Seismic Assessment of Retrofitted RC Structures Using Traditional and New Repair Techniques

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SUMMARY:
Many existing buildings, which were constructed according to old codes, are lacking adequate seismic resistance. In order to reduce the seismic hazards, there is an urgent need to upgrade existing RC buildings to meet the requirements of current seismic design codes. The seismic retrofit of RC buildings involves targeted strengthening of deficien regions, to increase the strength, stiffness and ductility of the structure. RC jacketing is the most commonly employed method for upgrading concrete columns. The use of FRP jackets is considered as one of the recent techniques that provide confinement and strength for RC columns. The current research work evaluates the seismic performance of old multi story RC buildings, prior and after retrofit process by different RC and FRB jacketing techniques. Static Pushover and dynamic time history analyses are employed in the evaluation. The results indicate that traditional RC Jacket technique is more effective FRP technique.

Keywords*: Seismic Performance, pushover analysis, Seismic retrofit, RC Jacket, FRP.*

1. INTRODUCTION

The seismic performance of existing reinforced concrete (RC) framed structures designed for gravity loads or according to old codes has showed inferior behavior during recent earthquakes; this behavior is believed to be due to insufficient lateral load-carrying capacity and limited ductility. Such structures possess an inherently low resistance to horizontal loads, resulting in large inelastic deformations during earthquakes (Bracci et al, 1992). The seismic behavior of those buildings can be distinguished by their weak column strong beam type; which results in soft-story or column side sway collapse mechanisms during strong ground motions. In order to reduce the risk of structural collapse during strong earthquakes, there is an urgent need to upgrade existing RC buildings to meet the requirements of current seismic design codes (Hueste, and Bai, 2007).

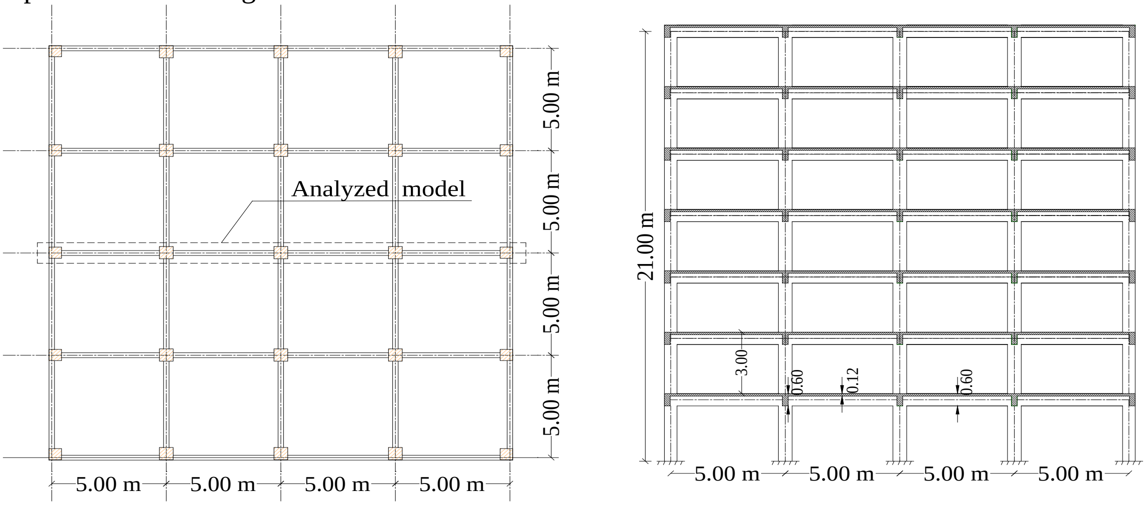
The seismic retrofit of an RC building may involve strengthening of deficient regions to increase the strength, stiffness and/or ductility of the structure, or to provide redundant load-carrying mechanisms. The selection of a specific retrofit strategy should be based on the retrofit objectives as well as on economic considerations (Ghobarah et al, 2000). The retrofit design should be performed according to appropriate performance criteria to ensure that a defined level of damage is not exceeded or the collapse of the building is prevented during specified ground motions. The overall seismic retrofit strategy for an RC framed structure must consider a number of key issues in an integrated manner; these issues include strengthening of beams, columns and beam-column joints to prevent brittle failure modes such as shear failure. Once these brittle failure modes are suppressed, the seismic retrofit design depends on the strength and ductility of the columns to satisfy specific demands of earthquake resistance (Thermou and Elnashai, 2005).

Columns' retrofitting is one of the most widely used seismic upgrading approaches for RC framed structures which improve the column behavior. It typically involves increasing the column strength, ductility, stiffness or in most cases a combination of these parameters (Konstantinos and Stephanos, 2008). Jacketing of columns implies installing new steel reinforcement bars (lateral ties and vertical bars), and increasing column cross section, in order to increase strength and ductility of existing concrete members. The more recent techniques include using of fiber reinforced polymers (FRP) jackets to confine columns. In such jackets, the fibers are oriented only or predominantly in the hoop direction to confine the concrete so that both its compressive strength and ultimate compressive strain are significantly enhanced (Rebecca and Vistasp, 2007). Compared to conventional techniques, FRP jacketing is easier and quicker to implement; moreover, it adds virtually no weight to the existing structure. As a result, FRP jacketing has been found to be a more cost-effective solution than conventional techniques in many situations; thus, it has been widely accepted (Zou et al, 2006).

