# HYSTERETIC EVALUATION OF SEISMIC BEHAVIOR OF RC SHEAR WALLS STRENGTHENED WITH FRP SHEETS

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**ABSTRACT :**

The development of nonlinear finite element methods with increasing computational capacity, has improved the reliability of seismic analysis of complex structure. The effectiveness of Fiber Reinforced Polymer (FRP) externally bonded reinforcement has been widely recognized with respect to increasing shear strength of RC members, particularly of those not satisfying the requirements of modern seismic codes, and also providing confinement to critical regions of such members. Application of externally bonded Fiber Reinforced Polymer sheets is an effective seismic strengthening procedure in order to improve the behavior of reinforced concrete shear walls. In the retrofit method using FRP sheets, the flexural and shear strength would be increased by applying the FRP sheets with the fibers oriented in the vertical or horizontal direction. The carbon fiber sheets are used to increase the pre-cracked stiffness, the cracking load and the ultimate flexural capacity of RC walls. Finally, wrapped FRP sheet around plastic hinge area of RC wall in parallel with boundary elements, provides not only enough shear strength which results in a ductile flexure failure mode but also confinement of concrete in the plastic hinge leads to increase the ductility of the RC wall.The main purpose of this research project is to present results from numerical analysis that was obtained during the analyzing of RC wall structural models strengthened using FRP reinforcement. The strengthening of these walls aimed at the increase of both the flexural and shear strength, whereas in seismic interventions with FRPs only the latter is usually attempted. Issues that are critical with respect to the seismic performance, i.e. horizontal displacement, ductility, and energy dissipation capacity are presented and discussed. Also envelopes of cyclic load vs. displacement curves were compared. The total displacement of an RC member is made up of three components, each contributed by a different deformation mechanism, namely flexure, shear, and sliding shear; the relative contribution of each mechanism varies with the level of inelasticity. Also the hysteretic responses of structural models are presented in order to achieve the capacity of energy dissipation of the RC walls and effectiveness of using FRP sheets on them. Hysteretic loops are somehow fat that shows the excellent capacity of energy dissipation during earthquake event. Also by comparing the results between models it can be declared that by using an extra layer of FRP on the plastic hinge area of the shear wall, its behavior during the seismic loading would be improved. This result is very similar to the result that had been obtained when applying the monotonic loading on shear walls.

