A Low Cost Retrofit Scheme for Masonry-Infilled Non-Ductile Reinforced Concrete Frames

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SUMMARY:

A low cost and effective scheme has been developed for retrofitting masonry-infilled reinforced concrete (RC) frames. Three ¾ scaled models of single bay, single story non-ductile RC frames with un-reinforced masonry (URM) infill panels were tested under horizontal cyclic loading and a constant vertical load. The experimental results indicate that an un-retrofitted specimen suffers corner crushing and abrupt shear failure in the columns at a very small drift ratio of 0.50%. The retrofitted masonry panel is separated from the columns so that no shear is transferred to them. Steel brackets are provided to transfer the interactive forces between the RC frame and URM panel. The peak lateral load decreases approximately in proportion to the area reduction ratio of the panel with desirable gradual drop in capacity whereas the drift capacity increases to about 1.50%. The retrofit scheme compares favorably with others incorporating either heavy mesh reinforcement or carbon fiber reinforced polymer.

Keywords: Non-Ductile Frame, Reinforced Concrete, Un-reinforced Masonry Infill, Seismic Retrofit

1. INTRODUCTION

Reinforced concrete (RC) frame buildings with un-reinforced masonry (URM) infill panels are prevalent in developing countries. Earthquake reconnaissance in past earthquakes in high seismic prone countries has witnessed poor performance of such structural systems, especially when the RC frames are detailed as non-ductile. Undesirable abrupt shear failure of the bounding columns or beam-column joints often follows due to transfer of the huge strut forces resisted by the infill to the columns. This is true not only in strong earthquakes, but also in moderate shaking such as that in Chiang-Rai, Thailand caused by the M6.8 Myanmar earthquake near Chiang-Rai border on March 24, 2011. Model tests as well as full scale tests on real buildings have also yielded similar results (Mehrabi et al. 1996, Korkmaz et al. 2010, Corte et al. 2008). It is important to note that such failure can occur at a relatively small drift ratio, in the order of 0.5%. On the other hand, there have been incidents of actual performance of such buildings in earthquakes (e.g., Hassan and Sozen 1997) which demonstrate beneficial effect of un-reinforced infills. Laboratory tests with masonry reinforced with wire mesh or the like have also demonstrated the potential of transforming the brittle masonry panels to a more ductile one suitable for retrofitting. However, past attempts have accomplished limited success. Since infills are cheap building materials for constructing non-structural partitions, it would be economical and beneficial, especially in developing countries, if they could be utilized to contribute to earthquake resistance, either in new construction or in retrofit work. A simple and low cost retrofit scheme is proposed herein, and key seismic performance parameters are assessed through cyclic load tests of ¾ scale specimens.

2. RETROFITTING SCHEME

In order to be able to effectively utilize the masonry walls for seismic resistance, one has to address and minimize the following major problems: shear failure of the (non-ductile) RC columns and beam-column joints; crushing of the corners of the infill and sliding of horizontal bed joints in the infill, including the masonry-beam interfaces. Guided by failure mechanisms observed in the literature, the following measures are adopted for resolving weaknesses in non-ductile infilled URM-RC frames. The retrofit scheme separates the URM panel from the vertical columns by a gap so that the strut force in the masonry panel cannot be transferred directly to them. Steel brackets are provided to transfer the interactive horizontal forces between the RC frame and the masonry panel. The corners of the infill are reinforced with wire meshes and high strength mortar. Furthermore, small vertical steel members are anchored to the vertical boundaries of masonry infill to prevent sliding joint failure of the masonry panel. The proposed scheme is depicted in Fig. 1.

3. TEST SPECIMENS

In this study, three ¾ scaled models of single bay, single story non-ductile RC frames with infilled un-reinforced masonry were tested under horizontal cyclic loading and a constant vertical load of 20% the ultimate capacity of the columns based on the concrete gross section. Specimen MIRCF01 was the original un-retrofitted assembly with panel aspect ratio (width/height) of 2.0. Specimens MIRCF02 and MIRCF04 were retrofitted with the scheme proposed above. The details of the specimens are shown in Table 1 and Table 2. It should be noted that the RC frames are typical of non-ductile detailing in Thailand. Low strength non-structural clay tiles were used for the 75 mm thick infill (including 10 mm cement plaster on each face). Widely spaced small dowel bars were provided to connect the URM panels to the RC columns only, typical of construction in Thailand.

