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 and their interaction with the enclosing frame is usually ignored in design. The contribution of these elements to seismic response of non-ductile building frames has been the cause of many structural failures in the past. The behavior of reinforced concrete with masonry infill panels as participating structural element has been investigated analytically. A finite element model based on an equivalent strut method was used to represent the behavior of masonry panels. The strut model was calibrated using the results of the companion experimental program, which examined the cyclic behavior of infill panels with and without FRP sheets. A nonlinear spring element and a shell element were used to simulate the behavior of masonry strut elements and FRP sheets, respectively. Nonlinear static analysis (Push over analysis) was employed using SAP2000 structural analysis software. A 10-story building, strengthened with FRP sheets, was analyzed under gravity and lateral loading. The results indicate that the analysis method provides reasonably accurate estimates of structural response for both unretrofitted and retrofitted frames. FRP sheets increase the strength and stiffness of structures substantially, but are unable to improve structural ductility. Therefore; a seismic retrofit strategy involving FRP sheets must be based on elastic response during strong earthquakes.

Keywords: Masonry infill panel; FRP sheet; Retrofit; R/C Frame; Nonlinear analysis; Seismic loading;

1. Introduction

Masonry panels are widely used as interior portions and exterior panels in frame structures. They are usually considered as non-structured elements, and their interaction with the bounding frame is often ignored in design. Many R/C frame buildings were designed prior to the enactment of seismic design codes and hence lack 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 can stiffen a flexible frame and change the distribution of lateral loads to the other parts of the building. Therefore, ignoring 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 reach a suitable behavior as a seismic resistant structural element. Infill panels can provide seismic resistance capabilities when used properly; 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. In order to succeed in the seismic retrofit of a building, a new method is being developed using FRP sheets. FRP sheets are formed by combining epoxy-based components. They are easy to apply, with minimum destruction in old building.

2. Experimental observations

An experimental study was done at University of Ottawa by F.Serrato and M.Saatioglu [1]. 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. These specimens were designed based on the prior enactment code to the development of seismic provisions in building code of particular importance was 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 constant gravity load applied on the columns and the beam [see **Figure 1**].

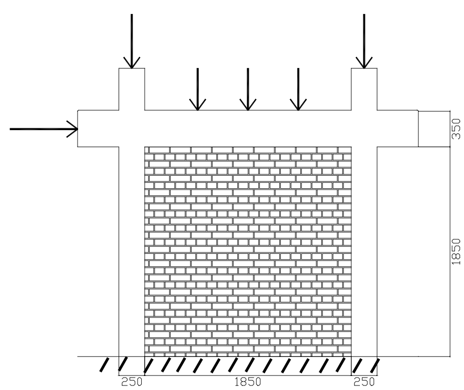


Figure 1- Applied loads in each specimen

The cyclic load–displacement hysteretic relationships for two specimens are shown in **Figure 2**. 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 a factor of 3. 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 due to 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.

