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Nonlinear behavior of RC shear walls externally bonded with FRP sheets

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ABSTRACT: Composite shear wall system considered in this paper refers to a Reinforced Concrete (RC) wall where Fiber Reinforced Polymer (FRP) sheets are externally attached to the wall. The results of an analytical and parametric study on effectiveness of using externally bonded FRP sheets have been investigated in this research in order to evaluate the capacity curves (Load-Displacement relationships) of composite shear wall system. Verification of control RC wall has been carried out by comparing the results of finite element model and available experimental data. In the strengthening procedure using CFRP sheets, shear and flexural strength would be increased by applying CFRP sheets with the fibers oriented in the vertical and/or horizontal direction. The CFRP sheets are applied in order to increase the pre-cracked stiffness, the cracking load limit (up to 35 percent), ultimate flexural capacity (up to 20 percent) and the total hysteretic response of RC walls. In this case, displacement ductility factors, energy dissipation and contribution of structure's modes to lateral deformation are presented. Finally as a parametric study, results of using wrapped CFRP sheets around plastic hinge area of wall indicated not only enough shear strength which provides a ductile failure mode but confinement of concrete would lead to increase the total ductility of RC wall.

1 INTRODUCTION

Reinforced concrete shear walls are an ideal choice for a lateral load- resisting system in a RC structure due to their high initial stiffness and lateral load capacity. Stiffness of a RC component depends on material properties (including current condition), component dimensions, reinforcement quantities, boundary conditions, and stress levels. They must provide not only adequate strength, but also sufficient ductility to avoid brittle failure under strong lateral loads, especially during an earthquake. (Oesterle et al. 1984; Hwang et al. 2001)

Externally bonded fiber reinforced polymers (FRP) in the form of continuous carbon, glass or aramid fiber bonded together in a matrix made of epoxy or polyester, are being employed extensively throughout the world in retrofitting reinforced concrete structures. 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. Although it is generally accepted that the concrete confinement rendered by provision of externally bonded FRP sheets would increase the strength and ductility of a shear wall, none of the analysis methods given in the design codes allows for such effect. This may be due to the complicated failure mechanism of shear walls and the over-simplified modeling of the properties of RC in the codes. Nevertheless, by the use of the finite element method, it should be possible to analyze the effect of concrete confinement on the behavior of shear walls. In this paper it is tried to investigate the behavior of RC shear walls after being composited using externally bonded 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.

2 NONLINEAR ANALYSIS OF REINFORCED CONCRETE

2.1 *Finite Element Model*

The solid element Solid65 in the ANSYS program is used in the analysis (ANSYS 2004). It can be used for three-dimensional modeling of solids with or without reinforcing bars. Eight nodes define the element, each having three translation degrees of freedom. Reinforcement can be defined in three different directions. The solid part of the element, e.g., the concrete, is capable to describe cracking, plastic deformations and crushing. The plasticity model for concrete is based on the flow theory of plasticity, von Mises' yield criterion, isotropic hardening and associated flow rule. Cracking is permitted in three orthogonal directions at each integration point. The cracking is modeled through an adjustment of the material properties (i.e., by changing the element stiffness matrixes) that effectively treat the cracking as “smeared” cracks. The shear transfer coefficient, β_t, represents conditions of the crack face. The value of β_t ranges from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer) (ANSYS 2004). The value of β_t used in many studies of reinforced concrete structures, however, varied between 0.05 and 0.25 (Bangash 1989; Hemmaty 1998; Huyse, et al. 1994). A number of preliminary analyses were attempted in this study with various values for the shear transfer coefficient within this range, but convergence problems were encountered at low loads with β_t less than 0.2. Therefore, the shear transfer coefficient used in this study was equal to 0.2.

2.2 *Verification against Experimental Data*

The experimental data for the RC walls are obtained from Barda (Barda 1972). Laboratory tests of eight scaled, low-rise shear walls with boundary elements have been described. The boundary elements were supposed to simulate the effect of cross walls and an overlying floor slab. In Figure 1 the tilt-up from the laboratory tests and also the measured and computed load displacement curves are shown for one of the shear walls. As can be seen, the Finite Element analysis can simulate the test results fairly well. The main conclusion from the verification against experimental data is 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.