The displacement controlled loading sequence consisted of displacement-controlled mode with 2 increments of 0.125% drift ratio followed by 0.25% drift increments up to 2% drift, after which the increments were 0.5%. Two cycles were repeated at each drift level to ensure stable hysteretic behavior was attained. The test was performed until the lateral load capacity was practically lost, or terminated if it was deemed unsafe to continue.

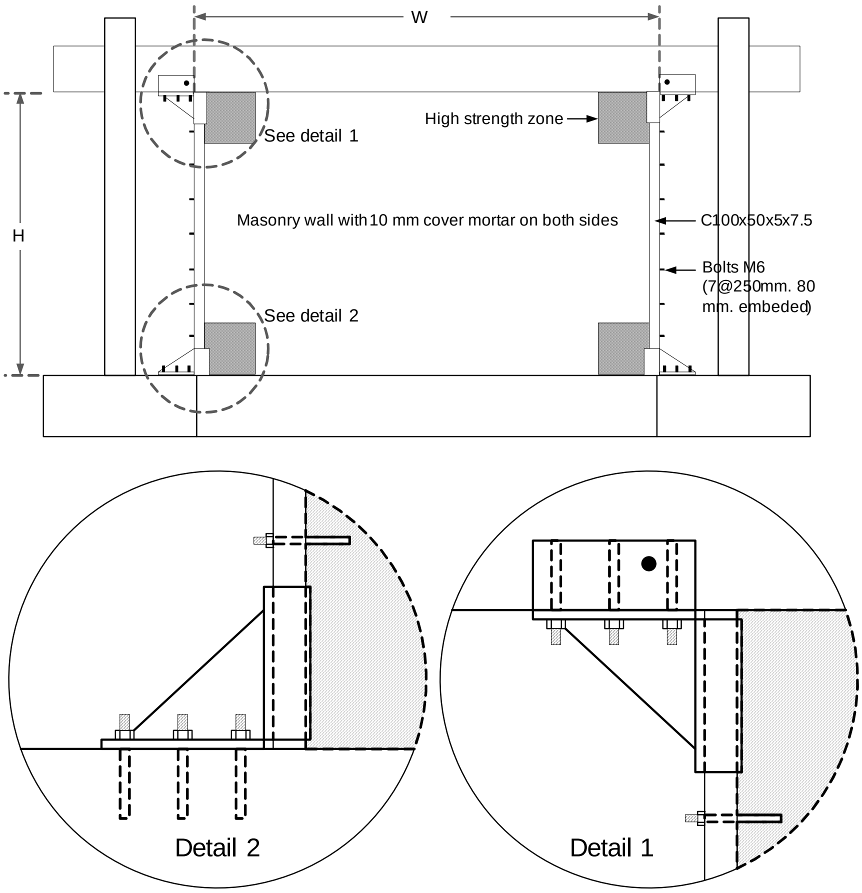


Figure 1. Retrofit scheme of URM infilled RC frames

Table 1. Details of RC members

Parameters	Prototype	¾-Scale Test Specimen
Specimen Dimensions	3000 x 6000 mm	2250 x 4500 mm
Beam Section	200 x 450 mm	150 x 340 mm
Top Steel	5-DB16 (ρ = 0.0136)	5-DB12 (ρ = 0.0136)
Bottom Steel	3-DB16 (ρ = 0.0081)	3-DB12 (ρ = 0.0081)
Transverse Steel	RB9@150 mm (ρ'' = 0.009)	RB6@100 mm (ρ'' = 0.009)
Columns Section	300 x 300 mm	225 x 225 mm
Longitudinal Steel	8-DB16 (ρ = 0.018)	8-DB12 (ρ = 0.017)
Transverse Steel	RB6@250 mm (ρ'' = 0.0009)	RB4@150 mm (ρ'' =0.001)

Note: DB x denotes deformed bar of diameter x mm, RB y denotes round bar of diameter y mm.

