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EFFECTIVENESS OF FRP WRAPS FOR RETROFITTING OF EXISTING RC SHEAR WALLS

Hamid ARABZADEH
PhD Student, Concordia University, Canada
h_ar@encs.concordia.ca

Khaled GALAL
Professor, Concordia University, Canada
galal@bcee.concordia.ca

ABSTRACT: Reinforced concrete (RC) shear walls are best known as efficient lateral resisting systems in buildings because of their high stiffness and their high flexural and shear capacities. Continuous advancements in seismic design codes and regulations and the aging and deterioration of existing RC structures are two major reasons for the necessity of seismic strengthening and retrofitting of shear wall structures. In this respect, different retrofitting methods have been proposed, but reliable means of estimating the behaviour of RC shear walls is required to choose the most effective retrofit method. In this article, response of FRP-retrofitted RC shear walls subjected to lateral loads is studied using the general-purpose finite element code ABAQUS. The numerical modeling is first validated against available experimental results from the literature, and the numerical results in terms of the load–displacements are in good agreement with experimental data. Squat shear walls and walls with intermediate aspect ratio having different dominant behaviour including flexural, shear and sliding are considered in the study. Geometric and material nonlinearities in the concrete wall, steel rebars and FRP wraps have been taken into consideration. Shear walls with different geometries were modeled in order to study the effectiveness of FRP wraps with different configurations on the wall's behaviour in terms of strength and ductility. It was found that the addition of an external layer of vertical FRP layer results in increased wall's ultimate load bearing capacity without a significant increase in the stiffness in both squat and flexural walls, especially in walls with weak boundary elements. The displacement ductility of squat walls and walls with intermediate aspect ratio are affected differently by the addition of a vertical or horizontal FRP layer.

1. Introduction

Reinforced concrete (RC) shear walls have been widely used as lateral load resisting systems in buildings. Past earthquakes reconnaissance showed that RC walls governed by shear failure have performed poorly due to probable brittle-type failures with low ductility (Kim, 2004). In past two decades, researchers have performed various investigations to develop proper methods for designing shear walls that have ductile behaviour while providing high shear capacity in proportion to flexural capacity (Mousavi, 2008). On the other hand, many studies focused on strengthening and repairing RC shear walls by using other methods such as steel jacketing and fibre reinforced polymer (FRP) composite wrapping.

Adding vertical FRP layer(s) around the wall's boundary regions was found to be an effective way for improving RC shear walls performance, which can enhance both the ultimate load bearing capacity and ductility of shear wall system (Khalil and Gobarah, 2005, Mostofinejad and Anaei, 2012, El-Sokkary and Galal, 2013). This retrofit method can be effective for RC shear walls with weak boundary elements (Wood, 2014).

In addition to the vertical FRP layers, using horizontal wraps around the bottom part of a wall system could improve the shear resistance of the wall. As such, local debonding of the vertical FRP layers as well as the undesirable shear sliding mode of failure could be prevented.

The present study focuses on investigating the effectiveness of FRP strengthening on the pushover behaviour of RC shear walls using finite element (FE) modeling technique. The FE meshes, boundary conditions and nonlinearity implementation methods have been calibrated/validated by comparing the predictions of the closest available experimental data. Subsequently, effects from FRP strengthening on the lateral response of RC shear walls were studied. Two groups of walls, known as squat and walls with intermediate aspect ratio according to ASCE-41 (2013), have been selected to investigate the effect of FRP strengthening method on the lateral response of RC shear walls. Geometrical and material nonlinearities in the concrete material, steel reinforcements and also FRP wraps have been taken into consideration. Effects from the variation of FRP covered area of wall on the ultimate load capacity, as well as the ultimate drift, energy dissipation and ductility have been evaluated.

2. Numerical Modeling

The software package used for FE modeling in this study was the general-purpose nonlinear finite element package ABAQUS, which offers a comprehensive material constitutive law for simulation of concrete material. This section describes the modeling approach used for the finite element analyses.

2.1. Geometry and Mesh

Eight node three dimensional reduced integration elements with a Gaussian integration point in the element C3D8R have been used for simulating the concrete medium in the numerical model. Using lower integration point can help to reduce the time of analysis. However, using this procedure can cause zero-energy mode called *hourglassing*, which leads to severe flexibility and no straining at the integration points. ABAQUS uses a small artificial stiffness to prevent this phenomenon (Hibbitt, 2007). Steel reinforcements are modeled using truss elements T3D2 and positioned in the exact locations as in the experimental works. Adjacent nodes have then been coupled using embedment constraint. For simulating the FRP layers, four node reduced-integration shell elements S4R were used.

