IJST, Transactions of Civil Engineering, Vol. 39, No. C2, pp 385-394
Printed in The Islamic Republic of Iran, 2015

"Research Note"

STRENGTHENING OF SLENDER RC SHEAR WALL WITH FRP SHEETS*

D. MOSTOFINEJAD** AND M. MOHAMADI ANAEI

Dept. of Civil Engineering, Isfahan University of Technology (IUT), Isfahan, 84156-83111, I. R. of Iran
Email: dmostofi@cc.iut.ac.ir

Abstract– Concrete shear walls are the most prevalent structural systems resisting lateral loads due to earthquakes in high-rise buildings. Very large in-plane stiffness of shear walls provides an excellent drift control in the structure. However, structural damages and early code shortcomings threaten the efficiency of existing structural walls against earthquake. Recently, fiber reinforced polymer (FRP) materials have been used considerably in strengthening and retrofitting of structural elements. High tensile strength and excellent tensile modulus along with other unique features of FRP materials make them the first alternative in the strengthening projects. However, the literature shows that few analytical and/or experimental studies have been conducted on the strengthening of slender reinforced concrete (RC) shear walls with FRP materials so far. In this paper, the effect of strengthening of boundary elements in slender RC shear walls with FRP on the overall behavior of shear walls is investigated. Nonlinear finite element is used to analyse the RC walls, using damage plasticity model and tension stiffening effects. Results of the current study show that applying FRP sheets vertically on the lateral faces of the boundary elements causes the load-displacement curves of the strengthened walls to have a larger load carrying capacity up to 20% compared to that of wall specimens without FRP strengthening. Furthermore, applying the FRP sheets on the boundary elements only in the plastic hinge region of wall can improve the wall load carrying significantly.

Keywords– Reinforced concrete, shear wall, finite element analysis, damage plasticity model, tension stiffening, FRP composites, strengthening

1. INTRODUCTION

Structural shear walls are the most common systems resisting lateral loads in concrete buildings. Shear wall rigidity results in reduction of the overall lateral floor displacement of the structure. Shear walls limit the seismic damage intensity by reducing the floor displacement. Other advantages that make the shear walls a favourite lateral load resisting system are their construction simplicity and low cost [1].

There are some expectations from the seismic design and design criteria of reinforced concrete shear walls that must be satisfied. A shear wall must prohibit the damage to non-structural components during low intensity earthquakes. Furthermore, a shear wall is expected to prevent structural damages during moderate earthquakes. Besides, during a severe earthquake, shear wall must prohibit total destruction of the building and minimize major structural damage by responding in a ductile manner [2].

Many concrete shear walls all over the world are suffering damages from previous earthquakes or have poor detailing in design or performance, and are in urgent need of rehabilitation. Recently, new rehabilitation or retrofitting systems and materials have been developed, among them new products based on advanced composite materials known as Fibre Reinforced Polymers (FRP) can be mentioned [3]. FRP

*Received by the editors January 10, 2012; Accepted May 6, 2015.
**Corresponding author

materials benefit several advantages in material properties and performance compared to the older building materials, causing much interest in their use in civil engineering areas. Among many unique characteristics of FRP materials, low density or weight, very high tensile strength to weight ratio, high tensile modulus to weight ratio, corrosion resistance, good fatigue characteristic and ease of handling can be noted [4, 5]. On the other hand, FRP materials suffer from disadvantages like low fire resistance, non-susceptibility to bend in the field, and high cost.

