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VULNERABILITY ASSESSMENT OF SEISMIC RETROFIT MEASURES FOR FRAME AND WALL PRE-CODE BUILDINGS

AMAN MWAFY and ANAS ISSA

Civil and Environmental Engineering Dept, United Arab Emirates University, Al Ain, UAE

The number of existing buildings that may be at risk because of insufficient seismic design provisions cannot be underestimated. Recent studies have confirmed the pressing need for the seismic retrofit of pre-code structures to reduce their probability of collapse. A number of retrofit approaches are therefore assessed in this study, namely reinforced concrete jacketing, fiber reinforced polymers wrapping, and installing externally unbonded steel plates. Detailed structural design and fiber-based modeling are carried out for five reference structures representing frame and shear wall multi-story buildings before and after retrofit. Forty earthquake records are selected to represent potential earthquake scenarios in a region of medium seismicity that was selected as a reference study area. A large number of inelastic pushover and dynamic analyses are performed to assess the lateral capacity and to derive a wide range of fragility relationships for the reference structures. The highest positive impact of retrofit is observed on the pre-code flat slab-column systems. The reductions in the vulnerability of the retrofitted structures confirmed the effectiveness of the selected techniques for mitigating the earthquake losses of pre-code building inventory.

Keywords: Fragility, Substandard structures, Mitigation techniques, Response upgrade, Dynamic collapse analysis, Pushover analysis.

1 INTRODUCTION

Pre-seismic code buildings usually undergo low levels of strength and ductility as they were designed and constructed without proper seismic design provisions. Earthquake loss mitigation of the substandard structures represented in the building inventory may require the adoption of efficient retrofit techniques. The mitigation measures include for instance: Reinforced Concrete (RC) jacketing, Fiber Reinforced Polymers (FRP) wrapping, adding new shear walls, and use of Externally Unbonded Steel Plates (EUSP), (e.g. Moehle 2000). Recent seismic events in the UAE indicated that the region may be prone to damaging earthquakes (e.g., USGS 2014). Although no human or monetary losses were reported from recent seismic events, the repeated earthquakes have raised concerns regarding the vulnerability of pre-seismic code buildings in the region and the associated risk. Few vulnerability and seismic loss assessment studies have been carried out recently for the UAE (e.g. Mwafy *et al.* 2015). However, previous studies have not considered the inventory data of substandard buildings in the study region; different reference structures to represent the pre-code building stock; a wide range of input ground motions representing different seismic scenarios; or refined limit states for vulnerability assessment. This underlines the pressing need for seismic vulnerability assessment of proper retrofit techniques for the pre-seismic code built environment in the UAE.

A systematic seismic vulnerability assessment of a diverse range of buildings representing the pre-seismic code structures in a highly populated and seismically active area in the UAE has been recently undertaken (Issa and Mwafy 2014). The main objective of the present study is to propose suitable retrofit techniques for the reference structures that proved to have unsatisfactory performance in the above-mentioned study, and reassess their seismic performance after retrofit through fragility functions.

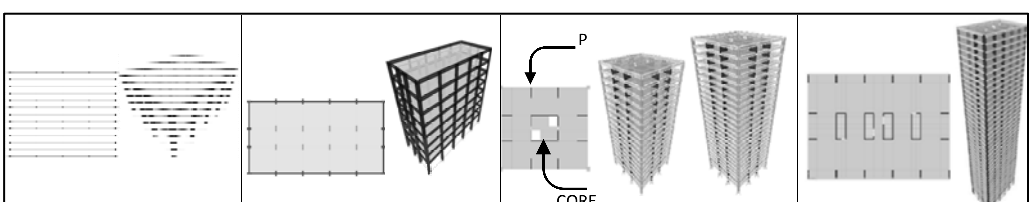
2 REFERENCE BUILDINGS

The reference structures are selected in the present study to represent the pre-code buildings inventory in a highly populated and seismically active area in the UAE, namely Dubai, Sharjah and Ajman. The building inventory data of this area was collected in another study by means of site visits and high resolution satellite images (Mwafy 2012). Most old buildings in the study area were not designed to resist seismic loads since the UAE was classified as zone ‘0’ as per the UBC provisions (1997). Revised seismic design criteria have been adopted later in the UAE based on recent seismic hazard studies (e.g., Mwafy *et al*. 2006). The building survey indicated that almost half of the building stock represents pre-code buildings. Based on the above-mentioned survey, five pre-code RC buildings of 2, 8, 18, 26, and 40 stories are selected and fully designed for the purpose of this comprehensive study according to the building codes that were implemented at the time of construction (BS8110 1986, Issa and Mwafy 2014), as shown in Table 1. Figure 1 depicts the three-dimensional (3D) finite element (FE) models developed for the design of the five reference buildings.