The solid elements located in boundary regions and also in the bottom part of the wall have a dimension of approximately 1% of wall length in all three directions. This leads to a quite fine mesh in concrete. To optimize the computational efforts, a relatively coarser mesh up to 5% percent of the wall length was adapted for the rest of the model. Compatible meshes were also considered for steel reinforcements and FRP layers. Fig. 1.a shows the employed mesh in the finite element model.

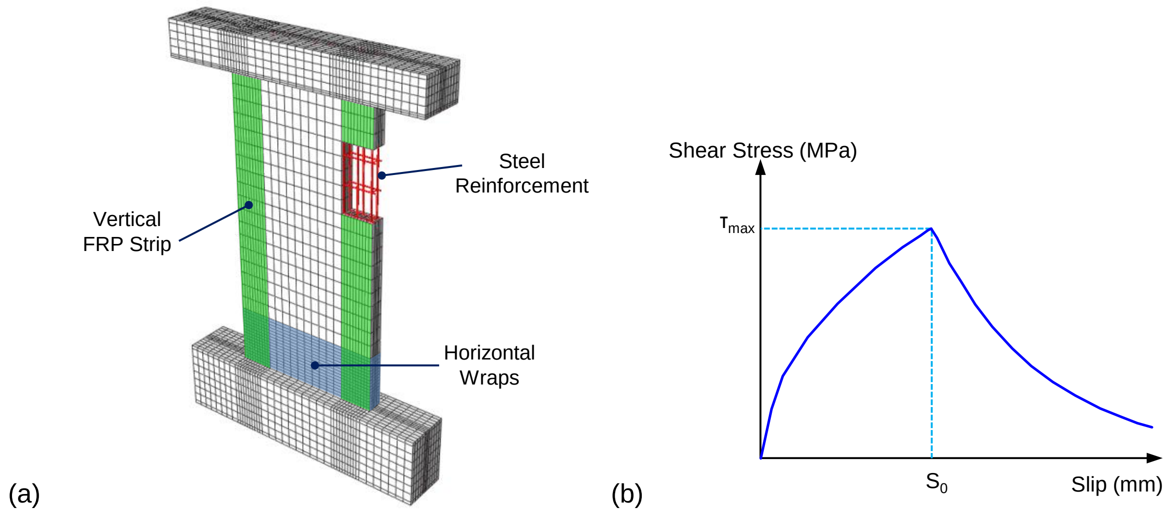

Fig. 1 – a) Finite element mesh, b) Schematic FRP bond-slip relationship model proposed by Lu et al. (2005)

2.2. Material Constitutive Laws

There are a number of concrete constitutive models available in the literature based on principles of elasticity, plasticity and continuum damage mechanics. In the current study, Concrete Damage Plasticity (CDP) model was used to define the mechanical properties of concrete in the model. Modified Hognestad equation is used to define the compressive stress-strain behaviour of concrete material. The tension strength of concrete (f_t) is considered to be equal to 0.3 $fc^{2/3}$ according to the CEO-FIB2010 (fib, 2013). In addition to the user-defined compressive and tensile responses, two other parameters are required to define the yield function for the CDP model. The ratio of initial biaxial compressive yield stress to initial uniaxial compressive yield stress (σ_{b0} / σ_{c0}) was considered equal to 1.16. The ratio of the second deviatoric stress invariant on the tensile meridian to that on the compressive meridian (K_c) was used equal to 0.67 for the analyses (Lubliner et al., 1989). The dilation angle of concrete material was also set equal to 55 degree as proposed by Dey (2014).

For steel reinforcements, combined hardening plasticity was considered by providing the nonlinear half cycle stress-strain data equal to reported values in the experimental tests.

FRP material is considered orthotropic and transversely isotropic, i.e. the mechanical properties are the same in any direction perpendicular to the fibres. In this study, FRP material was modelled by defining lamina type of elasticity along with failure sub option offered by ABAQUS. Table 1 shows the mechanical properties of CFRP wraps used by El-Sokkary and Galal (2013). Same material properties is considered in evaluating the effectiveness of FRP strengthening of shear walls in the next section.