2. PARAMETERS AFFECTING BEHAVIOR OF SHEAR WALL

The overall behavior of shear walls is affected by some factors, most importantly as follows:

a) Aspect ratio

The aspect ratio (the height to length ratio) of shear wall classifies it as a squat or slender shear wall. For low aspect ratios (less than 2), the behavior of shear wall is similar to a deep beam and it is, in fact, shear dominant [2] and is categorized as a squat wall. On the other hand, shear walls with aspect ratios greater than this dividing limit are usually assigned as slender or tall walls, where their behavior can be investigated with conventional beam theory [6].

b) Top beam

Top beam, which can be the floor slab or a tie beam, uniformly transfers the applied horizontal loads to the shear wall and causes the applied loads to be efficiently transferred to the foundation. Furthermore, this element minimizes the possibility of lateral torsional buckling in the walls with thin web [6].

c) Steel reinforcement

The steel reinforcement and its distribution in the wall directly affects on the wall strength and ductility. It is proposed that for a flanged high-rise shear wall, the steel reinforcement be concentrated toward the extreme fibers of the wall. Such distribution of reinforcement leads to additional flexural capacity and ductility in the wall [7]. On the contrary, for squat shear walls the distributed flexural reinforcement along the length of the wall, which causes lower ductility compared to that in a flanged wall, is preferred [2].

d) Applied loads

Besides the horizontal loads applied to the wall due to earthquake or wind loads, a shear wall is also subjected to axial compression loads (gravity loads). The compression loads provide several benefits for the wall including increased shear strength, reduced horizontal and vertical displacement, and increased flexural capacity [2, 7].

Investigation of previous researches on the application of FRP composites on concrete shear walls shows more interest on squat shear walls and less attention to slender walls. Ghobarah and Youssef [8] developed a macro model to represent the behavior of shear walls. They used nonlinear spring elements connected by linear beam elements. The predicted response of the model was in a good agreement with the experimental observations. Antoniades et al. [9] tested 11 squat shear walls with and without FRP sheets. One of the interesting results of their experimental program was that the anchorage system used in connecting the vertical composite sheets to the wall base is a key parameter on the strengthened wall function. Furthermore, the results of this experimental program were used to validate the current relationship for estimating flexural and shear strength of FRP strengthened RC walls. The analytical results showed if failure of the composite material is considered, analytical flexural strength is higher than the experimental result; but if failure of anchorage or debonding of FRP is considered, predicted flexural strength is lower than the experimental result [10].

There is also some research focused on the behavior of slender shear wall without composite application. For instance Tasnimi [11] experimented four 1 to 8 scaled shear walls with aspect ratio of 3 and concluded that for all specimens, the plastic hinge was formed at the extreme fiber of the wall section near the base. The results showed that the strength and deformational responses of the specimens were independent of the cyclic loading sequence. Su and Wong [12] investigated the effect of axial load ratio (ALR) on slender wall performance. Their experiments showed that ALR has a considerable effect on deformability and failure mode of the specimens. High value of ALR showed harmful effect on strength degradation and energy dissipation of reinforced concrete shear walls under reversal loading. Thomsen and Wallace [13] performed an experimental study on 4 slender shear walls. The test results indicated that the displacement-based design is a powerful and flexible method in estimating the shear wall detailing requirements.

Perry et al. [14] conducted a test on a large scale model of a high-rise concrete shear wall with height to length ratio of 7.2. The wall was subjected to a constant axial compression of $0.1f'_c A_g$ to simulate the gravity loads; where f_c' is the compressive strength of concrete and A_g is the gross section area of the wall. In their test the concrete spalled due to buckling of a vertical steel bar and its fracture after a few post-buckling cycles. This phenomenon resulted in a flexural failure mode. Honggun et al. [15] evaluated the moment-curvature behavior of shear walls with partial steel confinement at two ends of the walls through nonlinear finite element analysis. They concluded that the confinement of the end zones of the walls section reduces the depth of the compressive region and increases the deformability of the walls.

The studies on slender shear walls with FRP strengthening are limited to investigating the dynamic properties of the strengthened walls [16-18], where the effect of FRP application on the wall frequency and its lateral stiffness were investigated through finite element techniques.

While there has been less attention on the behavior of FRP strengthened slender shear walls under monotonic loading in the literature, this paper is focused on the FRP strengthening of the boundary elements of slender shear walls under monotonic loading through finite element simulating.

3. MODELING OF SHEAR WALL

Since the reinforced concrete shear walls are lateral load resisting systems against earthquake in regions of high seismicity, they behave inelastically during a severe earthquake and may confront impending failure. On the other hand, it is uneconomical to design the lateral load resisting elements to remain in the elastical range during strong shakings [2]. Thus, analysis of reinforced concrete shear walls designed to resist earthquake loads involves consideration of nonlinear material behavior and plasticity theories [19].

