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Analysis of Masonry Infill Panels Retrofitted with FRP Sheets in R/C Frames

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Abstract

Masonry infill walls are often used as non-structural elements. According to the past structural failure, ignorance of interaction between infill walls and enclosed frame may lead to the different seismic response for non-ductile building frames. The main contribution of this paper is to analytically investigate the behavior of reinforced concrete with masonry infill panels as participating structural. In doing so, a finite element model based on an equivalent strut method is conducted to represent the behavior of masonry panels. The strut model is calibrated using the results of the companion experimental program, which examined the cyclic behavior of infill panels with and without FRP sheets. Accordingly, a nonlinear spring element and a shell element are used to simulate the behavior of masonry strut elements and FRP sheets, respectively. The nonlinear static analysis (Push over analysis) is accomplished using SAP2000 [1] structural analysis software for a 10-story building with FRP sheets subjected to the gravity and lateral loading. The results indicate that the analysis method provides accurate estimation of structural response for both unretrofitted and retrofitted frames. Also, it was observed that although the FRP sheets increase the strength and stiffness of structures substantially, structural ductility remain without any considerable variation. Therefore a seismic retrofit strategy involving FRP sheets must be based on elastic response during strong earthquakes.

Keywords: *Masonry infill; FRP sheet; Retrofit; Reinforced concrete; nonlinear analysis; seismic loading; finite element model*

1. Introduction

Masonry panels are widely used as interior portions and exterior panels for frame structures. They are can be considered as non-structured elements, and their interaction with the bounding frame is often ignored in design. Many R/C frame buildings were designed to with no sufficient ductility and drift control. They often have masonry infill walls that were not designed as part of the lateral load resisting system. Infill walls expose more stiffness and flexibility to the frame by distributing lateral loads to the other parts of the building. Therefore, ignorance of the interaction of these panels with frame may substantially reduce the strength and stiffness of building. Since these walls are usually brittle, therefore, they may not reckon as a seismic resistant structural element. However, when infill panels used properly, they can provide seismic resistance-ability. These panels not only may contribute to increase of strength and stiffness, but also may provide energy absorption. If damage to panels is not serious, energy absorption may be achieved. Obviously, effective seismic retrofit technique for masonry infilled frames should aim at decreasing damage to masonry materials. It should be the critical earthquake out of the consideration of this paper [2-3].

Binici et al. [4] conducted a practical study to investigate the influence of FRP strengthened infill walls on inter-story deformation. In their study infill walls were integrated to the boundary frame members using FRP anchors. They found that the FRP retrofit decrease the damage induced to columns by means of controlling story deformations. ALmusallam and Al-Salloum [5] experimentally investigated the influence of FRP strengthened infill walls subjected to the in-plane seismic loading for concrete frames. They

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observed that that using FRP strengthen enhance deformation capacity and increase the integrity of the frames. Lunn and Rizkalla [6] conducted an experimental study to evaluate the out-of-plane resistance of infill walls subjected to the tornado pressure using FRP anchorages (Ozbakkaloglu and Saatcioglu [7]). Their observations showed that the load carrying capacity of the concrete frames increase when appropriate anchorage of the FRP laminate is provided. El-Sokkary and Galal [8] performed the experimental study to propose the retrofit schemes for enhancement of the flexural and shear capacities of wall panels. It should be noted that the safety level of all structural member and system should be clearly specified. A new generation of the reliability index is one of the proper measures to evaluate the safety level of the system which was proposed by Ghasemi and Nowak [9-10]. To do so, the resistance and loading of the system should statistically collected [11-12]. The optimum level of the reliability of the system should also calculate based on the optimization or engineering judgment [13-14].

In this study, in order to succeed in the seismic retrofit of a building, a new method is developed using FRP sheets. FRP sheets are formed by combining epoxy-based components. They are easy to apply, with minimum destruction in old building.

An experimental study was accomplished at University of Ottawa by Serrato [15]. This study included laboratory tests of two-half-scale specimens. The test specimens consisted of two identical reinforced concrete frames infilled with unreinforced masonry walls. Due to the lack of confinement reinforcement in the column and potential plastic hinges in the beam, one specimen was retrofitted with epoxy-bonded FRP sheets. Both specimens were tested under reversed cyclic loading, with a constant gravity load applied on the columns and beam [see Figure 1].

The cyclic load–displacement hysteretic relationships for two specimens are shown in Figure 2.