Table 1 – FRP Material Properties

Parameter	Value
Tensile Strength (MPa)	1062
Elastic Modulus (MPa)	102000
Rupture Strain (%)	1.05

2.3. FRP-Concrete Interaction

The bond interface between concrete and FRP sheets, which was generated by utilizing a layer of epoxy resin as adhesive material, has a significant effect on the seismic performance of the strengthened shear wall (Rezaiefar, 2013). In some experimental works, mechanical anchorage devices also used to ensure the prevention of de-bonding (Hiotakis et al., 2004), (Ghobarah and Khalil, 2004), (Elnady, 2008). In the simulations of the adherence between FRP layers and the concrete surface, some other researchers (Kezmane et al., 2012) have used a perfect adherence. Some others also used the method of penalizing to model the contact between two surfaces with a coefficient of friction acting between the master surface and slave surface.

In cases where the epoxy resin is the only adhesive medium, debonding failure mechanism should be considered into the model corresponding to the mechanical properties of concrete and FRP material. The bond-slip relationship model proposed by Lu et al. (2005) has been implemented into the model by using nonlinear connector elements in ABAQUS. A schematic of the proposed relationship is depicted in Fig. 1.b. Tributary area of adjacent nodes are calculated using a Matlab script. Then, different slip based relationships are defined to couple the adjacent concrete-FRP nodes in the model.

2.4. Numerical Analysis

To perform a quasi-static pushover analysis, either a static or a dynamic analysis could be used. In order to reduce the convergence issues, Dynamic/Explicit analysis in ABAQUS is used in this study. Sensitivity analysis was done and a total time equal to 10 seconds was found to be long enough to prevent dynamic waving effect in the results. Displacement controlled analysis was defined by applying a smooth stepping mode through the analysis in the way that provide a quasi-static situation for the analysis. This method was also previously employed by other researchers (Rafiei, 2011, Dhanasekar and Haider, 2008) and was found to be able to achieve reasonable results.

3. Model Validation

In this section, the validation of the proposed model for accurate follow of the response of RC shear walls under lateral loads has been performed by comparing the simulation results with available experimental data. Recently, few researchers (Rafiei, 2011, Wood, 2014) validated the capability of ABAQUS to simulate the lateral response of RC shear wall systems subjected to lateral loads.

To ensure the precision of modeling approach, validation of numerical predictions against two experimental tests by Lefas et al. (1990) were performed. The tests were carried out for examining lateral capacity of RC shear walls with different slenderness ratios. Moreover, to ensure that the strengthened wall response would be also covered by numerical model, a comparison between the pushover numerical results and test records of a FRP strengthened shear wall by Elsokkary and Galal (2013) was also performed in the second part.

Two wall specimens SW15 and SW22 from the tests by Lefas et al. (1990) with slenderness ratio (i.e. height/shear span) equal to 1 and 2 respectively were selected to be used in the model validation stage. Wall SW15 was an RC shear wall constructed with 40 MPa concrete (cube strength) and 470 MPa and 520 MPa yield strength steel reinforcement for vertical and horizontal reinforcement, respectively. The wall had 750mm height, 750mm length, and 70mm thickness. The wall reinforcement consisted of two layer of reinforcement, d8mm @ 60mm and d6.25mm @ 80mm bars, providing a reinforcement ratio of 2.4% and 1.1% in the vertical and the horizontal directions, respectively. Wall SW22 has 1300mm height, 650mm length, and 65mm thickness, constructed with 50.6 MPa concrete (cube strength). The wall reinforcement consisted of two layer of reinforcement, d8mm @ 62mm and d6.25mm @ 115mm bars, providing a reinforcement ratio of 2.5% and 0.8% in vertical and horizontal direction respectively. Both walls were first subjected to a normalized axial load equal to 0.1, then the lateral load was applied in displacement control situation. These two walls were used as control wall in the current study to investigate the effect of FRP strengthening in the lateral response of RC shear walls.

Wall RW1 was also selected from tests by El-Sokkary and Galal (2013), which had 1200mm height, 1045mm length, and 80mm thickness. The wall was constructed with 37MPa concrete (cylinder) and grade 400, 10M steel bars for the reinforcement. Details of mechanical properties of material were presented in section 2.2. Normalized axial force equal to 0.02 was acting on the wall during the test.

Modeling approach presented in previous section was used for simulation and analysis of the aforementioned specimens. Fig. 2 illustrates the comparison between numerical predictions and experimental data. As it can be observed in the figure, the numerical model can reasonably predict the lateral response of RC shear walls. For original shear walls SW15 and SW22, very good agreement was observed between the results. Small discrepancies between the results might be because of some uncertainties in material strength and also effect of some residual stresses because of probable imperfections. These effects have not been considered in the numerical model.

