SEISMIC PERFORMANCE ASSESSMENT OF MASONRY-INFILLED RC FRAMES RETROFITTED WITH ECC OVERLAYS

Ioannis Koutromanos\(^1\), P. Benson Shing\(^2\)

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This analytical study focuses on the in-plane seismic behavior of retrofitted masonry-infilled reinforced concrete (RC) frames. The retrofit method is based on the addition of engineered cementitious composite (ECC) overlays on infill walls. The ECC material is characterized by significantly enhanced tensile ductility as compared to normal cementitious materials. The analyses have been conducted using refined finite element models that can capture the cyclic behavior of the RC members, the infill walls and the ECC overlays. A simplified method is proposed to account for the effect of the construction sequence and of material creep on the gravity load distribution between the RC frame columns and the infill walls. The analysis scheme has been validated by data from shake-table tests on a retrofitted infilled frame specimen.

Parametric static analyses have shown that the performance of a retrofitted structure can be greatly improved by preventing the failure of shear dowels that connect the retrofit overlays to the frame. This allows to fully exploit the ductile inelastic behavior of the ECC material. A simplified analytical method to assess the shear capacity of an ECC overlay and to determine the required strength of the shear dowels is proposed.

Finally, dynamic analyses have been conducted for infilled RC frames subjected to a collection of eight ground motions which have been scaled to match the design-level intensity for downtown Los Angeles. The results demonstrate that the addition of a relatively thin ECC overlay can significantly enhance the seismic performance by limiting the extent of cracking in the infill walls and in the RC frame.

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Introduction

Masonry-infilled reinforced concrete (RC) frames represent a significant portion of the building inventory in earthquake-prone areas around the world. Typical old construction of this type does not include any separation between the infill walls and the RC frame members. Thus, under lateral loads, the infill frame will interact with the surrounding frames, significantly increasing the lateral stiffness and resistance of the system. However, undesired failure modes such as shear cracking in the columns can occur, due to the development of large contact stresses along the infill-to-frame interfaces. Such failure modes are very probable for structures with strong infill walls and relatively weak frame members, as observed in an experimental study by Mehrabi et al. [1]. In many cases, the premature occurrence of undesired failure modes leads to inadequate performance, despite the significant strength increase contributed by the infill walls. For this reason, retrofit is often deemed necessary for old infilled RC frame construction.

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Several studies have examined the effectiveness of retrofit measures such as ferrocement [2] or FRP overlays [3] on the performance of infilled frames. While useful insights have been obtained on the effectiveness of various retrofit techniques, validated analysis methods and design guidelines for the retrofit of infilled frames are still lacking. Available guidelines for the evaluation of existing unretrofitted and retrofitted infilled frames [4] are also far from complete.

A recently completed collaborative research project was aimed to develop analytical tools to assess the performance of older non-ductile infilled frames [5] and examine the effectiveness of a retrofit method using Engineered Cementitious Composite (ECC) overlays on masonry infill walls. In this project, a 2/3-scale, three-story, two-bay infilled frame specimen was tested on a shake-table to validate the effectiveness of the retrofit method to mitigate earthquake damage [6], and a detailed modeling approach has been developed to simulate the inelastic behavior of infilled frames with ECC overlays [7].

This paper presents an analytical evaluation of the effectiveness of ECC overlays in enhancing the performance of non-ductile infilled RC frame construction. Refined finite element models have been used to simulate the behavior of infilled frames and retrofit materials. Parametric analyses have been conducted to determine the influence of the overlay on the behavior of a retrofitted structure and to validate simplified formulas proposed for the design of the retrofit. Finally, a series of dynamic analyses is presented to demonstrate the beneficial influence of a relatively thin ECC overlay in the seismic performance of a multi-story infilled frame.

**Description of Retrofit Method and Experimentally Observed Performance**

The retrofit method considered here was developed by Kyriakides and Billington [8] and is based on the application of overlays of ECC material on the infill walls. The major advantage of ECC [9] as compared to conventional cementitious materials is its enhanced tensile ductility that delays the tensile strain localization and the subsequent tensile strength degradation. This increased ductility is accomplished through the addition of a relatively small amount of poly-vinyl-alcohol (PVA) fibers (about 1% by volume) with random orientations to a cementitious matrix.

