

## SEISMIC STRENGTHENING AND REPAIR OF REINFORCED CONCRETE SHEAR WALLS

Josh LOMBARD<sup>1</sup>, David T LAU<sup>2</sup>, Jag L HUMAR<sup>3</sup>, Simon FOO<sup>4</sup> And M S CHEUNG<sup>5</sup>

### SUMMARY

This paper presents the results obtained in a feasibility study on the effectiveness of using externally bonded carbon fibre tow sheets for the seismic strengthening and repair of reinforced concrete shear walls. The present study consists of both experimental and analytical components. Four 2.0 x 1.5 x 0.1 m reinforced concrete shear wall specimens have been tested, which include a control wall, a repaired wall and two strengthened walls. The test specimens are loaded to failure in the in-plane direction according to a predetermined quasi-static cyclic loading sequence. In addition to the experimental results, the paper also describes an inelastic analysis model developed for the prediction of the load-deflection envelopes of both plain and retrofitted reinforced concrete shear walls suitable for the design application. Based on the test results and the good correlation between the measured data and the analytical predictions, it is concluded that the new retrofit technique is an effective seismic strengthening and repair procedure for reinforced concrete shear walls. The carbon fibre system can be used to recover the initial elastic stiffness and to increase the yield load and ultimate flexural capacity of seismically damaged walls, as well as to enhance the stiffness and strength capacity in the strengthening application of undamaged walls. Compared to other conventional repair and strengthening techniques, the carbon fibre system is very efficient, less disruptive during construction, and thus reduces the construction cost. The study is part of a comprehensive collaborative research program between Carleton University and Public Works and Government Services Canada

### INTRODUCTION

Reinforced concrete shear walls are a common type of lateral load resisting system found in earthquake resistance structures located in seismically active regions. Many of the older shear wall buildings in Canada are at risk of suffering severe damage, or even collapse, during large earthquakes because of insufficient in-plane stiffness, flexural and shear strengths and/or ductility. The inadequacy in the lateral load resistance of these shear walls can often be attributed to the fact that seismic design provisions in older building codes did not properly account for the demands imposed on the shear wall structures by major earthquakes. As many of the existing buildings approach the end of their service life, the deterioration of the structural elements further exacerbates the problem.

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 infills, 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 labour intensive

<sup>1</sup> Dept. of Civil and Environmental Engineering, Carleton University, Canada, K1S 5B6. Email: dtl@ccs.carleton.ca

<sup>2</sup> Dept. of Civil and Environmental Engineering, Carleton University, Canada, K1S 5B6. Email: dtl@ccs.carleton.ca

<sup>3</sup> Dept. of Civil and Environmental Engineering, Carleton University, Canada, K1S 5B6. Email: dtl@ccs.carleton.ca

<sup>4</sup> Technology, Real Property Services, Public Works and Government Services Canada, Hull, Quebec, Canada

<sup>5</sup> Technology, Real Property Services, Public Works and Government Services Canada, Hull, Quebec, Canada

and disruptive to the occupancy of the building during the construction period, which often means the complete shutdown of the facility and the relocation of the occupants.

As an alternative to the traditional retrofit techniques, the use of advanced composite materials have been found to be quite effective for the strengthening and repair of existing reinforced concrete structures [Heffernan and Ekri, 1996]. The application of advanced fibre reinforced plastic (FRP) composite materials in the retrofit of bridge columns have been investigated by many researchers [Priestly et al., 1992, Saadatmanesh et al., 1994]. Despite the present high cost of the FRP materials, the non-metallic advanced composite materials have several advantages in terms of material properties and performance over conventional steel reinforcing materials, such as a high strength to weight ratio, excellent corrosion resistance, and ease of handling [Meier et al., 1992].