Numerical results for strengthened wall RW1 are also presented in Fig 2.b which shows a very reasonable agreement with the experimentally measured response. In fact, although there is a difference between the descending branches of force-deformation curves, the general trends are quite similar. Moreover, the model successfully predicted the initial stiffness, ultimate load and corresponding drift, and ultimate drift of the strengthened wall.

Numerical models are then utilized to perform a parametric study on FRP-strengthening of RC shear walls.

4. Results of Numerical Analysis

4.1. Wall Strengthening Schemes

Five different levels of FRP strengthening were investigated for both SW15 and SW22 walls in this study, which consist of walls with area covered by horizontal FRP wraps equal to 10 to 100 percent on each side of the wall. All walls had vertical FRP layers on both sides of their boundary elements with the width equal to 20% of wall length. The strengthening schemes are as follows:

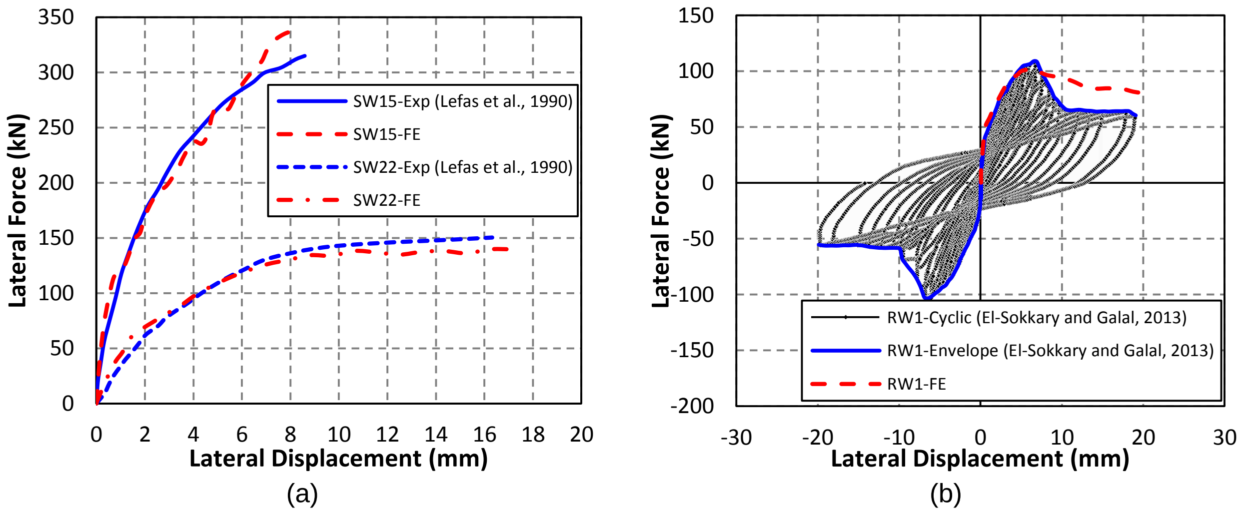

Fig. 2 – Verification of Numerical Model, a) Concrete Shear Walls Tested by Lefas et al. (1990), b) Retrofitted Wall Tested by El-Sokkary and Galal (2013)

- Original walls with no FRP strengthening
- Walls with vertical layer and 0.1*h* horizontal wraps at bottom
- Walls with vertical layer and 0.1*h* horizontal wraps at bottom and top
- Walls with vertical layer and 0.2*h* horizontal wraps at bottom
- Walls with vertical layer and 0.2*h* horizontal wraps at bottom and top
- Walls with vertical layer and horizontal wraps fully covered the wall

where *h* represents the height of wall. Fig. 3 presents a typical strengthening scheme of wall with vertical and horizontal FRP wraps. It should be mentioned that, for walls with extremely low (or high) geometrical aspect ratio, more than two vertical (or horizontal) FRP layer could be used for strengthening the wall as proposed by Nguyen et al. (2014).