Table 2. Test Specimens

Specimens	Definition	W/H	f'm (MPa)	Compressive Strength of Concrete (MPa)		Yield Strength of Steel Reinforcement (MPa)			
				beam	columns	beam		columns	
						Long.	Trans.	Long.	Trans.
MIRCF01	original	2.0	6.6	19.6	20.0	360.9	307.7	360.9	246.5
MIRCF02	retrofitted	1.6	6.6	20.2	20.8	360.9	307.7	360.9	246.5
MIRCF04	retrofitted	1.0	7.2	19.5	21.9	339.4	311.6	339.4	244.5

Note: W/H is URM panel aspect ratio (width/height), f'm is masonry prism compressive strength.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Minute horizontal cracks occurred along the wall-beam and wall-footing interfaces of the control specimen MIRCF01 at 0.125% drift ratio. Impending corner crushing was observed at one corner at 0.25% drift. This frame assembly attained an average peak load of 296 kN at 0.25% drift, after which the capacity suddenly dropped to less than 40% at 0.5% drift (see Fig.2) with the formation of damaging shear cracks in RC columns and beam-column joints and corner crushing of the masonry infill as depicted clearly in Fig. 3. Note that the URM panel was essentially undamaged except for the crushed corners. In fact, the URM panel of this specimen was retained (with part of the panel adjacent to the columns removed) in the retrofitted specimen MIRCF02.