**KEYWORDS:** RC Shear Wall, Hysteretic, FRP, Plastic Hinge, Strengthening.

## 1. INTRODUCTION

Simulating the non-linear behavior of Reinforced Concrete (RC) walls subjected to severe earthquake ground motion is an important problem for the engineering community. The development of nonlinear, the finite element methods with increasing computational capacity, has improved the reliability of seismic analysis of complex structure. The stresses induced in structures under seismic loads exceed yield capacities and generate large inelastic deformations in critical regions. Since the seismic response of structures depends on the hysteretic behavior of these regions, reliable models of such behavior need to be developed. Thus, the use of nonlinear structural analysis requires computationally efficient models for performing analyses with sufficient accuracy. These models must describe essential geometrical and material characteristics as well as the basic mechanisms that control the hysteretic behavior of reinforced concrete structures.
Due to their high initial stiffness and lateral load capacity, shear walls are an ideal choice for a lateral load-resisting system in a RC structure. Stiffness of a RC component depends on material properties, component dimensions, reinforcement quantities, boundary conditions, and stress levels. Each of these aspects should be considered and verified when defining effective stiffness; Shear walls are major members in RC buildings for resisting lateral loads. They must provide not only adequate strength, but also sufficient ductility to avoid brittle failure under strong lateral loads, especially during an earthquake. The term ‘‘composite wall system’’ refers to a number of possible configurations including: (1) cantilever composite walls, where steel or FRP components are embedded in or attached to RC walls, (2) Hybrid coupled walls, where steel beams are used to couple two or more RC or composite walls in series, and (3) Hybrid dual systems, where RC walls are placed in parallel with steel moment frames (Spacone et al., 2004).
The effectiveness of Fiber Reinforced Polymer (FRP) externally bonded reinforcement has been widely recognized with respect to increasing shear strength of RC members, particularly of those not satisfying the requirements of modern seismic codes, and also providing confinement to critical regions of such members. Despite the relatively high cost of the FRP material, its high strength-weight ratio, high resistance to corrosion, and easy handling and installation have made FRP jackets the material of choice in an increasingly large number of projects where increased strength or inelastic deformation capacity (ductility), or both, must be achieved for seismic retrofitting (Triantafillou 2003); Also, the effect of FRP strengthening on the energy dissipation capacity under horizontal loading is much less established. The latter is particularly true in the case of RC walls, a type of member for which very little is known with respect to seismic retrofit using FRP reinforcement.
Research on the behavior of reinforced concrete members with externally bonded FRP sheets has mainly focused on columns or piers where its use is more common (Priestley et al. 1996; Penelis and Kappos 1997; Triantafillou 2001). Application of FRP sheets on RC walls, although not uncommon as a practical retrofit measure (Ehsani and Saadatmanesh 1997), has attracted much less attention by researchers. In reality, the only experimental studies involving FRP-strengthened RC walls are those by Lombard et al. (2000) who applied FRP sheets with fibers in the vertical direction on the side faces of walls that were subjected to cyclic shear and flexure, and of Neale et al. (1997) who tested wall-like columns (aspect ratio of wall cross section equal to 6) with different arrangements of externally bonded FRP reinforcement under uni-axial compression only.
In previous studies, the authors tried to investigate the behavior of RC shear walls after being composited using externally bonded steel plates and FRP sheets and comparing the analysis results of them to the results of RC shear walls (with no composite component) in order to indicate the effectiveness of using composite elements (Kheyroddin and Naderpour, 2008). The main conclusion from the verification against experimental data was that the Finite Element program can be used to simulate the whole load-deformation curve, i.e., the elastic part, the initiation of cracking, shear cracks and crushing fairly well. However, the determination of ultimate load is difficult as it is affected by the hardening rule, convergence criteria and iteration method used. Three retrofitted RC walls were analyzed using externally bonded steel plates but after eliminating the over-hanged part of the boundary elements. The results showed that a ductile behavior close to the behavior of RC wall with boundary elements could be achieved from the model with suitable thickness of steel jacket that leads to this theory that steel jacketing could be an alternative for the boundary elements of RC shear walls. Analysis results showed that the application of externally bonded carbon fiber sheets is an effective seismic strengthening procedure for RC shear walls. The carbon fiber sheets could be used to increase the pre-cracked stiffness, the cracking load

(up to 35%), the yield load and the ultimate flexural capacity (up to 18%) of RC walls. The wrapped CFRP sheet around plastic hinge range of RC wall provided not only enough shear strength which resulted in a ductile flexure failure mode with the concept of strong shear and weak flexure, but also confinement of concrete in the plastic hinge lead to increase the ductility of the RC wall. With the confinement of CFRP, a desirable ductile flexural failure mode rather than a brittle shear failure mode would be achieved.
The main purpose of this research project is to present results from numerical analysis that was obtained during the analyzing of RC wall structural models strengthened using FRP reinforcement. The strengthening of these walls aimed at the increase of both the flexural and shear strength, whereas in seismic interventions with FRPs only the latter is usually attempted. Issues that are critical with respect to the seismic performance, i.e. horizontal displacement (drift), ductility, and energy dissipation capacity are presented and discussed. Also envelopes of cyclic load vs. displacement curves, their bi-linearized skeleton curves, and the associated displacement ductility factors were compared.

## 2. EXPERIMENTAL TEST

The experimental data for the RC walls were obtained from Barda (1972). Laboratory tests of eight scaled, low-rise shear walls with boundary elements have been described. All the shear-walls have the same geometry, but the reinforcement varies between the tests. The boundary elements were supposed to simulate the effect of cross walls and an overlying floor slab. The horizontal length of the test walls was 1900 mm; the height was 610 mm, and the thickness was 100 mm. In Figure 2 the tilt-up from the laboratory tests is shown.

