# A NUMERICAL ANALYTICAL STUDY ON THE DAMAGED RC SHEAR WALLS WITH OPENINGS RETROFITTED BY FRP SHEETS

Ahmadreza SHIRNESHAN
*MSc Student, Isfahan University of Technology, Isfahan, Iran*
*Ahmadshirneshan@yahoo.com*

Kiachehr BEHFARNIA
*Associate Professor, Department of Civil Engineering, Isfahan University of Technology, Isfahan ,Iran*
*Kia@cc.iut.ac.ir*

**Keywords:** Shear Wall, Openings, Retrofit, FRP, Finite Element

## ABSTRACT

This paper presents the analytical results of a study investigating the effectiveness of using fiber-reinforced polymer (FRP) sheets for repairing of reinforced concrete shear walls with regular openings. The majority of research studies on the behavior of reinforced concrete members with externally bonded fiber reinforced polymer (FRP) sheets have been focused on beams, columns, and beam-columns joints. However, limited studies have been conducted to investigate the performance of structural walls retrofitted by FRP sheets, especially on structural walls with regular openings. Nonlinear finite element analysis is performed on two repaired shear wall with regular openings. The performance of the repaired walls was observed to be better than the original walls before repairing in terms of the flexural behavior, shear strength, ductility capacities and ultimate lateral load resistance. Therefore it could be concluded that application of FRP sheets is proper way to retrofit shear wall with regular openings.

## INTRODUCTION

Reinforced concrete shear wall is a resistance system against lateral load induced by earthquake and wind in high rise buildings.The functional requirements such as architectural and even mechanical requirements entail openings to be installed in structural walls. These openings may significantly influence its behaviors, such as changing its force transfer mechanism, deducting its strength and stiffness, and decreasing its ductility level. Therefore, repair and retrofit of the shear walls with openings is both necessary and important (Meftah et al, 2007).

In recent years, fibre reinforced polymers (FRP) have been greatly used in strengthening and retrofitting of structural elements because of their high strength-to-weight ratios, corrosion resistance, ease of application, and tolerability (Behfarnia and Sayah, 2012).

This paper presents the effect of repairing shear wall with regular openings that were initially subjected to lateral loading and damaged in lateral loading and subsequently repaired with FRP sheets and re-loaded.

A review on the previous studies showed that very limited analytical and experimental studies have been conducted on the FRP repairing of RC shear wall with regular openings under monotonic loading. Bing Li and la addressed the effect of using CFRP sheets on the lateral strength and ductility of the non-seismic RC shear walls. The work compared the behavior of damaged RC walls after they had been repaired to that of its original counterparts. From the experiments, the repair of damaged walls using FRP sheets could serve to restore the strength and ductility of damaged RC walls (Li and lim, 2010).
Cruz-Noguez et al studied the repairing and strengthening of nine RC shear walls using externally bonded FRP tow sheets. In repair applications, the FRP reinforcement system was shown to recover most of the initial elastic stiffness and increase the maximum flexural capacity of seismically damaged walls. In

strengthening applications, the FRP system was found to be effective in significantly increasing the stiffness and the ultimate flexural capacity of the undamaged walls (Cruz-Noguez et al, 2014).

## VALIDATION OF MODELING

In this study, nonlinear finite element analysis was utilized to study the effects of fiber reinforced plastic (FRP) on the maximum load capacity and ultimate lateral displacement of concrete shear walls with regular openings that were initially subjected to lateral loading and damaged using the finite element software ABAQUS. Nonlinear finite element analysis of reinforced concrete shear wall was performed using damage plasticity model and tension stiffening effect.

The constitutive model used to analyze the concrete was a concrete damaged plasticity model. This model is a continuum plasticity-based damage model for concrete (ABAQUS Inc, 2012).

The steel re-bars and stirrups were modeled as two dimensional truss elements (T3D2) embedded in C3D8R solid elements. The steels were considered as elastic perfectly plastic materials in both tension and compression (ABAQUS Inc, 2012).

The FRP materials were assumed to be orthotropic and transversely isotropic and the brittle material was supposed to be with zero compressive strength.