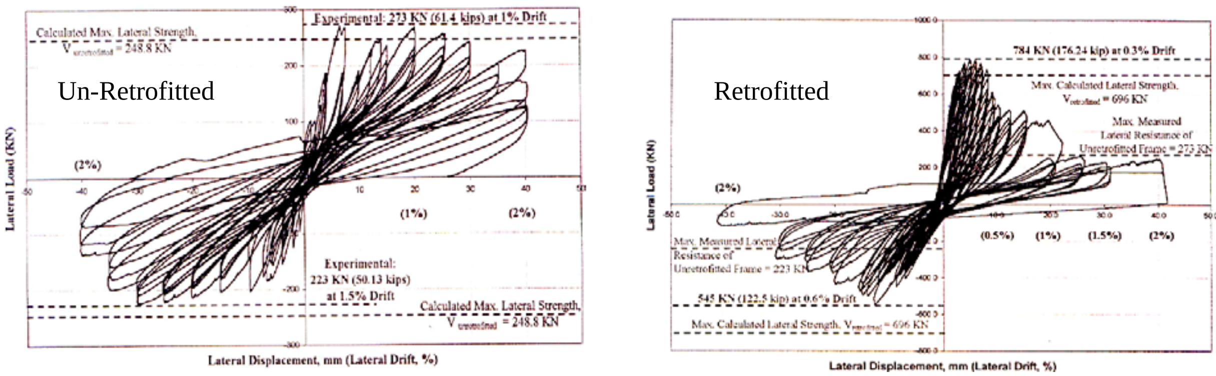
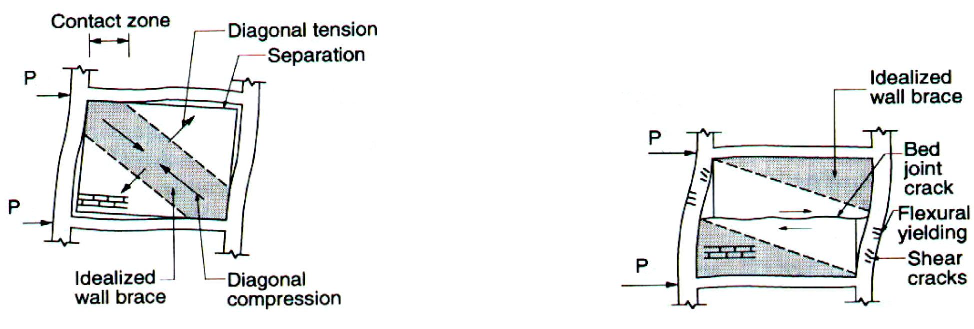


Figure 2- Time history curve for un-retrofitted and retrofitted specimen

3. Analytical simulation and its verification

Expected behavior of infill panel: Each infill frame building has two lateral resisting systems that involve the bare frame and infill panels. Since infill panels are constructed separate of the frame, 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 expectable for this type of building. Concerning, it's important to avoid the knee-brace failure system. The simplest and most common approach to model is the use of an equivalent diagonal brace element that replaced to masonry infill walls [2-6]. Holmes [3] has proposed that the effective width of an equivalent strut depends primarily 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 [7]. Stafford Smith [4] 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. By analogy to a beam on elastic foundation, he has defined a dimensionless relative stiffness parameter to determine contact lengths of wall with beam (α_L) and column (α_h) (see **Figure 4**). The following equations are proposed to α_h and α_L:

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

In which E_m and t are the elastic modulus and thickness of the infill, $E_f I_b$ and $E_f I_c$ 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 [8] proposed the following equation to determine the equivalent strut width w, where the strut is assumed to be subject to uniform stress:

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

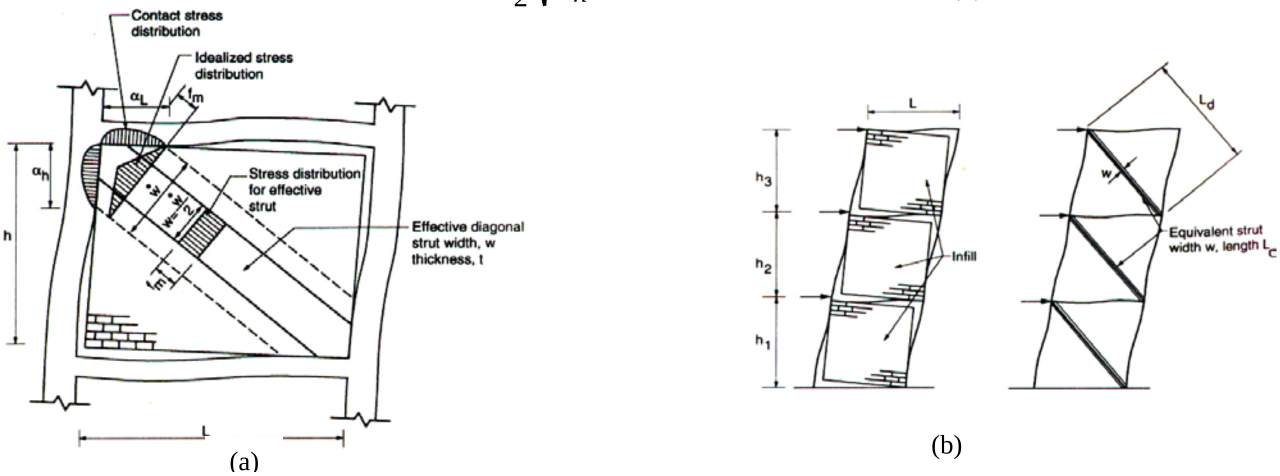
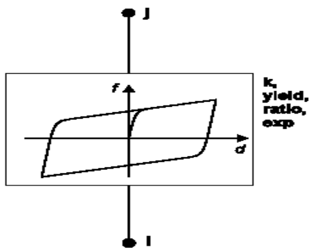