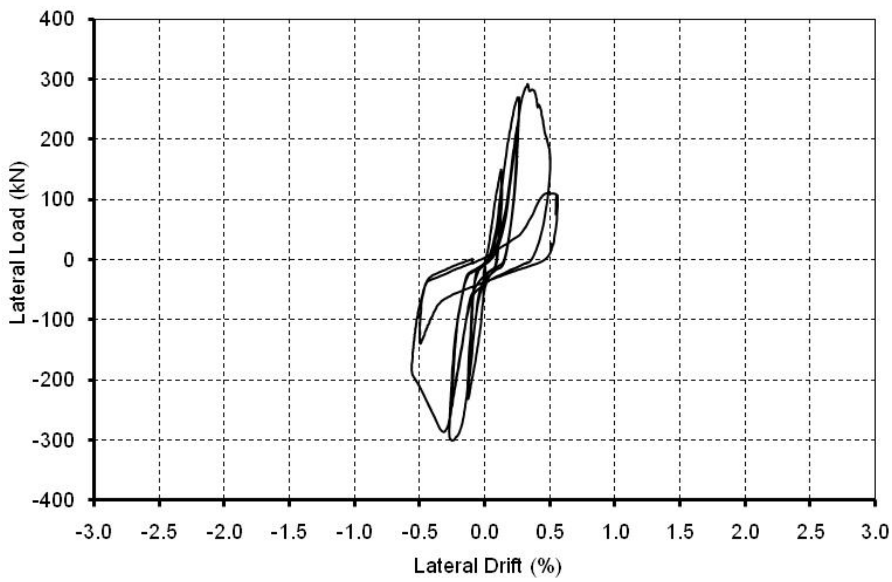


Figure 2. Hysteretic loop of specimen MIRCF01

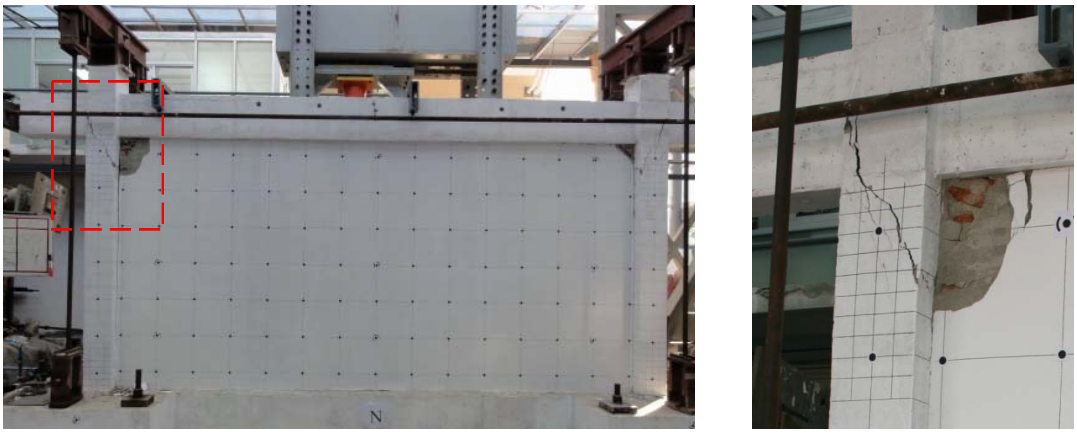
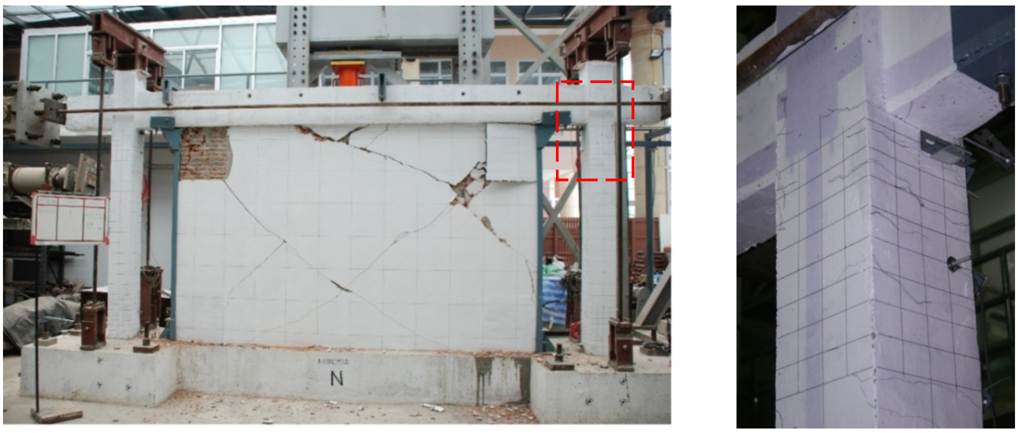


Figure 3. Un-reinforced masonry infilled non-ductile (MIRCF01) with column shear failure and infill panel corner crushing at 0.50% drift

Specimen MIRCF02, with 10% of the URM panel adjacent to the columns removed reveals a remarkable improvement in performance over the original system. At 0.125% drift, hairline diagonal cracks started to develop in the panel. The compression strut mechanism could be seen clearly at about 0.50% drift. Splitting of the boundary between the strengthened corner and the rest of the panel was observed at 1% drift. This frame assembly attained an average peak load of around 246 kN at 1.25% drift. Corner crushing was severe at 1.75% drift with the wire mesh reinforced plaster spalled off (see Fig. 4). It is interesting to note that removal of 20% of the wall slightly reduces the peak horizontal load capacity by about 17% compared with the original specimen. The drift capacity of 1.5% is achieved at a sustainable lateral load of 80% of the peak capacity with subsequent gradual drop in load capacity (see Fig. 5). The test was terminated at 2.0% story drift for safety reason since significant out-of-plane deformation was observed in the URM panel. Although severe damage occurred in the URM panel at impending failure, mainly flexural-cracks developed in the RC columns without threatening shear cracks or splitting of concrete cover as evident in Fig. 4b.



a) **b)**

Figure 4. a) Retrofitted masonry-infilled RC frame (MIRCF02) with the innovative scheme at 2% drift; b) damage condition in the column