In this paper the damage plasticity model introduced in the commercially available software package, ABAQUS6.7 is used to simulate the full behavior of shear wall specimens. This plasticity model can simulate all types of concrete elements and can be used in conjunction with a viscoplastic regularization of the constitutive equations in software to improve the convergence rate in the softening regime [20].

For damage plasticity model presentation, it is necessary to accurately define the full stress-strain relationship of the concrete in compression and tension to predict the nonlinear behavior of the walls. In compression a two-branch stress-strain relationship proposed by Hognestad is employed. The constitutive model for the modified Hognestad's stress-strain relationship for concrete in compression is introduced through Fig. 1 and Eqs. (1) and (2) [1]:

$$f_c = f_c'' \left[\frac{2\varepsilon_c}{\varepsilon_0} - \left(\frac{\varepsilon_c}{\varepsilon_0} \right)^2 \right] \tag{1}$$

$$f_c'' = k_s f_c' \tag{2}$$

The value of the coefficient k_s is 1.0 if the cylinder compression strength of concrete, f_c', is equal to 15 MPa. For f_c' equal to 20, 25, 30 and over 35 MPa, k_s is taken equal to 0.97, 0.95, 0.93 and 0.92, respectively [1].

Descending branch of the modified Hognestad's model for stress- strain relationship is a line from (ε_0, f_c'') to $(0.0038, 0.85 f_c'')$, where ε_0 is the strain of concrete corresponding to f_c''. The compression strain of concrete at failure, ε_u, in this study is taken equal to 0.0038**.**

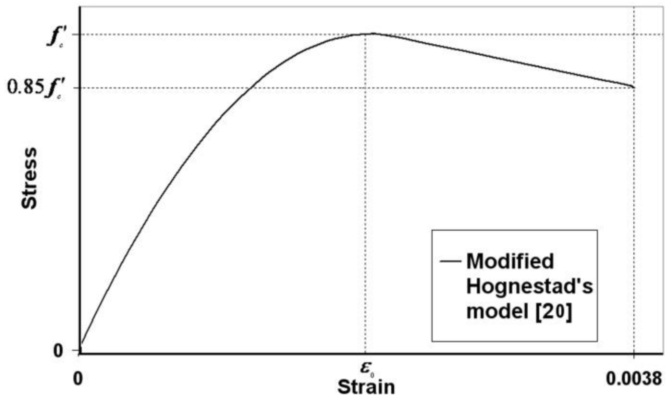

Fig. 1. Modified Hognestad's curve [1]

The concrete tensile stress-strain relationship is linear-elastic with slope E_0 (the initial modulus of elasticity of concrete) up to concrete tensile strength. After reaching this point and in the post-cracking region, the tensile stress-strain relationship is presented as a line reaches to zero strength at tensile strain 10 times that of cracking strain [1]. The post-cracking capacity of concrete increases when a larger value is selected for failure tensile strain. This branch of tensile stress-strain relationship includes the effects of steel reinforcement interaction with tensile concrete and is named as tension stiffening effect.

Solid elements with eight nodes and three degrees of freedom at each node which has the capability of plastic deformation is used to model reinforced concrete. In this study time dependent nonlinearities such as creep and shrinkage are not considered.

A link element with two nodes and three degrees of freedom at each node models the discrete steel reinforcement. In order to avoid numerical instability for perfect plastic behavior, a small positive value is assigned to the slope of the stress-strain curve in the plastic region [21-23]. The FRP material is modelled as an orthotropic and transversely isotropic material with the same mechanical properties in any direction perpendicular to the fibers. FRP composites are simulated with 8-node solid elements having linear elastic behavior.

4. MODELING VERIFICATION

Before any case study on the effect of strengthening of the walls, confidence from simulating procedure explained in the previous section is necessary. For this purpose, one experimented wall specimen is simulated by damage plasticity model in the software and the analytical results are compared with experimental results through the load- displacement curves.

