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EVALUATION OF PROGRESSIVE COLLAPSE IN URM-INFILLED RC FRAMES WITH AND WITHOUT FRP RETROFIT: 3-D COMPUTATIONAL SIMULATION OF A ONE STORY BUILDING

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ABSTRACT

Structural systems of reinforced concrete (RC) frames with unreinforced masonry (URM) infill walls are common building systems, especially for historical buildings. In this study a one-story reinforced concrete building was simulated until collapse using scaled records of ground motion, before and after retrofitting the URM infill wall with Fiber Reinforced Polymer (FRP) bars. The nonlinear behavior of the URM-infilled RC frame was modeled using the finite element (FE) software DIANA and laboratory test results from the literature, then idealized using a calibrated strut-and-tie model. The infill walls were then modeled, along with the RC frames, using the open source FE code OpenSEES (Open System for Earthquake Engineering Simulation). The OpenSEES modeling uses a direct element removal procedure which accounts for sudden loss of brittle elements taking into account dynamic equilibrium and the transient change in the structural system kinematics. Static and dynamic analytical simulations were conducted to study the effect of retrofitting the infill walls on the overall behavior of the building system. Finally, the overall building performance after retrofitting was compared to the as-built building system. This study concludes that, after retrofit of the infill walls with FRP bars, the overall displacement ductility and the building system performance were enhanced, without significant increase in the stiffness of the lateral resisting system.

Introduction

Reinforced concrete (RC) frames with unreinforced masonry (URM) infill is a common building system. Generally in the design process, infill walls are considered non-structural elements. However, when the seismic performance of such building is evaluated, the effect of the URM infill walls as lateral resisting elements within the frame has to be considered. Past earthquakes have shown vulnerability of such infill systems. Therefore, it is important to understand how infill walls affect the overall RC frame behavior, and how strengthening these walls will affect the overall structural behavior. The lateral stiffness of the infill walls shortens the structure’s vibration period and

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attracts larger seismic forces. Brittle failure of the infill walls occur at low drift levels and can result in shear failure of the RC frame columns surrounding them. Shear-damaged RC columns become susceptible to collapse at relatively lower gravity loads due to shear-axial interaction. In the 1994 Northridge earthquake, many of the infill walls in several buildings showed different damage characteristics (failure modes) such as bed-joint sliding, diagonal cracking, toe-crushing and out of plane failure (FEMA 306, 1999).

Structural System Description and Loading

In this study we considered a stiff infill wall; the initial stiffness of the solid wall was equal to the RC frame stiffness and the resulting stiffness of the hybrid system was thus doubled. The building model was made of three RC frames with the middle frame infilled with a URM wall (Figure 1). The ultimate capacity of the infill wall, however, was lower than that of the RC frame.

The building model represents a specimen subjected to shake-table tests. The RC frames were designed to be ductile, so that shear failure in the frame does not occur before the wall. The out-of-plane failure modes are not considered. The RC frame height, width, and spacing were 127, 163, and 72 in., respectively. The connecting RC slab thickness was 3.75 in. Concrete compressive strength was 4.5 ksi. Reinforcing steel yield stress was 66.5 ksi. Cross-section details are shown in Figure 1 (Talaat and Mosalam, 2007). The bricks had nominal dimensions of 4x8x2⅔ in. The wall uses ASTM C270 Type N mortar. The average 28-day masonry prism compressive strength and Young's modulus of elasticity were 2.46 and 898 ksi, respectively (ASTM C1314). The average shear strength was 263 psi (ASTM E519). For more details, see (Hashemi and Mosalam, 2007).