Figure 4- a) Equivalent diagonal strut b) Equivalent diagonal strut method

Expected behavior of FRP sheets: FRP sheets with combining epoxy resin form a composite material. When it is used on the surface of building, there are some considerations such as using anchor in the beam and column that prepare enough cohesion between FRP sheets and surface of building. It implies that there is no buckling for FRP sheet layers in the surface of building. As a result, it's predicted that FRP sheet had been a behavior similar to shear wall. This means that 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, using shell element has more accuracy in compare to bar element.

Analysis method: Finite Element Method (FEM) is used for the analysis of each specimen. Considering this method, the SAP2000 program has enough capability for modeling the frame, strut and FRP sheets [11]. The SAP2000 has some nonlinear spring elements that can be used 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 done by SAP2000. In push over analysis, each frame element has plastic hinge property in each joint. General behavior of force-deformation in push over analysis is shown in **Figure 6**. For concrete frame in **Figure 6**, the yield deflection is assumed zero and slope between point B and C is taken as 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. Isotropic material property is only used for shell and frame element.



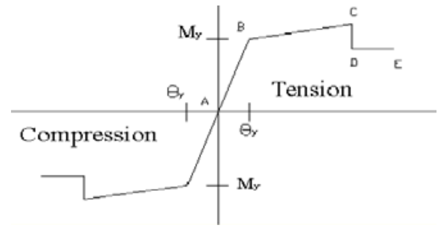


Figure 5- Nonlinear behavior of Nlink element **Figure 6- Flexural behavior of frame element**

Modeling of specimens: For modeling each specimen, the frame element, nonlinear spring element and shell element are used to 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 [1]. Regarding the nonlinear behavior of equivalent masonry strut element, the strength of element and force-deformation curve is necessary for modeling 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 [9]. The following equation adopted from Paulay and Priestley (1992), was used:

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

TABLE-1 MATERIAL PROPERTY

Type	*Compressive strength (Mpa)*		*Tensile strength (Mpa)*	*Modulus of elasticity (Mpa)*
	Unretrofit	Retrofit		
Concrete	41.46	35.9	-	26000
Masonry	12.8	13	-	6400
Steel	-	-	425	212000
FRPsheet	-	-	700	61000

Values for the constants τ_0 and μ vary with test method and type of masonry. From experimental program, 0.02f'$_m$ and 0.3 are taken for τ_0 and μ that f'$_m$ is the compressive strength of masonry wall. For masonry material like to concrete, the nonlinear behavior beyond about 50% of the peak stress is evident. The results from most compression tests indicate a sudden brittle failure shortly after reaching the ultimate strain [10]. With respect to this behavior, the nonlinear compression load-displacement for strut element is shown in **Figure 7**. As indicated, equivalent masonry strut element has linear behavior prior to 50% of strength. In order to model this behavior, two nonlinear spring elements, K_1 and K_2 are used and more details of their geometry properties are shown in **Figure 8-a**. The details of FEM model for each