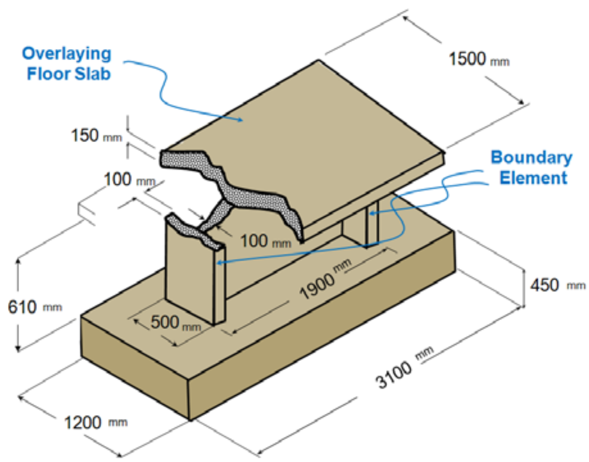


Figure 1 laboratory tested shear wall with boundary elements

## 3. NONLINEAR FINITE ELEMENT MODELING

Nonlinear response of RC is caused by cracking, plastic deformations in compression and crushing of the concrete and plastic deformations of the reinforcement. Other, usually less important, time-independent nonlinearity arises from bond slip between steel and concrete, aggregate interlock of cracked concrete and dowel action. Time-dependent effects, such as creep, shrinkage and temperature change, also affect nonlinear response but can be ignored for short-duration earthquake loads. Cracking is the most important factor on material nonlinearity of concrete. In the following, only nonlinear properties due to cracking, plastic deformations of concrete and steel, and aggregate interlock are considered.
The previous study by the authors was focused on modeling both the load-displacement characteristics of the shear walls and also the initiation of cracking. The load was iterated step by step using the Newton-Raphson method. In the static analysis, the stress-strain relations of concrete were modified to represent the presence of cracking (Kheyroddin, Hoseini Vaez and Naderpour2008). Newton-Raphson equilibrium iterations were used

for nonlinear numerical analysis. After calibration the analytical results of load-displacement curves against the available experimental data, the effect of using externally bonded FRP sheets on the behavior of the shear walls was investigated.

## 4. APPLYING EXTERNALY BONDED FRP SHEETS TO RC WALLS

Over the last years, the use of fiber reinforced polymers for the strengthening of existing buildings has increased due to the ease of application, the high strength-to-weight ratio, and the high resistance to corrosion that these materials can develop. On the other hand, consideration of their mechanical properties, in particular their linearly elastic behavior up to tension failure, raise questions concerning their effectiveness in strengthening structural elements subjected to seismic loading. Several techniques are currently available to retrofit and strengthen buildings with insufficient stiffness, strength and/or ductility. These techniques include the strengthening of existing shear walls by the application of shotcrete or Ferrocement, filling in openings with RC and masonry in fills, and the addition of new shear walls and steel bracing elements (FEMA, 1992). While these techniques are effective in improving the earthquake resistance of a building, they may add significant weight to the structure and thus alter the magnitude and distribution of the seismic loads. Also, the existing techniques are generally very labor intensive.

Fiber reinforced polymer materials are composite materials consisting of high strength fibers immersed in a polymer matrix. The fibers in an FRP composite are the main load-carrying element and exhibit very high strength and stiffness when pulled in tension. An FRP laminate will typically consists of several million of these thin, thread-like fibers. The polymer matrix protects the fibers from damage, ensures that the fibers remain aligned, and allows loads to be distributed among many of the individual fibers in the composite. In the retrofit method using CFRP sheets, the flexural strength of a shear wall is increased by applying the CFRP sheets with the fibers oriented in the vertical direction. Essentially, the added CFRP sheets contribute to the flexural strength of the wall in similar mechanisms as the vertical steel reinforcements. For enhancement to the shear strength of a shear wall, the CFRP sheets are bonded externally to the wall with the fibers oriented in the horizontal direction (Hiotakis et al., 2000; Lombard et al., 2000; Saadatmanesh et al., 1994).

In order to investigate the effect of using externally bonded FRP sheets on the behavior of shear walls, three different models with different configurations of FRP layers (concentrating on number of layers) were developed. The first wall (SW1) was strengthened with one vertical ply of carbon fiber sheets; The second wall (SW2) was strengthened with two vertical plies of carbon fibers and the third wall (SW3) was strengthened with two vertical plies of carbon fibers and one in the horizontal direction. The geometry and meshing of the models is available in Figure 2 Number of elements in this model is equal to 1354.

A layered solid element was used to model the FRP composites. The element allows for up to 100 different material layers with different orientations and orthotropic material properties in each layer. The element has three degrees of freedom at each node and translations in the nodal x, y, and z directions. To simulate the perfect bonding of the CFRP sheets with concrete, the nodes of elements were connected to the nodes of concrete elements at the interface so that two materials shared the same nodes. The material properties for FRP composites are available at Table1.