To evaluate the effectiveness of the retrofit technique, a three-story, two-bay, masonry-infilled frame specimen with ECC overlays applied on an infill wall in the bottom story was tested on a shake table [6]. The configuration of the specimen considered here is shown in Fig. 1a. Construction details of the retrofit applied on the shake-table specimen are shown in Fig. 1b. A mesh of Welded Wire Reinforcement (WWR) was added in the ECC to enhance its performance. Shear dowels were used for shear transfer between the ECC overlays and the RC beam and base slab. No shear dowels were used in the ECC-to-column interfaces. The dowels along the ECC-to-base interface were debonded by wrapping with duct tape, which was then covered with grease. The overlays were applied on both sides of the wall. The total thickness of the two ECC overlays was about 50 mm (2 in) in the middle portion of the wall and was increased to 100 mm (4 in) near the top and bottom of the wall to provide sufficient cover for the shear dowels, as shown in Fig. 1b. For an actual structure, the retrofit overlays would most probably be added only on one side of an infill wall.

The specimen was subjected on a series of ground motions of increasing intensity. All the imposed motions were scaled versions of the Gilroy 3 record from the 1989 Loma Prieta Earthquake. After a first sequence of tests, moderate damage occurred in the unretrofitted second story. Testing was stopped and the infill walls in the second story were repaired with Koutromanos, I., Shing, P. Seismic performance assessment of masonry-infilled RC frames retrofitted with ECC overlays. *Proceedings of the 10th National Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.
epoxy injections and strengthened with a Glass-Fiber Reinforced Polymeric (GFRP) overlay. The structure was then subjected to a final sequence of motions of increasing intensity, until damage occurred in the bottom story. An initial sequence of five motions, whose intensity reached the MCE-level intensity for downtown San Diego [6], did not introduce any observable damage to the specimen. Severe damage was finally induced by a ground motion with intensity significantly greater than the MCE-level [6]. More specifically, the shear dowels between the overlay and the beam failed. The sudden increase of the shear force transferred through the exterior bottom beam-to-column joint in the bottom story led to the failure of that joint. The damage obtained after the completion of the tests is shown in Figs. 2a and 2b.

**Figure 1.** Shake-table test specimen and retrofit layout.

**Figure 2.** Crack pattern and damage after completion of tests.

**Analysis Method**

The shake-table tests need to be supplemented with an analytical study to allow a better understanding of the seismic behavior of retrofitted infilled frames. The study has an extensive set of static and dynamic analyses to quantify the beneficial effect of the retrofit and to allow the establishment of simplified design formulas for the ECC overlays and the shear dowels.
The analyses presented herein are based on the finite element modeling approach described in [7],[10]. Plane-stress, smeared-crack continuum elements are combined with discrete-cohesive crack interface elements to capture the nonlinear behavior of the RC frame members and of the infill walls, including the effect of inclined shear cracks in the concrete members and the localized damage along masonry mortar joints. The modeling approach for the reinforced concrete members and for the masonry walls is shown in Figs. 3a and 3b, respectively. The steel reinforcement is modeled with elastoplastic truss elements. To account for the reinforced ECC overlay, a layer of plane-stress, smeared-crack elements is superimposed on the mesh representing the masonry infill. As shown in Fig. 4a, the smeared-crack elements representing the ECC have a stress-strain law that closely mimics the experimental data obtained from ECC beam specimens.

Nonlinear horizontal springs are introduced in the numerical models to simulate the shear dowel connections between the overlays and the beams of the RC frame. The nonlinear behavior of these springs, shown in Fig. 4b, includes strength degradation to account for the damage in the ECC surrounding the shear dowels, shown in Fig. 2. The strength of the dowels is determined based on an equation by Walraven [11], while the stiffness of the dowels is calculated in accordance with the work of Shirai and Sato [12].