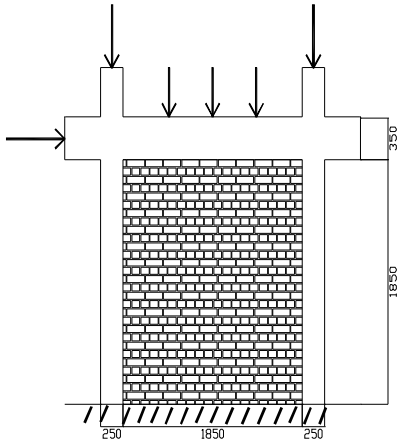


Figure 1. Applied loads in each specimen

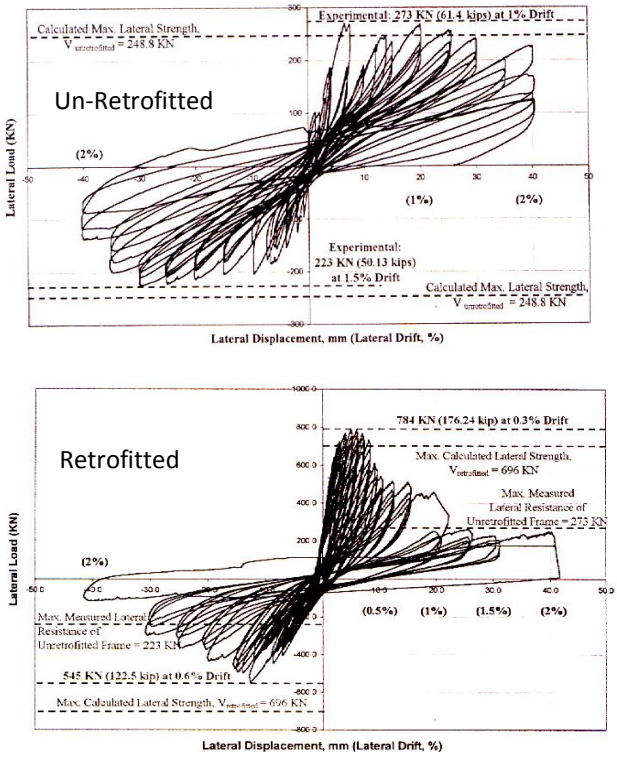


Figure 2. Time history curve for un-retrofitted and retrofitted specimen

The hysteretic relationships show that the maximum lateral strength for unretrofitted frame is 273 KN at 1% lateral drift while for retrofitted frame is 784 KN at 0.3 % laterals drift. In other words, using 2 plies FRP sheet in each side of masonry panel, placed diagonally, may result in substantial improvements in lateral strength of frame approximately by three times. In this experiment, it was observed that FRP sheets

increase stiffness and strength but not ductility. Considering Figure 2, the retrofitted specimen developed substantial gains in stiffness and strength, but lost the extra strength provided by FRP at about 0.5% lateral drift. So for unretrofitted frame, the load resistance leveled off beyond 0.5 % lateral drift and approximately remained at the same level until about 1.75 %. With respect to experimental results, the maximum tension stress in diagonal direction of FRP sheets was about 100 MPa that in comparison to ultimate tension stress in FRP sheets, 700 MPa, is small and the failure happened because of delaminating of FRP sheets in surface of frame.

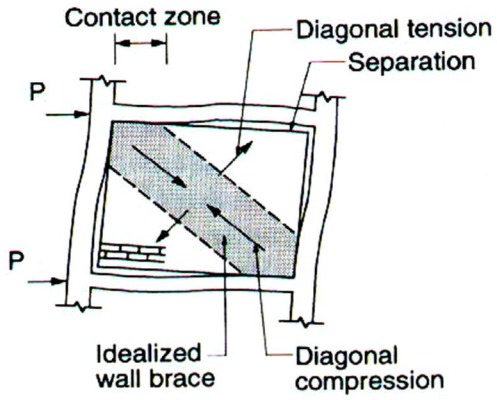
The experimental investigation indicates that FRP sheets can be used to retrofit masonry infill panels in reinforced concrete frame structures. Both masonry and FRP sheets are brittle materials and the combination should not be expected to result in improved ductility. This implies that a seismic retrofit strategy of unreinforced masonry with FRP sheets should be directed to improving the elastic capacity of the member beyond the elastic seismic force demand.

In this paper a numerical study is conducted to investigate the behavior of reinforced concrete with masonry infill panels as participating structural. Based on an equivalent strut method a finite element model is created to exhibit the behavior of masonry panels. The strut model is calibrated using the mentioned study by Serrato [14] as the fundamental simulation verification for current research. The nonlinear static analysis (Push over analysis) is lunched using SAP2000 structural analysis software for a 10-story building with FRP sheets subjected to the gravity and lateral loading. A nonlinear spring element and a shell element are used to simulate the behavior of masonry strut elements and FRP sheets, respectively.

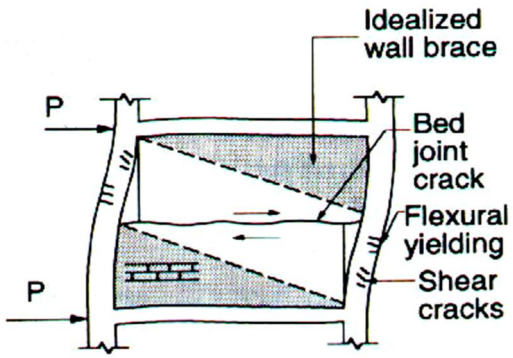
2. Analytical simulation and its verification

2.1 Expected behavior of infill panel

Most of the infill frames building consist of two lateral resisting systems that involve the bare frame and infill panels. Since infill panels are constructed separately, the behavior of infill panel is not the same as shear wall. The interaction mechanism between infill panels and the confined frame depends on the contact area between two components. Two interaction mechanisms can be developed for infill walls [see Figure 3]. Figure 3-a shows a diagonal compression strut behavior within the frame for masonry wall that converts the structural system to a type of truss. Alternatively, the wall may behave as a knee-braced system with sliding shear failure of the masonry infill, as shown in Figure 3-b.