In most RC elements repaired/strengthened with FRP, de-bonding of the FRP material from the concrete substrate controls the failure mode and the overall response of the element. In this study, for modeling the FRP de-bonding, we used the cohesive element. The cohesive element was located between the concrete element and the FRP element. The bond-slip curves given by Lu were used to model the cohesive element. Lu et al provided a critical review and assessment of the existing bond strength models and bond–slip models (Lu et al, 2005).

In order to confirm the applicability of the proposed numerical models used in this study, the numerical model was calibrated and verified with the experimental data. There were a number of experimental tests available in the literature which could be used for the primary verification of possible numerical analyses. For this reason, one shear wall and one repaired shear wall by FRP sheets were simulated by concrete damage plasticity model with the software and the results were compared with the experimental results. The comparisons were represented by lateral load–top displacement curves.

These walls were experimentally tested by Cruz-Noguez et al. The walls section and reinforcement details of the walls are given at Figure 1. Both the walls inventory included one control wall (CW), and one repaired wall (RW). The walls were subjected to lateral load applied through displacement control. Material properties of concrete, steel, and dry FRP fibers are shown in Table 1.

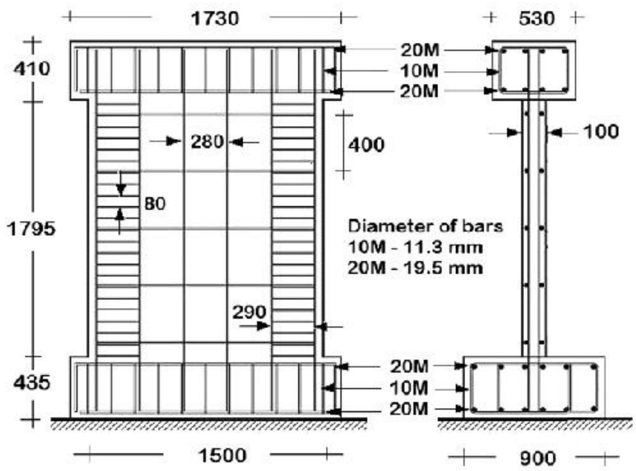



Figure 1. Reinforcement details of shear walls CW and RW (Cruz-Noguez et al, 2014)

Table 1. Material Properties (Cruz-Noguez et al, 2014)

| Concrete and steel rebar | | FRP | |
|---|---|---|---|
| Material property | Value | Material property | Value |
| $F'_c$ | 41 MPa | $f_{FRP;u}$ | 3.84 GPa |
| $F'_y$ | 412 MPa | $E_{FRP}$ | 230 GPa |
| $\varepsilon_y$ | 0.0026 | $\varepsilon_{FRP;u}$ | 0.0151 |
| $f_u$ | 0.0121 | $t_{FRP}$ | 0.11 mm |

The control wall was not tested to failure because the purpose of the FRP repair scheme was to evaluate its efficiency in walls with seismic damage. Moderate damage in the CW specimen was defined as the structural state of significant concrete cracking and yielding of the vertical steel reinforcement.

The experimental and analytical load displacement responses are compared through the load displacement curves shown in Figure 2. The measured maximum lateral force and the corresponding displacement in the reference wall were 170.5kN and 14.28mm, respectively. On the other hand, the numerical predictions obtained for the maximum lateral force and the corresponding displacement were 170.3kN and 17.67mm, respectively.

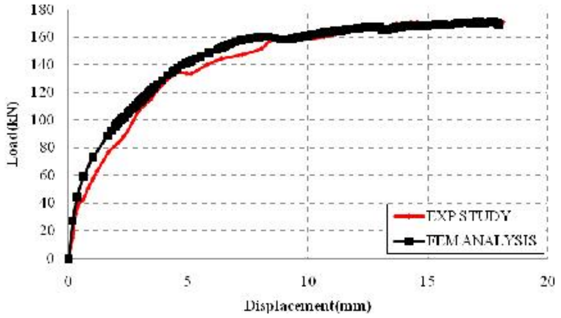



Figure 2. Comparison of FEM analysis and experimental load displacement curves for shear wall CW

Shear wall RW was repaired by FRP sheets oriented in the vertical direction prior to testing. In this wall, the sheets were not wrapped around the walls but attached to the front and back faces only (Figure 3).