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

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

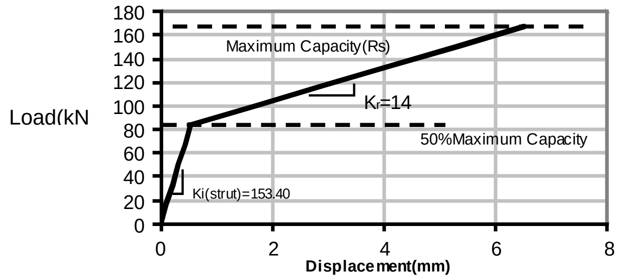


Figure 7- Equivalent behavior of strut

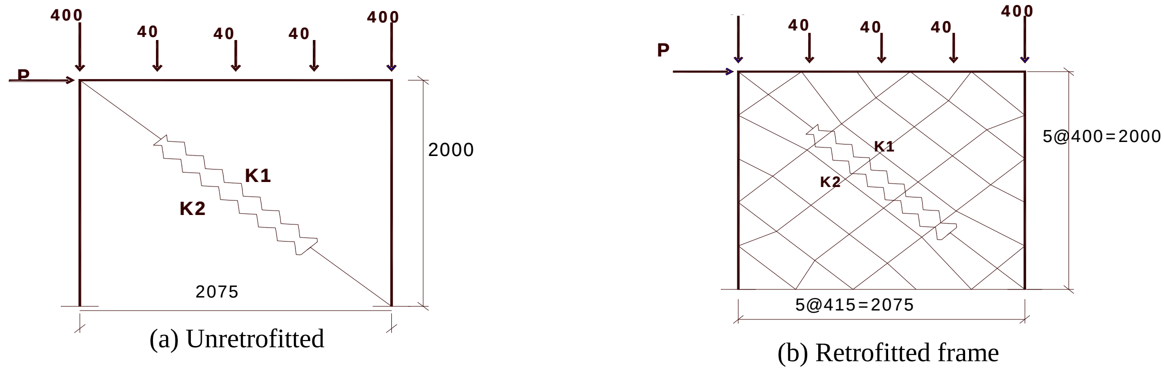
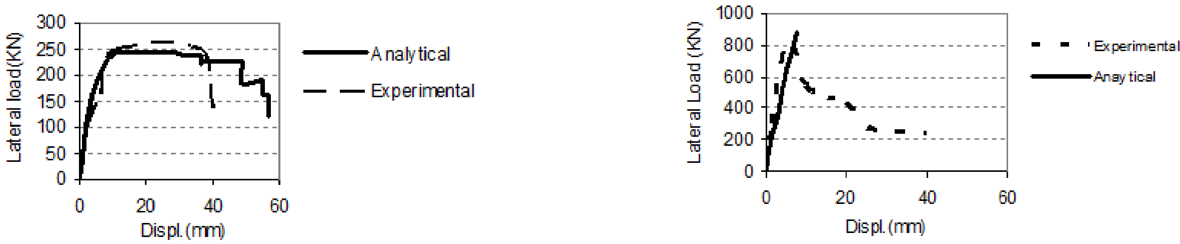


Figure 8- FE model for unretrofitted and retrofitted frame

[All dimension (KN-mm)]

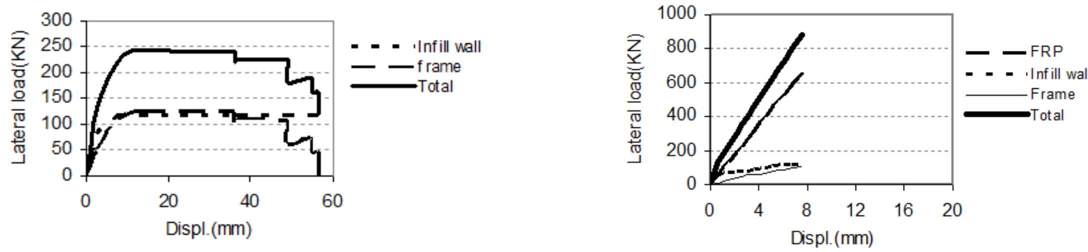
Verification: The results of push over analysis for two models are shown in **Figure 9** in compare to experimental results. The unretrofitted model has good accuracy rather than experimental results and the system fail at the point of failure in the test as shown in **Figure 9-a**. Because of elastic 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 is the same, 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 3times of unretrofitted frame strength that more than 70% of this strength is due to FRP sheets. The distribution of stress 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**. Regarding analytical and experimental results, the special FE models have reasonable accuracy for both unretrofitted and retrofitted frames. The behavior of FRP sheets in spite of masonry infill panel is in two directions similar to thin shear wall that 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 has adequate accuracy in results.