The objective of this study is to assess the seismic performance of existing RC framed structures and to evaluate the effectiveness of the different selective rehabilitation techniques for columns. The study is conducted on a seven story RC residential building. The effects of the different retrofit strategies are examined using two district analyses: the non-linear static pushover analysis and the step-by-step time history dynamic analysis by using the computer program Zeus-NL (Elnashai et al., 2004). These analyses are conducted in order to estimate the performance levels of the original, as well as, the retrofitted structures in terms of their drift limits.

2. MODEL CONFIGURATIONS AND RETROFIT SCENARIOS

In the present study, models of a seven story four bay RC residential building are employed. These models are composed of moment resisting frames spaced at 5.0 m with a constant floor height of 3.0 m; no shear walls are utilized. Two distinct models are analyzed: Model 1, which represents a building that is designed according to (E.C.P., 1991) regulations; for such an old code, there were no seismic design recommendations. Model 2, which represents a building designed according to (E.C.P., 2008), where comprehensive seismic design recommendations are implemented. For both investigated models, slabs are taken to be 0.12 m in thickness; the cross sectional dimensions of all beams are 0.25 m and 0.6 m for width and depth, respectively. The building layout is shown in Fig. 2.1. which shows the plan of the building and the sectional elevation.



(a) Plan (b) Section elevation

Figure 2.1. Plan and elevation of Regular R/C frame buildings

Two retrofitting techniques have been applied: RC and FRP jacketing for columns of Model 1. In each retrofitting techniques, three column retrofitting scenarios have been studied, where jacketing is applied in: (1) the first two stories, (2) the first four stories, and (3) all stories of the building. The reinforcement steel, used for Models 1 and 2, is the mild and high tensile steel, respectively. For RC jackets, high tensile steel have been used for additional reinforcement steel of jackets for retrofitted models. For FRP jackets, wrapping of columns by FRP sheets are used; sheet thickness is taken as 2mm. The cross sectional dimensions of the columns for Model 1, Model 2, and the retrofitted models are presented in Table 2.1. Fig. 2.2. shows cross sections of some selected columns used in different models.

Table 2.1. Cross section dimension and reinforcement of columns

Floor	Model	Model 1 (E.C.P., 1991)		Model 2 (E.C.P., 2008)		Retrofitted model RC jacket (1^{st}-2^{nd})		Retrofitted model RC jacket (1^{st}-4^{th})		Retrofitted model RC jacket (1^{st}-7^{th})	
	Column	Exterior column	Interior column	Exterior column	Interior column	Exterior column	Interior column	Exterior column	Interior column	Exterior column	Interior column
1st & 2nd	dim (cm)	55 x 55	60 x 60	75 x 75	80 x 80	75 x 75	80 x 80	75 x 75	80 x 80	75 x 75	80 x 80
	RFT (mm)	16 Y 16	16 Y 16	20 T 22	20 T 22	20 T 22	20 T 22	20 T 22	20 T 22	20 T 22	20 T 22
3rd & 4th	dim (cm)	50 x 50	55 x 55	70 x 70	75 x 75	50 x 50	55 x 55	70 x 70	75 x 75	70 x 70	75 x 75
	RFT (mm)	12 Y 16	16 Y 16	16 T 22	20 T 22	12 Y 16	16 Y 16	16 T 22	20 T 22	16 T 22	20 T 22
5th & 6th	dim (cm)	45 x 45	50 x 50	65 x 65	70 x 70	45 x 45	50 x 50	45 x 45	50 x 50	65 x 65	70 x 70
	RFT (mm)	12 Y 16	12 Y 16	20 T 18	16 T 22	12 Y 16	12 Y 16	12 Y 16	12 Y 16	20 T 18	16 T 22
7th	dim (cm)	40 x 40	45 x 45	60 x 60	65 x 65	40 x 40	45 x 45	40 x 40	45 x 45	60 x 60	65 x 65
	RFT (mm)	8 Y 16	12 Y 16	16 T 18	20 T 18	8 Y 16	12 Y 16	8 Y 16	12 Y 16	16 T 18	20 T 18
Y : represent mild steel (fy=240 N/mm^2)						T : represent high tensile steel (fy=360 N/mm^2)					

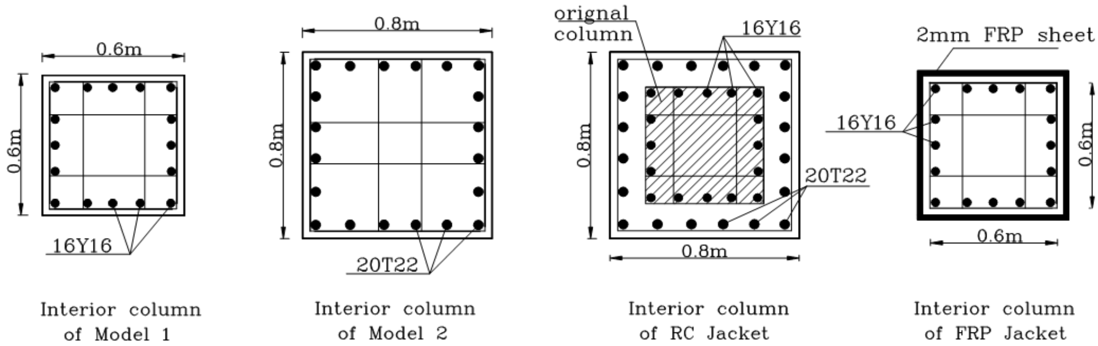


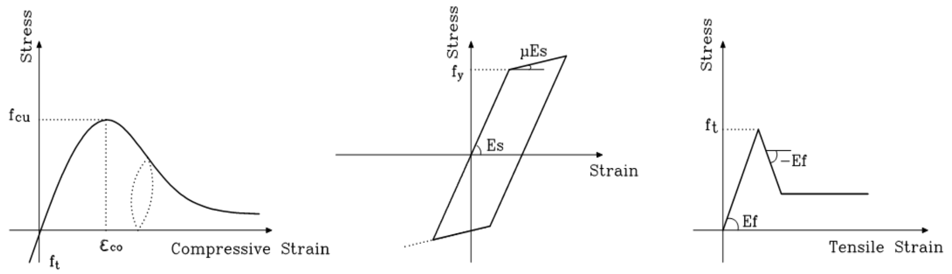
Figure 2.2. Cross sections of some selected columns used in different models.