Figure 3. Experimental repaired shear walls (RW) (Cruz-Noguez et al, 2014)

In ABAQUS, it is possible to simulate repair procedures by using previously result from initial loading. For example, if a certain structure is to be repaired with a layer of surface-bonded FRP sheets after being subjected to damage, the analyst may activate a previously results and the structure can then be analyzed later in the repaired condition, accounting for the stressed (damaged) state of the previously loading. To simulate the response of the wall shear wall RW, we are used these procedures. After analyzing the shear wall CW, the results were saved in INP files and after that, these files were used for repairing damaged shear wall. Figure 4 shows the calculated force-displacement responses of shear wall RW. The overall correlation between the calculated and measured response is good and the predictions of initial stiffness and maximum strength are reasonable (the differences between the analytical and experimental maximum load was 6%). These results indicate that ABAQUS software can simulate the damaged structures and bond slip model can predict de-bonding in shear walls.

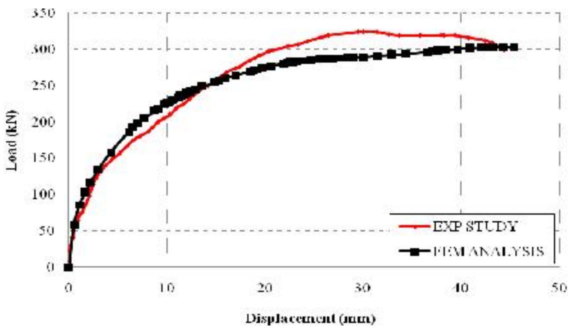
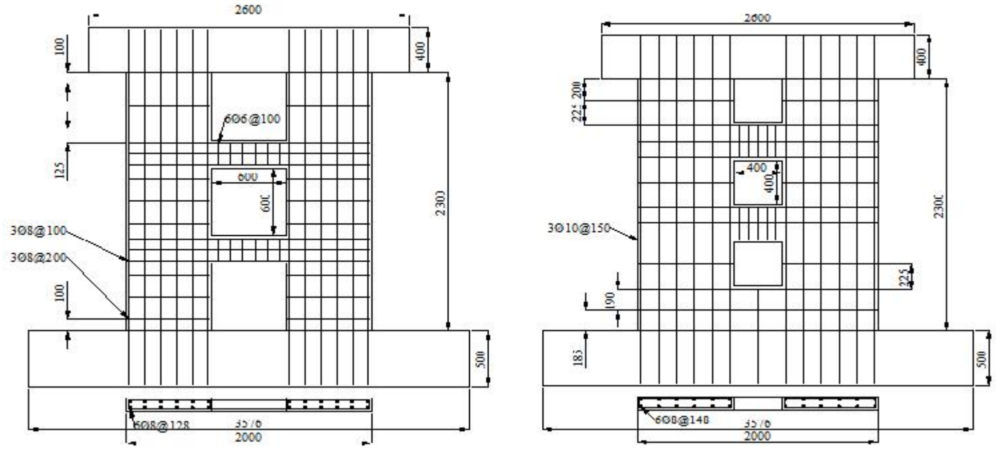



Figure 4. Comparison of FE analysis and experimental load–displacement curves for shear wall RW

## PARAMETRIC STUDY

After the verification of the finite element method with the proposed reference model, in order to study the effects of FRP repairing in shear walls with openings, two shear walls with regular openings (W1 and W2) was repaired by CFRP sheets with different configurations and different thicknesses of sheets.

This shear walls were designed according to strut and tie model by Yanez (Yanez et al, 1992). Dimensions and reinforcement details of this walls and openings size are given in Figure 5. The concrete compression strength was 34MPa and steel bars with the nominal yield strength of 475MPa and the ultimate strength of 690MPa were used. In this study, all walls were subjected to lateral load applied through displacement control.



