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Experimental study of reinforced concrete shear walls strengthened with fibre reinforced plastic sheets

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ABSTRACT

Large scale testing is being conducted to evaluate the feasibility and effectiveness of using externally bonded carbon fibre tow sheets for the seismic strengthening of reinforced concrete shear walls. The experimental study reported here consists of tests on three 2.0x1.5x0.1m reinforced concrete shear wall specimens. The three specimens include a control wall, and two strengthened walls, that are loaded to failure in the inplane direction according to a predetermined quasi-static loading sequence. The study is part of a comprehensive collaborative research program between Carleton University and Public Works Canada. The objectives of the research program are to investigate the effectiveness of using externally bonded carbon fibre tow sheets to recover the inplane stiffness and to increase the inplane flexural strength of seismically damaged walls, as well as to increase the inplane shear and flexural strength of undamaged walls.

INTRODUCTION

A reinforced concrete shear wall is a common lateral load resisting system for buildings 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 inplane stiffness, flexural and shear strength and/or ductility. The inadequate lateral load resistance of these shear walls can often be attributed to the seismic design provisions in older building codes which do not properly account for the demands imposed on the shear wall structures by major earthquakes. The deterioration of the structural elements, as the buildings approach the end of their service life, exacerbates the problem.

Several techniques are commonly used to retrofit buildings which have 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 braced frames (FEMA, 1992). While these techniques are effective in improving the earthquake resistance of a building, they may increase the weight of the structure which can significantly affect the magnitude and distribution of the seismic loads. Also, these techniques are generally labour intensive and quite disruptive to the occupancy of the building during the construction period.

Advanced composite materials may be used for the strengthening and repair of existing reinforced concrete structures as an alternative to the traditional strengthening techniques, and have been found to be quite effective (Heffernan and Ekri 1996), especially for the retrofit of bridge columns (Priestley et al. 1992, Saadatmanesh et al. 1994). Non-metallic advanced composite materials have several advantageous properties, these include a high strength to weight ratio, excellent corrosion resistance, and ease of handling (Meier et al. 1992).

This paper describes a large scale testing program currently underway at Carleton University. The objectives of the research are to evaluate the feasibility and effectiveness of using externally bonded carbon fibre tow sheets for strengthening and the repair of reinforced concrete shear walls, to develop and evaluate an anchoring system for the carbon fibre tow sheets, and to develop a design model for shear walls strengthened and repaired with externally bonded carbon fibre sheets.

CARBON FIBRE STRENGTHENING SYSTEM

The advanced composite material strengthening system used in the present study consists of high strength unidirectional continuous carbon fibre tow sheets that are externally bonded to reinforced concrete elements by an epoxy matrix. The material properties of the carbon fibre sheets used in the experimental study are presented in Table 1.0.

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To increase the inplane flexural strength and stiffness of a reinforced concrete shear wall by using the carbon fibre strengthening system, the sheets should be 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, so as to transfer the load from the sheets to the footing. To increase the inplane shear strength of a reinforced concrete shear wall, the carbon fibre sheets should be applied to the face of the wall with the fibres oriented in the horizontal direction or at an angle of 45 degrees.

Figure 1.0 shows the anchoring system developed in the present study for anchoring the vertical carbon fibre sheets to the foundation of the strengthened shear wall test specimens. The anchoring system consists of a structural angle which is epoxied to the carbon fibre sheets and bolted to the foundation using anchors. Expansion anchors were used for strengthened wall #1 and were found to be inadequate when subjected to cyclic loads. Adhesive anchors were used in place of the expansion anchors for strengthened wall #2.

The tensile load carried by the carbon fibre sheets is transferred by shear bond through the epoxy to the vertical flange of the structural angle. The load is then transferred from the structural angle to the foundation through the anchors.