2.1.Material properties

The material properties of the reinforced concrete, reinforcing bars, and the FRP used in Model 1, Model 2, and jackets are given in Table 2.2. Fig. 2.3. shows the material models for concrete, reinforcing steel, and FRP which have been implemented in models (Zeus-Nl, Elnashai et al, 2004).

Table 2.2. Material properties used in models.

Model	Concrete			Steel			FRP		
	E_c GPa	f_{cu} MPa	ε_{co} %	E_s GPa	fy MPa	μ	E_F GPa	ft GPa	t mm
Model 1 (E.C.P., 1991)	21.70	25	0.3	200	240	0.05	__	__	__
RC jacket	21.70	25	0.3	210	360	0.05	__	__	__
FRP Jacket	21.70	25	0.3	210	360	0.05	137.9	2.21	2.0
Model 2 (E.C.P., 2008)	21.70	25	0.3	210	360	0.05	__	__	__



a. Material model of the concrete b. Material model of the steel c. Material model of FRP

Figure 2.3. Stress – strain relationships for (a) concrete, (b) Reinforced steel, (c) FRP

3. NONLINEAR STATIC PUSHOVER ANALYSIS

Pushover analysis is an approximate analysis method in which the structure is subjected to monotonically increasing lateral load of a predetermined pattern until a target displacement is acheived. As the load increases, critical zones deform beyond the yield limit and the structure degrades. At each load step, the relation between the base shear and lateral drift is acquired. This procedure continues until the structure collapses or reaches a predetermined lateral deflection. Hence, the target top displacement may be used to estimate the expected deformation due to earthquake or the expected drift corresponding to structural collapse. At the end, the relationship between the base shear and the lateral deflection (roof displacement), that is called capacity curve, is determined (Papanikolaou and Elnashai, 2005).

Static pushover analysis has been conducted with an inverted triangular load pattern for Model 1, Model 2, and all of the retrofitted models. Again, retrofited models include three scenarios: (1) retrofiting of the first two stories, (2) retrofiting of the first four stories, (3) and retrofiting of all stories. These scenarios are conducted for both RC jacket and the FRP wrapping retrofitting techniques. Capacity curves, maximum inter-story drift ratio, and the maximum story shear are shown in Figs. 4, 5, and 6; respectively for the RC jacketing, FRP wrapping techniques.

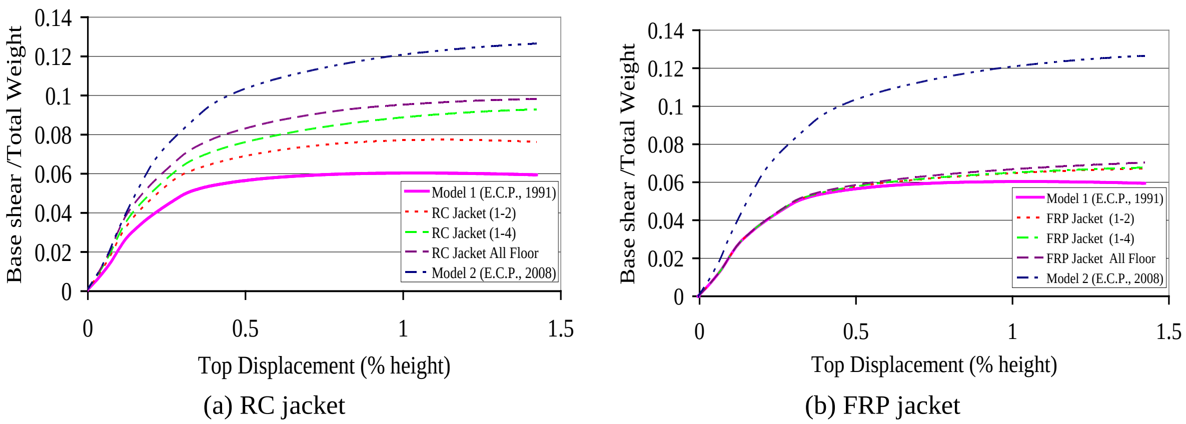
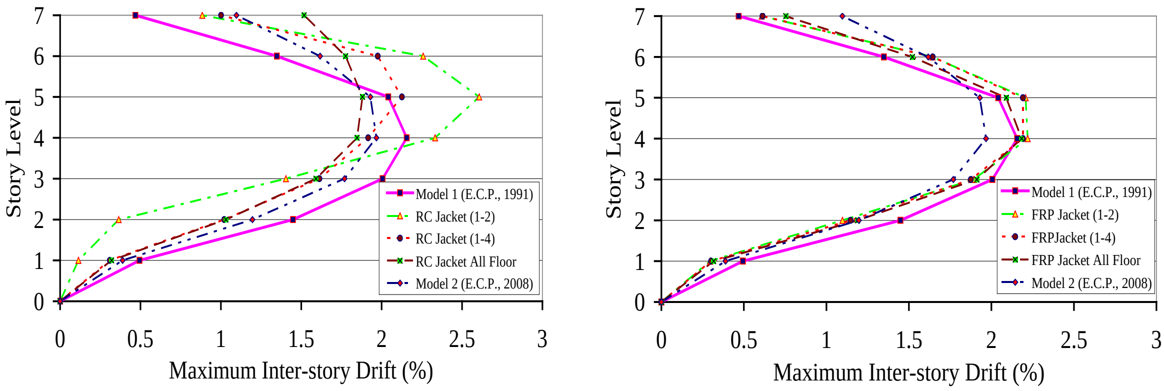