(a) Compression strut



(b) Knee brace

Figure 3. Deformation and failure modes of infilled frames

Consequently; infill panel behavior was not expected for the mentioned type of building. Concerning, it is important to avoid the knee-brace failure system. The simplest and most common approach to model is to use an equivalent diagonal brace element that replaced to masonry infill walls (Stafford Smith [15-16], Holmes [17], and Mainstone [18]). Holmes [19] has stated that the effective width of an equivalent strut primarily depends on the thickness and the aspect ratio of the infill and also, he recommended a width equal to one-third of diagonal length of the panel for strut element. Stafford Smith [20] used an elastic theory to show that this width should be a function of the stiffness of the infill with respect to that of the

bounding frame. Analytically, he has defined a dimensionless relative stiffness parameter to determine contact lengths of wall with beam (αL) and column (αh) (see Figure 4).

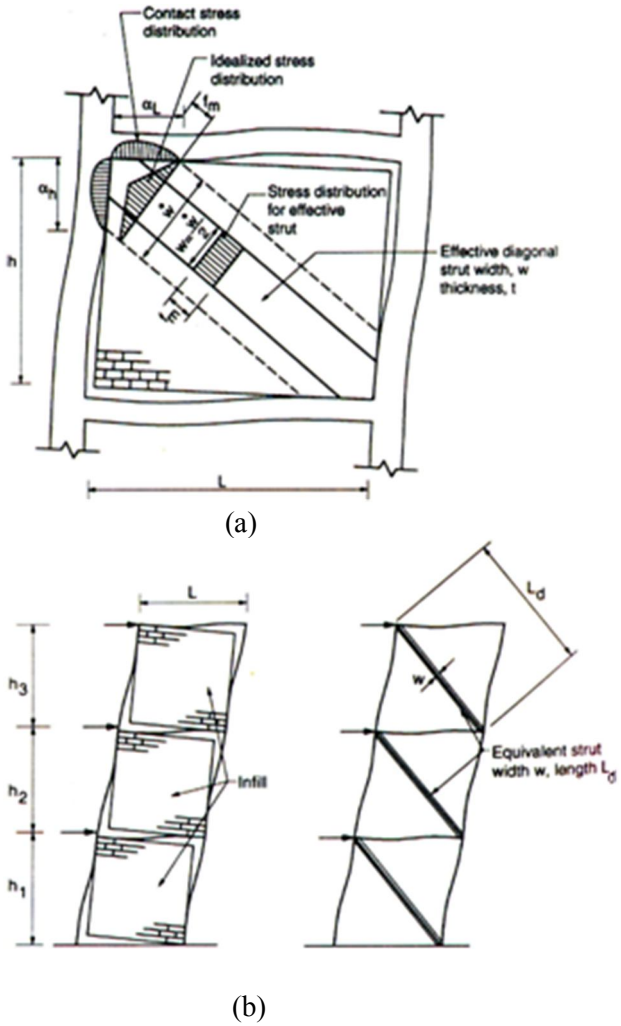


Figure 4.(a) Equivalent diagonal strut, (b) Equivalent diagonal strut method

The following equations are proposed to αh and αL:

$$\alpha_h = \frac{\pi}{2}\sqrt[4]{\frac{4 E_f I_c h}{E_m t \sin 2\theta}} \qquad (1)$$

$$\alpha_L = \pi \sqrt[4]{\frac{4 E_f I_b L}{E_m t \sin 2\theta}}$$

In which Em and t are the elastic modulus and thickness of the infill, EfIb and EfIc are the bending stiffness of the beam and the column, and h, L and θ are the height, the length and the angle between the diagonal and horizontal of the infill. Hendry [21] proposed the following equation to determine the equivalent strut width w, where the strut is assumed to be subject to uniform stress:

$$\omega = \frac{1}{2}\sqrt{\alpha_h^2 + \alpha_L^2} \qquad (2)$$

2.2 Expected behavior of FRP sheets

When FRP sheets with combining epoxy resin form a composite material are used on the surface of building, there is need for several deliberations such as using anchor in the beam and column that prepare enough cohesion between FRP sheets and surface of building. This fact implies that there is no buckling for FRP sheet layers in the surface of building. As a result, it can be predicted that FRP sheet can be behaved similar to shear wall. Therefore, it can be recommended that the FRP sheet should be modeled as a shell element in two dimension model or frame element in one dimension model. Regarding this behavior in actual model, shell element can represent more accurate results in comparison with bar element.

2.3 Analysis method

In order to numerically analyze of the specimens, Finite Element Method (FEM) is lunched. SAP2000 program has enough capability for modeling the concrete frame, strut and FRP sheets (1998). SAP2000 includes several nonlinear spring elements that can be utilized for nonlinear analysis. One of them is Nlplastic element that its nonlinear behavior was shown in Figure 5. Push over analysis for frame element can be preceded using SAP2000.

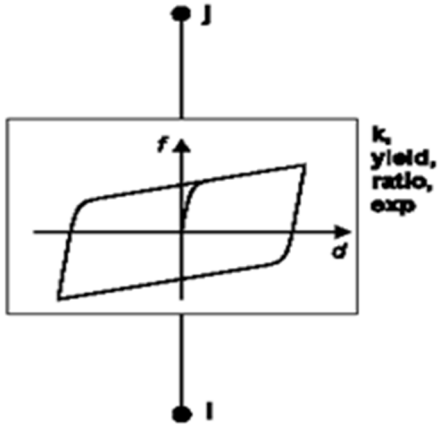


Figure 5. Nonlinear behavior of Nlink element (Plastic1)

In push over analysis, for each frame element the plastic hinge property is defined. General behavior of force-deformation in push over analysis is shown in Figure 6.

