RETROFIT AND REPAIR

Retrofit Methods

Seismic retrofitting introduces features into an existing structure specifically to improve its earthquake resistance. Many of today's infill frame buildings located in regions of high seismic risk were constructed without consideration of seismic demands. In addition, many buildings were designed according to seismic codes that do not consider infill walls, despite the demonstrated influence of infill panel behavior on concrete frames. This failure to consider infill walls during the design process can result in unexpected vulnerabilities, particularly in cases when the infill walls possess high strength. Typical vulnerabilities in today's infill frame buildings include soft story effects, short column effects, low ductility and extreme torsional irregularities. Several retrofit techniques have been proposed to address such vulnerabilities, to improve the strength and ductility of infill frames, and to enhance the earthquake resisting ability of the structures.

For Individual Panels

One common retrofit technique involves applying carbon fiber reinforced polymer (CFRP) wrap or carbon fiber cement matrix on both sides of individual infill panels. Several investigators, including those mentioned below, have conducted experimental investigations of how reinforced concrete infill frames retrofitted with CFRPs perform.

Saatcioglu et al. (2004) performed quasi-static load tests on two half scale, single bay infill frames with and without CFRP retrofitting. The CFRP sheets were surface bonded to the masonry wall and anchored to the surrounding frame using specially developed CFRP anchors. The CFRP retrofit was shown to increase the lateral strength of the infill frame by 300%; no contribution to ductility was observed.

El Dakhakhni et al. (2004) carried out similar tests on steel frames with masonry infill retrofitted with CFRP. The researchers noted that the CFRP laminates eliminated sliding shear and out of plane failure in the infill panels and caused the more predictable corner crushing failure mode. They also noted that an equivalent diagonal strut model would be adequate for analyzing the retrofit system, since the corner crushing mode is the main failure mechanism for the equivalent diagonal strut model.

Garevski et al. (2004) performed dynamic shake table tests on 1/3 scale specimens of infill frames retrofitted with CFRP strips. Results were similar to quasi-static testing programs: the CFRP retrofit was found to increase the lateral strength and stiffness of the infill frames.

Binici and Ozcebe (2006) proposed a set of guidelines for analyzing infill frames retrofitted with CFRP strips. The guidelines suggest using a diagonal compression-strut and tension tie, with a tri-linear stress strain response, to model the strengthened infill wall integrated with the surrounding frame. Static pushover analyses were conducted to verify the proposed models and the models' responses were compared with results from experimental investigations.

Kurt et al. (2012) provide a good summary of fiber reinforced polymers (FRPs) and precast concrete panel retrofit methods. According to this summary, Albert et al. (2001) showed that the shear capacity of the walls increased on retrofitting, while Ehsani et al. (1999), Hamilton et al. (1999), Velazquez et al. (2000) showed an enhancement in the walls' flexural capacity. Schewegler (1994) and Laursen et al. (1995) demonstrated that the ductility of the masonry infill walls increased when they were retrofitted with FRPs. Hamoush et al. (2001) evaluated the increase in out-of-plane resistance of the infill walls. Finally, Tankut et al. (2005), Baran (2005), Baran and Tankut (2011) and Baran et al. (2011), among others, have worked on using precast concrete panels as retrofit solutions for the existing masonry walls.

In summary, the CFRP retrofit has been shown to increase the strength and stiffness masonry infill walls without significantly influencing the ductility of infill frames. This increased stiffness reduces the natural period of the structure, which, in turn, leads to a potentially increased force demand for typical low to medium-rise RC infill frames. The relative increase of the force demand and strength determine the ductility demand on the retrofitted structure. Given that ductility is not significantly affected, the use of CFRPs as a retrofit scheme to an infill frame may require justification. For this, simulations or experimental tests (whenever applicable) of the considered particular structure can be conducted before the CFRP application. For a similar justification, Kurt et al. (2012) conducted hybrid simulations on a 1/2 scale, two story, three bay, low-rise infilled RC building in as-built, CFRP retrofitted and precast concrete panel retrofitted cases. They observed that local and global deformation demands were reduced by both of the retrofit methods for all intensity levels.

Kyriakides and Billington (2008) proposed a retrofit technique for non-ductile concrete infill frames, in which a thin layer of ductile fiber-reinforced mortar material (also referred to as Engineered Cementitous Composites (ECC)) is sprayed onto the infill panel with an additional layer of reinforcement. A 1/5 scale specimen of the first story ECC retrofitted frame within the 2-bay frame was tested using quasi-static loading. The results showed that the ECC retrofit system can add significant strength and ductility to the structural system under cyclic loading.

Another common retrofit method used for infill frames is applying mesh reinforcement and cover plaster over the infill walls. This technique is widely used in developing countries, where cost is a major factor: material costs for this retrofit method are lower than for composites such as CFRP or ECC retrofit.