Shear wall RW1 [13]

The 1 to 4 scaled shear wall RW1 was tested by Thomsen and Wallace [13]. The wall height is 3600 mm and other geometric properties and reinforcement are shown in Fig. 2. The material properties are as follows: The concrete cylinder strength and the concrete strain at peak compression stress were 31.6 MPa and 0.0023, respectively. The steel yielding and ultimate strength were 420 and 600 MPa, respectively. The specimen is subjected to an axial compression equal to 10% of the axial compressive capacity of the section and lateral load at the top of the wall up to failure. The meshed simulated model of the wall is presented in Fig. 3. Comparison between the analytical and experimental load-displacement curves at the top of the wall is shown Fig. 4. Good agreement is found between experiment and FE results in all parts such as linear, nonlinear and steel hardening behavior of the wall specimen.

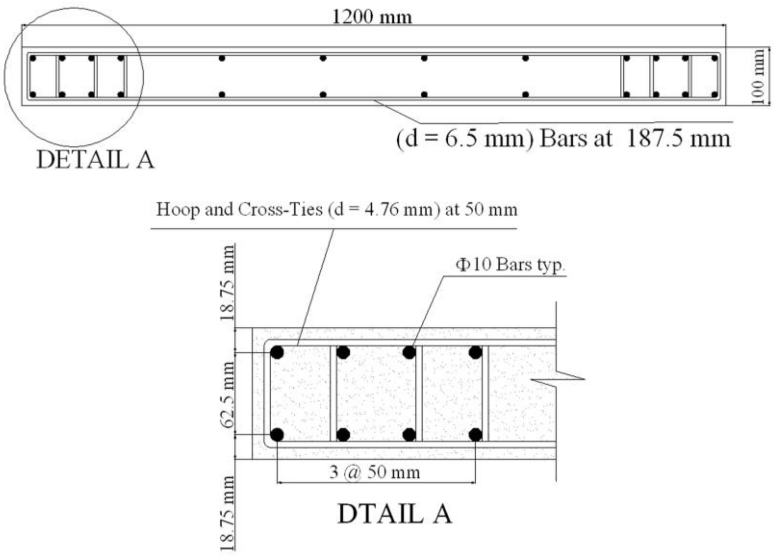

Fig. 2. The detail of the specimen RW1 tested by Thomsen and Wallace [13]

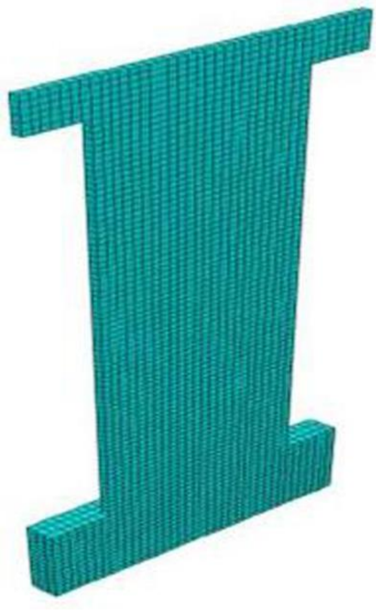

Fig. 3. The meshed model of wall tested by Thomsen and Wallace

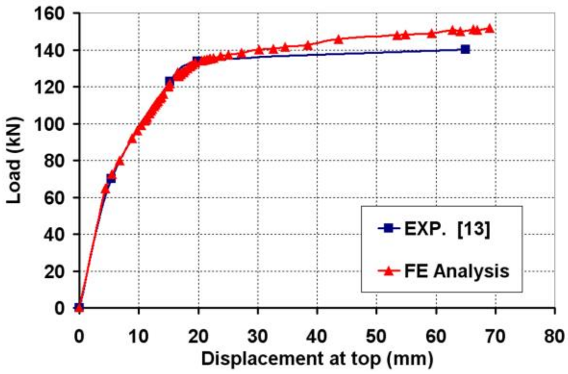

Fig. 4. Comparison of experimental and FE analysis envelope curves for wall RW1tested by Thomsen and Wallace [13]