Figure 3.1. Capacity curves in case of repair by (a) RC jacket, (b) FRP

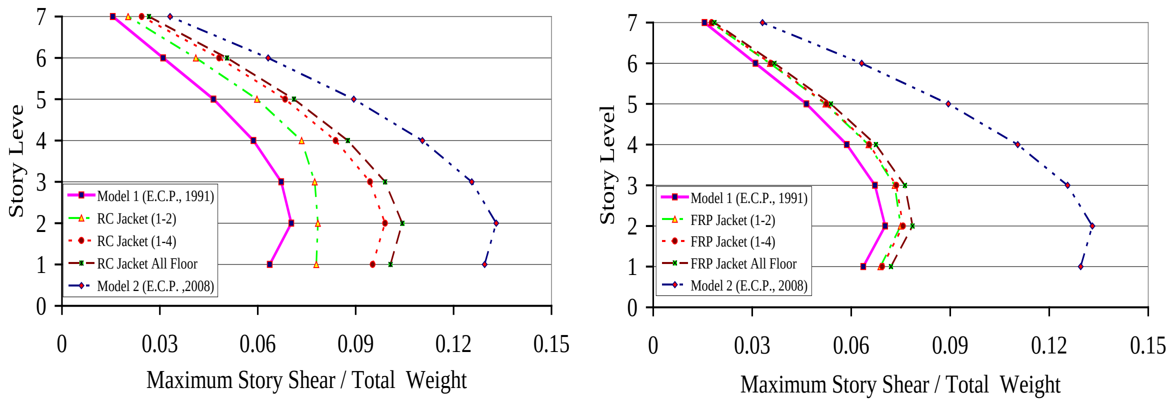
Fig. 3.1. shows the relationship between base shear versus top displacement (capacity curve) for Model 1, Model 2, and the three retrofitted scenario models. The Figure indicates that, the shear capacity of Model 2 is approximately twice that of Model 1. Accordingly, it may be concluded that old buildings, represented herein by Model 1, would generally require retrofitting to increase its base shear capacity in order to be conforming to current design code. Fig. 3.1.a. shows significant improvement in shear capacity when using the RC jacketing technique. The amount of enhancements increases with the number of retrofitted stories; yet it does not reach the shear capacity of Model 2 even when all stories are retrofitted. The percentages of improvement are 33.3%, 53.3%, and 63.3% for scenarios 1, 2, and 3 of retrofitting, respectively. The comparable values of enhancement of shear capacity, when using FRP jacket technique (Fig.3.1.b.), are 11%, 13%, and 16.3% for the three retrofitting scenarios, respectively.

Fig. 3.2 shows the values of the maximum inter-storey drift for each story level, in case of using RC and FRP jackets, in retrofitting. The figure indicates that, the maximum value of inter-storey drift occurs around the middle stories. In addition, the figure depicts that buildings, designed according to (E.C.P., 1991), would generally experience higher values of drift ratios than those designed according to (E.C.P., 2008); the percent of increase of drift ratios in old buildings is in the range of almost 10%. Using RC jacketing technique in the lower stories, of a building, would generally enhance the structural behavior and result in reduction in drift ratios; however, it may, in some cases, result in a soft story mechanism. This is due to the significant increase in columns stiffness of the lower stories compared to that of the non retrofitting columns at upper stories. The value of maximum inter-story drift may increase about 20% than that of Model 1, as shown in Fig. 3.2.a. (case of jacketing the first two stories). On the other hand, Fig. 3.2.b. show that using the FRP technique, may have small effects on the building performance compared to that when using RC retrofitting technique. Fig. 3.3. presents the maximum values of story shear at each story level for the investigated models. The figure indicates that using RC jacketing for columns has superior effects in enhancing story shear capacity compared to that when using FRP technique.



(a) RC jacket (b) FRP jacket

Figure 3.2. Maximum inter-story drifts for retrofitted structure with (a) RC jacket, (b) FRP



(a) RC jacket (b) FRP jacket

Figure 3.3. Maximum story shear for retrofitted structure with (a) RC jacket, (b) FRP