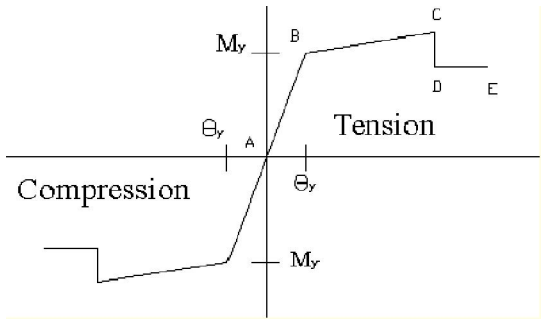


Figure 6. Flexural behavior of frame element

For concrete frame in Figure 6, the yield deflection is assumed to be zero and its slope is considered between point B and C by 10% total strain hardening for steel. Also, points C, D and E are based on ATC-40. The shell element in SAP2000 is used for modeling the shell, membrane, and plate behavior in planar and three-dimensional structures that is a three- or four-node formation. It is worth mentioning that the isotropic material property is only used for shell and frame element.

3. Modeling of specimens

For modeling each specimen, the frame element, nonlinear spring element and shell element are used for concrete frame, masonry strut element, and FRP sheets. The material properties and sectional properties of each element are shown in Table 1 and Table 2 that was resulted from experimental program by Serrato [14].
Regarding the nonlinear behavior of equivalent masonry strut element, the strength of element and force-deformation curve is necessary to model the nonlinear spring element. The compression strength (Rs) to initiate horizontal shear sliding depends on the shear bond strength of masonry and the aspect ratio of the panel. The following equation adopted from Paulay and Priestley [22], was used:

Table 1. Material Property

Type	*Compressive strength (MPa)*		*Tensile strength (MPa)*	*Modulus of elasticity (MPa)*
	Un retrofit	Retrofit		
Concrete	41.46	35.9	-	26000
Masonry	12.8	13	-	6400
Steel	-	-	425	212000
FRP sheet	-	-	700	61000

Table 2. Sectional Property of infilled frame specimen (mm)

Element type	Frame Section and Reinforcement		Thickness
	Top	Bottom	
Beam	350X250		-
	3#15	2#15	
Column	250X250		-
	8#15		
FRP Sheets (4layers)	-	-	3.9

$$R_s = \frac{\tau_0 \omega t}{[1 - \frac{\mu h}{l}]} \qquad (3)$$

Values for the constants τ0 and μ vary based on the test method and type of masonry material. From experimental program, 0.02f'm and 0.3 are taken for τ0 and μ that f'm is the compressive strength of masonry wall. The results from most compression tests indicate a sudden brittle failure shortly after reaching the ultimate strain. With respect to the mentioned behavior, the nonlinear compression load-displacement for strut element is shown in Figure 7.

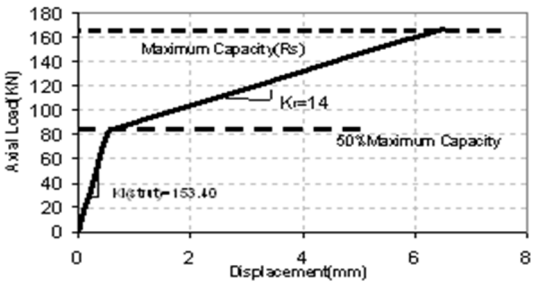
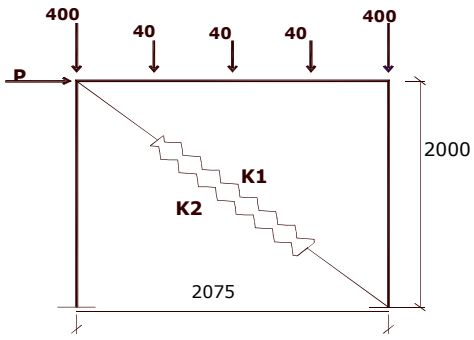
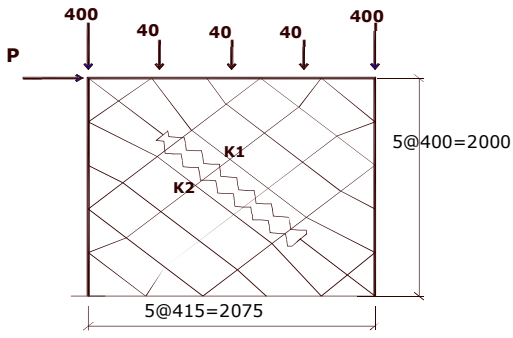


Figure 7. Equivalent behavior of strut element

As indicated, equivalent masonry strut element has linear behavior prior to 50% of strength. In order to model this behavior, two nonlinear spring elements, K1 and K2 are considered and more details of their geometry properties are shown in Figure 8-a. The details of FEM model for each specimen are shown in Figure 8.