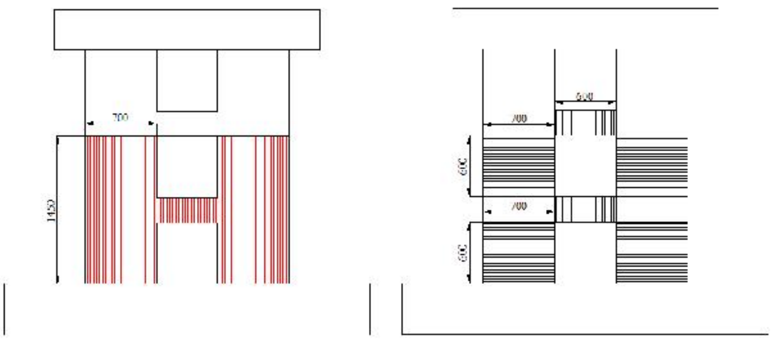
(a) (b)

Figure 5. Reinforcement details of shear walls: (a) W1, (b) W2 (Yanez et al, 1992)

The control wall was not tested to failure because the purpose of the FRP repair scheme was to evaluate its efficiency in wall with damage. Moderate damage in the shear walls W1 and W2 was defined as the structural state of significant concrete cracking and yielding of the vertical steel reinforcement. The repaired walls are referred to by a prefix of "R" to represent the original wall name. The specimens were loaded after repairing with two different configurations of CFRP sheets. The detailed descriptions of applied CFRP configurations are given in Figure 6 and Figure 9 for shear walls W1 and W2 respectively. A layer of CFRP sheets with fibers oriented in a horizontal direction was attached to the front and back faces of shear walls W1O1 and W2O1 and CFRP was wrapped at each piers and coupling beams for the shear walls W1O2 and W2O2. The thickness of CFRP used to strengthen the shear walls was T1, T2 and T3, equal to 0.12, 0.24 and 0.36 mm, respectively. Names of the models were based on the location of the CFRP sheets and the thickness, respectively. Table 2 illustrates the mechanical properties of the CFRP.

Table 2. Material properties of FRP

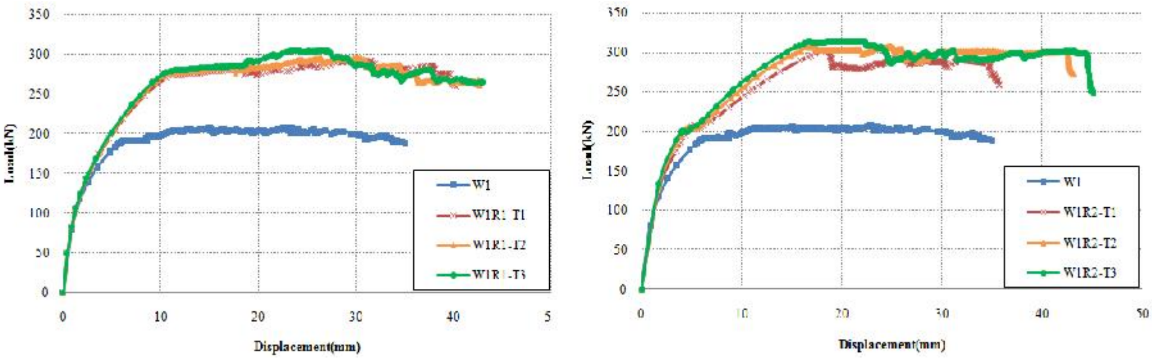
| FRP composite | Elastic modulus (GPa) | Poisson's ratio | Tensile strength (MPa) | Thickness of laminate (mm) |
|---|---|---|---|---|
| CFRP | $E_x$= 231<br>$E_y$= 38<br>$E_z$= 38 | $\upsilon_{xy}$= 0.22<br>$\upsilon_{xz}$= 0.28<br>$\upsilon_{yz}$= 0.28 | 4100 | 0.12 |



(a) (b)

Figure 6. Repairing schemes of shear wall W1: (a) W1R1, (b) W1R2

The load displacement curves of the shear walls W1R1 and W1R2 are presented in Figure 7. The lateral resisting capacity of shear walls W1R1 and W1R2 were better than the control wall before repairing in terms of the flexural behavior, shear strength, ductility capacities and ultimate lateral resistance. This was in both the lateral loading capacity and ultimate displacement. In shear wall W1R1 the CFRP sheets made better flexural behavior. In shear wall W1R2 that the CFRP sheets were wrapped, the concrete was confined on the piers and coupling beams. It was observed that the effect of increasing the thickness of CFRP in the models was mostly increasing the ultimate displacement and load carrying capacity was not changed. The shear walls W1R1 and W1R2 were failed due to FRP rupture and FRP rupture in piers edge respectively (Table 3).



