors respectively.

At Stanford, ECC retrofit techniques were tested and small-scale test specimens were fabricated. Nancy and I built several brick specimens for flexural tests (Fig. 10) and prism tests (Fig. 11).
5.0 Construction Process

This section discusses the construction process we followed during the fabrication of the non-ductile RC frames with masonry infill and ECC retrofitted brick beams.

5.1 Non-Ductile RC Frames with Masonry Infill

The wooden forms for specimen #1 and #2 were already constructed before Nancy and I started our internship. The plan was to recycle those two forms for specimens #3 and #4 after we strip the first two specimens. Construction of rebar cages for the bases of the first two specimens was also completed. Then, we started with strain gage attachment on some of the rebars and rods. After the gages were attached, we started placing the rebar cage in the base, reinforcing rods in the columns, and rebars in the top beam. Concrete was placed in the form after all the reinforcing steel was placed. After the concrete was cured, the specimens were stripped from the forms. Professional masons then worked on and completed the brick infill walls. Specimen #1, a control specimen without ECC retrofit, was positioned on the platform of the cyclic test apparatus. The instrumentation of LVDT and other devices was postponed several times since frequent design changes were ordered by the leading professors at the three participating universities. While we were waiting for the final design of the instrumentation, we cut and bent rebar for the reinforcement of specimens #3 and #4. Since some parts of the formwork from the first two specimens were not reusable, we also cut some plywood and repaired the forms.

5.2 ECC Retrofitted Brick Beams

For the flexural test of ECC retrofitted brick wall, we laid 9 layers of bricks and applied wire reinforcement and ECC reinforcement.

6.0 Descriptions of the Construction: RC Frames with Masonry Infill

This section discusses the details of each part of the infilled frame construction.
6.1 Strain Gage Attachment

The design specified that 12 strain gages would be used to record the strain of rebars and rods in each specimen under the cyclic loads. Fig. 12 and Fig. 13 illustrate the specific location of each strain gage.

Figure 12: The location of the strain gages on the rebars in the top beam

Figure 13: The location of the strain gages on the rods in the columns
The strain gage is made out of very thin plastic film. The dimension of the gage is; 0.4635 in long x 0.1600 in wide (Fig. 14). Since the diameters of the rebars and rods are 0.3535 in and 0.1860 in, respectively, the gage attachment required some practice. The surface of the rebars and rods needed to be extremely smooth and clean before attaching the gage. First, we needed to file the surface of the rebars and rods with a metal file and sand paper (Fig. 15, 16)

![Figure 14: Strain gage; size comparison](image1)

![Figure 15: Filing the rebar surface](image2)

![Figure 16: Sanding the rebar surface](image3)

The surface of the smoothed rebar was then washed with alcohol followed by acid and neutralizer wash (Fig. 17). The surface of the working area also needed to be clean since the gage would be laid on the surface and picked up with the tape. Then, the taped gage was glued to the rebar surface using cyanoacrylic glue (Fig. 18). The glued gage needed to be held under our thumb for at least 7 minutes before we peeled the tape from the gage. Figures 19 and 20 show the attached gage on the rebar and rod, respectively.

![Figure 17: Cleaning the rebar surface](image4)

![Figure 18: Cleaning the rebar surface](image5)
6.2 Reinforcement Assembly

For the RC base, a total of eight #5 rebars were used for the top and bottom reinforcement and fourteen #3 stirrups were tied to the rebars. For the RC top beam, a total of eight #3 rebars were used for the top and bottom reinforcement. In each column, four #2 rods were inserted, and they were tied with ten wire stirrups (Fig. 21).
We cut and bent all the rebars and rods for specimen #3 and #4 (Fig. 22 & 23) and assembled the rebar cages for the bases (Fig. 24). The other reinforcement, which includes the rebars and rods with strain gages attached, was placed in the top beam and side columns (Fig. 25).

6.3 Placement of Concrete

The form was oiled thoroughly before placing the concrete. A total of sixteen bags of 60 lb concrete mix were used for each specimen. After the concrete was mixed, we placed it over the reinforcement in the form while vibrating the concrete for compaction (Fig. 27). Figure 28 shows the completion of the concrete placement for specimen #1. The specimen was then covered and cured for fourteen days before it was taken out of the form (Fig. 29).
6.4 Raising the RC Frame and Fabrication of the Infill Wall

The RC frame was raised using overhead crane (Fig. 30, 31) and masonry work was done by professional masons (Fig. 32).