4. DYNAMIC ANALYSIS

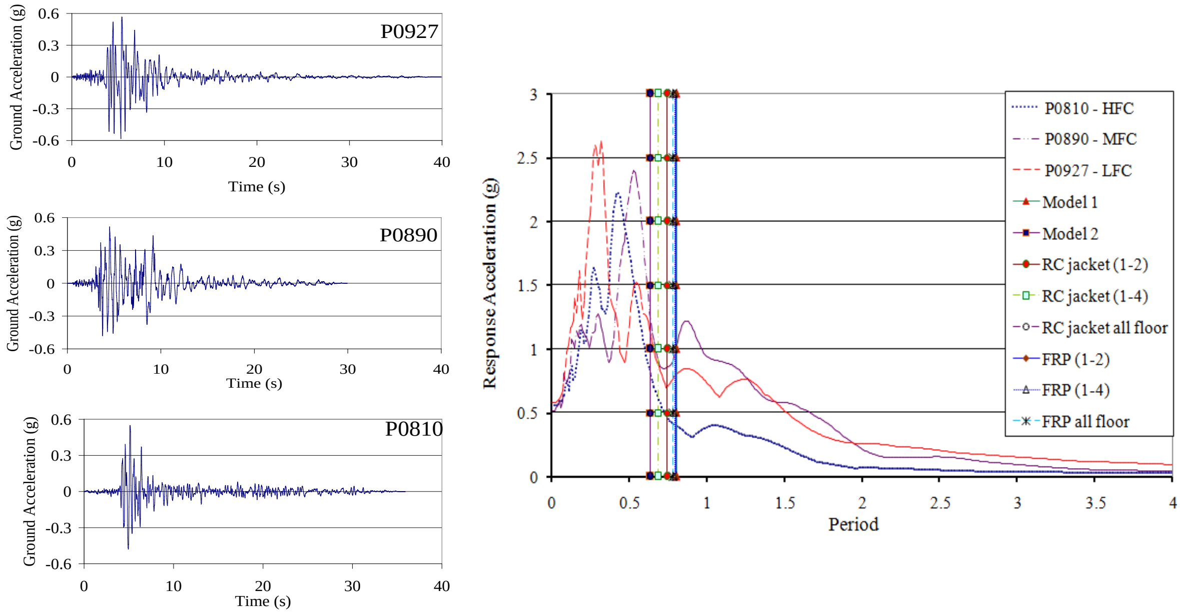
In this study, a step-by-step non linear time history analysis has been conducted to evaluate the seismic performance of all the studied buildings and retrofitting configurations. The fundamental periods of all studied models have been obtained through modal analysis. The natural periods of the first three mode shapes, have been listed in Table 4.1.

Table 4.1. The first three natural periods for all models

Period (s)	Model 1 (E.C.P., 1991)	Model 2 (E.C.P., 2008)	Retrofitted Model RC (1^{st}- 2^{nd})	Retrofitted Model RC (1^{st}-4^{th})	Retrofitted Model RC all floor	Retrofitted Model FRP (1^{st}-2^{nd})	Retrofitted Model FRP (1^{st}- 4^{th})	Retrofitted Model FRP all floor
T1	0.806	0.637	0.741	0.685	0.636	0.798	0.789	0.7825
T2	0.279	0.2028	0.257	0.248	0.2023	0.276	0.276	0.2687
T3	0.1639	0.109	0.1527	0.1448	0.109	0.162	0.161	0.156

4.1. Ground Motions

In order to evaluate the seismic performance of Model 1, retrofitted buildings, and Model 2, the analysis has been carried out using the horizontal component of three ground motions. The used ground motions were selected such that they represent wide range of frequency content. The basis, which has been used to classify ground motions according to their frequency content, is that introduced by (Kwon, and Elnashai, 2006). All of the used ground motion records are downloaded from the Pacific Earthquake Engineering Research Center (PEER, 2000) website. The characteristics of the used ground motions are listed in Table 4.2. The accelerograph of these records are presented in Fig. 4.1.a. In addition, the elastic response spectra of the those ground motions are demonstrated in Fig. 4.1.b.; 5% damping ratio is assumed. The figure depicts the spectral acceleration of record P0927; that is the Low Frequency Content, LFC, record. The figure presents as well, the spectral accelerations of records P0890 and P0810, which represent those of Medium (MFC) and High (HFC) Frequency Content ground motions, respectively. Finally, the fundamental periods of each studied model configuration are illustrated.



(a) Accelerograph of selected ground motions records

(b) The elastic response spectra of the used ground motions (5% damping)

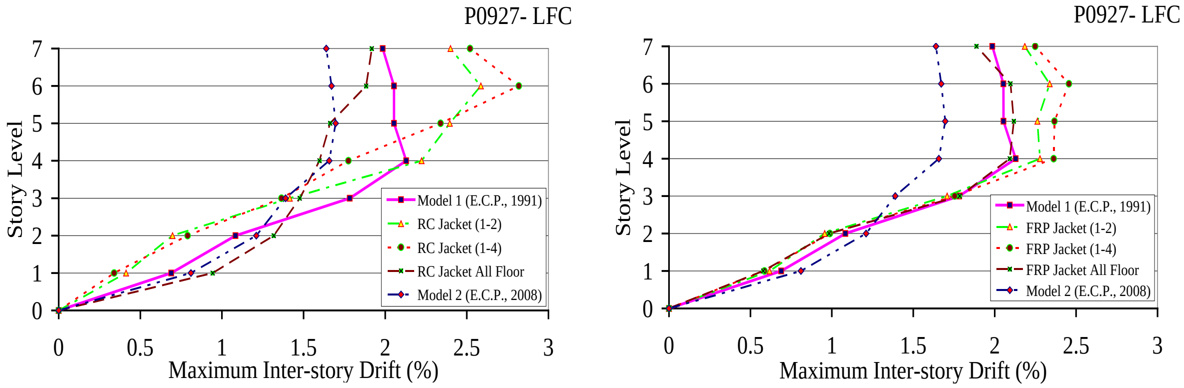
Figure 4.1. Ground motions records, and the elastic response spectra of the used ground motion

Table 4.2. Characteristics of the selected natural Ground Motions [PEER, 2000]

No	ID	Earthquake/ Component	Date	M	PGA (g)	PGV (m/s)	a/v	Frequency Content
1	P0927	Northridge / NORTHR/NWH090	17/01/1994	6.7	0.583	75.5	0.772	Low; LFC
2	P0890	Northridge / NORTHR/MUL279	17/01/1994	6.7	0.516	62.8	0.822	Medium; MFC
3	P0810	Cape Mendocino / CAPEMEND/RIO360	25/04/1992	7.1	0.549	42.1	1.304	High; HFC