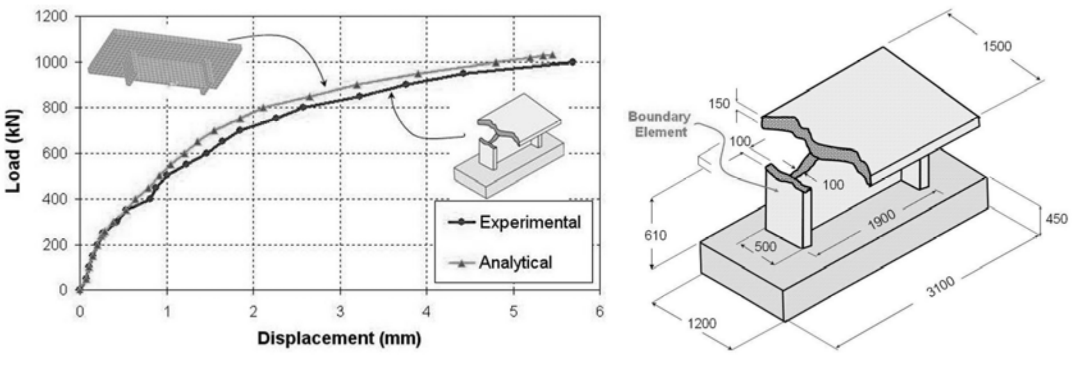

Figure 1. Comparison of experimental and FE analysis load-displacement curves for reinforced concrete shear wall with boundary elements.

3 FIBER REINFORCEMENT POLYMER SHEETS

3.1 *General*

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 reinforced concrete 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. 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 and Londono; Lombard et al. 2000; Saadatmanesh et al. 1994).

3.2 *Finite Element Model*

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.

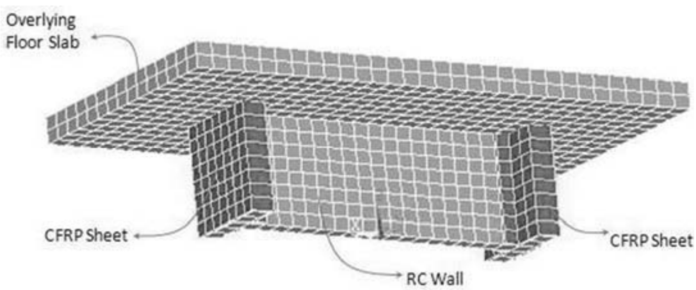

Figure 2. Finite Element model of strengthened walls by externally bonded CFRP sheets.

A layered solid element, Solid46, 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 Solid46 elements were connected to the nodes of Solid65 elements at the interface so that two materials shared the same nodes. The material properties for FRP composites are available at Table1.

Table 1. Summary of material properties for FRP composites.

FRP Composite	Elastic modulus (GPa)	Major poisson's ratio	Tensile strength (MPa)	Shear modulus (MPa)	Thickness of laminate (mm)
CFRP	$E_x = 230$ $E_y = 20$ $E_z = 20$	$\nu_{xy} = 0.22$ $\nu_{xz} = 0.22$ $\nu_{yz} = 0.30$	3500	$G_{xy} = 13100$ $G_{xz} = 13100$ $G_{yz} = 7700$	2.0

3.3 *Results of Finite Element Analysis of Strengthened RC Walls*

3.3.1 *Analysis Results of SW1*

The first strengthened wall was upgraded by the application of one vertical layer of carbon sheet on each side of the wall. The load versus top horizontal displacement curve of this 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. The lateral load capacity was determined to be 1150 kN at the ultimate displacement of 5.1 mm. Compared to the control wall, the application of the fiber reinforced polymer sheets resulted in a 12 percent increase in its ultimate failure.

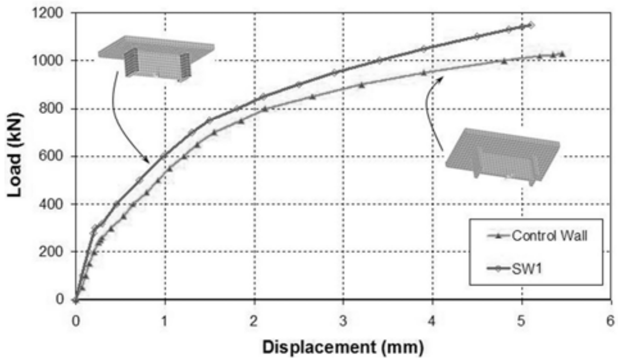

Figure 3. Comparison of FE analysis load-displacement curves for the "Control wall" and "Strengthened wall with one vertical CFRP layer".