6.5 Positioning the Specimen for the Cyclic Test

After the infill wall was cured for 14 days, the specimen #1 was positioned on the W-beam testing platform (Fig. 33). The overhead crane was used for this task also; however, we had to ensure that the RC base would fit on the platform before we raised the specimen. To be extra cautious, we decided to slightly grind the outer edge of the base for a perfect fit. Fortunately, the positioning of specimen #1 went smoothly on the first try (Fig. 34, 35).
7.0 **Descriptions of the Construction: ECC Reinforced Brick Beams**

For the four-point flexural test, we fabricated five 9-layered brick beams with wire mesh and ECC reinforcement. Figure 36 shows the dimensions of the specimen.

The mix ratio of mortar (Type I-II Cement = 1: Lime = 1: Sand = 5: Water = 1 ¾ ~2) mimicked 1920’s mortar composite. We laid a brick and applied mortar on top of it. The next brick was pressed onto the mortar without exceeding a thickness of 3/8”. After the top layer of bricks was laid, the specimen was covered with a plastic sheet and cured for 14 days.

In the meantime, wire reinforcement shown in Figure 36, as well as the paper clip chairs (Fig. 37) were fabricated. To improve the adhesion of the brick and ECC, bonding agent was applied to the brick beam before we attached the chair and the wire reinforcement (Fig. 38).
Fiber reinforcement (PVA) shown in Figure 39 was carefully separated before it was mixed into the rest of the ECC components. To ensure that the PVA was thoroughly distributed in the ECC, the composite was mixed for over one hour. Workable time of ECC is only 15 minutes, so the application of the ECC on the wire reinforced brick beam needed to be efficient and quick. The specimens were cured for at least 14 days before testing (Fig. 40).

8.0 Jobs Completed

Table 2 illustrates the jobs we completed during the 10 week internship period. Because of the time constraint, I was not able to observe the cyclic test which was conducted 10 days after my internship period ended.

<table>
<thead>
<tr>
<th>RC Frames with Masonry Infill</th>
<th>Frame 1</th>
<th>Frame 2</th>
<th>Frame 3</th>
<th>Frame 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC Frame</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rebar Cage</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Strain Gages</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Concrete Pouring</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Masonry Work</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retrofit</td>
<td>n/a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen Positioning</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Specimens for ECC Retrofit</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>
9.0 Conclusion

Specimen #1 was tested under cyclic loading 2 weeks after I completed my internship. Therefore, I was not able to observe the testing. According to my internship partner, Nancy Lee, who attended the testing, it took over 17 hours to complete the testing. The data collected from the test has been analyzed by our mentor, Marios Kyriakides. The date for the testing of specimen #2 is pending, and fabrication of specimens #3 and #4 has continued at Stanford University.

It was a great learning experience to go through the research process and to participate in the fabrication of the specimens. I learned that it is important to factor in unexpected problems during the transition process from design to fabrication. Often, the construction process did not go through as we planned. Therefore, some degree of flexibility in construction scheduling was necessary in order to make some alterations to solve the unexpected problems.

I also learned that it is essential to document everything during the research process for analysis of the test results. Some of the subjects we documented are: location of instrumentation, geometry of specimens, mixture of concrete, fabrication date, and detail of material properties. The photos of the construction process and the set up of apparatuses helped us significantly to analyze the procedure.

Our internship duty often required severe physical labor. To avoid injury and simplify the process, I learned that it is crucial to jury-rig using any tools and instruments available in the lab in order to make the process of fabrication easier.

I hope the upcoming tests for specimens #2, #3 and #4 will be successful and I would like to learn about the final results of this NEESR project. It was my great pleasure to participate in the construction phase of this project.

10.0 Acknowledgements

I would like to thank my advisor, Dr. Sarah Billington at Stanford University for her overall support. I would also like to thank my mentor, Marios Kyriakides, for his excellent guidance and tremendous amount of patience.

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11.0 References