5. PARAMETRIC STUDY

Before explaining the parametric study, it should be noted that excellent energy dissipation is expected from the overall behavior of shear wall against lateral loads, especially in seismic design. For this reason, most of the codes pay special attention to the reinforcement of shear walls along the boundary elements [1]. ACI 318-11 [24] introduces two design approaches for reinforcement of the boundary elements of shear wall in high seismic regions. The first method named as stress-based approach is, in fact, a traditional method in which the special transverse reinforcement in the boundary elements is required when the maximum stress at the extreme compression fiber of the wall section is more than $0.2f_c'$, and is continued up to a level where the maximum stress in the wall becomes less than a pre-determinstaed value, i.e. $0.15f_c'$. On the other hand, in the second method named as displacement-based approach, the special transverse reinforcement within the boundary elements is necessary when design displacement at the top of the wall goes beyond a critical value and, furthermore, the depth of neutral axis in the wall section becomes greater than a value given in the code.

Here, the parametric study which is focused on a shear wall is designed and laterally reinforced in its boundary elements based on the first of the aforementioned approaches. The specimen is shear wall SH3 from a 13-storey building in Iran designed according to stress-based approach. The wall with barbell section is categorized as slender shear wall due to its aspect ratio of 7.49. The concrete compressive strength of the 42.7 m high wall is 28 MPa; the yield strength of the longitudinal and transverse reinforcements used in the wall is 400 MPa and 300 MPa, respectively, and other geometrical section properties and reinforcement detail of the wall are given in Fig. 5.

To limit the volume of the calculations, a scale of 1 to 4 of this wall is selected for modelling and analysis. The scaled wall has 10675 mm height and its boundary elements are 3500 mm high (which is, in fact, the length of plastic hinge), and 1425 mm wide. Loading of the wall includes 10% of its axial compressive capacity simultaneous to horizontal lateral load up to failure.

Since the intention is to examine the efficacy of vertical FRP strengthening along the wall boundary elements to compensate poor vertical reinforcement in the boundary elements, first it is logical to evaluate the role of the longitudinal reinforcement in the boundary elements of shear walls. Hence, shear walls SH3-90%, SH3-80% and SH3-70% are introduced with their longitudinal reinforcement respectively equal to 90%, 80% and 70% of that of shear wall SH3, which is well-designed based on ACI 318-11. The walls are modelled and non-linearly analyzed; a comparison of their load-displacement behavior is given in Fig. 6. This figure shows that decreasing the longitudinal reinforcement of the boundary elements of shear wall reduces the load-carrying capacity of the walls. The decrease in the loading capacity of the specimens SH3-70% is 20%, as observed in Fig. 6.