(a) Unretrofitted



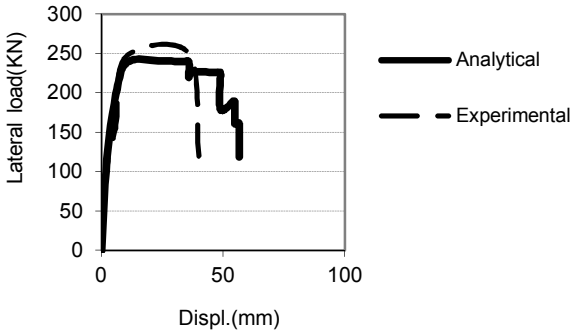
(b) Retrofitted frame

Figure 8. FE model for unretrofitted and retrofitted frame [All dimension (KN-mm)]

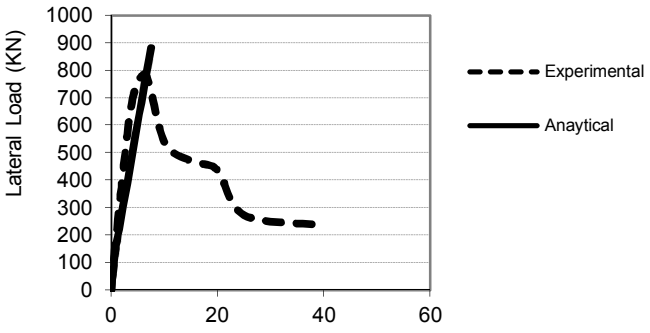
Since FRP sheets were used in diagonal direction, therefore, the meshing of shell elements in Figure 8-b is selected diagonally.

4. Verification

The results of push over analysis for two models are shown in Figure 9 in compare to experimental results. The unretrofitted model has an acceptable accuracy rather than experimental results and the system fail at the point of failure in the test as shown in Figure 9-a.

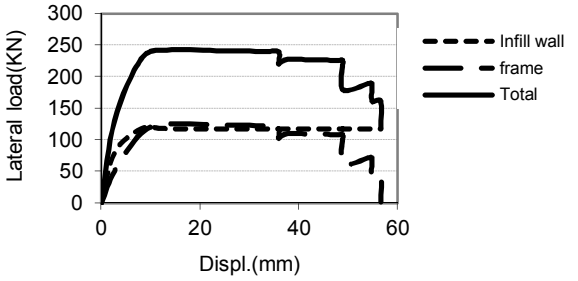


(a) Unretrofitted

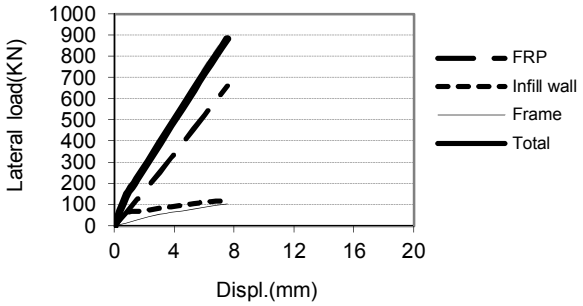


(b) Retrofitted infill frame

Figure 9. Comparison of analytical and Experimental results



(a) Un-retrofitted infill frame

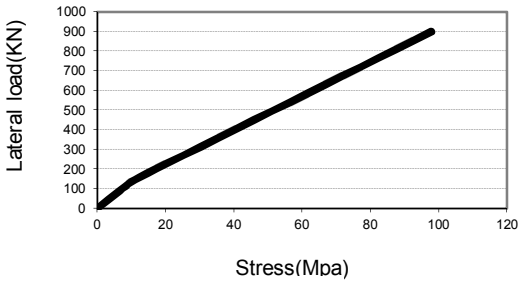


(b) Retrofitted infill frame

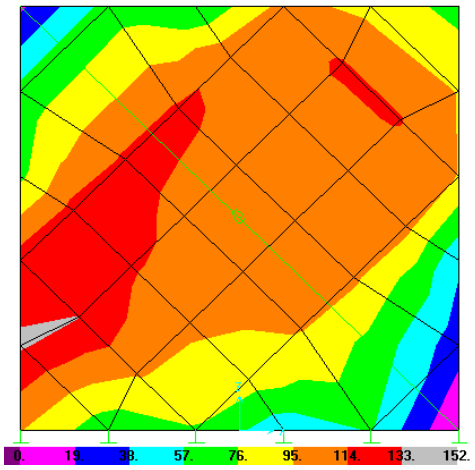
Figure 10. Load participation of each part

Because of elastic behavior of shell element, the retrofitted model behaves only in linear region of experimental results. Participation of frame, infill wall, and FRP sheets in bearing the lateral load is shown in Figure 10.

As shown in Figure 10, the participation of frame and infill wall are equal, while for FRP sheet, this is more than other parts. The maximum strength for frame and infill is about 130KN so this strength for FRP sheet is about 600KN. In other words, the retrofitted frame strength is about three times of unretrofitted frame strength that more than 70% of this strength is because of FRP sheets. The stress distribution in retrofitted model is shown in Figure 11-a. Since the maximum stress in central shell element is 100MPa from experimental results at failure, the Lateral load-stress curve in this element is shown in Figure 11-b that in 100MPa stress, the lateral load is about 850KN, equal to 600KN for FRP sheets in Figur10-b.