Model for gravity load distribution between the columns and the infill walls

The distribution of gravity loads between the reinforced concrete members and the infill walls can significantly affect the behavior of an infilled frame, since the strength and stiffness of the infill walls strongly depend on the normal compressive stresses on the mortar bed joints. An accurate assessment of the gravity load distribution is a challenging task, since the effects of the construction sequence and of the long-term creep deformation of the concrete and masonry need to be accounted for. For older structures, the effect of gradual water absorption by the bricks may also be important. Given the absence of experimental data on the gravity load distribution between the RC columns and masonry wall which would allow the calibration and validation of more refined models, a simplified approach is used to estimate the gravity load distribution for the infilled frame specimen. The rheological model
in Fig. 5a simulates the axial stiffness of the columns and infill walls and accounts for the viscoelastic (creep) properties of the concrete and masonry. An initial gap, \( u_0 \), is also introduced in the model to capture the effect of the gravity loads which are applied to the structure before the construction of the infill walls and is thus initially carried by the columns alone. The gravity load distribution at a given age can then be determined, as shown in Fig. 5b.

A more detailed description of the application of the rheological model, including the formulation of the governing differential equations, the solution of these equations, and the calibration of the spring-and-dashpot assemblages representing the frame columns and the masonry infills can be found in [10]. The same reference explains how the target gravity load distribution is introduced in the finite element models which do not account for viscoelastic effects.

![Diagram](image)

(a) Rheological model for creep  
(b) Distribution of gravity loads

Figure 5. Determination of gravity load distribution.

**Validation of Analysis Method with Experimental Tests**

The finite element modeling scheme was validated using the experimental test results of the specimen tested in [6]. Nonlinear static analyses were conducted to verify that the modeling scheme can predict the damage pattern observed in the experimental tests. The obtained damage pattern is shown in Fig. 6a and it closely matches the experimentally observed damage. Additionally, the load-displacement curves obtained from the nonlinear static analyses provide an excellent envelope of the experimentally recorded hysteretic curves, as shown in Fig. 6b. In this figure, the base shear, \( V_b \), has been normalized with the seismic weight, \( W \), of the specimen, which was equal to 1355kN. A dynamic validation analysis was also conducted for the series of ground motions which led to the failure of the dowel connection for the specimen. The dynamic analyses could capture the damage pattern, the drift and acceleration time histories and the hysteretic plots, although they slightly underestimated the peak displacement during the last motion of the sequence, as shown in Fig. 6c. The results of these analyses, described in great detail in [10], demonstrate the capability of the modeling scheme to capture the complicated behavior of the retrofitted structures.

**Determination of Effect of Overlay Thickness on Performance**

The shake-table tests on a retrofitted infilled frame indicated that an ECC overlay would prevent severe damage in the structure unless the ground motion intensity was significantly higher than the MCE level for downtown San Diego. However, the occurrence of shear dowel failure indicated that the tensile ductility of the ECC overlay might have not been fully exploited. A parametric investigation has been conducted to quantify the beneficial effect of the ECC overlay on the behavior of the shake-table specimen and the effect of the ECC thickness on the damage pattern and load-displacement response of the structure. More specifically, a series of nonlinear static analyses have been conducted for different values of ECC thickness on the retrofitted bottom story wall.
The base shear-vs.-bottom-story drift curves obtained for the three cases and for the case of an unretrofitted structure are compared in Fig. 7a. The figure shows that the addition of an ECC overlay leads to a significant increase in the lateral strength of the structure, but at the same time the strength degradation, which is caused by shear dowel failure, is rather abrupt. The response and the damage pattern for a 38-mm-thick ECC are identical to those obtained for a 51-mm ECC overlay. However, as Fig. 7a shows, a 25-mm overlay results in a slightly lower strength but a much more ductile response. Furthermore, as shown in Figs. 7b and 7c, the 25-mm overlay allows damage to develop in the masonry infill, which eventually leads to shear cracks in the columns. The shear cracks occur at a relatively large drift ratio of 0.55%, but do not lead to strength degradation in the structure, since the retrofitted infill walls can still carry a significant portion of the horizontal force. The more ductile response in this case as compared to the other two cases is attributed to the fact that it avoids shear dowel failures and can, therefore, take full advantage of the tensile ductility of the ECC.

Figure 6. Analytical results for shake-table specimen and comparison with experimentally recorded hysteretic curves.

Figure 7. Effect of ECC thickness on the response of the retrofitted structure and damage patterns with 25-mm (1-in.) ECC.