To ensure effective transfer of the load by the anchoring system, the height of the vertical flange of the structural angle was selected so as to attain a bond shear strength between the carbon fibre sheets and the structural angle that was greater than the bond shear strength between the carbon fibre sheets and concrete. Carbon fibre - steel bond shear strength tests were performed to determine the required length of the structural angle's vertical flange. The anchors were designed to resist a tensile load calculated using an assumed load distribution. The anchors were selected in accordance to the specifications provided by the manufacturer.

SHEAR WALL TESTS

Construction, Setup and Instrumentation

Three reinforced concrete shear walls were tested to failure under a predetermined inplane quasi-static cyclic loading sequence. The walls were constructed using 45 MPa concrete and 400 MPa 10mm reinforcing steel bars. All the walls were 2000 mm high, 1500 mm wide and 100 mm thick, and had a vertical steel reinforcing ratio of 0.8% and a horizontal steel reinforcing ratio of 0.5%. The flexural reinforcement consisted of six vertical pairs of 10 mm bars spaced at 280 mm and the shear reinforcement consisted of five horizontal pairs of 10 mm bars spaced at 400 mm.

The three test specimens consisted of a control wall and two strengthened walls. The control wall was tested in its original state without the additional strengthening system, in order to have a baseline for the evaluation of the two strengthened specimens. The strengthened specimens were retrofitted by applying carbon fibre sheets to the walls. The first strengthened specimen was retrofitted with one vertical layer of carbon fibre on each face of the wall, while the second was retrofitted with one horizontal and two vertical layers of carbon fibre on each face of the wall. No load was applied prior to strengthening. After the shear wall specimens were strengthened they were tested to failure.

Figure 2.0 shows the test setup used for the inplane shear wall tests. The test setup consists of a test specimen, a hydraulic actuator and a reaction frame. The test specimens were bolted to the floor by six 60mm diameter high strength bolts which passed through the specimen's heavily reinforced footing and provide the fixed end condition required for the vertical cantilever. All the specimens were loaded in the inplane direction according to a predetermined quasi-static cyclic loading sequence. The load was applied to the wall's heavily reinforced top beam by a 500 kN hydraulic actuator which was mounted on a reaction frame at a height of 2.435 m.

The Instrumentation used to collect data during the testing consists of 12 potentiometers, 48 strain gages and a load cell. The potentiometers were used to measure the top and mid-level horizontal deflections, the base slip and the rotations at the top and bottom of the wall. The strain gages were placed on the vertical and horizontal reinforcing bars to measure the longitudinal strains in the flexural and shear reinforcement.

Loading Program

The reinforced concrete shear wall test specimens were loaded according to a predetermined quasi-static loading sequence. The loading sequence consisted of cyclic loading of the walls in load control up to the yield load, and then continuing to failure in displacement control at predetermined steps of increasing displacement ductility . The walls were loaded in four load steps up to the calculated yield load. The yield load was determined by plane section analysis. The walls were subjected to two load reversal cycles at each load step. Beyond the yield load level the walls were subjected to three load reversal cycles at each ductility level up to ultimate failure. Figure 3.0 shows the load history used for the control wall specimen. The load histories for the strengthened wall specimens are similar to that shown in Figure 3.0.

SHEAR WALL TEST RESULTS

Control Wall

Figure 4.0 shows a plot of the load versus the horizontal displacement at the top of the control wall, as recorded during the test. The first crack in the concrete of the wall was observed at a load of +/- 105 kN which corresponded to 75% of the yield load. The cracks were horizontal and formed at the edges of the wall near the base. Yielding of the extreme vertical bars occurred at a load of +/- 120 kN and a displacement of 4.0 mm. As the loads increased, the edge cracks progressed toward the centre of the wall and started to incline. Ultimate failure of the wall occurred at a ductility level of 12 (+/- 48.0mm) at the load of 230 kN. The failure occurred by crushing of the compression toe as well as the fracture of one of the extreme vertical reinforcing bars.