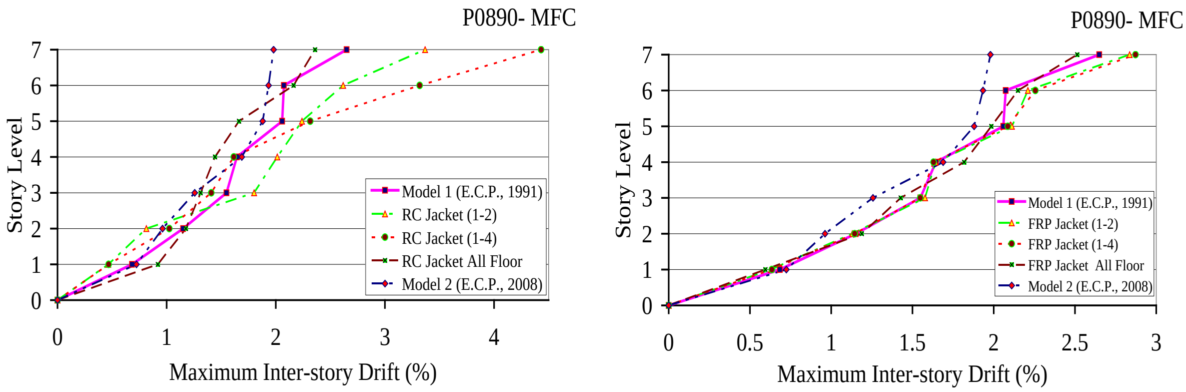
4.2. Dynamic Analysis Results

Plots for the maximum inter-story drift ratios are presented in Fig. 4.2., for all model buildings and retrofitted configurations, when subjected to the LFC ground motion, record (P0927). Similar plots are provided for the MFC (P0890) and HFC (P0810) records in Figs. 4.3., 4.4.; respectively. Fig. 4.2. shows that the maximum inter story drift ratios of Model 2 are generally less than those of Model 1, by almost 20 %; it should be noted that this amount was estimated to 10% in the pushover analysis (Fig. 3.2.). Therefore, it can be concluded that buildings, designed according to new code, would generally be experiencing less values of inter story drift than those of old buildings, by almost 10% to 20%, according to the used method of analysis. On the other hand, the figure depicts enhancement of drift ratio for the lower stories of Model 1, when retrofitted by RC jackets (Fig. 4.2.a). However, as revealed in static analysis, soft story mechanisms, in upper stories may occur, in some cases, resulting in higher values of drift ratio in upper stories. Similar behavior is demonstrated for the case, when using FRP retrofitting technique (Fig. 4.2.b); yet with trivial enhancement of drift ratios for the lower stories.



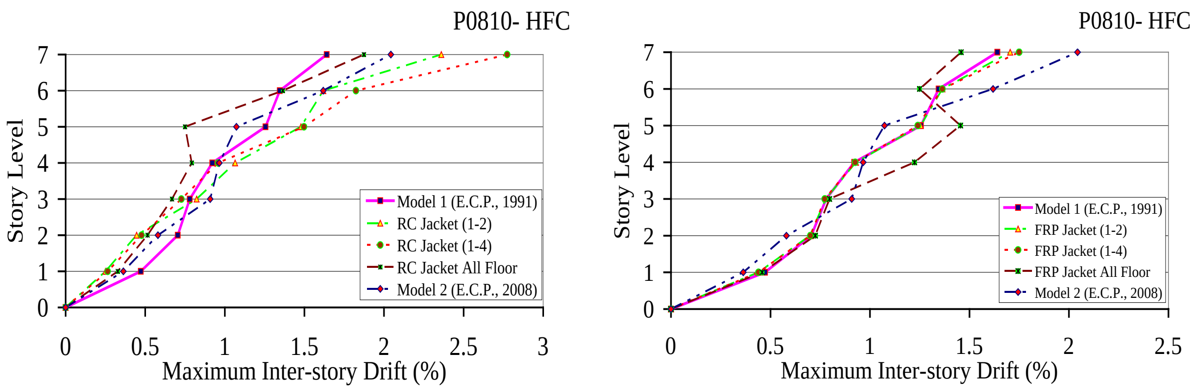
(a) RC jacket (b) FRP jacket

Figure 4.2. Maximum inter-story drifts for all investigated models including retrofitted structures with RC and FRP jackets, when subjected to LFC (P0927) record



(a) RC jacket (b) FRP jacket

Figure 4.3. Maximum inter-story drifts for all investigated models including retrofitted structures with RC and FRP jackets, when subjected to MFC (P0890) record



(a) RC jacket (b) FRP jacket

Figure 4.4. Maximum inter-story drifts for all investigated models including retrofitted structures with RC and FRP jackets, when subjected to HFC (P0810) record

For the cases of excitation resulting from MFC and HFC ground motions, contradictory behavior is noticed in Figs. 4.3. and 4.4, where the highest drift ratios occur at the upper stories, rather than stories around the mid height. This behavior is not in agreement with that obtained either through static pushover analysis (Fig. 3.2.) or through dynamic analysis for the case of LFC (Fig. 4.2). Again, soft story mechanisms may occur if RC jackets are used for lower stories only (scenario 1 or 2 of retrofitting technique). For those cases, higher values of drift ratios are depicts for the upper stories, when compared to that of Model 1. Finally, Fig. 4.4. shows a further unexpected behavior, where Model 2 of building subjected to HFC record, and designed according to (E.C.P., 2008), is suffering higher values of drift ratios, in the upper stories, when compared to those of Model 1 (E.C.P., 1991).