**Calculation of Overlay Strength and Design of Shear Dowel Connections**

An equation giving the strength contributed by an ECC overlay is required to allow the determination of the required ECC thickness to carry a target shear force. Such equation will also allow the estimation of the required strength of the shear dowel connections so that the material ductility of the ECC overlays is exploited before the occurrence of dowel failure. A simplified model is proposed here to establish such an equation. The model is based on the...
assumptions that the infill wall and the overlay act in parallel, that the entirety of the shear force carried by the overlay is transferred through the shear dowels and that the force is equally distributed to the individual dowels of the connection. The determination of the shear strength of the overlay is based on the additional assumptions that the behavior of the ECC is dominated by diagonal tensile cracking and that the distribution of shear stresses at the midheight of the overlay is parabolic, as shown in Fig. 8a. The maximum shear stress, $\tau_{\text{max}}$, can be expressed with respect to the corresponding shear force, $V$, carried by the overlay from the following expression:

$$\tau_{\text{max}} = \frac{3}{2} \frac{V}{t_{\text{ECC}} \cdot L}$$

where $t_{\text{ECC}}$ is the thickness of the overlay and $L$ is the length of the infill wall.

The uniaxial tensile stress-strain laws assumed for the ECC and WWR in this calculation are presented in Figs. 8b and 8c, respectively. The material behavior is examined at two states. The first corresponds to the initiation of cracks in the ECC, and the second to the onset of tensile strength degradation in the ECC. The stress and strain values for the ECC and the WWR corresponding to these two states are marked in Figs. 8b and 8c as points 1 and 2. Cracking in the ECC occurs at a strain that is much lower than the yield strain of the WWR. Thus, the effect of the wire reinforcement on the cracking shear force can be neglected, as shown for the stress state in Fig. 8d. If the tensile strength of the ECC is equal to $f_{t,\text{ECC}}$, the overlay shear force which will introduce cracking (i.e., will lead to a strain in the materials equal to that of point 1 of the stress-strain curves) is given by the following expression:

$$V_{\text{cr}} = \frac{2}{3} f_{t,\text{ECC}} \cdot t_{\text{ECC}} \cdot L$$

The shear resistance of the overlay will continue to increase until the strain of the ECC reaches the value $\varepsilon_2$ as shown in Fig. 8b. It is reasonable to assume that the wire reinforcement of the ECC has yielded in this state, as shown in Fig. 8e, since the value of $\varepsilon_2$ is quite higher than the yield strain of the WWR. For example, based on the curves shown in Fig. 4a, the value $\varepsilon_2$ is approximately equal to 0.008. The shear strength $V_u$ corresponding to the onset of tensile strength degradation in the ECC is the sum of the ECC contribution, $V_{\text{cr}}$, (since there is no tensile strength degradation as the ECC strain increases from $\varepsilon_1$ to $\varepsilon_2$), and the wire reinforcement contribution, $V_s$, which is given by

$$V_s = \frac{2}{3} \rho_x \cdot \rho_y \cdot f_y \cdot t_{\text{ECC}} \cdot L$$

where $\rho_x$ and $\rho_y$ is the steel ratio in the x- and y- directions, respectively, and $f_y$ is the yield stress of the wire reinforcement. For the usual case that the steel ratios in the two directions are identical, $V_u$ is given by the following expression.

$$V_u = V_{\text{cr}} + V_s = \frac{2}{3} (f_{t,\text{ECC}} + \rho \cdot f_y) \cdot t_{\text{ECC}} \cdot L = \Omega \cdot V_{\text{cr}}$$

where $\Omega = \left(1 + \frac{\rho \cdot f_y}{f_{t,\text{ECC}}}ight)$. Equation (4) can be used for the determination of the required ECC thickness so that the overlay can carry a target shear force. Additionally, to prevent the premature failure of shear dowels before the tensile ductility of the ECC is exhausted, the total shear dowel resistance, $F_{ud,t}$, should be at least equal to $\Omega \cdot V_{\text{cr}}$. 
The capability of the aforementioned equations to provide the required dowel resistance has been validated using the results of the parametric static analyses shown in Fig. 7a. More specifically, the obtained total dowel resistance in the analytical models has been compared to the value $V_u$ obtained with Eq. (4), for various values of thickness. The comparison is presented in Table 1. For ECC thickness equal to 51mm and 38mm, the simplified equation would indicate that the dowels would fail before $V_u$ was attained. Such dowel failure was indeed obtained in the static analyses for these thickness values. For ECC thickness equal to 25mm, for which no dowel failure was obtained in the analyses, the simplified equation indicates that the dowel resistance exceeds the value of $V_u$. Thus, the results of the parametric nonlinear analyses do agree with the predictions provided by Eq. (4).