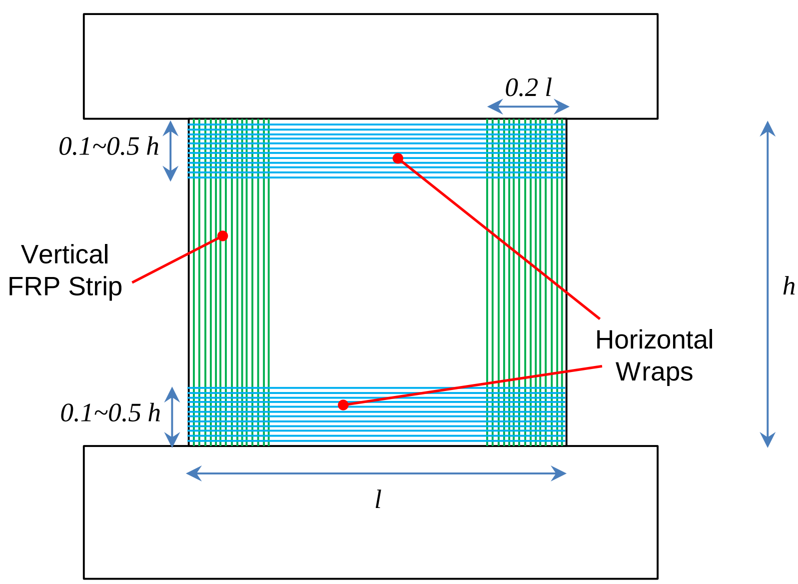

Fig. 3 – Strengthening Scheme of Walls by using FRP Wraps

4.2. Pushover Behaviour

In this section, lateral responses of the studied walls are retrieved in order to evaluate the effectiveness of FRP strengthening on enhancing the wall lateral resistance. Load-displacement pushover curves for both squat walls and walls with intermediate aspect ratio are presented in Fig. 4. In general, the FRP strengthening schemes have enhanced the lateral resistance of walls, but in different levels, as expected. Moreover, similar strengthening configurations led to different improvements in the walls. It should also be noted that although both walls achieved higher resistance. The enhancement in the wall strength seems to be more affected by the vertical FRP strips. As it can be seen, the results obtained from the case of covering 0.1h at the bottom of the wall is so close to the case of covering 0.1h at bottom and top. By increasing the height of horizontal FRP wraps, higher stiffness as well as higher ultimate drift are obtained from both walls. However, differences in walls with intermediate aspect ratio are not significant.

A quantitative comparison between results is presented in Table 2. Evaluating the results shows that 7 to 45 percent increase in the ultimate load capacity of squat wall is achieved by using the studied strengthening schemes. This corresponds to 9 to 41 percent increase in ultimate drift of squat wall before failure point. In the walls with intermediate aspect ratio, using the studied strengthening schemes improved the ultimate load capacity from 26 to 49 percent in comparison with the original shear wall. Corresponding ultimate drifts were increased by 6 to 13 percent.

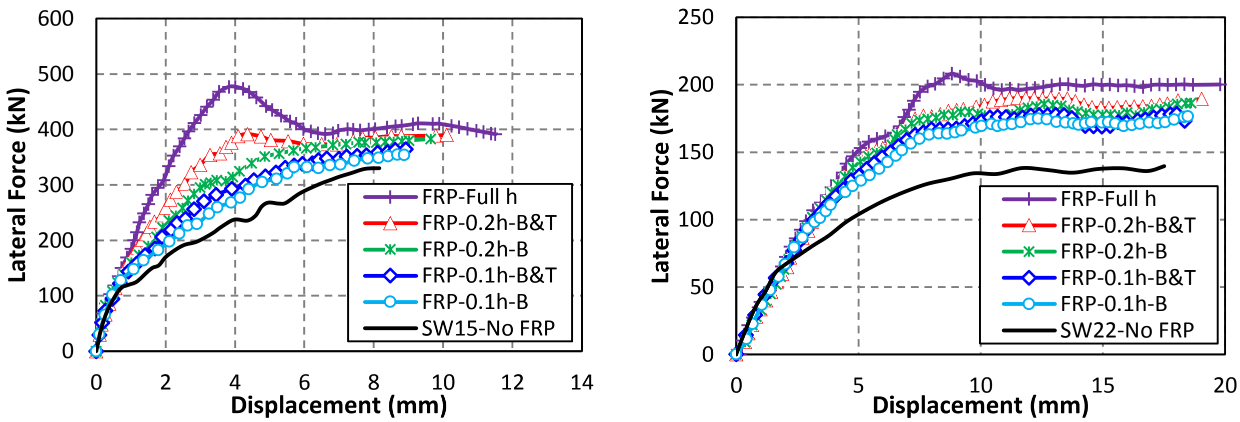

Fig. 4 – Pushover Response of Walls, a) Squat Walls, b) Walls with Intermediate Aspect Ratio