3.3.2 *Analysis Results of SW2*

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 shown in Figure 4. 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; because the amount of the CFRP reinforcement material was relatively small compared to the total area of concrete and steel reinforcement. 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. The lateral load capacity was determined to be 1165 kN at the ultimate displacement of 4.9 mm. Compared to the control wall, the application of the fiber reinforced polymer sheets resulted in a 14 percent increase in its ultimate failure.

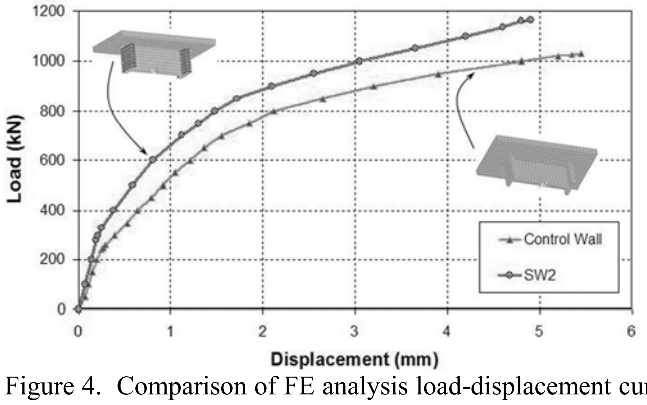

Figure 4. Comparison of FE analysis load-displacement curves for the "Control wall" and "Strengthened wall with two vertical CFRP layers".

3.3.3 *Analysis Results of SW3*

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 5. 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. Compared to the control wall, the application of the fiber reinforced polymer sheets resulted in an 18 percent increase in its ultimate failure. At ultimate, the concrete at the base of the wall was completely crushed.

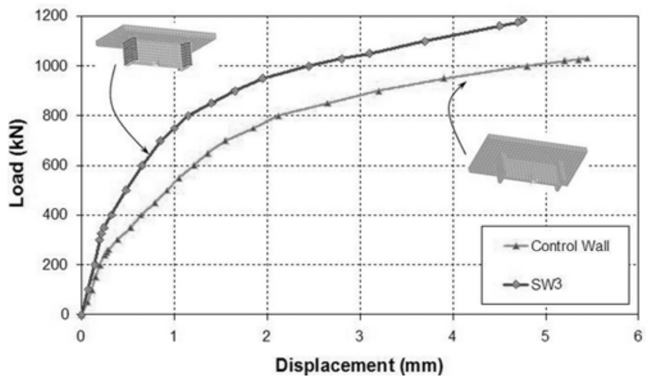

Figure 5. Comparison of FE analysis load-displacement curves for the “Control wall” and “Strengthened wall with two vertical and one horizontal CFRP layers”.

3.4 *Application of CFRP Sheets around Plastic Hinge Area*

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). Finite Element model of strengthened wall by externally bonded CFRP sheets in boundary elements and web of the wall is available in Figure 6.

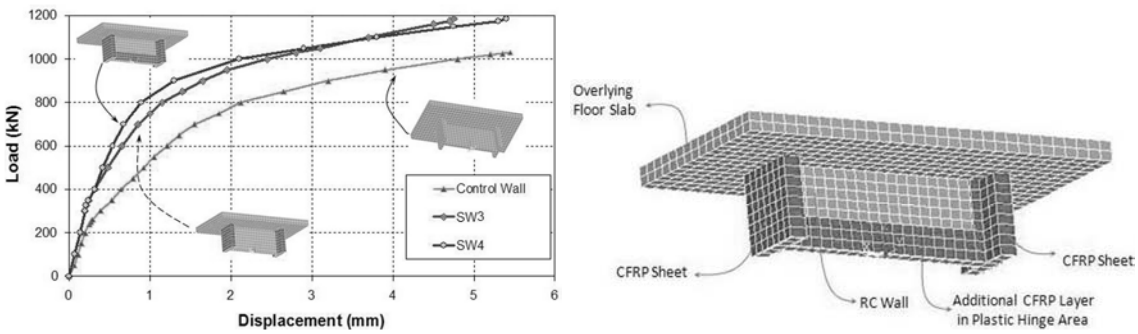

Figure 6. Comparison of FE analysis load-displacement curves for “Control wall”, “SW3” and “SW4”.

Figure 6 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.

4 CONCLUSIONS

From the discussion of results obtained by analyzing different Finite Element models, the following conclusions can be drawn:

- The main conclusion from the verification against experimental data is 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.
- Analysis results show that the application of externally bonded carbon fiber sheets is an effective seismic strengthening procedure for reinforced concrete shear walls. The carbon fiber sheets can be used to increase the pre-cracked stiffness, the cracking load, the yield load and the ultimate flexural capacity 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 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.

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