![Figure 8](image-url)

(a) Distribution of shear stresses  
(b) Stress-strain law for ECC under tension  
(c) Stress-strain law for steel

Point (1)

$$f_{t,ECC}$$  
$$\phi$$

Point (2)

$$f_{t,ECC}$$  
$$\phi$$

(d) Stress at point 1  
(e) Stresses at point 2

Figure 8. Model of ECC resistance used for the design of shear dowels.

**Parametric Dynamic Analysis for Unretrofitted and Retrofitted Structures**

To determine the effectiveness of an ECC overlay on the dynamic performance of infilled RC frames, a three-story structure was analyzed for a collection of eight strong ground motions. The frame configuration was very similar to that of the shake-table specimen presented above, except that there were no infill walls in one of the two bays in each story. The collection of ground motions, which is presented in detail in [7], was scaled to match the design spectrum for downtown Los Angeles over a period range of interest. The target design spectrum was established based on ASCE/SEI 7-05 [13]. The analyses were conducted for both an unretrofitted frame and a retrofitted frame with a 25-mm thick ECC overlay on the infill walls of all three stories.

Figures 9a and 9b show the typical damage patterns obtained for the unretrofitted and retrofitted frame, respectively. Additionally, Fig. 10 shows the hysteretic response of the unretrofitted and retrofitted structure for all eight ground motions. Based on the results of these analyses, the unretrofitted structure would incur very severe damage and would probably collapse when subjected to the collection of the ground motions. The early occurrence of diagonal and sliding cracks in the infill walls would in turn lead to shear failures in the columns. On the other hand, the results for the retrofitted frame show that the addition of a thin ECC overlay would profoundly improve the in-plane behavior, and the structure would survive the motions with minor damage.
Table 1. Prediction of dowel failure with simplified method as compared to finite element analysis ($F_{ud,t}$ = total dowel force).

<table>
<thead>
<tr>
<th>ECC thickness (mm)</th>
<th>$F_{ud,t}$ (kN)</th>
<th>$V_{cr}$ (kN)</th>
<th>$\Omega$</th>
<th>$1.25V_{cr} = 1.25\Omega V_{cr}$ (kN)</th>
<th>$F_{ud,t} &gt; 1.25V_{cr}$?</th>
<th>Damage Pattern from FE Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>649.7</td>
<td>276.2</td>
<td>1.63</td>
<td>563</td>
<td>Yes</td>
<td>Significant damage in overlay</td>
</tr>
<tr>
<td>38</td>
<td>649.7</td>
<td>414.3</td>
<td>1.63</td>
<td>844</td>
<td>No</td>
<td>Dowel failure</td>
</tr>
<tr>
<td>51</td>
<td>649.7</td>
<td>552.4</td>
<td>1.63</td>
<td>1125</td>
<td>No</td>
<td>Dowel failure</td>
</tr>
</tbody>
</table>

Figure 9. Damage pattern for infilled frame subjected to ground motion scaled to the design-level intensity for downtown Los Angeles.

Figure 10. Bottom story hysteretic plots for three-story infilled frame subjected to eight ground motions scaled to the design-level intensity for downtown Los Angeles.

Conclusions

This study analytically examined the performance of infilled RC frames with overlays of Engineered Cementitious Composite (ECC) material on the masonry infill walls. Based on the results of simulations using refined finite element models, the addition of a relatively thin ECC overlay can significantly enhance the in-plane seismic behavior. The analysis of an infilled frame for a set of ground motions representing the design-level intensity of downtown Los Angeles has shown that while an unretrofitted structure may incur significant damage and even collapse, an identical structure with thin ECC overlays can survive the motions with minor damage. While a thicker retrofit overlay may enhance the strength of the structure, it may negatively affect the ductility, because the shear dowel connections between the overlays and the beams may fail before the tensile ductility of the composite material is exhausted. A
set of simplified design equations has been established to design the dowel connections, so that the inelastic tensile deformability of the overlay material is fully exploited. The set of equations can also be used to determine the required overlay thickness so that the retrofit can carry a given amount of shear force.

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