(a) Unretrofitted

(b) Retrofitted infill frame

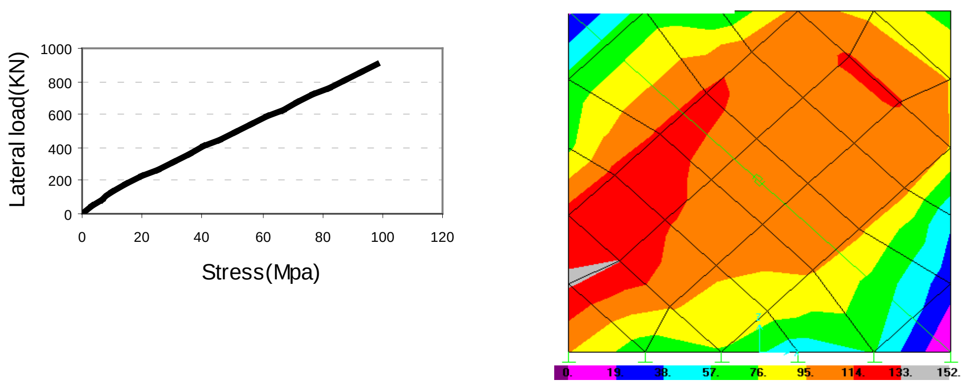
Figure 9- Comparison of analytical and Experimental



a) Un-retrofitted infill frame

(b) Retrofitted infill frame

Figure 10- Load participation of each part



(a)

(b)

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

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

In prior section, it was indicated that FRP sheets could be modeled with shell element with FEM analysis. Considering this behavior, the effects of this material on stiffness and strength of structure are important. Thickness and aspect ratio of FRP materials are the most important parameters that should be considered in analysis. In this section, response of building against some variable parameters such as the number of FRP sheet plies, number and location of FRP strengthened panels are evaluated. With respect to this evaluation, a 10-story building that subjected to gravity and earthquake loads is taken for analysis with retrofit system. The plan and elevation are shown in **Figure 12** and the details of sectional properties for frame elements are shown in **Table 3**.

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

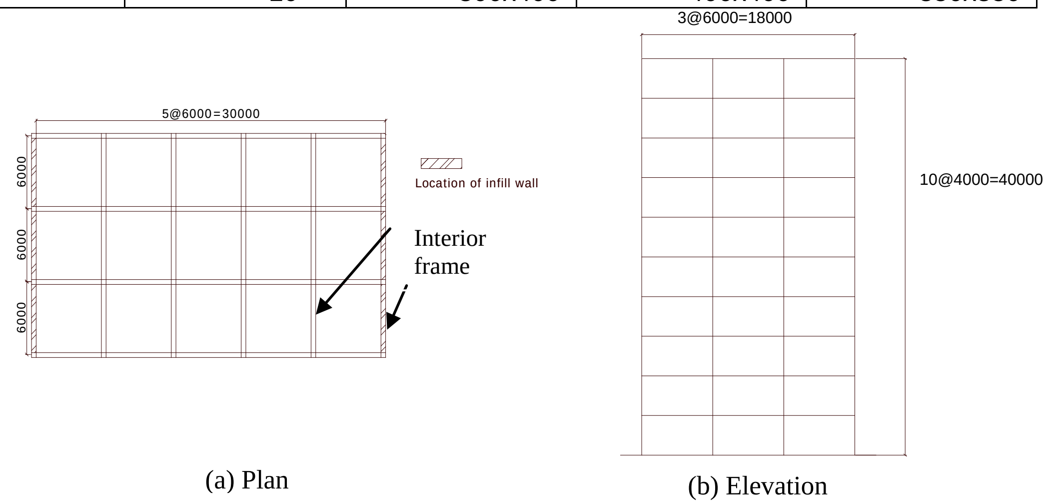
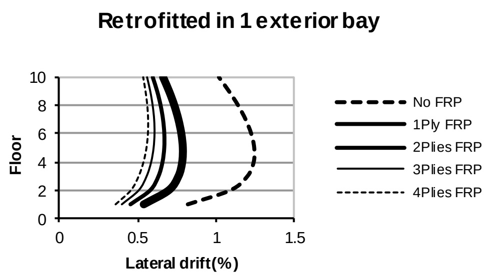
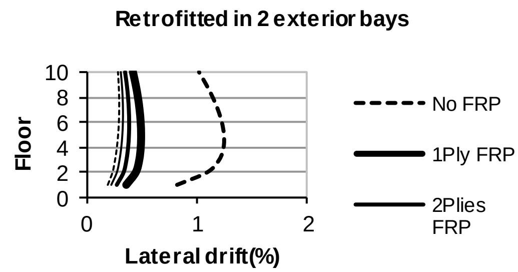