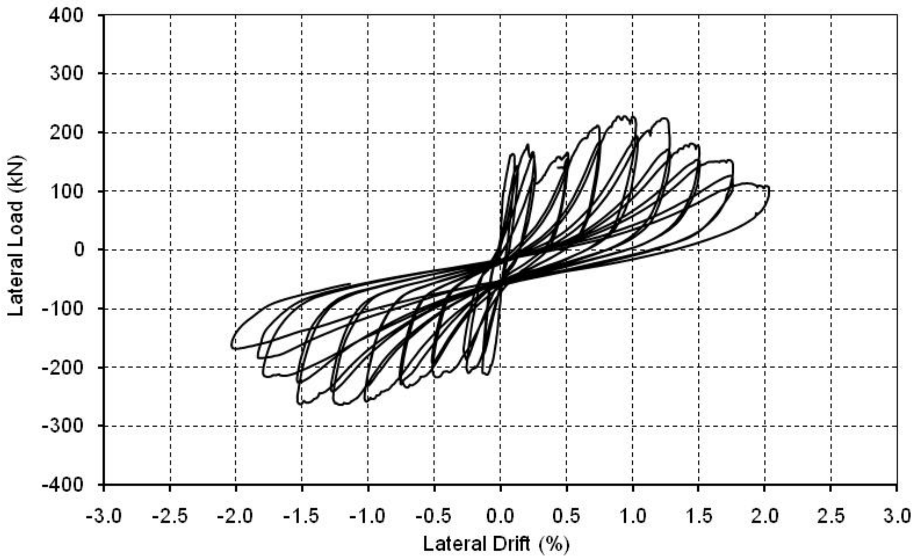
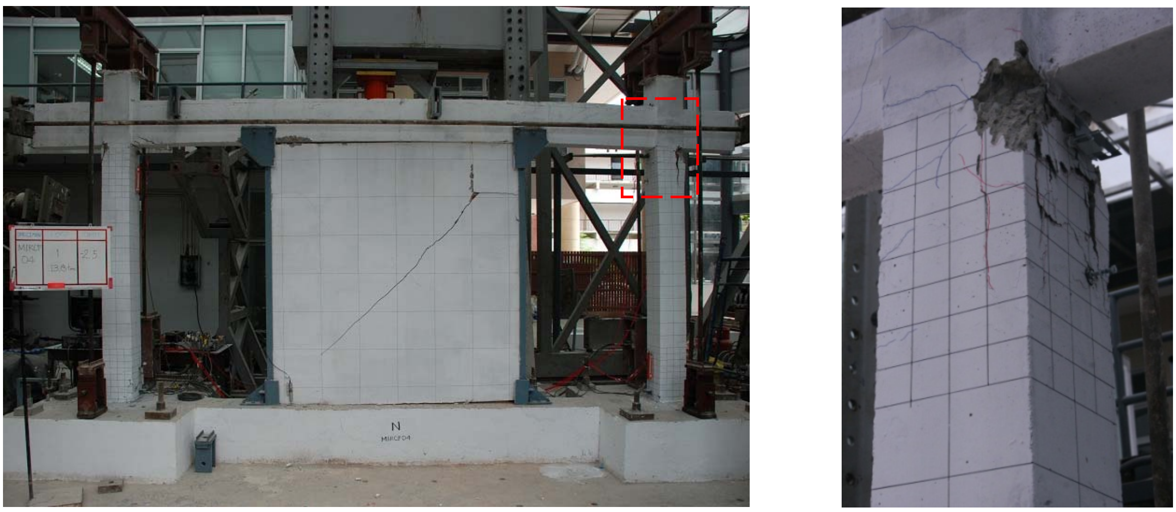


Figure 5. Hysteretic loop of specimen MIRCF02

For specimen MIRCF04 with 25% of the URM panel adjacent to the columns removed resulting in wall aspect ratio of 1.0 (Fig. 6), more flexural and shear cracks developed in RC columns and less diagonal cracks in the masonry infill compared with MIRCF02. The specimen could sustain a drift of 1.75% at 20% drop in lateral load capacity (see Fig. 7). However, significant rocking occurred. At a drift of 2.5%, severe splitting of concrete developed near the beam-column joint, and longitudinal steel bars in the columns buckled. The gap widening at the base of the wall due to rocking was as large as 30 mm.



a) b)