This paper describes the results of an experimental testing program conducted at Carleton University. The objective of the experimental research is to evaluate the feasibility and effectiveness of using externally bonded carbon fibre tow sheets for the seismic strengthening and repair of reinforced concrete shear walls. In addition to the experimental results, the paper also describes an inelastic analysis model developed for the prediction of the load-deflection envelopes of both plain and retrofitted reinforced concrete shear walls suitable for the design application.

## **EXPERIMENTAL STUDY**

### **Carbon Fibre Strengthening System**

The advanced composite material used to strengthen and repair the shear wall test specimens consists of high strength unidirectional continuous carbon fibre tow sheets externally bonded to the face of the shear walls by an epoxy matrix. The carbon fibre sheets have an elastic tensile modulus of 230 GPa, a tensile strength of 3480 MPa, and a failure strain of 1.5%. The tensile behaviour of the carbon fibre sheets is essentially linear-elastic up to fracture.

To increase or recover the inplane flexural strength and stiffness of a reinforced concrete shear wall, the carbon fibre sheets are applied to the face of the wall with the fibres oriented in the vertical direction. For the system to be effective, the sheets must be anchored to the foundation or the supporting elements of the wall panel so as to transfer the load from the sheets to the adjacent structural elements. The anchoring system is critical to the success of the retrofit technique. To increase or recover the inplane shear strength of a reinforced concrete shear wall, the carbon fibre sheets are applied to the face of the wall with the fibres oriented in the horizontal direction.

Figure 1 shows the system developed in the present study for anchoring the vertical carbon fibre sheets to the foundation block of the test specimens. The anchoring system consists of a structural angle that is epoxied to the carbon fibre sheet and bolted to the foundation using anchors.

### **Test Specimens and Set-up**

Four reinforced concrete shear wall specimens have been tested in the present study. Details of the test specimens are shown in Figure 2. The walls are constructed using 40 MPa concrete with identical reinforcement of 400 MPa, 10 mm reinforcing steel bars. The height of the walls from the base of the wall panel to the centre of the cap beam is 2000 mm, the length is 1500 mm, and the thickness is 100 mm. The vertical reinforcement consists of six pairs of 10 mm reinforcing bars spaced at 280 mm, providing a reinforcement ratio of 0.8%. The horizontal steel consists of five pairs of 10 mm bars, spaced at 400 mm for a reinforcement ratio of 0.5%.

The shear walls are tested to failure under a predetermined in-plane quasi-static cyclic loading sequence in load control up to the yield load, and then continuing to failure in displacement control at predetermined steps of increasing displacement ductility. The wall specimen is anchored at the base. The lateral load is applied at the top of the specimen through a horizontal cap beam by a hydraulic actuator supported by a reaction frame. The test set-up for the in-plane shear wall tests is shown in Figure 2.

The four test specimens include a control wall, a repaired wall and two strengthened walls. The control wall is tested in its original state to serve as a baseline for the evaluation of the repair and strengthening techniques. The repaired wall is first tested in its original state without the carbon fibre sheets to simulate a wall that has

experienced a moderate to large earthquake. Following the initial test, the damaged wall is repaired by applying one vertical layer of FRP to each face of the specimen. After the wall is repaired it is retested to failure.

The two strengthened shear wall specimens are strengthened by applying carbon fibre sheets to the walls without pre-damage. The first strengthened specimen has one vertical layer of FRP externally bonded on each face of the wall, whereas the second specimen has one horizontal and two vertical layers of carbon fibre on each face of the wall. No load is applied prior to strengthening. After the shear wall specimens are strengthened they are tested to failure.

## **SHEAR WALL TEST RESULTS**

### **Control Walls**

Figure 3 shows the lateral load versus the top horizontal displacement curve for the pre-damaged control shear wall specimen. The initial cracks in the concrete occurred at an average measured load of +/-55 kN. The cracks were horizontal and formed at the edges of the wall near the base. Yielding of the extreme layer of vertical steel reinforcement occurred at an average measured load of 122 kN and an average displacement of 3.7 mm. As the loads increased, the edge cracks progressed toward the centre of the wall and started to incline. The control wall was observed to have already reached the ultimate load determined to be 178 kN when the test was stopped due to crushing failure of the concrete at the compression toe of the wall. The pre-damaged control wall specimen was repaired with carbon fibre sheets and then retested to failure.