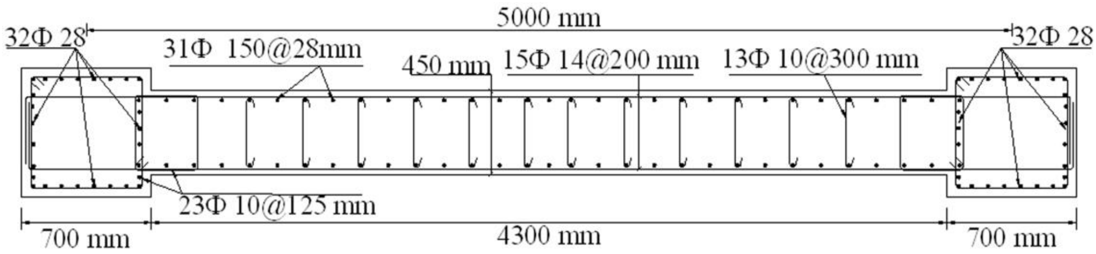

Fig. 5. Section properties of the shear wall SH3

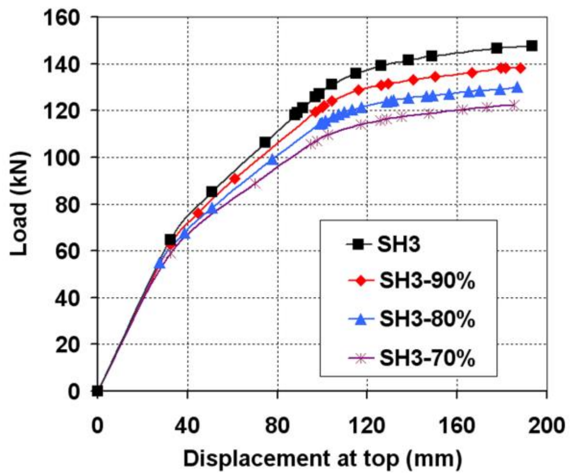

Fig. 6. Effect of wall boundary elements longitudinal steels reduction in specimen SH3

To investigate the effect of FRP strengthening along the boundary elements of shear wall, one specimen from the aforementioned walls in Fig. 6 is selected. The shear wall is the poor-designed specimen SH3-70% with inadequate longitudinal reinforcing bars along the boundary elements. The characteristics of the strengthening CFRP are given in Table 1 [25]. In the first stage, effect of height of three strengthened specimens from the basis of the wall SH3-70% is defined; specimen SH3-8500 with FRP attached along 80% of its height of wall, i. e. 8500 mm; specimen SH3-70%-3500 with FRP attached along the plastic hinge of its boundary element, i. e. 3500 mm; and specimen SH3-70%-1425 with FRP on its boundary element only up to a height equal to the horizontal length of the wall, i. e. 1425 mm. The load-displacement curves of the 3 aforementioned strengthened shear walls given in Fig. 7 show that one layer of strengthening CFRP does not considerably increase the loading capacity of the wall. However, when the number of strengthening CFRP along the plastic hinge length of the boundary elements of the walls is increased to 5, the load-carrying capacity of the walls is increased about 20%, as is observed from Fig. 8.

Table 1. Material properties for FRP composite [25]

FRP composite	Elastic modulus (GPa)	Poisson's ratio	Tensile strength (MPa)	Thickness of laminate (mm)
CFRP	$E_x = 230$ $E_y = 20$ $E_z = 20$	$\upsilon_{xy} = 0.22$ $\upsilon_{xz} = 0.22$ $\upsilon_{yz} = 0.22$	3500	0.16

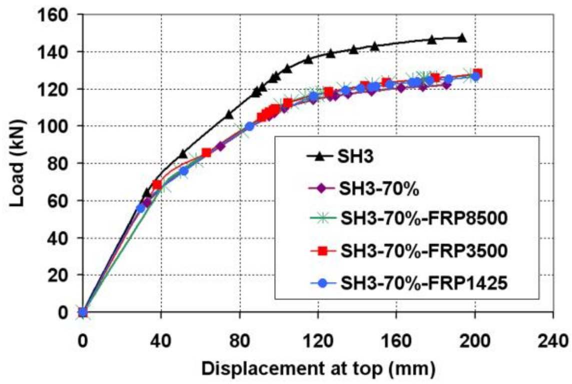

Fig. 7. Effect of wall height in which boundary elements are strengthened with FRP sheet in specimen SH3-b70%

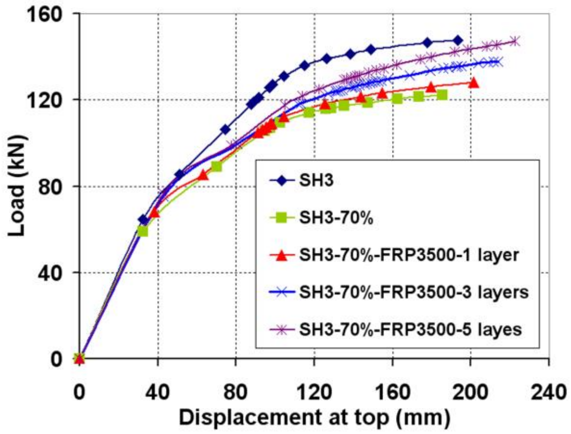

Fig. 8. Effect of number of FRP sheet layers at wall boundary elements in specimen SH3-b70%

To investigate the effect of width of strengthening FRP across the boundary elements of shear wall, the specimens SH3-70%-W, SH3-70%-2/3W and SH3-70%-1/3W are defined where the walls are strengthened with 5 layers of CFRP along the plastic hinge length of the boundary elements. The load-displacement curves of the strengthened specimens from the basis of shear wall SH3-70% are shown in Fig. 9. It is observed from the figure that strengthening of the shear wall across one-third of their boundary elements only decreases the load carrying capacity of the wall 10 % compared to the wall strengthened across the full width of its boundary elements.