(a)



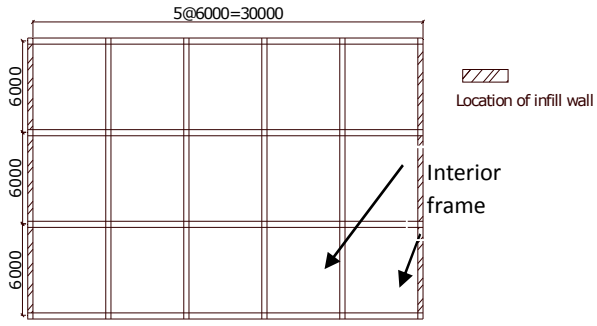
(b)

Figure 11. (a). Lateral load-Stress curve in central shell element, (b) Maximum stress distribution in FRP shell element

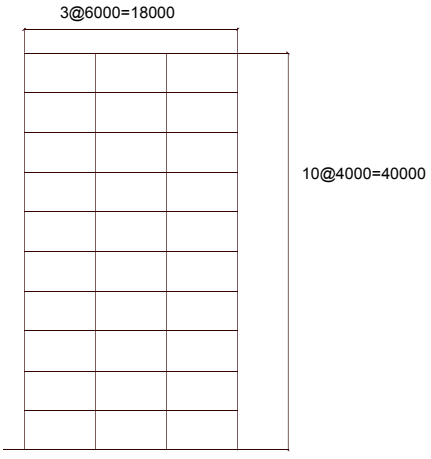
Regarding analytical and experimental results, the special FE models have rational accuracy for both unretrofitted and retrofitted frames. The behavior of FRP sheets in spite of masonry infill panel performes in two directions similar to thin shear wall, which only enhance the strength and stiffness of structure without increasing the ductility. In fact, the retrofitted infill frame is not as a ductile frame but the strength only increases substantially. Since the maximum stress in FRP element is low rather than the ultimate stress, 700 MPa, it implies that the elastic behavior assumption for FRP material is correct and using the linear shell element brings adequate accuracy in results.

5. Behavior of R/C Frames with Strengthened Infill Panels

As it was observed, FRP sheets could be modeled with shell element using FEM analysis. Since the effects of this material on stiffness and strength of structure are important, thickness and aspect ratio of FRP materials are considered as the most vital factors. In this study, response of building subjected to several variables such as the number of FRP sheet plies, number and location of FRP strengthened panels are evaluated. Herein, a 10-story building subjected to gravity and earthquake loads is considered for retrofit system analysis. The elevation of the panel is shown in Figure 12 and the details of sectional properties for frame elements are shown in Table 3.



(a) Plan



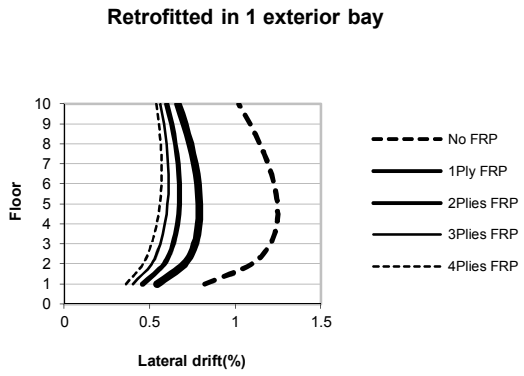
(b) Elevation

Figure 12. 10-story building subjected to retrofit system (All dimension, mm)

Table 3. Sectional dimensions of 10-story frame building (mm)

Frame	Floor	Beam section	Column section	
			Interior	Exterior
Interior	1-5	300x450	500x500	450x450
	6-9	300x450	500x500	450x450
	10	300x400	500x500	450x450
Exterior	1-5	300x450	400x400	350x350
	6-9	300x450	400x400	350x350
	10	300x400	400x400	350x350

The exterior frames are subjected to strengthened infill panels. One to four plies of FRP sheet are used to investigate the building behavior. Also, the bay number of infill walls is changed from one to three bays at exterior frames. In order to investigate stiffness and strength of structure, lateral drift and inter-story drift are taken as two major criteria for comparison of analysis results according to variable parameters. Lateral drift is defined as the ratio of lateral displacement of each floor to height of floor from basement. The inter-story drift is defined as the ratio of inter-story displacement to height of floor (4000 mm). Lateral drift is directly related to stiffness of structure while inter-story drift indicates amount of internal force and strength of frame elements. Comparison of lateral drifts with respect to number of FRP sheet ply is shown in Figure 13.



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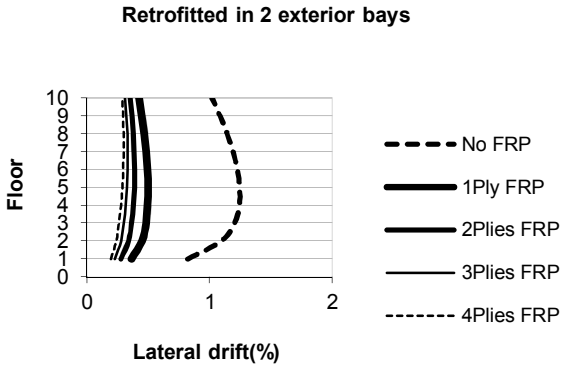

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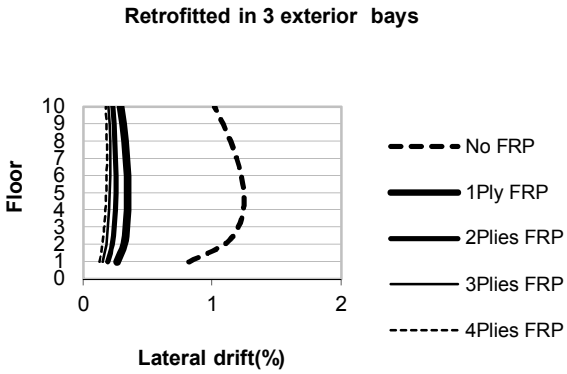


(c)

Figure 13. Comparison of lateral drifts with different bays and plies

The first ply has the most important effect to reduce displacement of structure. So with increasing the number of FRP ply, the lateral drift reduces in lower rate than the first laminate. Figure 14 shows the variation of inter-story drift with elevation for four different thicknesses of FRP sheets.