Due to limitation of space, the results of another control wall specimen tested up to ultimate failure are not presented in this paper. In this second wall test similar results were obtained. Ultimate failure occurred at a ductility level of 12 (+/- 48 mm).

### **Repaired Control Wall**

After the above control wall was pre-damaged, it was repaired by applying one layer of vertical carbon fibre to each face of the wall. The repaired wall was then retested to failure. Figure 4 shows a plot of the load versus the top horizontal displacement of the repaired specimen. From the load-deflection curve, it was determined that yielding of the extreme layer of vertical steel reinforcement occurred at an average measured load of 158 kN and an average displacement of 5.4 mm. This corresponded to a 29 % increase in the yield load of the repaired wall compared to the original and a recovery of 90% of the initial elastic stiffness. The average measured ultimate load carrying capacity of the repaired wall was determined to be 320.7 kN. Comparing the behaviour of the repaired wall with the control wall, it was observed that the FRP sheets increased the ultimate load carrying capacity of the repaired wall by 80%. The ultimate failure mode of the repaired wall was observed to be a ductile flexural failure.

### **Strengthened Wall #1**

Strengthened shear wall #1 was retrofitted with one vertical layer of carbon fibre sheets applied to each side of the wall. The lateral load versus the top horizontal displacement curve of the strengthened shear wall #1 is presented in Figure 5. The first flexural cracking of the concrete was observed at an average measured load of 100 kN which corresponded to 62% of the yield load. This indicates that the application of the carbon fibre sheets resulted in an 82% increase in the cracking strength of the wall. The cracks were horizontal and formed at the edges of the wall near the base. From the load-deflection curve, it was determined that yielding of the extreme layer of vertical steel reinforcement occurred at an average measured load of 153 kN and an average displacement of 1.6 mm. Comparing the behaviour of the control wall with that of the strengthened wall #1, it was determined that the application of the FRP sheets increased the yield strength of the strengthened wall by 25%. In addition, the carbon fibre sheets also increased the secant stiffness of the wall at yielding by 190%.

The ultimate failure of the strengthened wall occurred at an average load of 258 kN, which corresponded to a 46% increase in the ultimate load carrying capacity of the strengthened wall. The ultimate failure of the strengthened wall occurred by crushing of the compression toe as well as the fracture of one of the extreme vertical reinforcing bar. Comparing the results of the repaired wall with that of the strengthened wall, it was determined that the net increase in the ultimate load carrying capacity of the strengthened specimen was only 80 % of that achieved in the repaired wall. This was attributed to the failure of the anchoring system caused by the premature slippage of the expansion anchor bolts used in this strengthened wall specimen. Because of the

anchorage slip, the full strength of the carbon fibre sheets was not realized. There was very little delamination of the carbon fibre sheets observed during the test.

### **Strengthened Wall #2**

Strengthened wall #2 was retrofitted with one horizontal and two vertical layers of carbon fibre applied to each side of the wall. The lateral load versus the top horizontal displacement curve of the strengthened shear wall #2 is presented in Figure 6. The first flexural crack in the concrete of the wall appeared at an average load of +/- 102 kN. Comparing the results of the two strengthened walls, the application of the second vertical FRP layer and the horizontal FRP sheets had no significant effect on the cracking strength of the wall. The crack pattern in this specimen was similar as before. From the load-deflection curve, it was determined that yielding of the extreme layer of the vertical steel reinforcement occurred at an average measured load of +/- 201kN and an average displacement of 2.4 mm. This corresponded to a 39% increase in the yield strength and a 54% increase in the stiffness of the wall.

