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Simulation of Masonry Beams Retrofitted with Engineered Cementitious Composites

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1 INTRODUCTION

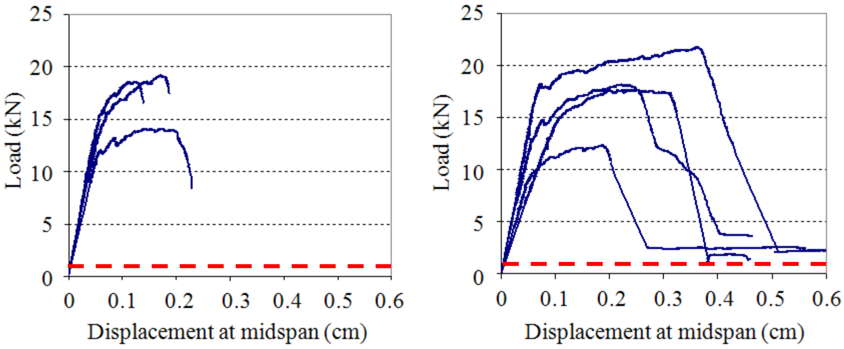
A thin layer of ductile fiber-reinforced mortar material referred to as Engineered Cementitious Composites, or ECC has been experimentally investigated as a seismic retrofit for unreinforced masonry infill walls in non-ductile reinforced concrete frames. Compression tests of masonry prisms retrofitted with 13mm of ECC were conducted representing the compression strut of a masonry infill under in-plane lateral loading. Similarly, flexural tests of brick beams using a quarter point bending configuration with the constant moment region intended to approximately represent direct tension (in particular in the ECC), were performed to investigate the response of the tension strut of the masonry infill. In-plane cyclic tests of 1/5th scale non-ductile concrete frames with ECC retrofitted masonry infills using different retrofit techniques were also conducted and the results indicated that the ECC can help keep unreinforced masonry walls intact to large lateral drifts, adding significant ductility to the structural system (Kyriakides & Billington, 2008). Different 2D modeling approaches using the commercial finite-element software DIANA to predict the performance of retrofitted masonry under 4-point bending are investigated and are presented here. This study supports on-going research to develop reliable methodologies for researchers and practitioners to assess the performance of non-ductile concrete unreinforced masonry infilled structures retrofitted with ECC using nonlinear finite-element analysis.

2. MASONRY BEAMS WITH UNREINFORCED AND REINFORCED ECC RETROFITS

ECC is a class of high performance fiber-reinforced cement-based composites that exhibits fine, multiple cracking and strain hardening behavior in direct tension. A sprayable version of this material was recently reported to be sprayed on to a concrete wall achieving a thickness of 45mm (Kim et al., 2003). The mix design consists of Type I Portland cement, class F fly ash, calcium aluminate cement, fine silica sand and 2% by volume of short, chopped polyvinyl alcohol fibers that have been treated with oil to allow for frictional debonding during cracking.

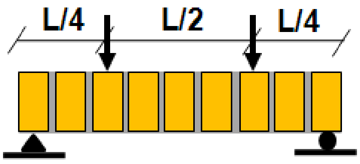
Flexural tests have indicated that the strength and more importantly the ductility of a retrofitted brick beam under four-point bending are increased tremendously (Figure 1). Especially when the thin layer of ECC is slightly reinforced with a steel wire mesh, more cracks are developed and propagate in the constant moment region leading to a more ductile response

(Figures 1 and 2) than when unreinforced ECC is used. On the other hand, plain brick beams demonstrated very brittle failure with approximately 20-25 times lower strength.



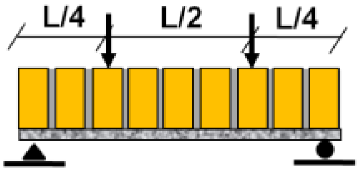
(a) (b)

Figure 1 Flexural response of masonry beams with a 13mm layer of (a) ECC, and (b) ECC with 0.125% by area steel reinforcement, troweled to the brick surface



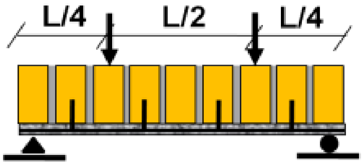
Unretrofitted brick beam

Brittle failure of brick beam



Unreinforced ECC

Multiple cracking at joints



0.125% Reinforced ECC

Multiple cracking at constant moment region

(a) (b)