Strengthened Wall #1

Strengthened wall #1 was retrofitted with one vertical layer of carbon fibre applied to each face of the wall before it was tested. The retrofitting involved preparing the wall surface with a coat of epoxy primer and filling the voids with an epoxy based putty. Once the surface was prepped, a first coat epoxy adhesive was rolled onto the wall and the carbon fibre sheets were placed into the wet saturant. After the carbon fibre sheets were placed into the saturant, another coat of the epoxy adhesive was applied to the wall. Two days after the carbon fibre sheets were applied, the carbon fibre anchoring system was installed. The anchoring system was not installed immediately, to ensure that the carbon fibre sheets were not disturbed or damaged before the curing was completed.

Figure 5.0 shows a plot of the load versus the horizontal displacement at the top of the wall as recorded during the test. The first cracking of the wall was observed at a load of +/- 105 kN which corresponded to 62% of the yield load. The results show that the carbon fibre sheets had no effect on the cracking strength of the wall. Again, the cracks were horizontal and formed at the edges of the wall near the base. Yielding of the extreme vertical bars occurred at a load of +/- 170 kN and a displacement of 2.8 mm. This corresponded to a 42% increase in the yield strength of the wall. The application of the carbon fibre sheets resulted in a significant increase in the stiffness of the wall at yielding of the vertical reinforcement.

Ultimate failure of the wall occurred at a displacement ductility level of 10 (+/- 28.0mm) at the load of 265 kN, which corresponded to a 13% increase in the flexural strength of the wall. The ultimate failure of the wall occurred by crushing of the compression toe as well as the fracture of one of the extreme vertical reinforcing bar. As shown in Figure 5.0 the fracture of the reinforcing bar resulted in a 20% loss in the load carrying capacity of the wall. The net increase in the ultimate flexural strength for this specimen was significantly lower then predicted. This was attributed to the failure of the anchoring system. The failure of the anchoring system was caused by the premature slippage of the anchor bolts. There was very little delamination of the carbon fibre sheets observed during the tests.

Strengthened Wall #2

Strengthened wall #2 was retrofitted with one horizontal and two vertical layers of carbon fibre applied to each face of the wall before it was tested. The carbon fibre sheets were applied to the wall following the same procedure used in the strengthening of wall #1. The carbon fibre anchoring system used for strengthened wall #2 was similar to that used for strengthened wall #1 except that adhesive anchors were used in place of the expansion anchors.

Figure 6.0 shows a plot of the load versus horizontal displacement at the top of the wall as recorded during the test. The first cracking of the wall was observed at a load of +/- 95 kN which corresponds to 38% of the yield load. Again, the carbon fibre sheets had no effect on the cracking strength of the wall. The cracks were horizontal and formed at the edges of the wall near the base. Yielding of the extreme vertical bars occurred at a load of +/- 250 kN and a displacement of +/- 5.0 mm. This corresponded to a 108% increase in the yield strength of the wall. The application of the carbon fibre sheets resulted in an increase in the stiffness of the wall both after cracking and after yielding of the steel reinforcement.

The ultimate strength of the wall occurred at a displacement ductility level of 6 (+30.0mm) for the push cycle and at a displacement ductility level of 7 (-35.0mm) for the pull cycle. The ultimate strength of the wall was +450 kN and -370 kN for the push and pull cycles respectively. This corresponds to a 105% and 68% increase in the flexural strength of the wall. The ultimate failure of the wall occurred in three stages. The first mode of failure was crushing of the compression toe which occurred at a displacement ductility level of 5 (+/- 25mm). For the push cycle the next stage of failure was the fracture of the extreme vertical reinforcing bars which occurred at a ductility displacement level of 7 (+35.0mm). This was followed by the tearing of the carbon fibre sheets at the base of the wall which occurred at the displacement ductility levels 8 (+40mm) and 9 (+45mm). For the pull cycle the second stage of failure was the tearing of the carbon fibre sheets at the base of the wall at a displacement ductility level of 8 (-40mm). This was followed by the fracture of the extreme vertical reinforcing bars at a ductility displacement of level 11 (-55.0mm). As shown in Figure 6.0 the tearing of the carbon fibre sheets resulted in an immediate 50-60% loss in the load carrying capacity of the wall, where as the fracture of the extreme vertical reinforcing bars resulted in a loss of only 15-30%. The adhesive anchors showed no sign of slippage and were intact at the end of the test.