The average measured ultimate load carrying capacity of the strengthened wall was 413 kN. Comparing the results of the strengthened wall specimen #2 with the control wall, it was noted that the application of the FRP sheets increased the ultimate load carrying capacity of the strengthened wall by 132%. The ultimate failure of the strengthened wall occurred in three stages. The ultimate failure was initiated by crushing of the compression toe. This was followed by the fracture of the extreme vertical reinforcing bars. The final stage was tearing of the carbon fibre sheets at the base of the wall. As shown in Figure 6, the tearing of the carbon fibre sheets resulted in an immediate loss of 50-60% in the load resistance of the wall. In comparison, the fracture of the extreme vertical reinforcing bars resulted in a loss of only 15-30%. The adhesive anchors used in this specimen showed no sign of slippage and were intact at the end of the test.

## **ANALYTICAL MODEL**

### **General**

From the results of the experimental investigation, a semi-empirical model has been developed to predict the load-deflection envelopes of plain reinforced concrete shear walls and reinforced concrete shear walls strengthened or repaired with externally bonded fibre reinforced plastic sheets. The analytical model is intended for reinforced concrete shear walls, which have aspect ratios greater than 1.0, and are designed to fail in a ductile flexural manner. The model has been calibrated using the experimental test results. The proposed analytical model and correlation of the analytical results with the measured data are presented in the following sections.

### **Load Deflection Model**

The horizontal deflection at the top of the reinforced concrete shear wall is the combined result of four different deformation mechanisms: the flexural and shear deflections, the base slip, and the deflection due to rocking rotation caused by the anchorage slip of the vertical reinforcement. Results from previous experimental investigations of low-rise shear walls have shown that the components related to shear and flexural deformations are the dominant factors in the deflection of the shear wall, accounting for more than 80% of the total deflection [Doostdar, 1994]. Thus assuming the contributions from the other two components are negligible, the semi-empirical load-deflection model developed here considers only the flexural and shear components of the total deflection. The total horizontal deflection of a reinforced concrete beam is expressed as follows

$$\Delta_T = \Delta_f + \Delta_{sh} \quad (1)$$

where  $\Delta_f$  is the flexural deflection, and  $\Delta_{sh}$  is the shear deflection.

The deflections due to bending in the proposed analytical model are determined from the moment-curvature relationship using the moment-area method. The moment-curvature relationship of the shear wall is derived from the consideration of strain compatibility, which takes into account the contributions of the concrete, the reinforcing steel and the vertical carbon fibre sheets. The assumption of plane section remains plane is adopted. The effect of strain hardening in the tensile steel reinforcement is ignored.

To account for the effects of the non-uniform deterioration of the walls, and the debonding and tearing of the vertical carbon fibre sheets resulting from cyclic loading under large deflections, an equivalent stress block of average uniform tensile stress is assumed in the tensile region of the carbon fibre sheets for calculating the

moment resistance of the shear wall. Details of the calibration and verification of the analytical model using the test data and experimental observations can be found in the reference [Lombard, 1999].

From the minimization of the potential energy, the deflection of the wall due to shear can be derived as follows based on linear elastic behaviour from a cantilever beam

$$\Delta = \frac{2(1+\mu)Ph}{E_c(bd)} \quad (2)$$

where  $\mu$  is the Poisson's ratio,  $P$  is the applied lateral load,  $h$  is the height of the wall,  $E_c$  is the modulus of elasticity,  $b$  is the thickness and  $d$  is the effective depth of the wall.

In the present model, a factor  $\chi$  is introduced to account for the non-linear behaviour of the shear wall panel due to the inelastic behaviour of the concrete, the non-linear stress distribution in the shear wall and the load resistant effect of the carbon fibre sheets. The shear deflection of a reinforced concrete shear wall is assumed to have the form

$$\Delta_{sh} = \frac{\chi Ph}{E_c(bd)} \quad (3)$$

where the values of  $\chi$  have been calibrated using the experimental test data at four different load levels for plain, repaired, and strengthened walls [Lombard, 1999].