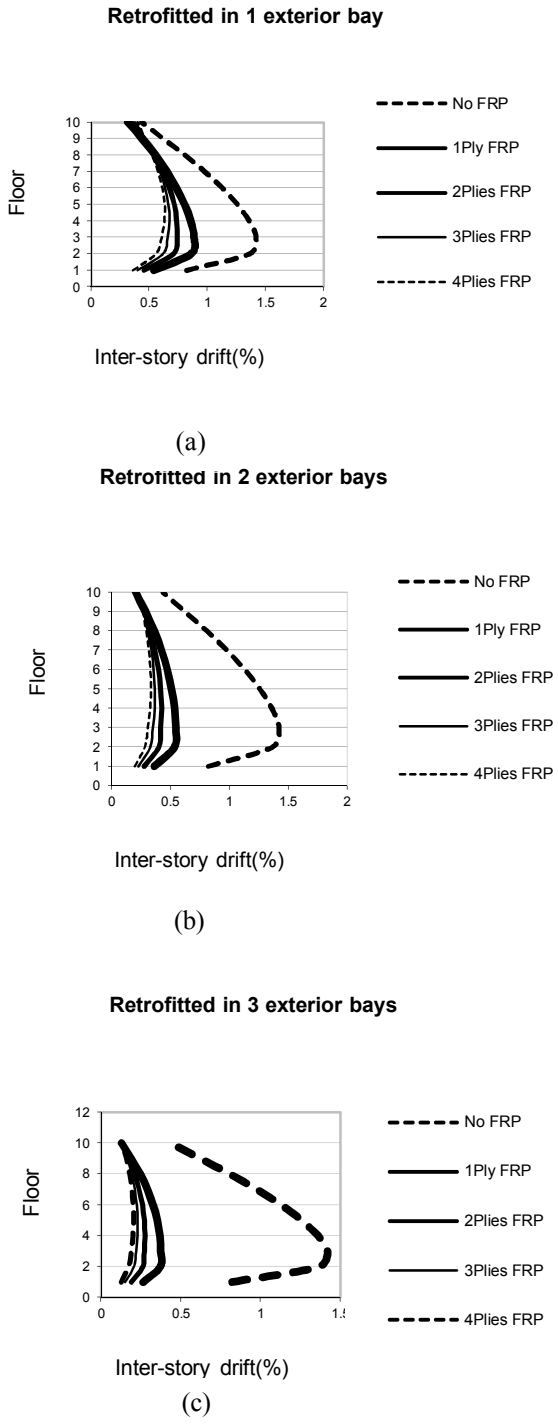


Figure 14- Comparison of inter-story drifts with different bays and plies

The maximum inter-story drift is at third floor while the maximum lateral drift from Figure 13 appears at fifth floor. This indicates that the critical floor for controlling the maximum internal force is third floor and fifth floor has the maximum lateral displacement. Also, inter-story drifts at top floor are the same. In other words, by increasing the thickness of FRP sheet, there is no substantial reduction in inter-story drift at top floor. Figure 15 shows the variation of inter-story and lateral drift against to the number of FRP plies at top floor and maximum drift floor (third floor for inter-story and 5th floor for lateral drift) of building that retrofitted at three exterior bays.

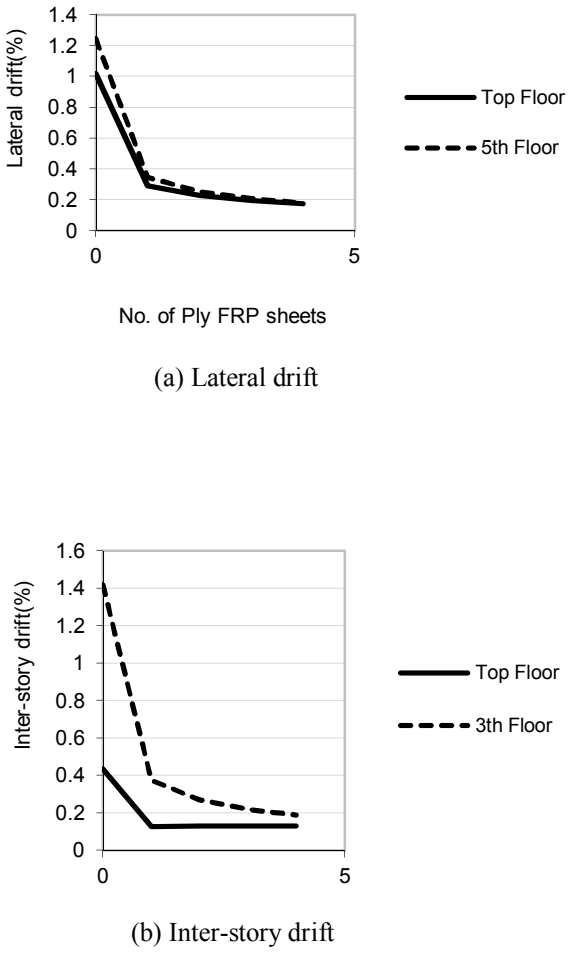
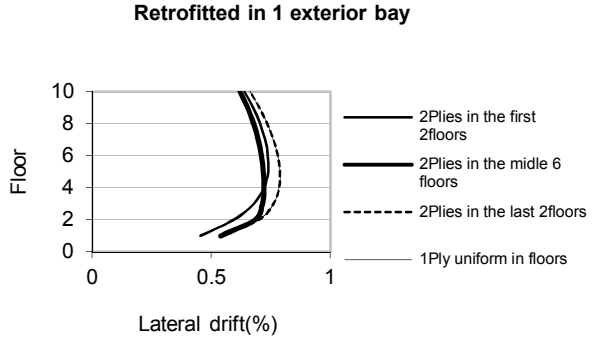