The maximum story shear at each story level is presented for Model 1, Model 2, and retrofitted models in Figs. 4.5., 4.6. and 4.7.; those figures demonstrate the absolute structural behavior when subjected to the LFC, MFC, and HFC records, respectively. In general, result due to dynamic time history analyses are conforming to those obtained from static pushover analysis (compare Figs. 4.5., 4.6., and 4.7. with Fig. 3.3.). Therefore, the conclusions, drawn in the section 3. of static pushover analysis, can be extended herein, where using the RC jacketing technique is considered superior than using FRP technique, regarding the amount of enhancement in shear capacity of investigated models. In addition, the enhancement in shear capacity will not reach that of Model 2, even when all stories are retrofitted.

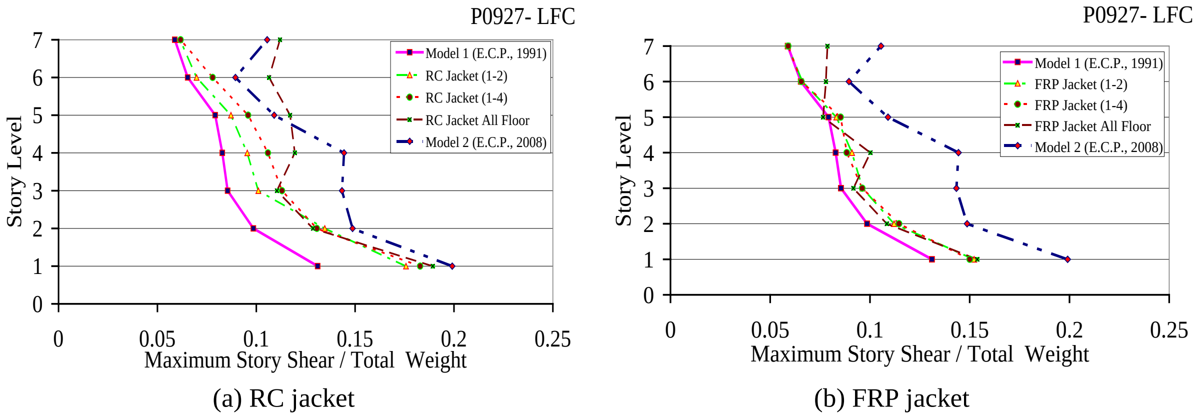


Figure 4.5. Maximum story shear for all investigated models including retrofitted structures with RC and FRP jackets, when subjected to LFC (P0927) record

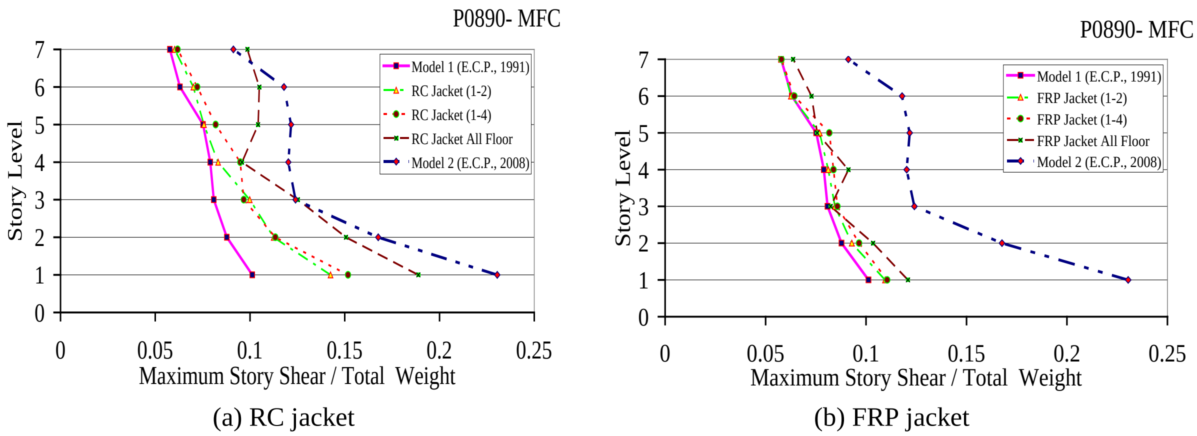
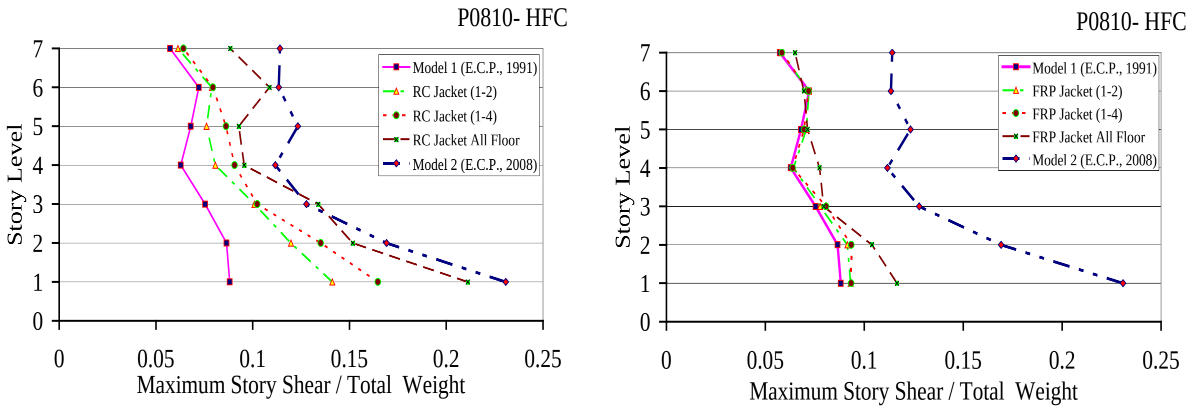