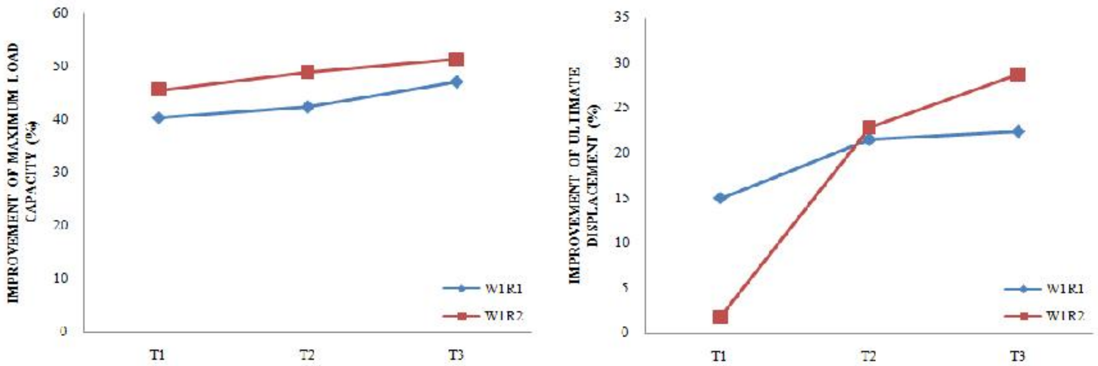

(a) (b)

Figure 7. Load displacement curve from the numerical analysis: (a) W1R1, (b) W1R2

Table 3. Analytical results for repairing of damaged shear wall W1

| Specimen | Ultimate Displacement(mm) | Maximum load carrying capacity(kN) | %Ultimate Displacement improvement | %Maximum load carrying capacity improvement | Ultimate failure mode |
|---|---|---|---|---|---|
| W1 | 35 | 207.6 | | | Concrete crushing |
| W1R1-T1 | 40.3 | 291.4 | 14.9 | 40.3 | FRP de-bonding |
| W1R1-T2 | 42.6 | 295.7 | 21.5 | 42.6 | FRP de-bonding |
| W1R1-T3 | 42.9 | 305.5 | 22.4 | 47.12 | FRP de-bonding |
| W1R2-T1 | 35.7 | 302.5 | 1.82 | 45.56 | FRP rupture |
| W1R2-T2 | 43 | 309.1 | 22.84 | 48.87 | FRP rupture |
| W1R2-T3 | 45.1 | 314.3 | 28.69 | 51.36 | FRP rupture |

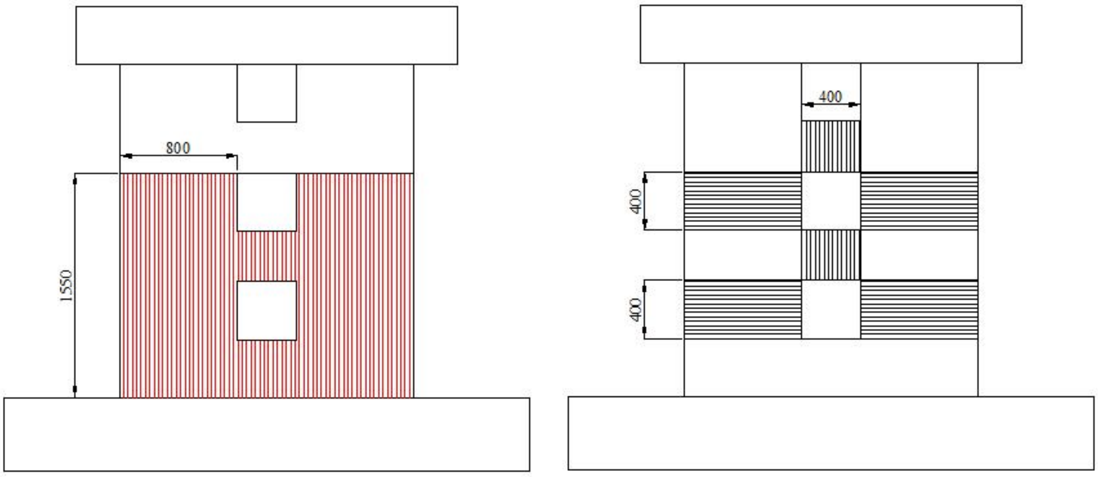
Figure 8 shows the improvement of maximum load capacity and ultimate displacement, respectively. As can be seen from this figure, shear walls W1R2 had the best performance.