### Correlation Study

The load-deflection envelopes as determined from the experimental data and the corresponding predictions from the analytical model are presented in Figures 8-11. Comparing the experimental test results with the analytical predictions, the analytical results are generally in good agreement with those obtained experimentally. The proposed load-deflection model generally overestimates the cracking load and underestimates the yield load of the reinforced concrete shear wall specimens. The difference between the predicted yield load and the actual measured yield load of the wall increases with the number of vertical carbon fibre sheets applied to the wall. The predicted cracking and ultimate loads show good agreement with the experimental results. The proposed load-deflection model accurately predicts the increases in the yield and ultimate loads with the increase in the number of vertical FRP sheets.

## CONCLUSIONS

This paper presents the results obtained in a feasibility study on the repair and strengthening of reinforced concrete shear walls using externally bonded carbon fibre tow sheets. Four shear wall specimens have been tested in the present study. An analytical model suitable for design has been developed for the prediction of the behaviour of shear walls reinforced with FRP sheets. Based on the test results and the good correlation between the measured data and analytical predictions, it is concluded that the application of externally bonded carbon fibre sheets is an effective seismic strengthening and repair procedure for reinforced concrete shear walls. The carbon fibre repair system can be used to recover the initial elastic stiffness and to increase the yield load and ultimate flexural capacity of seismically damaged walls. In strengthening applications, the carbon fibre sheets can be used to increase the precracked stiffness, the secant stiffness at yield and the cracking load, the yield load and the ultimate flexural capacity of undamaged walls. The anchoring system for the vertical carbon fibre sheets is an important element of the carbon fibre strengthening system. The semi-empirical analytical model developed here is accurate for the prediction of the load-deflection envelopes of reinforced concrete shear walls strengthened or repaired with the carbon fibre system.

## ACKNOWLEDGMENTS

The financial support provided by Public Works and Government Services Canada, and the technical assistance provided by Mr. D. Lamb and Master Builders Technologies in this research are gratefully acknowledged

## REFERENCES

- FEMA. (1992), *NEHRP Handbook of Techniques for Seismic Rehabilitation of Existing Buildings*, National Earthquake Hazards Reduction Program, Federal Emergency Management Agency, Building Seismic Safety Council, Washington, D.C.
- Heffernan, P.J. and Erki, M.A. (1996), "Equivalent Capacity and Efficiency of Reinforced Concrete Beams Strengthened with Carbon Fibre Reinforced Plastic Sheets", *Canadian Journal of Civil Engineering*, 23, pp21-29.
- Lombard, J. (1999), *Seismic Strengthening and Repair of Reinforced Concrete Shear Walls using Externally Bonded Carbon Fibre Tow Sheets*, Masters Thesis, Carleton University, Ottawa, Ontario, Canada.
- Meier, U., Deuring, M., Meier, H. and Schwengler, G. (1992), "Strengthening of Structures with CFRP Laminates: Research and Applications in Switzerland", *Proceedings of the 1st International Conference on Advanced Composite Material in Bridges and Structures*, Sherbrooke, Quebec, pp243-251.
- Priestley, M.J.N., Seible, F. and Fyfe, E. (1992), "Column Seismic Retrofit using Fiberglass/Epoxy Jackets", *Proceedings of the 1st International Conference on Advanced Composite Material in Bridges and Structures*, Sherbrooke, Quebec, pp287-298.
- Saadatmanesh, H., Ehansi, M.R., and Li, M.W. (1994), "Strength and Ductility of Concrete Columns Externally Reinforced with Fiber Composite Straps", *ACI Structural Journal*, 91, 4, pp434-447.