Table 1. Summary of the selected reference buildings.

Number	Building Reference	No. of stories	Story height (m)			Total height (m)
			B	GF	TF	
1	BO-02	2	-	5.0	3.5	8.5
2	BO-08	8	-	5.0	3.5	28.5
3	BO-18	18	3.2	4.5	3.2	58.9
4	BO-26	26	3.2	4.5	3.2	84.5
5	BO-40	40	3.2	4.5	3.2	129.3

B: Basement, GF: Ground Floor, TF: Typical Floor



BO-02, 2 story | BO-08, 8 story | BO-18 & BO-26,18 & 26 story | BO-40, 40 story

Figure 1. Layouts and three-dimensional design models of the reference structures.

3 DESIGN AND MODELLING OF STRENGTHENING TECHNIQUES

Different retrofit techniques are designed for the reference buildings depending on their efficiency and suitability. RC jacketing of columns is applied to the 2 and 8-story buildings. All columns are enlarged to achieve the required strength as per the recommended seismic design load. In the second retrofit approach, existing columns cross-sections are wrapped with high strength FRP overlays, which have a thickness of 0.33 mm/layer, elastic modulus of 257 GPa and tensile strength of 4,519 MPa. All columns are wrapped with three overlays to reach the target lateral strength. FRP wrapping is only applied to the 2-story building, in which the FRP wrapping criteria is fulfilled (FEMA-547 2006). The FRP retrofit technique is not recommended for other buildings since they have large columns and wall cross-sections with high aspect ratios. In the EUSP scheme considered in the current study, steel plates are bolted to the wall by anchor bolts and steel angles. The level of strength increase is controlled by the steel area. Steel plates are designed using the 3D FE models in the form of an additional steel area at the ends of the shear and core walls. For the sake of brevity, the design results of the retrofit approaches carried out for the reference structures are presented and discussed in detail by Issa (2014).

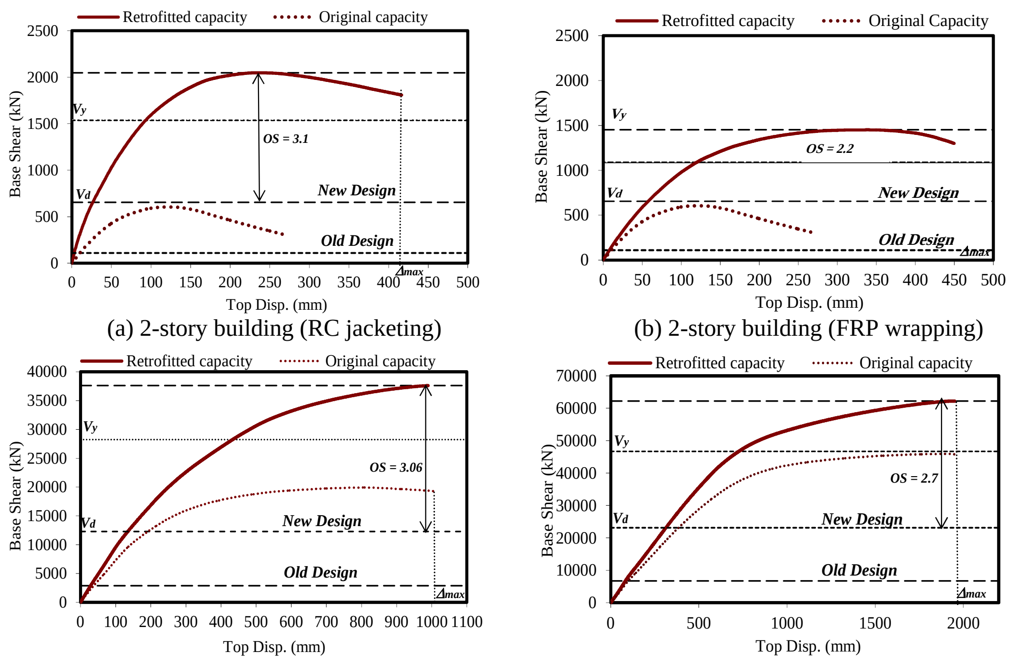
The above-mentioned three retrofit techniques of the five reference buildings are idealized and assessed using an efficient fiber-based modeling and analysis platform (Elnashai *et al*. 2012). RC jacket with a rectangular cross-section is used to model the retrofitted RC columns of the 2-story and 8-story pre-code buildings. The original concrete strength of the reference structures is used to obtain the required composite action. A trilinear FRP model is used for the modeling of FRP overlays (Elnashai *et al*. 2012). The FRP overlays are added to the original concrete sections with the required thickness obtained in design. Finally, the steel plates obtained from the design are modeled using steel reinforcement with the same yield strength and area. The added steel area is represented at the ends of the shear walls and core walls.