The load versus top horizontal displacement curve of SW1 wall specimen is presented in Figure 3. As it can be seen from the curves, the initiation of cracking of concrete was on the load of 320 kN. This represented a 23 percent increase in the cracking strength of the control wall. Compared to the control wall, the application of the fiber reinforced polymer sheets resulted in a 12 percent increase in its ultimate failure.

Also the application of two vertical layers of CFRP sheets instead of one on each side of the wall further enhanced the flexural capacity of the wall. The load versus top horizontal displacement curve for this specimen is also shown in Figure 3. The application of double the amount of CFRP sheets, as compared to the previous strengthened wall specimen, did not significantly increase the crack load of the wall.

Before the cracking of concrete, the contribution of the CFRP sheets in the flexural resistance of the wall was relatively small. The flexural resistance from CFRP sheets greatly increased after crushing of concrete. The initiation of cracking of concrete was on the load of 330 kN. This represented a 27 percent increase in the cracking strength of the control wall. Compared to the control wall, the application of the fiber reinforced polymer sheets resulted in a 14 percent increase in its ultimate failure.

Strengthened Wall No. 3 (SW3) had two vertical layers of CFRP sheets and one horizontal layer on each side of the wall. The load versus top horizontal displacement curve is presented in Figure 11. The initiation of cracking of concrete was on the load of 350 kN. This represented a 35% increase in the cracking strength of the control wall. The lateral load capacity was determined to be 1185 kN at the ultimate displacement of 4.75 mm.

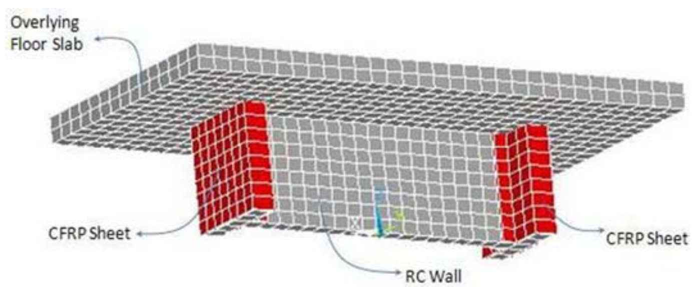


Figure 2 Finite Element model of RC walls externally bonded with FRP sheets.

Table 1. Summary of material properties for FRP composites

| FRP Composite | Thickness of Laminate | Elastic Modulus (GPa) | Tensile Strength | Major Poisson's Ratio | Shear Modulus (MPa) |
|---|---|---|---|---|---|
| **CFRP** | 2.0 mm | $E_x = 230$ | 3500 MPa | $\nu_{xy} = 0.22$ | $G_{xy} = 13100$ |
| | | $E_y = 20$ | | $\nu_{xz} = 0.22$ | $G_{xz} = 13100$ |
| | | $E_z = 20$ | | $\nu_{yz} = 0.30$ | $G_{yz} = 7700$ |