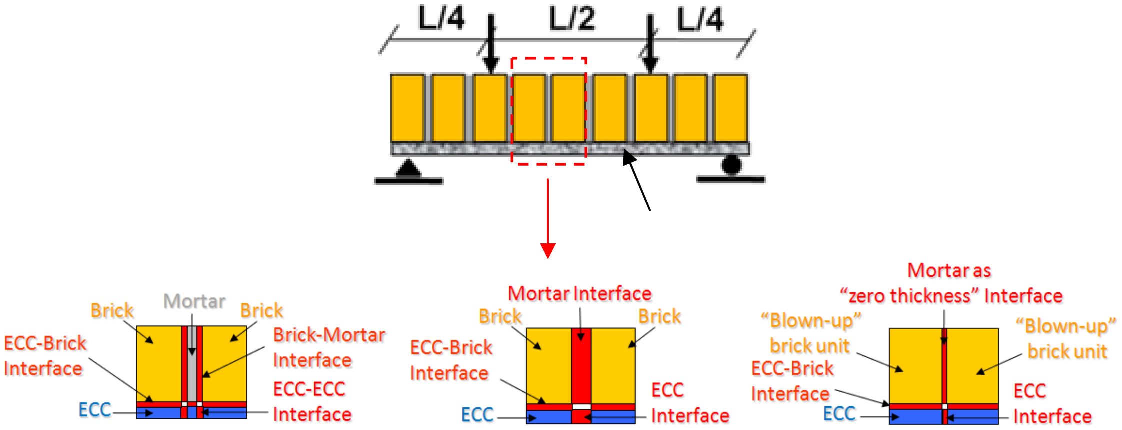
Figure 2 (a) Load application and (b) cracking response of 4-point bend specimens with no retrofit (top), unreinforced ECC (center) and with ECC reinforced with 0.125% by are steel and attached to anchors ("Stitch dowels") grouted into the masonry (bottom).

3. NUMERICAL INVESTIGATION OF RETROFITTED MASONRY

The ability to predict adequately the performance of a masonry infilled reinforced concrete structure has been a significant area of research over the last several decades in large part due to its importance for practitioners. This effort becomes more complicated when a retrofit technique is applied on the masonry infill. In this research, the ability of state-of-the-art nonlinear finite element analysis methods to predict the performance of 4-point bending masonry components retrofitted with a thin layer of ECC with and without reinforcement is being investigated.

Three different 2D finite-element modeling approaches are investigated (Figure 3). In all three approaches, 8-noded plane stress elements are used to model the brick units and a total strain, fixed crack model (Feenstra et al., 1998) is used to capture the brick cracking behavior.

Plane stress elements are also used to model the ECC layer areas directly below the brick units, with a multi-linear (in tension) crack model (also total strain, fixed crack). To simulate the bond between the ECC layer and the brick units, linear elastic interface elements are used. The primary difference of the three modeling approaches is found in the way the mortar joints and the ECC layer directly below the mortar joints is modeled. In the first model, continuum elements are used for the mortar joints and the ECC below, with interface elements introduced between the brick units and the mortar to capture the brick-mortar interface failure (Figure 3a). In the second approach, interface elements are used for the entire mortar joint and the ECC below the mortar joint (Figure 3b). With the third approach, "blown-up" brick units and zero thickness interface elements for mortar joints and the ECC directly below are used (Figure 3c).



(a) (b) (c)

Figure 3 Schematic representation of the three modeling approaches (a) Continuum elements for mortar joints and ECC with interface elements between the brick and the mortar, (b) interface elements for the mortar joints and the ECC directly below, and (c) blown-up brick units with zero thickness mortar joints.

The first and the third modeling approaches were able to capture adequately the experimental responses of both the unreinforced and reinforced ECC retrofitted brick beams in terms of strength, ductility and failure mode. In both of these models, failure of the mortar-brick interfaces at the constant moment region occurred first, followed by cracking of the ECC under the mortar joints that led to a stiffness degradation of the beam, and eventually failure of the ECC below the 3rd mortar joint (in the constant moment region) (Figure 4). In all analyses, a higher initial stiffness was obtained compared to the experiments (Figure 5). Especially with the second approach, the analytical stiffness was even higher compared to that predicted by the other models, as the second model does not satisfy the moment equilibrium due to the finite thickness of the mortar joints. While the first and third modeling approaches gave a similar load vs. displacement response, the third approach is a less complicated in terms of developing the model and is considered preferable for evaluation of larger-scale, structural simulations.