CONCLUSIONS

The test results show that the strength and stiffness of reinforced concrete shear walls can be significantly improved by the application of externally bonded carbon fibre tow sheets. The enhancement to the ductility behaviour and performance of reinforced concrete shear walls is not as significant as it is for the case of columns confined by fibre reinforced plastic jackets. In the present study, the stiffness of the strengthened shear wall specimens was clearly enhanced by the application of the carbon fibre tow sheets. The cracking strength of the shear wall specimens was not effected by the addition of the carbon fibre sheets. The yield strength of the shear walls was increased 38-108% by the carbon fibre sheets. The ultimate strength of strengthened wall #1 was not significantly improved because the carbon fibre anchoring system failed prematurely and the load carried by the sheets was not transferred to the foundation. The ultimate strength of strengthened wall #2 was significantly improved by the carbon fibre sheets. The improved carbon fibre anchoring system developed for the experimental study was effective in transferring the load carried by the carbon fibre sheets to the foundation. The observation clearly shows the importance of an adequate anchoring system in the flexural strengthening of reinforced concrete shear walls using fibre reinforced plastic sheets.

ACKNOWLEDGMENTS

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Table 1.0 Material Properties of the Carbon Fibre Sheets

Material	Tensile Modulus (GPa)	Tensile Strength (MPa)	Ultimate Tensile Strain (%)
Carbon Fibre Tow Sheets	230	3480	1.5