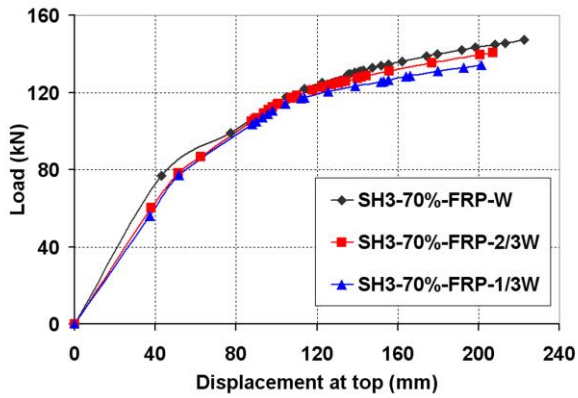

Fig. 9. Effect of FRP sheet width reduction at wall boundary elements in specimen SH3-b70%

6. CONCLUSION

In this paper the effect of strengthening of boundary elements of slender shear walls with FRP on the wall behavior under monotonic loading was studied. It is worth mentioning that despite the fact of availability of some studies on FRP strengthening of slender shear walls under complex time-history dynamic loads and many researches on the squat walls behavior, to the authors' best knowledge no documents are available thus far on the effect of application of FRP on slender wall behavior under monotonic loading. The following conclusions are extracted from the current study.

1. The concrete damage plasticity is able to accurately simulate the flexural behavior of slender shear walls.
2. It was indicated that the longitudinal steel reinforcement in boundary elements plays a major role on the wall load carrying capacity rather than wall displacement ductility. Thus, reducing the amount of longitudinal reinforcement in boundary elements decreases the load capacity but has no significant effect on the initial stiffness and ultimate displacement of the wall.
3. Applying multi-layer of FRP composites along the plastic hinge length of wall may increase the ultimate loading capacity.
4. Decreasing the width of strengthened boundary elements with FRP deceases the initial stiffness of the load-displacement curve.

REFERENCES

1. Mostofinejad, D. (2014). *Reinforced concrete structures*. Vol. I & II. 34th Ed., Arkan Danesh Publications, Iran, 716 pp. (In Persian).
2. Lombard, J. C. (1997). Seismic strengthening and repair of reinforced concrete shear walls using externally bonded carbon fiber tow sheets. *PhD Thesis*, Carleton University.
3. Lombard, J., Lau, D., Humar, J., Foo, S. & Cheung, M. (2000). Seismic strengthening and repair of reinforced concrete shear walls. *Proc. 12th World Conf. Earthquake Engineering*, Paper No. 2032.
4. Mostofinejad, D. & Shameli, S. M. (2013). Externally bonded reinforcement in grooves (EBRIG) technique to postpone debonding of FRP sheets in strengthened concrete beams. *Construction and Building Materials*, Vol. 38, pp. 751-758.
5. Mostofinejad, D. & Tabatabaei Kashani, A. (2012). Experimental study on effect of EBR and EBROG methods on debonding of FRP sheets used for shear strengthening of RC beams. *Composites: Part B*, Vol. 45, No. 1, pp. 1704-1713.
6. Nasir Pour, N. (1999). *Non-linear finite element analysis and parametric investigation of low-rise reinforcement concrete shear walls. PhD Thesis*, University of Ottawa, Canada.
7. Ahmed, M. M. (2000). *Linear and nonlinear flexural stiffness models for concrete walls in high-rise buildings. PhD Thesis*, University of British Columbia.
8. Ghobarah, A. & Youssef, M. (1999). Modeling of reinforced concrete structural walls. *Engineering Structures*, Vol. 21, pp. 912-923.
9. Antoniades, K. K., Solonikios, T. N. & Kappos, A. J. (2003). Cyclic tests on seismically damaged reinforced concrete walls strengthened using fiber-reinforced polymer reinforcement. *ACI Structural Journal*, Vol. 100, No. 5, July-August, pp. 510-518.
10. Antoniades, K. K., Thomas, S. N. & Kappos, A. J. (2007). Evaluation of hysteric response and strength or repaired R/C walls strengthened with FRPs. *Engineering Structures*, Vol. 29, pp. 2158-2171.
11. Tasnimi, A. A. (2000). Strength and deformation of mid-rise shear walls under load reversal. *Engineering Structures*, Vol. 22, pp. 311-322.