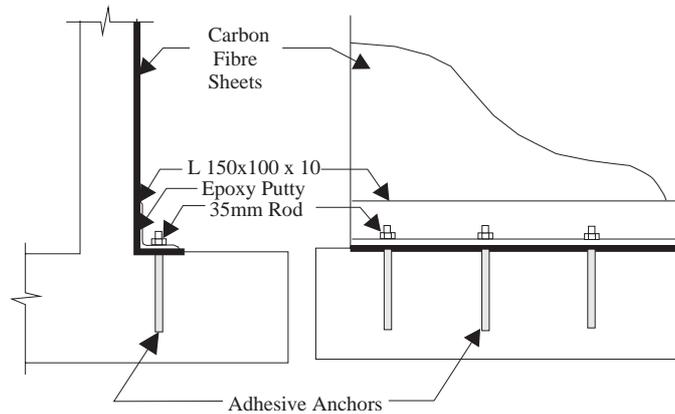


Figure 1: Anchoring system for the carbon fibre sheets

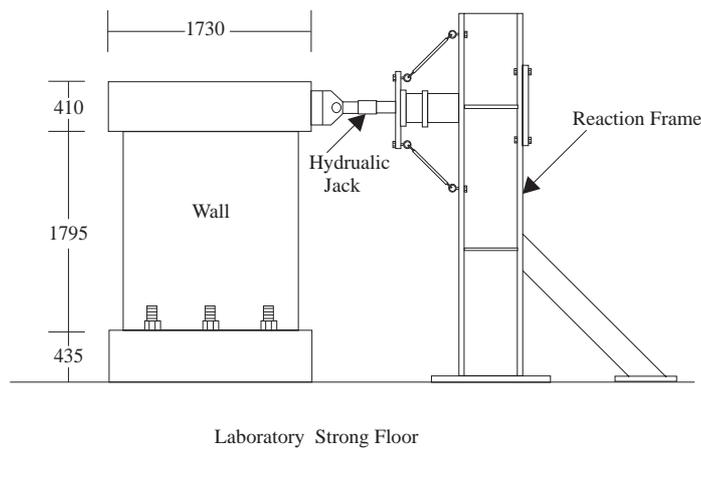


Figure 2: Test set-up showing the wall, the reaction frame and the laboratory strong floor