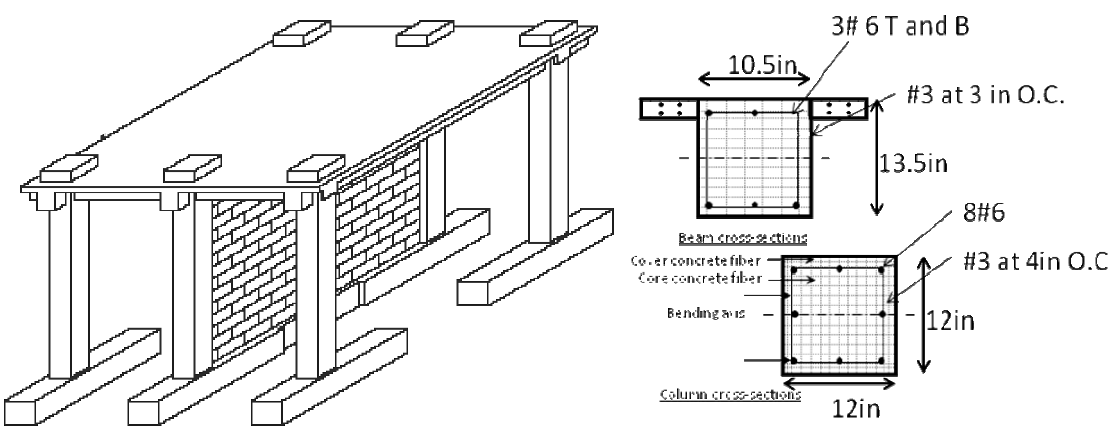

Figure 1. Specimen geometry and RC frame cross-section (FE discretization)

The seismic load excitation used in the study is obtained from Northrigde, CA (1994), Tarzana Station in the 90° direction with peak ground acceleration (PGA) = 1.78 g (Figure 2). An incremental dynamic analysis (IDA) was conducted using this single record whereby the ground motion was scaled up incrementally to induce collapse of the system. The scaling of ground motion was based on the period range between the as-built system fundamental period of vibration and its period of vibration when the URM wall is totally collapsed and only the bare RC frames resist the lateral loads. These vibration periods were predicted by the FE model to be 0.12 and 0.19 seconds, respectively.

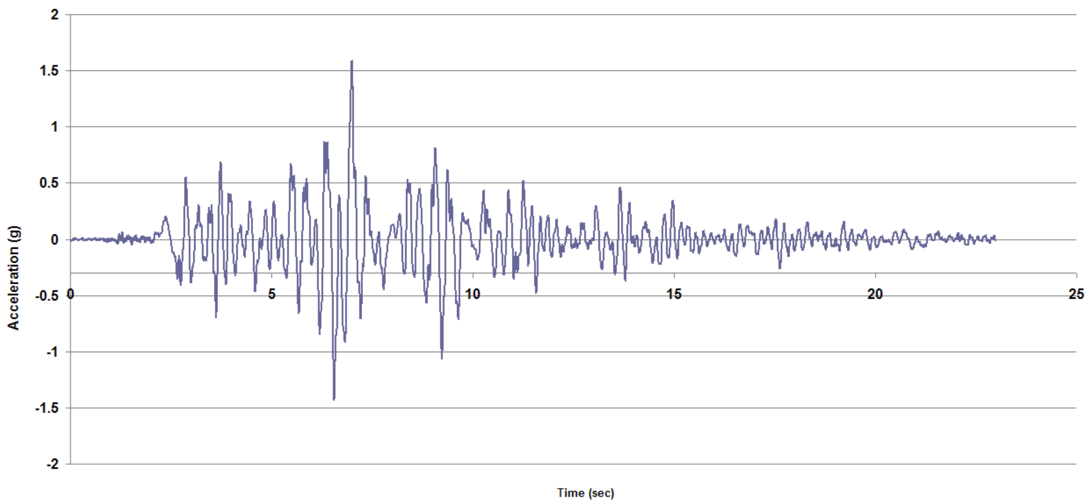

Figure 2. Northridge(1994) ground acceleration record (Tarzana, 90°)

The URM wall retrofit was performed using GFRP (Glass FRP) reinforcing bars of 0.25 in. diameter, embedded longitudinally inside the ⅜ in. mortar bed joint using epoxy paste (Figure 3). The GFRP bar behavior is elastic until rupture which occurs at a stress of 120 ksi. Young's modulus of elasticity is 6000 ksi. The GFRP bars were mounted near the wall surface, so called "Near Surface Mount" (NSM). They were placed only on one side of the wall, as often times only one face of a wall is accessible or permitted for retrofit application (e.g., the inside face of historic buildings). The design and configuration of the GFRP bars was accomplished using ACI 440.2R-08 design guidelines (ACI 440, 2008).