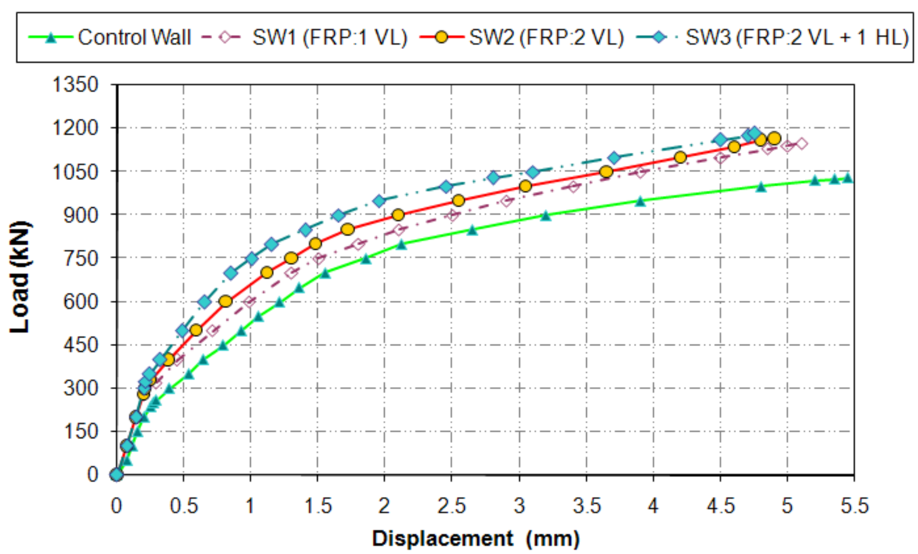


Figure 3 FE analysis load-displacement curves for structural models

By reviewing the analysis results of strengthened RC walls using externally bonded CFRP sheets on the boundary elements, the SW3 case would be the best model that provides better lateral load capacity and also better ductility, but still cannot satisfy the ductile flexure failure. In order to achieve the ductile flexure failure, one horizontal layer of CFRP sheet around plastic hinge can be wrapped (SW4). Figure 4 shows that the wrapped CFRP sheet around plastic hinge area of RC wall provides not only enough shear strength which results in a ductile flexure failure mode with the concept of strong shear and weak flexure, but also confinement of concrete in the plastic hinge lead to increase the ductility of the RC wall. With the confinement of CFRP, a desirable ductile flexural failure mode rather than a brittle shear failure mode can be achieved.

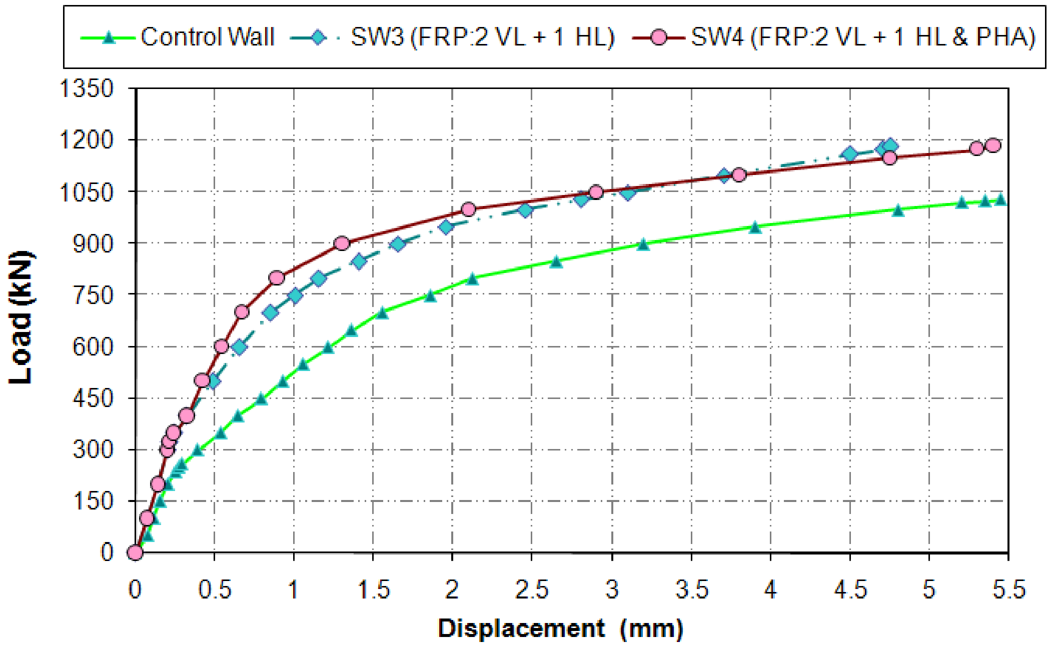


Figure 4 Comparison of load-displacement curves for "Control wall", "SW3" and "SW4".

## 5. HYSTERETIC RESPONSE OF STRUCTURAL RC MODELS

It is now well-known that the total displacement of an RC member is made up of three components, each contributed by a different deformation mechanism, namely flexure, shear (associated with diagonal cracking), and sliding shear (horizontal cracking); the relative contribution of each mechanism varies with the level of inelasticity. In this section the hysteretic responses of SW3 and also the SW4 structural models are presented in order to achieve the capacity of energy dissipation of the RC walls and effectiveness of using FRP sheets on them. As it can be seen from the figures 5 and 6, the hysteretic loops are somehow fat that shows the excellent capacity of energy dissipation during earthquake event. Also by comparing the results between these two models it can be declared that by using an extra layer of FRP on the plastic hinge area of the shear wall, its behavior during the seismic loading would be improved. This recent result is very similar to the result that had been obtained when applying the monotonic loading on shear walls which was described in previous sections.