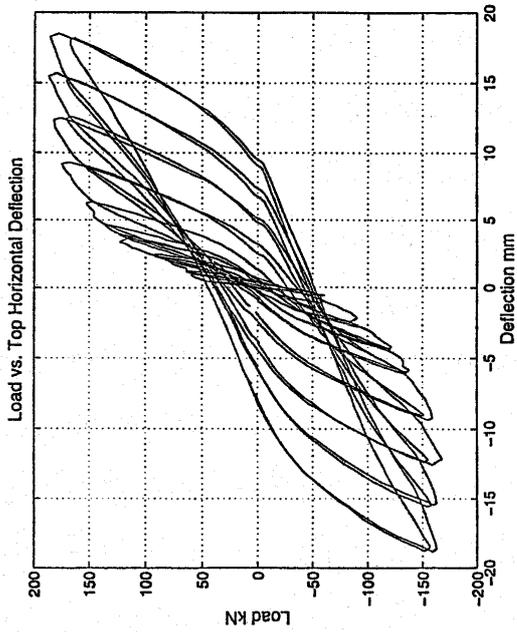


Figure 3: Load-deflection curve of control wall

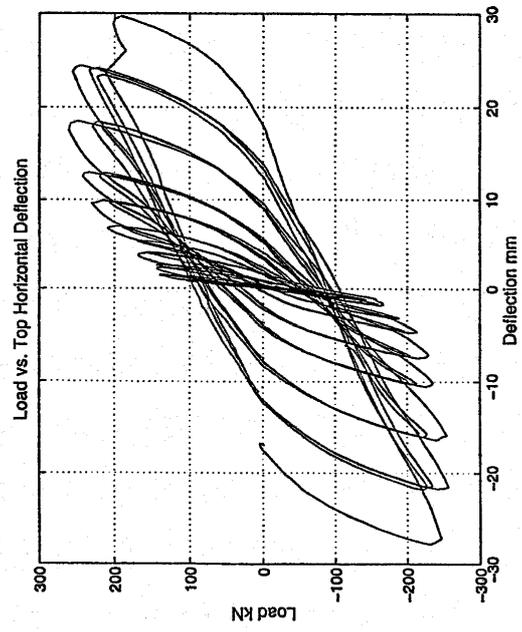


Figure 5: Load-deflection curve of strengthened wall #1

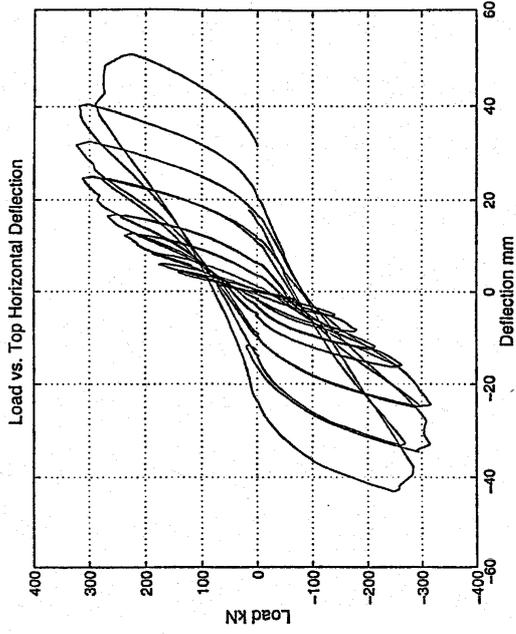


Figure 4: Load-deflection curve of repaired wall

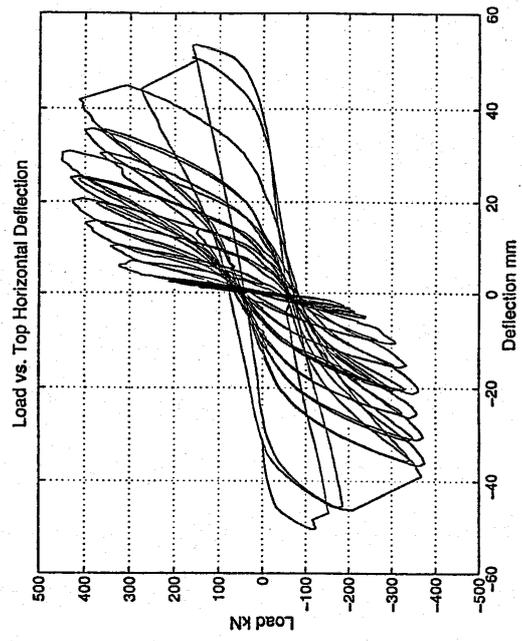


Figure 6: Load-deflection curve of strengthened wall #2