Figure 6. a) Retrofitted masonry-infilled RC frame (MIRCF04) at 2.5% drift;

b) damage condition near the beam-column joint

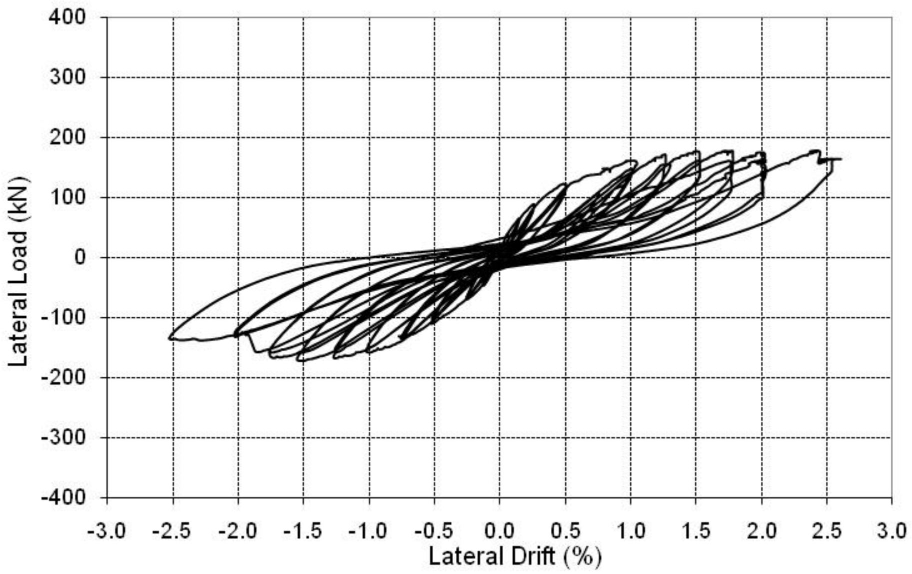


Figure 7. Hysteretic loop of specimen MIRCF04

The load displacement envelope curves, the secant stiffness versus drift ratio, and the energy dissipation with increasing loading cycles are depicted in Fig. 8-10, respectively. With reduction in the URM panel cross-sectional area, the peak lateral load decreases approximately in proportion to the area reduction ratio. Interestingly, the secant stiffness of the infilled URM - RC frame assembly MIRCF02 at 0.125% drift is slightly more than 90% of the solid specimen MIRCF01 even though 20% of the URM wall area is removed. The reason is that the former is less damaged at this drift level. However, the secant stiffness of MIRCF04 is reduced significantly, being less than 1/3 of the un-retrofitted specimen. The energy dissipation capacity of MIRCF04 is also much inferior to that of MIRCF02.

It is interesting to compare the performance of the proposed retrofit scheme with others in the literature. As evident in Table3, past retrofit schemes using heavy external mesh reinforcement with plaster composite achieved the best drift capacity of only 1.69% at 20% drop in peak capacity (Korkmaz et al. 2010), while the best from carbon fiber reinforced polymer retrofit was 1.7%. Our retrofit method proposed does not utilize any mesh or carbon fiber reinforcement, and yet it could attain a drift capacity of 1.5% or better at 20% drop in peak capacity. With reinforcement applied to the masonry panel, better performance is anticipated.