(a) (b)

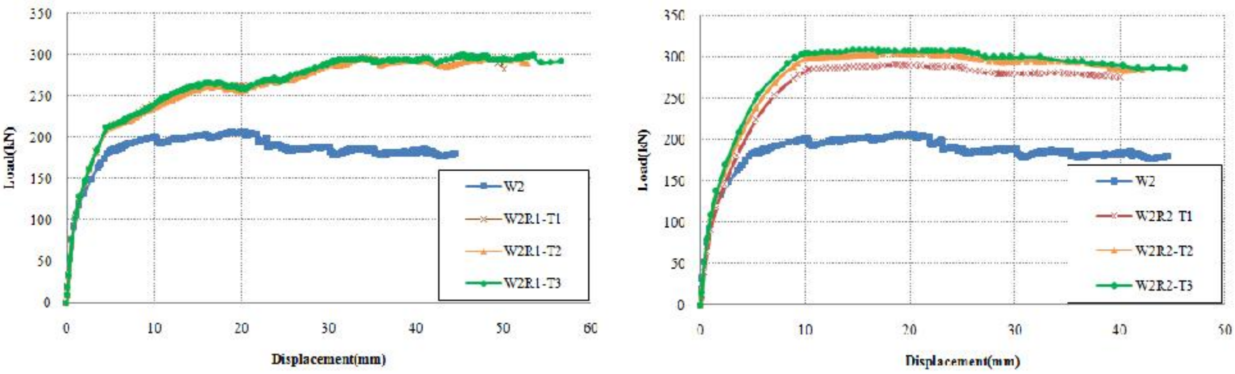
Figure 8. Comparison of repairing schemes: (a) Maximum load capacity, (b) ultimate displacement

Figure 9 shows the load displacement curves for the shear walls W2R1 and W2R2. The figure shows that the repairing of the wall in the configuration of W2R1 improved the wall load capacity an ultimate displacement, also the performance of the repaired wall was better than control wall, and in shear wall W2R2, the lateral resisting capacity was increased, whereas the ultimate displacement of the repaired wall was only slightly higher than that of their corresponding control shear wall. As can be seen in this figure, increasing the thickness of CFRP in the models was mostly increasing the ultimate displacement. Note that the repaired shear walls W2R1 and W2R2 failed due to FRP de-bonding and FRP rupture respectively (Table 4).




(a) (b)

Figure 9. Repairing schemes of shear wall W2: (a) W2R1, (b) W2R2



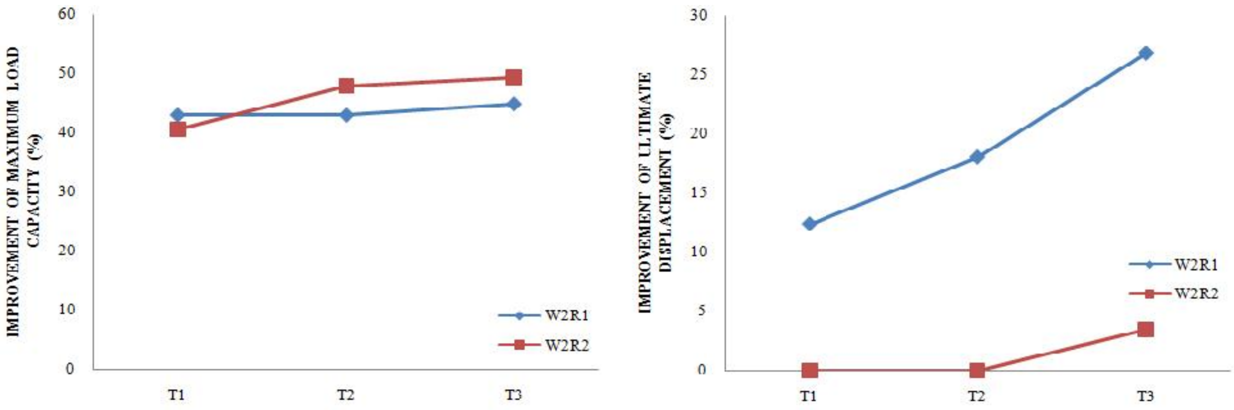

(a) (b)