4 IMPACT OF RETROFIT ON LATERAL CAPACITY

Inelastic pushover analysis (IPA) is performed for each building after implementing the above-mentioned retrofit approaches. The 2-story frame structure (BO-02) is provided with two retrofit alternatives, while one retrofit technique is employed for other buildings. Table 2 summarizes the IPA results for the five retrofitted structures. For the 2-story building, RC jacketing of columns results in higher stiffness and strength over the FRP retrofit approach due to increasing cross-section sizes, as shown in Figure 2(a-b). Both RC jacketing and FRP wrapping of columns significantly enhance the ductility of pre-code structures. As shown in Figure 2(c-d), adding EUSP to the shear walls of the pre-code wall structures has a minor impact on stiffness, while it increases strength to the required design level (i.e., V_d x overstrength). All of the retrofit techniques produce the required strength as per the target design loads. The higher impact of rehabilitation approaches are observed in the low-rise frame buildings since they were mainly designed to resist gravity loads in addition to insignificant wind loads.

Table 2. Summary of IPA results for existing and retrofitted structures.

Building	Lateral design load (kN)		Increase in	Original	Lateral strength (kN)	
	Original	Retrofitted	lateral load (%)	strength (kN)	Alternative # 1	Alternative # 2
BO-02	110	655	495	605	2048 (RCJ)	1450 (FRP)
BO-08	968	2341	142	3763	7167 (RCJ)	N/A
BO-18	1966	10852	452	24951	38162 (EUSP)	N/A
BO-26	2879	12298	327	19912	37896 (EUSP)	N/A
BO-40	6707	23117	245	45898	62226 (EUSP)	N/A



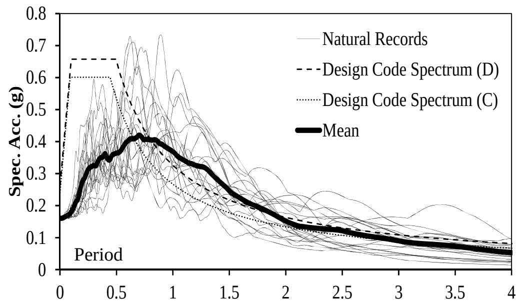
(a) 2-story building (RC jacketing) (b) 2-story building (FRP wrapping)

(c) 26-story building (EUSP) (d) 40-story building (EUSP)

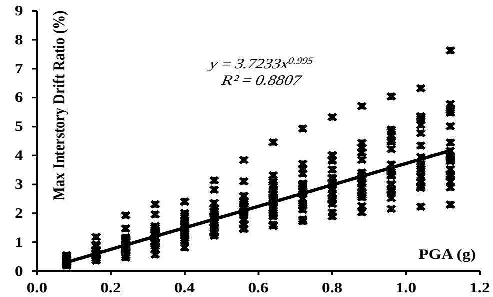
Figure 2. Impact of different retrofit options on the lateral capacity (sample results).

5 IMPACT OF RETROFIT ON SEISMIC PERFORMANCE

The fragility curves of the reference structures are developed before and after retrofit following the procedure adopted by Mwafy *et al*. (2015) and Issa and Mwafy (2014). Incremental dynamic analyses (IDAs) are performed using forty earthquake records representing two seismic scenarios for the study region. Figure 3(a) shows the response spectra of twenty records representing far-field earthquakes, while Figure 3(b) depicts sample of the regression analyses for the 40-story structure. It is noteworthy that the fragility curves are developed using 280 inelastic dynamic analyses undertaken for each of retrofitted buildings. In order to observe the performance enhancement, the fragility curves of both the original and retrofitted structures are plotted in Figure 4. It is shown that the slopes of the fragilities become less steep for the retrofitted structures. For the 2-story pre-code structure, both of the implemented retrofit techniques (RC jacketing and FRP wrapping of columns) improve the seismic performance but with a higher extent in the RC jacketing technique over the FRP wrapping approach.