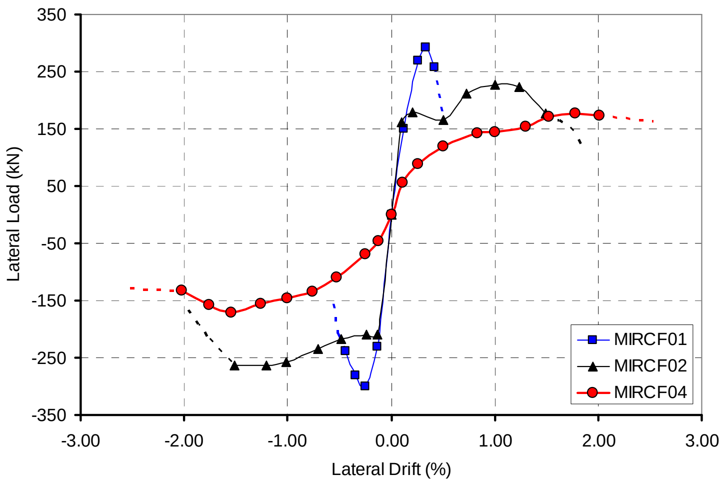


Figure 8. Envelopes of the hysteretic curves

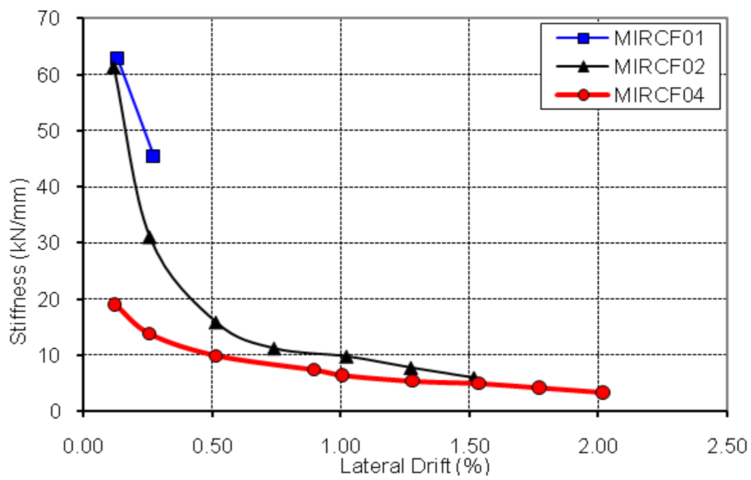


Figure 9. Secant stiffness reduction with lateral drifts

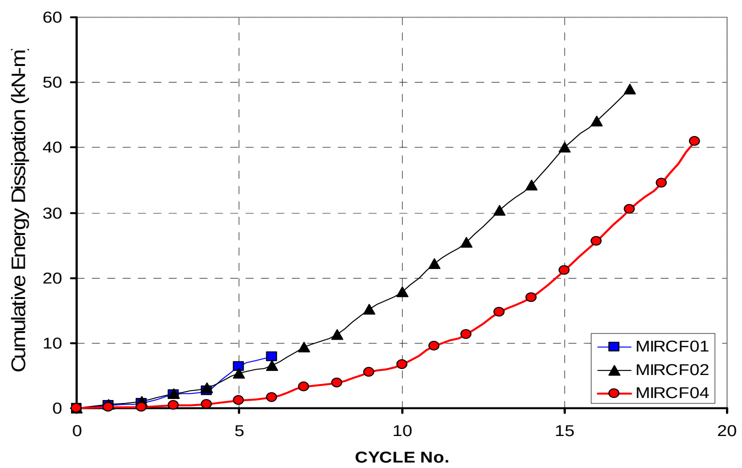


Figure 10. Cumulative energy dissipation with loading cycles

Table 3. Comparison of different retrofit schemes

No.	Samples by	Masonry panel W/H	Drift @ 20% drop in capacity	Remark
1	Billington et al. (2009)	1.79	1.2%	sprayable ductile cement-based composites and welded wire fabric
2	Korkmaz et al. (2010)	1.63	1.19-1.69%	heavy external mesh reinforcement with plaster composite
3	Acun and Sucuoglu (2006)	1.72	0.75% to 1.1%	external mesh reinforcement
4	Altin et al. (2008)	1.73	1.0%	carbon fiber reinforced polymer; CFRP ruptured
5	Yuksel et al. (2010)	1.17	1.0% to 1.7%.	various configurations of CFRP
6	This research MIRCF01 (2012)	2.00	0.25%	Un-reinforced panel
7	This research MIRCF02 (2012)	1.60	1.50 %	URM panel separated from columns, load transfer brackets, corner strengthening
8	This research MIRCF04 (2012)	1.00	1.75%	URM panel separated from columns, load transfer brackets, corner strengthening

5. CONCLUDING REMARKS

The innovative retrofit scheme presented seems to be promising judging from the satisfactory performance of the test specimens in the laboratory and the simplicity of the method which can be easily designed by ordinary practicing engineers. A few interesting findings can be observed:

a) For the specimens tested, a drift capacity of 1.5% or better could be achieved at 20% drop in lateral load capacity.
b) The removal of 10% of the URM panel width on each side of the panel appears to give good balance between ductility performance and strength, with the peak lateral load capacity reduced by about 17% while the drift capacity increased five folds compared with the solid assembly. With the gap increased to 25%, the improvement of drift capacity is irrelevant in view of the significant reduction in peak capacity, and inferior energy dissipation capacity.

Certainly, the practicality and the effectiveness of the schemes over a wide range of applications are subject to further extensive investigations.

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