Figure 10. Load displacement curve from the numerical analysis: (a) W2R1, (b) W2R2

Table 4. Analytical results for repairing of damaged shear wall W2

| Specimen | Ultimate Displacement(mm) | Maximum load carrying capacity(kN) | %Ultimate Displacement improvement | %Maximum load carrying capacity improvement | Ultimate failure mode |
|---|---|---|---|---|---|
| W2 | 44.5 | 206.5 | | | Concrete crushing |
| W2R1-T1 | 50.1 | 295.4 | 12.4 | 43 | FRP de-bonding |
| W2R1-T2 | 52.6 | 295.5 | 18 | 43.1 | FRP de-bonding |
| W2R1-T3 | 56.5 | 299.3 | 26.8 | 45 | FRP de-bonding |
| W2R2-T1 | 39 | 290.3 | 0 | 40.61 | FRP rupture |
| W2R2-T2 | 43.2 | 305.3 | 0 | 47.8 | FRP rupture |
| W2R2-T3 | 46.1 | 308.5 | 3.5 | 49.4 | FRP rupture |

Figure 11 shows the improvement of maximum load capacity and ultimate displacement, respectively. As can be seen from this figure, shear wall W2R1 had the better performance in ultimate displacement than W2R2 and shear wall W2R2 had the better performance in load capacity than W2R1.




(a) (b)

Figure 11. Comparison of repairing schemes: (a) Maximum load capacity, (b) ultimate displacement

## CONCLUSIONS

This paper presented the results obtained from an analytical study to show the repairing of damaged shear wall with regular openings using externally bonded FRP sheets. Shear walls contained 2 specimens with different size of openings. All shear walls were tested under monotonic lateral loading. From this study, the following conclusions can be drawn:

1- Concrete damage plasticity model could predict the lateral load displacement of a shear wall in all its linear and nonlinear stages accurately.
2- In repairing applications, the shear wall repaired by the vertical FRP sheets was effective in significantly increasing the load capacity and ductility capacity of the wall.
3- Applying wrapped CFRP sheets around the piers and coupling beams of shear wall with regular openings was found to have significant effects on the load careening capacity of the wall with openings.
4- Increasing the thickness of CFRP sheets had the biggest effect on the ultimate displacement of models repaired by CFRP sheets.

## REFERENCES

ABAQUS Inc (2007) ABAQUS/Theory User manual, Version 6.7

Behfarnia B and Sayah AL (2012) FRP Strengthening of Shear Walls with Openings, *Asian Journal of Civil engineering*, 12(5): 691-704

Cruz-Noguez C, Lau D, Sherwood E, Hiotakis S, Lombard J and Foo S (2014) Seismic Behavior of RC Shear Walls Strengthened for In-Plane Bending Using Externally Bonded FRP Sheets, *Journal of Composites for Construction*

Li B and Lim CL (2010) Tests on Seismically Damaged Reinforced Concrete Structural Walls Repaired Using Fiber-Reinforced Polymers, *Journal Of Composites For Construction*, 10(14): 597-608

Lu XZ, Teng JG, Ye LP and Jiang JJ (2005) Bond–slip Models for FRP Sheets/Plates Bonded to Concrete, *Engineering Structures*, 27(6):920-937

Meftah SA, Yeghnem R and Tounsi A (2007) Seismic Behavior of RC Coupled Shear Walls Repaired with CFRP Laminates Having Variable Fibers Spacing, *Construction and Building Materials*, 21(8):1661-1671

Yanez FV, Park R and Paulay T (1992) Seismic Behavior of Walls with Irregular Openings, *In Earthquake Engineering Tenth World Conference*, Balkema Rotterdam