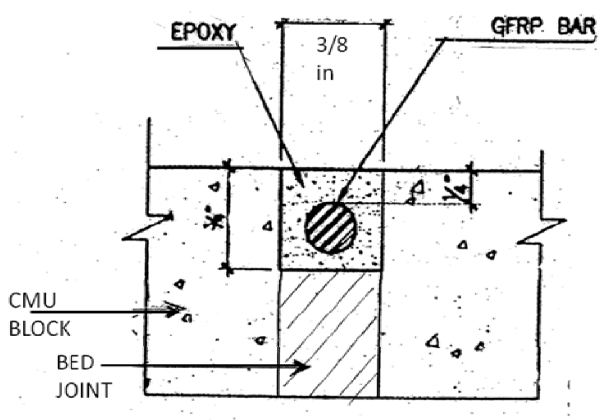

Figure 3. NSM GFRP bars in CMU bed joints

Finite Element Modeling

The strut-and-tie model of the as-built wall was calibrated using the results of DIANA FE simulations conducted in (Hashemi and Mosalam, 2007). This calibration is used here as described in (Talaat and Mosalam, 2007) to conduct collapse simulations.

In order to calibrate the strut-and-tie model for the infill wall retrofitted with FRP bars, we performed static pushover analyses of the FE models (RC frame + URM wall) before and after retrofit then compared the lateral load versus lateral displacement behavior to a number of similar laboratory tests published by (Gustavo et. al, in press) (Figure 4). The calibration of the strut-and-tie model of the retrofitted infill wall in OpenSEES (Mazzoni et al, 2004) was conducted using idealization of the static pushover curves.

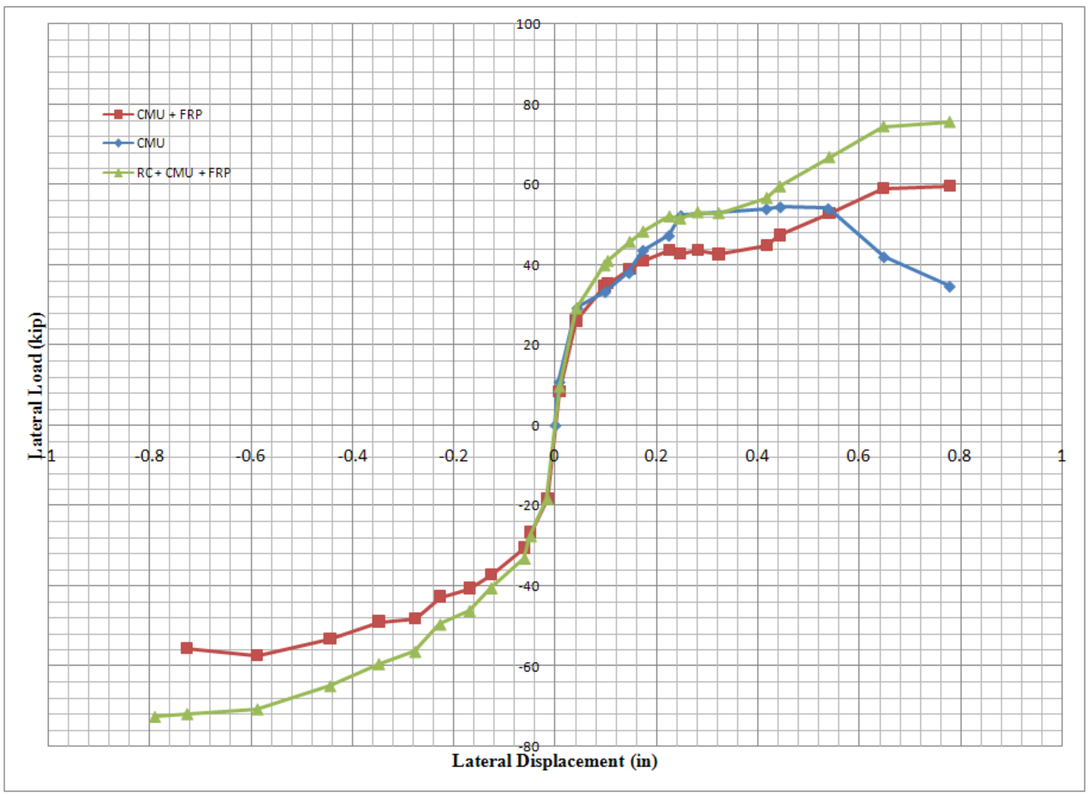

Figure 4. Masonry infill system laboratory test results by (Gustavo et. al. 2001)

The RC frame columns and beams were modeled using displacement-type beam-column elements. The column elements were connected to coupled shear-axial springs by which a shear damaged column is allowed to maintain its axial load while shedding its shear carrying capacity.