In the walls with intermediate aspect ratio, using the proposed strengthening schemes improves the ultimate load capacity by about 26 to 49 percent in comparison with the original shear wall. Corresponding ultimate drifts were increased by 6 to 13 percent. A side-by-side comparison could be done between strengthening schemes “FRP-V&0.1h-Bottom&Top” and “FRP-V&0.2h-Bottom”. Both cases have the same covered area equal to 20%, but the latter presents a better improvement in the wall response in both squat and intermediate aspect ratio mode. This represents the bottom side of the wall as a critical region, especially in squat walls, where relative increase in wall capacity (in comparison with corresponding value in the original wall) is almost 60% higher (i.e. 10% and 16%, respectively).

4.3. Energy Dissipation

In terms of lateral resisting systems, the energy dissipation during the lateral effort of the system is one of the main characteristics. In this section, a comparison between energy dissipation capability of walls is performed through energy-drift curves as presented in Fig. 5. As previously observed in the pushover curves, by increasing the area of the wall strengthened by FRP wraps, more energy need to be dissipated by the wall system at a certain drift level. Highest contribution in energy dissipation results from the specimens which are fully covered by horizontal FRP wraps, in which 135% and 67% increase in the energy dissipation are observed for squat walls and walls with intermediate aspect ratio respectively. More explicitly, the remarkable influence from horizontal FRP wraps on squat walls is observed.

Table 2 – Results of Pushover Analysis of Walls

Specimen	Strengthening Scheme	FRP Covered Area	Ultimate Load (kN)	Drift at Ultimate Load	Ultimate Drift	Energy Dissipated at IO (kN.m)	Energy Dissipated at LS (kN.m)	Total Energy Dissipated (kN.m)
SW15	No FRP Strengthening	0%	330.1	1.09%	1.09%	315	815	917
	FRP-V&0.1h-Bottom	10%	354.5	1.16%	1.18%	322	932	1170
	FRP-V&0.1h-Bottom&Top	20%	364.5	1.19%	1.19%	350	979	1230
	FRP-V&0.2h-Bottom	20%	383.0	1.29%	1.29%	390	1034	1465
	FRP-V&0.2h-Bottom&Top	40%	390.3	0.58%	1.35%	439	1156	1658
	FRP-V&Full h	100%	477.1	0.51%	1.54%	529	1345	2152
SW22	No FRP Strengthening	0%	139.6	1.35%	1.35%	251	676	76
	V&0.1h-Bottom	10%	176.5	1.42%	1.42%	291	832	100
	FRP-V&0.1h-Bottom&Top	20%	178.4	1.39%	1.41%	297	853	101
	FRP-V&0.2h-Bottom	20%	186.4	1.43%	1.43%	306	879	107
	FRP-V&0.2h-Bottom&Top	40%	190.2	0.89%	1.47%	311	905	113
	FRP-V&Full h	100%	208.2	0.68%	1.52%	323	961	127

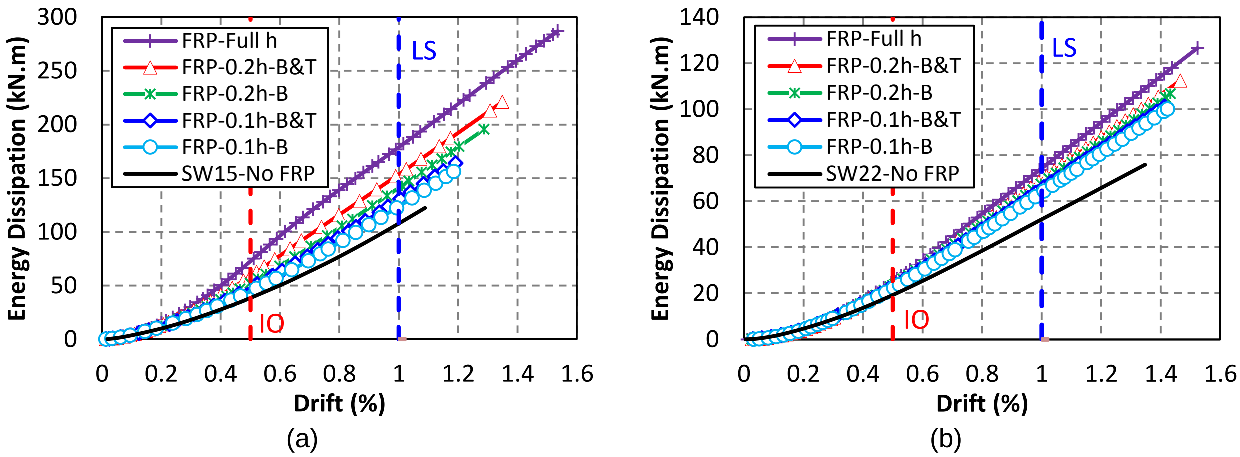

Fig. 5 – Energy Dissipation in Walls, a) Squat Walls, b) Walls with Intermediate Aspect Ratio