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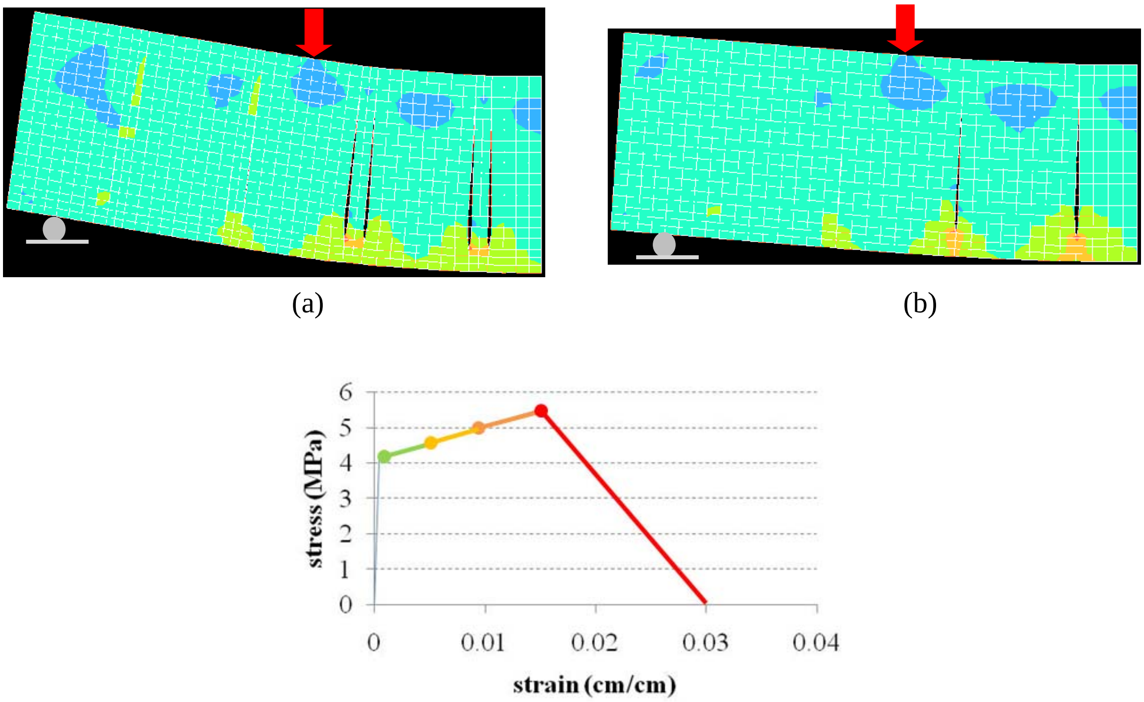

(a) (b)

(c)

Figure 4 Principal tensile stresses of half brick beam with ECC at failure using (a) Continuum elements for mortar joints and ECC with interface elements between the brick and the mortar and (b) blown-up brick units with zero thickness interface elements for mortar joints during failure of the ECC. Diagram (c) shows the tensile stress-strain response of the ECC with colors that correspond to the tensile strains shown in (a) and (b).

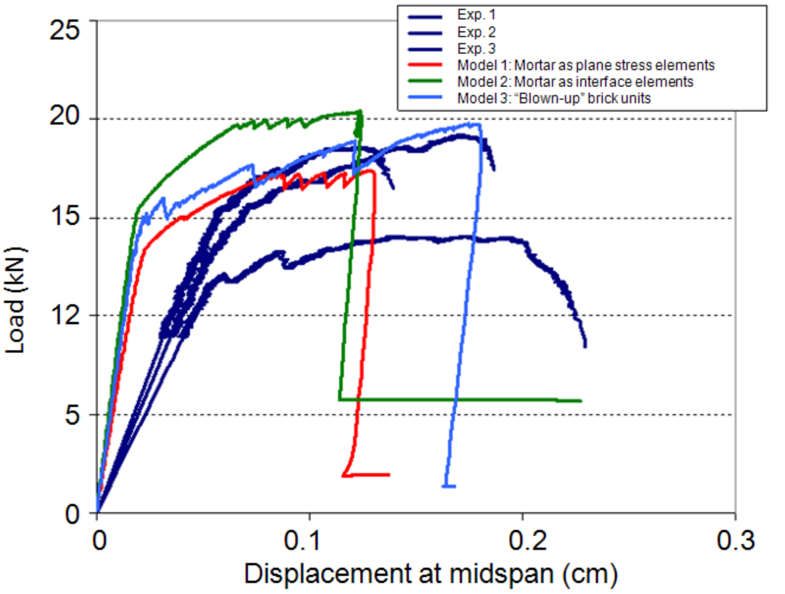

Figure 5 Load-displacement responses obtained from both experiments and all three model approaches.