Acun and Sucouglu (2006) tested three 1/3 scaled, one bay, two-story infill frames under quasi-static cyclic loading. The test specimens were strengthened with mesh reinforcement and cover mortar, with the reinforcement ratio and compression strength of mortar being the main test parameters. Results showed an increase in stiffness ranging from 1.25 to 5.5, and an increase in strength ranging from 1.25 to 2 for different mesh reinforcement ratios. Results also showed that the retrofit technique had very little influence on the ductility of the system. Quasi-static load tests of five non-ductile, one bay, two-story infill frame specimens by Korkmaz et al. (2010) produced similar results, with increases in strength and stiffness but very little impact on ductility seen.

Recently, Koutromanos et al. (2012) performed shake table tests on a 2/3-scale, three story, two-bay, masonry-infilled RC frame that had one first story wall retrofitted with ECC. They also studied glass fiber reinforced polymer (GFRP) overlays. The researchers observed that the ECC overlays applied on the first story wall enhanced the base-shear capacity by 70%. The capacity of the retrofitted structure was observed to be 20% higher than that of a similar structure that had both bays in the first story infilled with unretrofitted masonry walls.

At Global Level

Incorporating shear walls into the lateral resisting system of a building improves its seismic performance, provided that proper detailing is used to achieve the desired level of ductility. Added concrete shear walls constitute a primary system for seismic resistance while keeping the existing frame as a secondary system mainly responsible for carrying the gravity forces (Sucuoglu et al., 2004). In the case of shear walls, vulnerabilities present in the infill frame are automatically eliminated as the frame's function is changed from lateral load resistance to gravity load resistance. Although adding shear walls is a simple and robust retrofit method, it can be difficult to do while residents are living in their homes. Therefore, it is generally used to repair damaged buildings, while they are unoccupied after earthquakes.

Günay et al. (2009) proposed a retrofit technique that would use rocking spines of infill walls strengthened with reinforced shotcrete to resist earthquake forces. The goal of the retrofit technique is to generate a rocking behavior in the infill frames, which imposes uniform deformations over the height of the structure. Other deformation modes (column/beam flexure/shear hinging and infill shearing) tend to concentrate deformations at lower levels, thereby increasing the tendency to form "soft stories." Günay et al. investigated the proposed retrofit system through nonlinear static and dynamic analysis and they developed the fragility relationships between first mode pseudo-acceleration and maximum interstory drift ratio. The results of the analytical investigation showed that the proposed retrofit method is effective in distributing story drifts uniformly along the height of a building, thus reducing maximum story drifts.

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Repair Methods

Repairs are undertaken on damaged buildings to restore the loss of strength after an earthquake. Over the past few decades, a number of researchers have explored different repair methods for damaged infill frames. Irimies and Crainic (1993), Jabarov et al. (1985), Kahn (1984), Mander and Nair (1994) and Oliveria (2001), Amanat et al. (2007) are among those who have conducted experimental studies to verify that reinforced mortar overlays are good methods for rehabilitating damaged infill walls.

Amanat et al. (2007) carried out experiments to investigate the strength of masonry infilled walls in RC frames repaired with ferrocement laminates[1] after damage had occurred. Their results indicate that the repaired system had a higher strength carrying capacity under lateral loading.

Reinhorn et al. (1985) also investigated the performance of brick masonry walls strengthened with ferrocement layers. The researchers observed that the strength, stiffness and ductility of these walls were nearly double that of the uncoated walls; however, the increase in strength did not depend much up on the mesh spacing.

Alcocer et al. (1996) conducted four full-scale experiments on rehabilitated masonry walls under alternated cyclic lateral loads, in order to assess the technical feasibility of jacketing a masonry wall (with concrete mortar cover, reinforced with steel welded wire meshes) as a rehabilitation strategy. The researchers observed a more uniform inclined crack pattern and a significantly higher strength in the rehabilitated specimens.

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[1] The American Institute for Concrete definition of the ferrocement is 'a type of reinforced concrete in thin elements, currently constituted by micro-concrete of hydraulic cement, reinforced with thick layers of continuous netting, in wire, with a relatively small diameter.'

Shake table tests conducted by Koutromanos et al. (2012) gauged the performance of walls in the second story of a damaged structure, which had been repaired by injecting epoxy into cracked mortar joints, and strengthened with a Glass Fiber Reinforced Polymer overlay. The researchers observed that the GFRP overlays were very effective for strengthening masonry infills around window openings, which are usually the most vulnerable areas of an unreinforced masonry wall. They further observed that both the retrofit (mentioned earlier) and the repair techniques (mentioned above) significantly enhanced the seismic performance of the structure and helped to prevent diagonal shear failures of the RC columns.

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