For presenting the results in a more tangible way, dissipated energy by the walls was categorized in two structural performance levels according to FEMA 356 (2000); Immediate Occupancy (IO) and Life Safety (LS). FEMA 356 recommends drift limits equal to 0.5% and 1% as IO and LS performance levels respectively. These levels are indicated in Fig. 5 with red and blue dashed vertical lines respectively. Results are comprised for two wall groups in Fig. 6.

As shown in Fig. 6.a for squat walls, the effectiveness of FRP strengthening on increasing the energy dissipation capability is relatively significant in both IO and LS performance levels, ranging from 2% to 68% and 14% to 65% respectively. Similar comparison is performed for walls with intermediate aspect ratio in Fig. 6.b, in which a lower effectiveness from FRP strengthening can be observed. The increase in energy dissipation capability ranges from 16% to 29% and 23% to 42% in IO and LS performance level respectively.

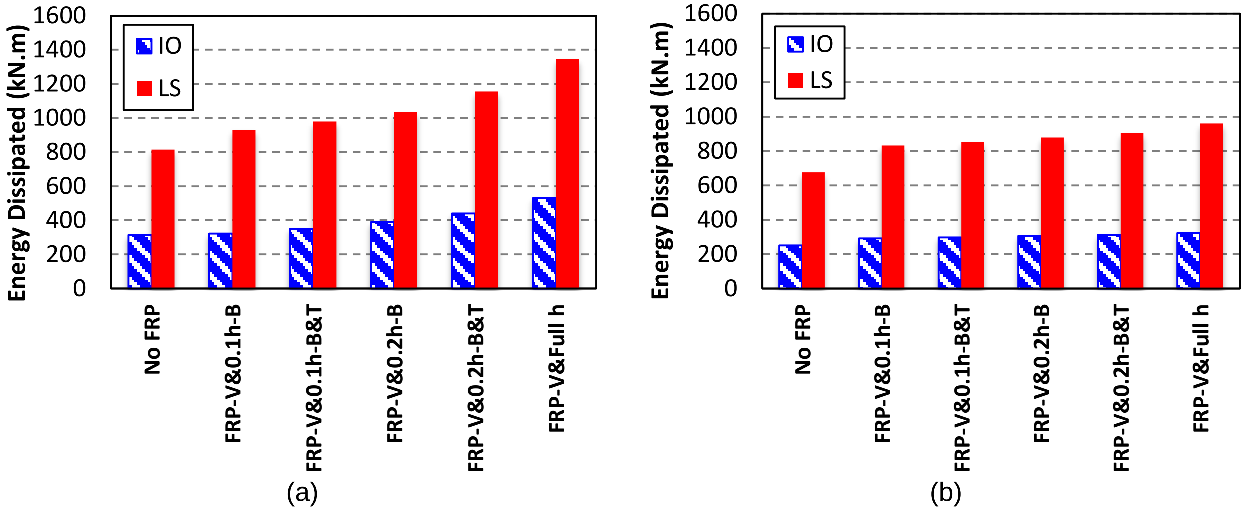

Fig. 6 – Energy Dissipated by Walls in Immediate Occupancy and Life Safety levels, a) Squat Walls, b) Walls with Intermediate Aspect Ratio