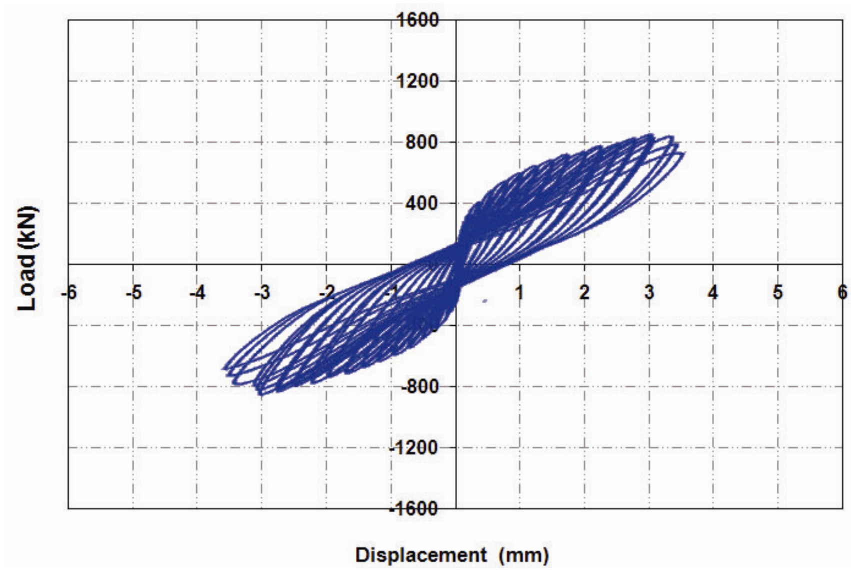


Figure 5 Hysteretic loops of SW3 model under cyclic loading

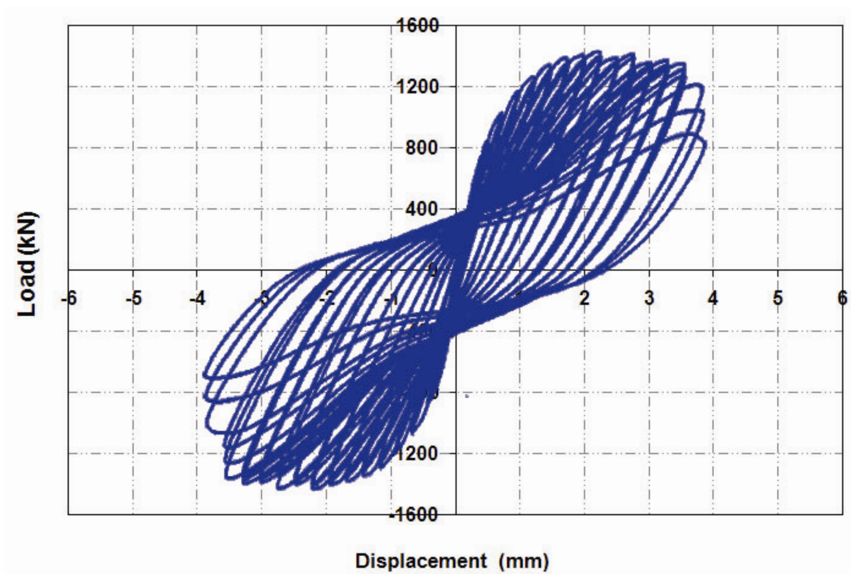


Figure 6 Hysteretic loops of SW4 model under cyclic loading

## 6. CONCLUSIONS

Nonlinear response of RC is caused by cracking, plastic deformations in compression and crushing of the concrete and plastic deformations of the reinforcement. Analysis results of this research work show that the application of externally bonded carbon fiber sheets is an effective seismic strengthening procedure for RC shear walls. The carbon fiber sheets can be used to increase the pre-cracked stiffness, the cracking load (up to 35%), the yield load and the ultimate flexural capacity (up to 18%) of RC walls.The wrapped CFRP sheet around plastic hinge range of RC wall provides not only enough shear strength which results in a ductile flexure failure mode with the concept of strong shear and weak flexure, but also confinement of concrete in the plastic hinge leads to increase the ductility of the RC wall. With the confinement of CFRP, a desirable ductile flexural failure mode rather than a brittle shear failure mode can be achieved. It is now well-known that the total displacement of an RC member is made up of three components, each contributed by a different deformation mechanism, namely flexure, shear (associated with diagonal cracking), and sliding shear (horizontal cracking); the relative contribution of each mechanism varies with the level of inelasticity. As a similar conclusion, by comparing the results between SW3 and SW4 models, it can be declared that by using an extra layer of FRP on the plastic hinge area of the shear wall, its behavior during the seismic loading (hysteretic response) would be improved.

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