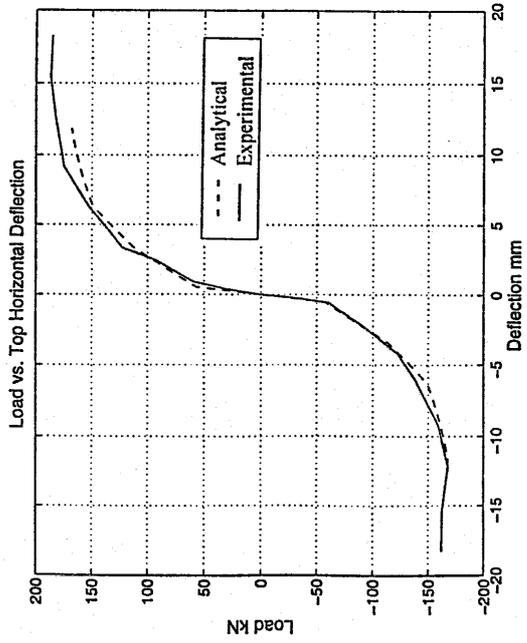


Figure 7: Load-deflection envelope of control wall

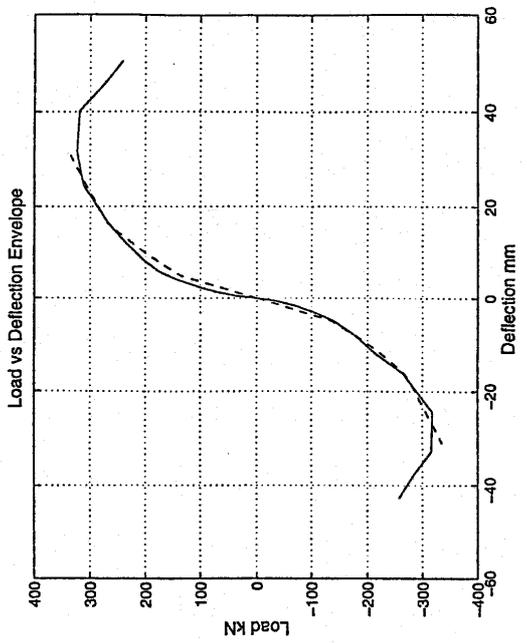


Figure 9: Load-deflection envelope of strengthened wall #1

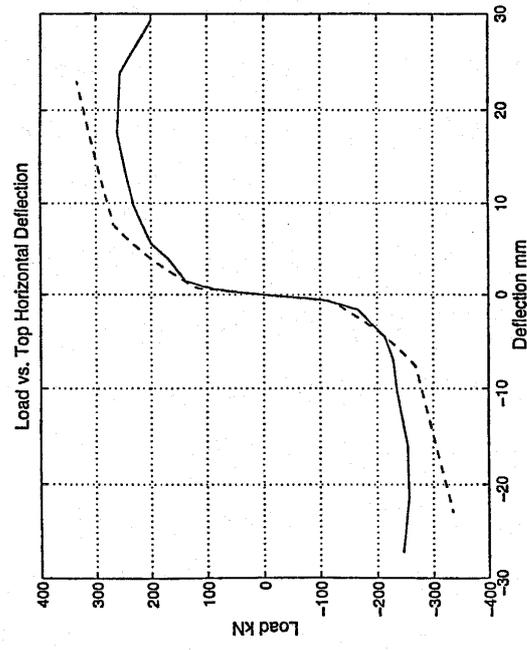


Figure 8: Load-deflection envelope of repaired wall

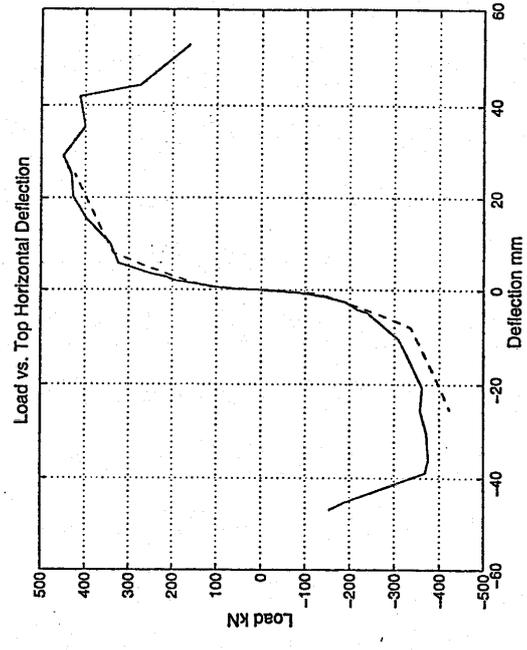


Figure 10: Load-deflection envelope of strengthened wall #2