Figure 4.6. Maximum story shear for all investigated models including retrofitted structures with RC and FRP jackets, when subjected to MFC (P0890) record

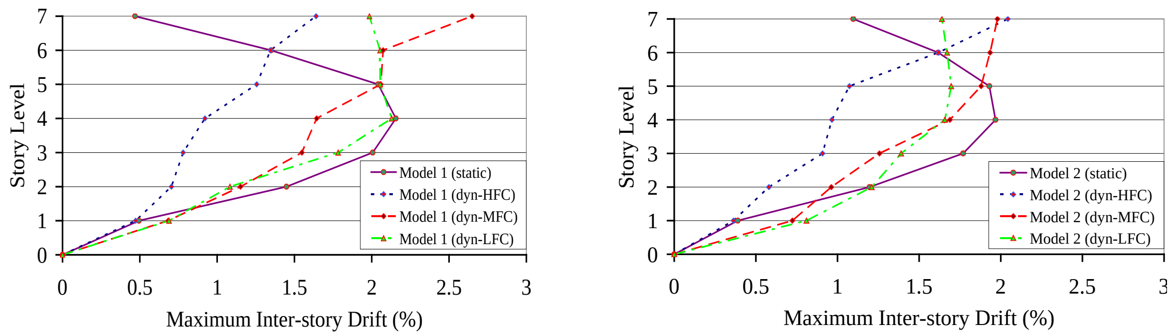


(a) RC jacket (b) FRP jacket

Figure 4.7. Maximum story shear for all investigated models including retrofitted structures with RC and FRP jackets, when subjected to HFC (P0810) record

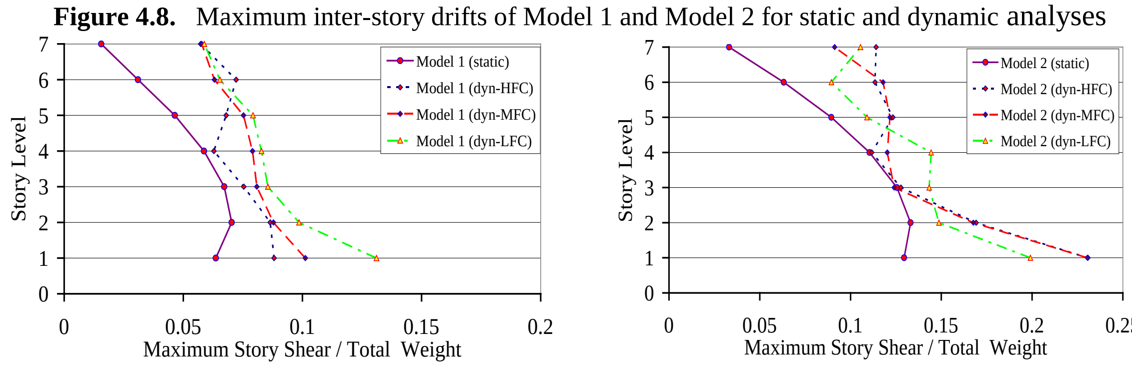
5. COMPARISON BETWEEN STATIC AND DYNAMIC ANALYSIS

A comparison has been carried out to show the differences between the outcomes of the two analysis types, which have been used in the study. The results obtained from the static pushover analysis have been judged against those from dynamic time history analysis for Models 1 and 2, in Figs. 4.8. and 4.9. Fig. 4.8. depicts the variation of maximum inter story drift, along the heights of Models 1 and 2. In general, the static pushover analysis could estimate the peak values of drift ratios, for most cases, except for the case of MFC ground motion applied at Model 1. Moreover, the values of drift ratios of upper stories, obtained through static pushover analysis, are generally under-estimated, when compared to those obtained by the more accurate analysis; that is the dynamic analysis. Furthermore, maximum story shear is, as well, under-estimated for the case of static pushover analysis, when compared to those obtained by dynamic analysis (Fig. 4.9.).



(a) Model 1 (b) Model 2

Figure 4.8. Maximum inter-story drifts of Model 1 and Model 2 for static and dynamic analyses



(a) Model 1 (b) Model 2

Figure 4.9. Maximum story shear of Model 1 and Model 2 for static and dynamic

6. CONCLUSION

Nonlinear static pushovers, as well as, dynamic time history analyses are conducted to investigate the seismic performance of old reinforced concrete buildings and to evaluate the effectiveness of using different repairing techniques. The results are limited to the cases considered; for those cases, the following conclusions may be drawn:

- Old buildings, would generally require retrofitting to increase its base shear capacity in order to be conforming to current design code.
- Old building will not reach base shear capacity of buildings, designed according to new codes, even if jacketing is employed for all columns in all stories of building.
- RC jacketing for columns has superior effects in enhancing story shear capacity, compared to that when using FRP jacketing technique.
- Buildings, designed according to new code, would generally be experiencing less values of inter story drift than those of old buildings, by almost 10% to 20%, according to the used method of analysis.
- Using RC jacketing technique in the lower stories, of a building, would generally enhance the structural behavior and result in reduction in drift ratios; however, it may, in some cases, result in a soft story mechanism.

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