Figure 12- 10-story building subjected to retrofit system (All dimension, mm)

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**. 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. 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, with 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. Place of thick layer of FRP sheet in elevation of structure is the other variable parameters.



(a)



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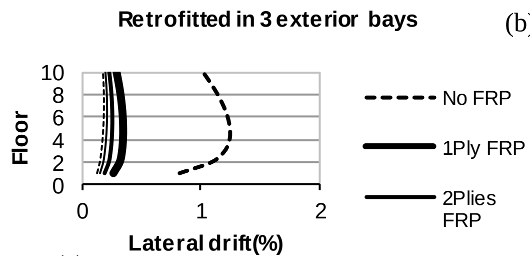
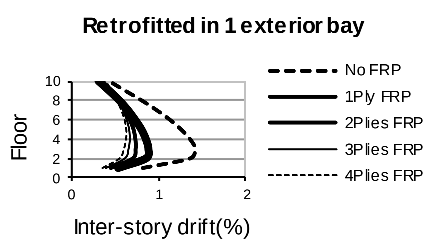


(c)

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



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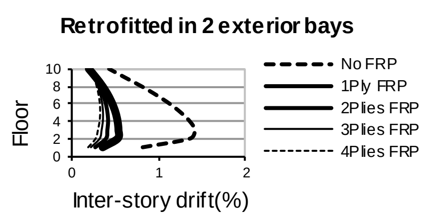

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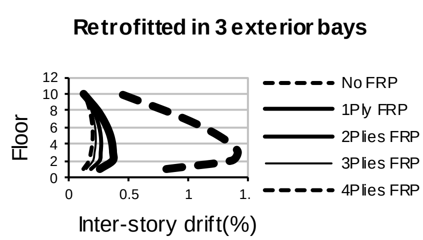
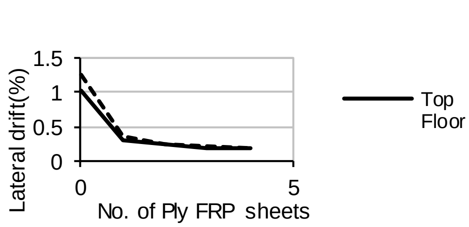
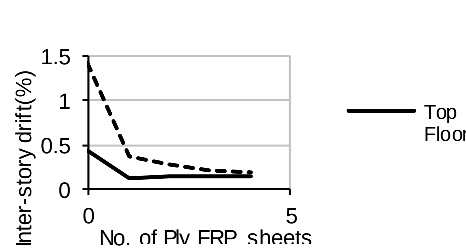


(c)