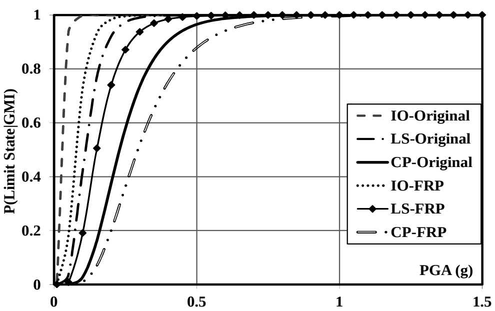


(a) Response spectra of far-field records

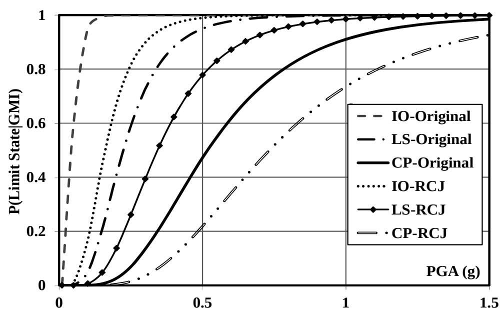


(b) 40-story building (EUSP)

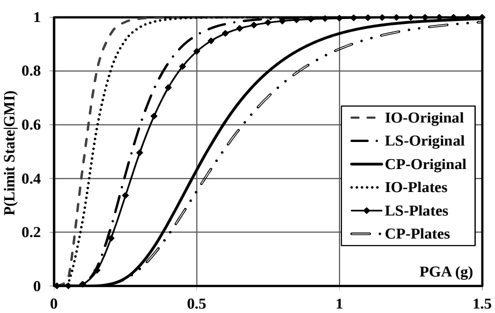
Figure 3. Sample of regression analysis results using 20 far-field earthquake records.



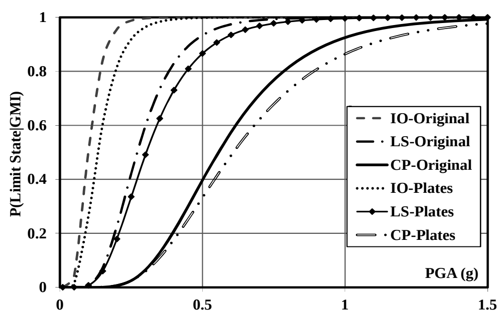
(a) 2-story building (FRP wrapping)



(b) 8-story building (RC jacketing)



(c) 18-story building (EUSP)



(d) 40-story building (EUSP)

Figure 4. Fragility curves before and after retrofit using 20 far-field records (sample results).

For the 8-story structure, an observable seismic performance improvement is achieved using the RC jacketing of columns. Fair seismic performance enhancement is also achieved after retrofitting shear wall structures using steel plates. The enhancements in the seismic performance of the retrofitted reference structures confirm the success of such retrofit techniques to upgrade the seismic performance to reach the target design levels and reduce earthquake losses. The pre-code frame structures have top priority when implementing mitigation programs in the study area due to their wide spreading and high vulnerability.

6 CONCLUSIONS

Probabilistic seismic vulnerability assessment of a diverse range of reference buildings representing substandard wall and frame structures in a highly populated and seismically active area is conducted in this study. Five buildings were selected and designed based on an on ground survey to represent the architectural layouts commonly adopted in the study area. Detailed fiber-based idealizations were developed to assess the seismic response of the buildings before and after retrofit using IPAs and IDAs. Forty far-field and near-source earthquake records were chosen to represent the study region. The seismic performance of the retrofitted buildings was consistent from both the IPA results and the derived fragility relationships using IDAs. RC jacketing of columns effectively increased both the initial stiffness and ultimate strength when compared with FRP wrapping. Lower vulnerability was also observed when the columns of the pre-code frame structures were retrofitted with RC jacketing compared with that of FRP wrapping. Marginal enhancements in seismic performance were achieved when implementing the EUSP retrofit technique to the pre-code wall structures. The observable improvements in the seismic performance of the pre-code frame structures were attributed to their original poor performance unlike the pre-code wall buildings. The reduced vulnerability of the retrofitted structures confirmed the effectiveness of the selected approaches for mitigation of earthquake.

Acknowledgments

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