12. Su, R. K. L. & Wong, S. M. (2007). Seismic behavior of slender reinforced concrete shear walls under high axial load ratio. *Engineering Structures*, Vol. 29, pp. 1957-1965.
13. Thomsen, J. H. & Wallace, J. W. (2004). Displacement-based design of slender reinforced concrete structural walls-experimental verification. *Journal of Structural Engineering,* Vol. 130, No. 4, pp. 618-630.
14. Perry, A., Ahmed, M. M. & Bryson, M. (2007). Test of high-rise core wall: effective stiffness for seismic analysis. *ACI Structural Journal,* Vol. 104, No. 5, pp. 549-559.
15. Honggun, P., Su, M. K., Lan, C. & Do, B. L. (2007). Moment-curvature relationship of flexure-dominated walls with partially confined end-zones. *Engineering Structures,* Vol. 29, pp. 33-45.
16. Meftah, S. A., Tounsi, A., Megueni, A. & Adda Bedia, E. A. (2006). Lateral stiffness and vibration characteristics of R/C shear walls with thin composite plates. *Composite Structures,* Vol. 73, pp. 110-119.
17. Meftah, S. A., Tounsi, A., Megueni, A. & Adda Bedia, E. A. (2008). Lateral stiffness and vibration characteristics of composite plated RC shear walls with variable fibers spacing. *Material and Design,* Vol. 29, pp. 1955-1964.
18. Meftah, S. A., Tounsi, A., Yeghnem, R. & Adda Bedia, E. A. (2007). Seismic behavior of R/C coupled shear walls repaired with CFRP laminates having variable fibers spacing. *Construction and Building Materials,* Vol. 21, pp. 1661-1671.
19. Tao, Y. U. (2006). *Structural behavior of hybrid FRP-concrete-steel double-skin tabular columns. PhD Thesis,* Hong Kong University.
20. ABAQUS Inc. (2007). ABAQUS/theory user manual, Version 6.7.
21. Mostofinejad, D. & Talaeitaba, S. B. (2006). Finite element modeling of RC connections strengthened with FRP laminates. *Iranian Journal of Science & Technology, Transaction B: Engineering,* Vol. 30, No. B1, pp. 21-30.
22. Dalalbashi Esfahani, A., Mostofinejad, D., Mahini, S. & Ronagh, H. R. (2011). Numerical Investigation on the behavior of FRP retrofitted RC exterior beam-column joints under cyclic loads. *Iranian Journal of Science & Technology, Transaction B: Engineering,* Vol. 35, No. C1, pp. 35-50.
23. Mostofinejad, D. & Mohammadi Anaei, M. (2012). Effect of confining of boundary elements of slender RC shear wall by FRP composites and stirrups. *Engineering Structures,* Vol. 41, pp. 1-13.
24. ACI Committee 318. (2011). Building code requirements for structural concrete (ACI 318-11) & Commentary. Farmington Hills, MI, USA.
25. Kheyroddin, A. & Naderpour, H. (2008). Nonlinear finite element analysis of composite RC shear walls. *Iranian Journal of Science and Technology, Transaction B, Engineering,* Vol. 32, No. B2, pp. 79-89.