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



(a) Lateral drift



(b) Inter-story drift

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

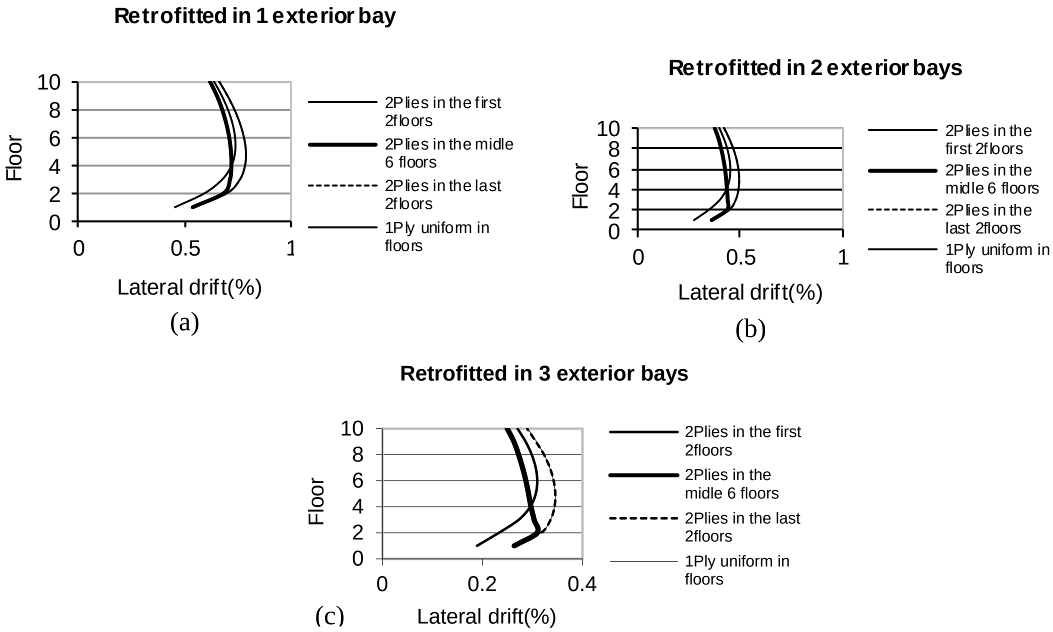


Figure 16- Variation of FRP ply at elevation with different bays

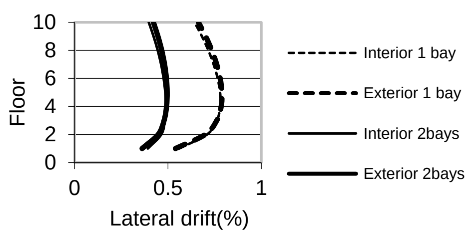


Figure 17- Effect of interior bay and exterior bay

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. 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.

5. Summary and conclusions

Simulation of strengthened infill panels with FRP sheet is proposed in nonlinear finite element analysis. An equivalent strut element is used to model infill panel. Since the behavior of FRP sheet is completely elastic; therefore, a shell model in two dimensional elements is applied for simulating FRP sheets. The analytical results are calibrated using results from a separate experimental program which examined the cyclic behavior of retrofitted infill panels with FRP sheets. The SAP2000 program is applied for push over analysis of infilled frame.

A 10-story building is 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 are taken for evaluation of strength and stiffness of structure as the structural behavior. The following results can be concluded out of current research:

- Masonry infill walls can be modeled with two nonlinear spring elements in SAP2000 program.
- FRP sheet material can be simulated as shell element in two dimensions with elastic isotropic material property.
- FRP sheets increase substantially the strength and stiffness of structure and the behaviors of structure are similar to brittle building without ductility. In other words, the ductility of structure is reduced due to using FRP sheets in infill panel.
- The first layer of FRP sheet has the greatest effect on reducing of inter-story and lateral drift.
- With increasing the thickness of FRP sheet, the drift reduces and the reduction rate move to zero in upper layers.
- The thickness of FRP sheet in the middle floors is more important in decreasing the drift rather than the first and top floors.
- Using more bays of strengthened wall, the lateral drift and inter-story drift reduce.
- Changing the location of strengthened wall from exterior frame to interior frame, there is no difference between the results.

6. References

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