Two batches of runs were conducted in OpenSEES. The first batch used the as-built URM infill wall within the RC frame, and the second batch used the FRP-retrofitted infill wall instead. The ground motion scale was incremented in each batch until gravity load collapse of the system. In addition, the ground motion level at which shear failure first occurred in the RC frame columns was recorded for each system. To represent brittle failure effects, individual elements were removed from the structural model progressively as the members they represent collapsed, using an element removal algorithm developed in (Talaat and Mosalam, 2007). The As-built and retrofitted infill walls were considered collapsed when their shear force capacities dropped to 40% and 10% of their respective peak values. The RC columns were considered collapsed when they reached the axial load–lateral drift limit-state envelope defined by (Elwood and Moehle, 2005).

Results and Discussion

In the as-built URM wall, toe crushing occurs when the mortar at the bed joints is stronger than the bricks. Therefore, abrupt transfer of large forces from the strong infill to the RC frame occurs at relatively small drifts over a short column transfer length, causing premature shear failure in the RC columns shortly after the wall failure (Figure 5).

The FRP retrofit helps mitigate the abrupt change in force transfer from the wall to the RC frame. Referring to the experimental results from (Gustavo et. al, 2001) in Figure 4, at drift values close to 0.2 in., diagonal cracks develop in the wall and the crack opening strain (elongate) the FRP bars and engage them to work compositely with the URM wall. FRP bars embedded in the wall are passive until activated which is characterized by the plateau from 0.25 in. to 0.4 in. drift. Upon engagement of FRP bars, the wall diagonal cracks are restrained from further opening by strain compatibility. Lateral load redistribution takes place between the wall units and the embedded FRP bars. Consequently, the FRP bars attract some of the wall forces in addition to increasing the overall shear resistance. As a result, the load transfer from the wall to the RC frame is gradual and occurs at relatively larger drifts.

Figure 5 shows the OpenSEES-simulated pushover curves for the different components of the as-built and retrofitted systems shown in Figure 1. The FRP retrofit increases the system strength and drift at peak load from 41 to 34 kip (20%) and from 0.7 to 1.2 in (71%), respectively. Moreover, the drift at the major event of column shear failure in the retrofitted system is increased from 1.1 to 1.2 in drift (10%). Figure 5 shows that the system exhibits little increase in initial stiffness yet gains markedly enhanced ductility beyond the initiation of RC frame flexural nonlinearity in the force-drift response.

The dynamic collapse capacity of the building before and after retrofit is shown in Figure 6. The ground motion scale causing collapse is increased from 0.86 to 1.16 (35%). The ground motion scale causing no immediate collapse yet shear damage in the RC columns causing costly replacement or later demolition is increased from 0.82 to 1.06 (29%). The study reported in (Talaat and Mosalam, 2007) identified a testbed site in the area affected by the Northridge earthquake (34.3N and -181.5W, intersection of I-5 and I-405 freeways). For this chosen site, the increase in the present system collapse capacity corresponds to a decrease in the annual frequency (probability) of PGA exceedance from 1/2035 to 1/6865 (70% decrease), based on USGS 2002 seismic hazard maps.