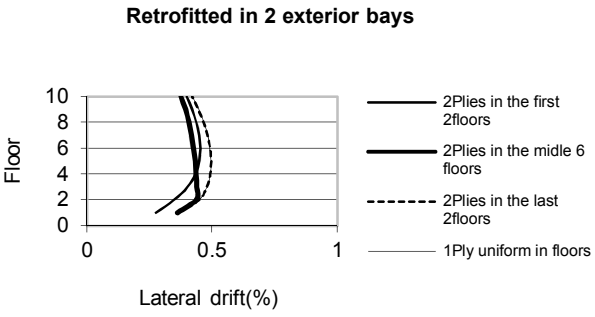
Figure 15. Effect of FRP thickness on drift (Uniform retrofitted at 3bays)

Place of thick layer of FRP sheet in elevation of structure is the other variable parameters. Two

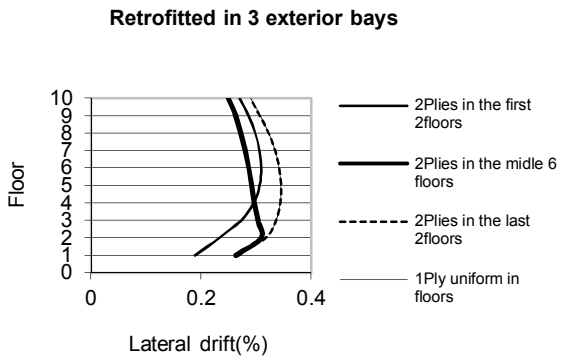
plies of FRP sheet are taken at the three-elevation region of building and the other floors have one ply uniform FRP sheet. The first region involves two first floors of basement, the second region is six-middle floors and the third region includes two top floors. The results of these analyses for 1st, 2nd and 3rd exterior bays are shown in Figure 16. The greatest effect of reduction on lateral drift appears when two layers of FRP sheets are used to the 6 middle floors. As indicated in Figure 16, response of structure with two layers of FRP sheet at two top floors is the same as behavior of structure with one uniform layer of FRP sheet.



(a)



(b)



(c)

Figure 16. Variation of FRP ply at elevation with different bays

The last variable parameter is the location of strengthened walls in interior frames. As it is shown in Figure 17, when the location of infill walls is changed to middle frames, with one ply of FRP sheet at one or two bays, there is insignificant variation on lateral drift. In other words, the change at location of infill walls has the same behavior as the exterior frame.

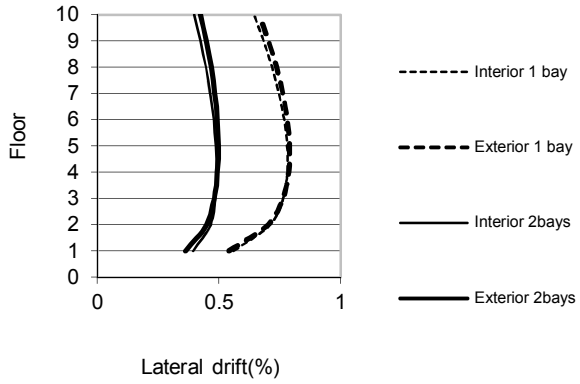


Figure 17. Effect of interior bay and exterior bay

6. conclusions

In this study, a simulation of strengthened infill panels with FRP sheet was created using nonlinear finite element analysis. An equivalent strut element was considered to model infill panel. Since the behavior of FRP sheet is completely elastic; therefore, a shell model in two dimensional elements was applied for FRP sheets simulating. The analytical results were calibrated using results from a separate experimental program which examined the cyclic behavior of retrofitted infill panels with FRP sheets. The SAP2000 program was lunched for push over analysis of an infilled frame.

A 10-story building was subjected to strengthened infill panels under gravity and earthquake load. Some variable parameters such as the number of FRP sheet layers, number and location of FRP strengthened walls were considered in order to evaluate the strength and stiffness of structure. The results were observed as follows:

1. In order to model an appropriate masonry infill walls using SAP2000 program, two nonlinear spring elements can be sufficient. Furthermore, a FRP sheet material can be simulated as a two-dimensional shell element using elastic isotropic material property.

2. FRP sheets substantially increase the strength and stiffness of structure, which leads the behaviors of structure to the brittle building with no extra ductility. The greatest effect on reducing of inter-story and lateral drift stems from the first layer of FRP sheet.
3. It was observed that by increasing the thickness of the FRP sheet, the story-drift reduces and the reduction rate move to zero in upper layers. Moreover, the thickness of FRP sheet at the middle floors plays an important role to reduce the inter-story drift rather than the first and top floors.
4. Using more bays of strengthened wall, the lateral drift and inter-story drift decreases. Changing the location of strengthened wall from exterior frame to interior frame, there is no difference between the results.

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