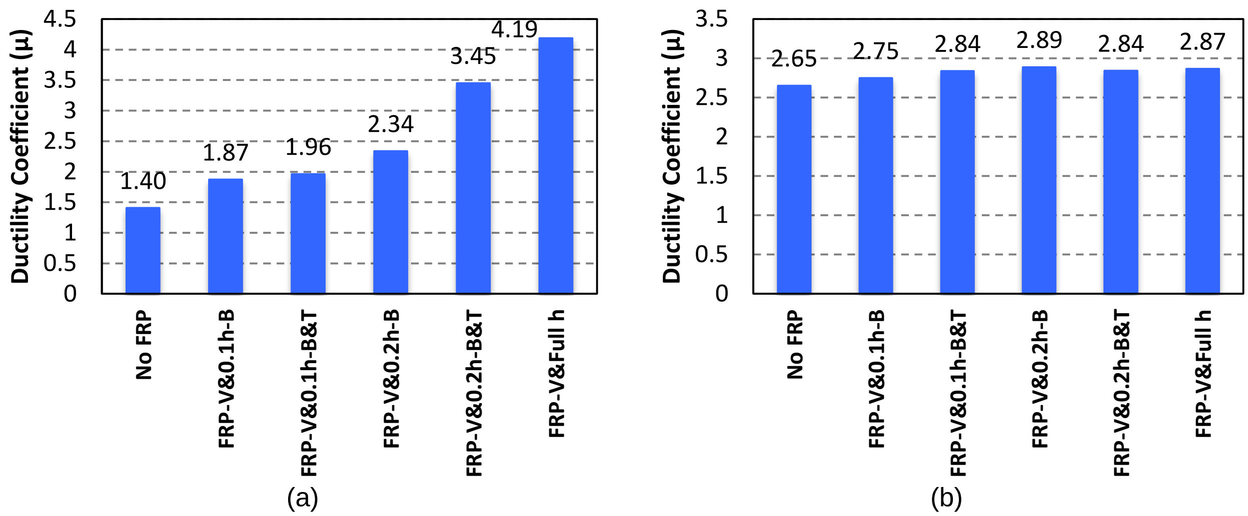

Fig. 7 – Evaluating the Displacement Ductility of Walls, a) Squat Walls, b) Walls with Intermediate Aspect Ratio

4.4. Evaluating the Ductility of Strengthened Walls

Since the relation between strength and deformation of RC members may not have a well-defined yield point, some approximate levels should be used to define yield and ultimate limits. In the current study, the proposed approach by Carrillo et al. (2014) called $\mu_{0.85}$ method was used to evaluate the ductility of wall specimens. This method, defines the ductility ($\mu = \Delta u/\Delta y$) as the ratio between ultimate displacement and the displacement corresponding to 0.85 of maximum load on the ascending branch of monotonic envelope (Todut et al., 2014). The term Δu corresponds to drift ratio at the point that horizontal load value falls to 80% of the maximum horizontal force (i.e. 20% degradation).

Fig. 7 shows the variation of ductility coefficient of wall specimens. Taking into account only squat wall specimens, it can be concluded that there is a direct relation between the wrapped area of the wall and the wall ductility coefficient; increase in the wrapped area significantly increases the ductility coefficient. This seems to be reasonable since the lateral behaviour of squat shear walls are mainly controlled by shear. This conclusion was also supported by the results of other researchers, such as Kheyroddin and Naderpour (2008).

Results for walls with intermediate aspect ratio in Fig. 7.b demonstrate that FRP strengthening has no significant effect on the ductility of these walls. Moreover, in this case, the wall fully covered by FRP wraps has developed a lower ductility compared to a wall with 20% covered area.
A quantitative comparison shows that by using studied FRP strengthening schemes, the ductility of wall could be raised by up to 198% and 9% in squat walls and walls with intermediate aspect ratio respectively.

5. Conclusion

The effectiveness of FRP-strengthening on lateral response of RC shear walls was investigated in the current study, using nonlinear FE analyses. Pushover analyses of shear walls were performed, and results showed that:

- FRP strengthening can enhance the lateral performance of RC shear wall by increasing the wall ultimate load capacity up to 49%, as well as the ultimate drift, energy dissipation and ductility.
- Energy dissipation capability of walls improved in both IO and LS performance levels. Total energy dissipation increased up to 135% and 67% for squat walls and walls with intermediate aspect ratio, respectively.
- By using the proposed strengthening schemes, ductility of squat walls jumped by up to 198% increase, while only 9% increase was observed in walls with intermediate aspect ratio.

- Energy dissipation capability of walls improved in both IO and LS performance levels. Total energy dissipation increased up to 135% and 67% for squat walls and walls with intermediate aspect ratio, respectively.
- By using the proposed strengthening schemes, ductility of squat walls jumped by up to 198% increase, while only 9% increase was observed in walls with intermediate aspect ratio.

In further studies, effect of FRP-strengthening on the response of non-planar shear walls with different geometries and rebar configurations can be conducted. Furthermore, the modeling approach can also be used in predicting the behaviour of repaired walls subjected to minor damages during the earthquakes.

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