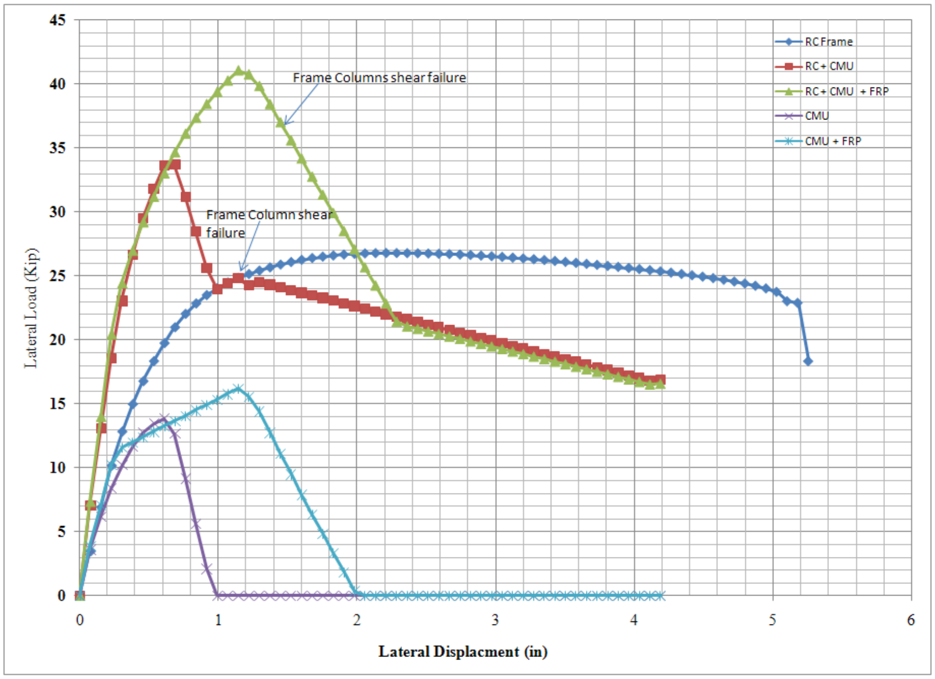

Figure 5. Pushover curve: in-plane loads versus lateral displacement

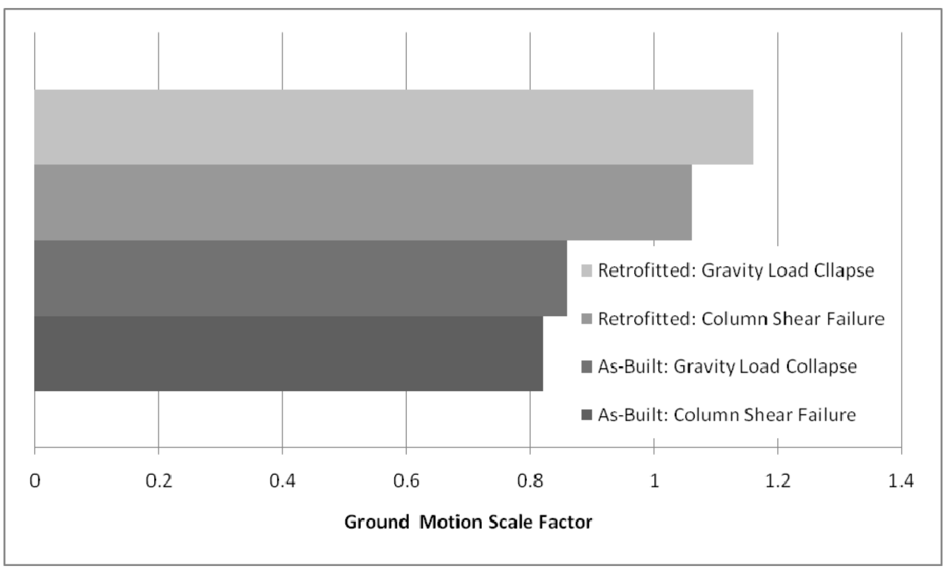

Figure 6. Ground motion scale factors at shear failure and gravity load collapse

Conclusions

1. The present retrofit design using the GFRP bars enhanced strength and ductility; the shear strength is 20% and the ductility is 70% higher than the as-built system.
2. FRP retrofit increased the URM wall shear strength without increasing its stiffness. The initial degradation of lateral stiffness in the strengthened wall does not lead to immediate decrease in the system's lateral load carrying capability due to the composite action of URM and FRP.

3. Retrofit of the URM infill walls in the RC frame delayed premature shear failure in the RC frame columns upon URM wall failure. By retrofitting the wall using FRP, a gradual load transfer path from the wall to the frame is created.
4. For the Northridge ground motion record used in this study, the FRP-retrofitted system showed 35% increase in the collapse capacity and 29% increase in the column shear failure capacity, both measured by the ground motion scale factor.
5. For a selected building site near the area affected by Northridge earthquake, the increased system collapse capacity corresponds to approximately 70% decrease in annual frequency of exceeding the corresponding peak ground acceleration.

Research Extension

1. The preliminary dynamic collapse assessment introduced in this paper selected one ground motion record. More rigorous collapse assessment will be conducted using incremental dynamic analysis and a suite of ground motion records.
2. The results presented herein are specific to an infill wall whose as-built lateral force capacity is lower than the RC frame. The authors wish to investigate the sensitivity of the present findings to the case of stronger as-built infill walls.

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