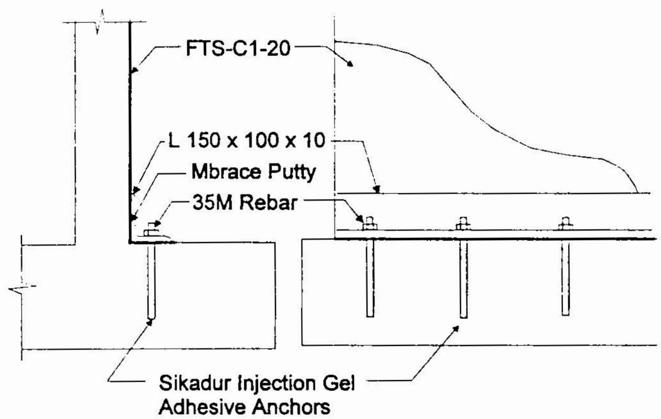

Figure 1.0 Schematic diagram of the carbon fibre anchoring system

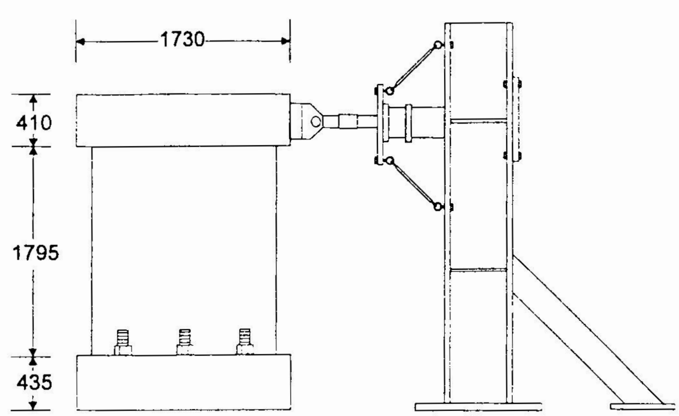

Figure 2.0 Schematic diagram of the test setup

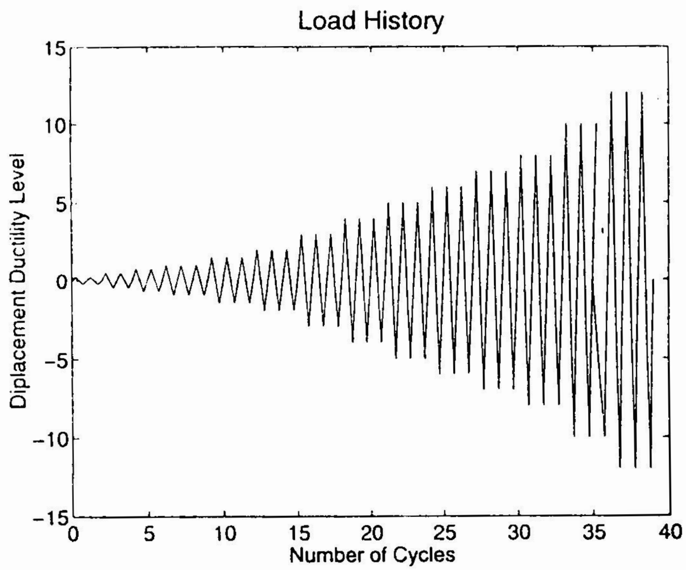

Figure 3.0 Load History for the control wall

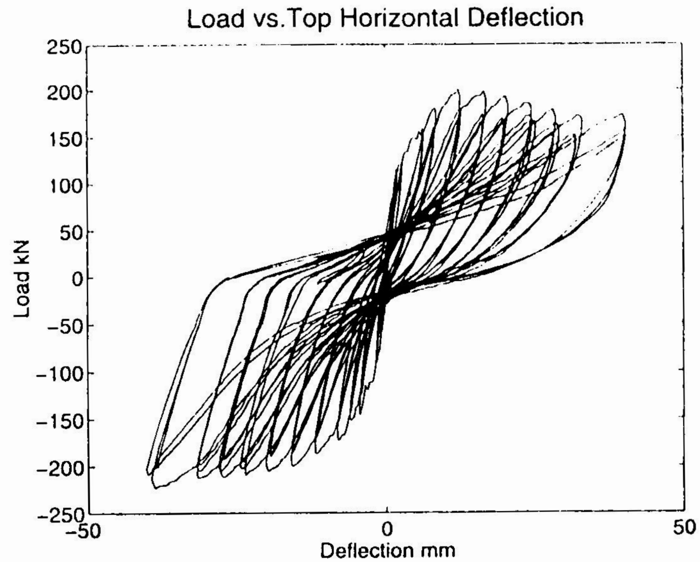

Figure 4.0 Load versus top horizontal deflection for the control wall

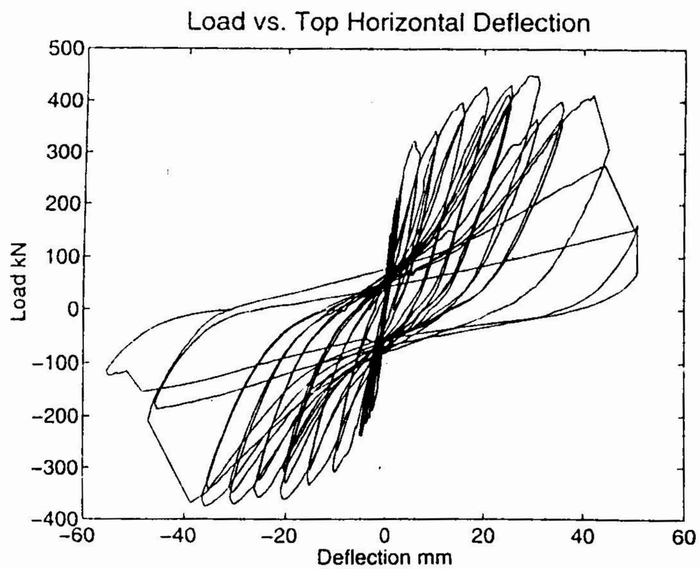

Figure 6.0 Load versus top horizontal deflection for strengthened wall #2

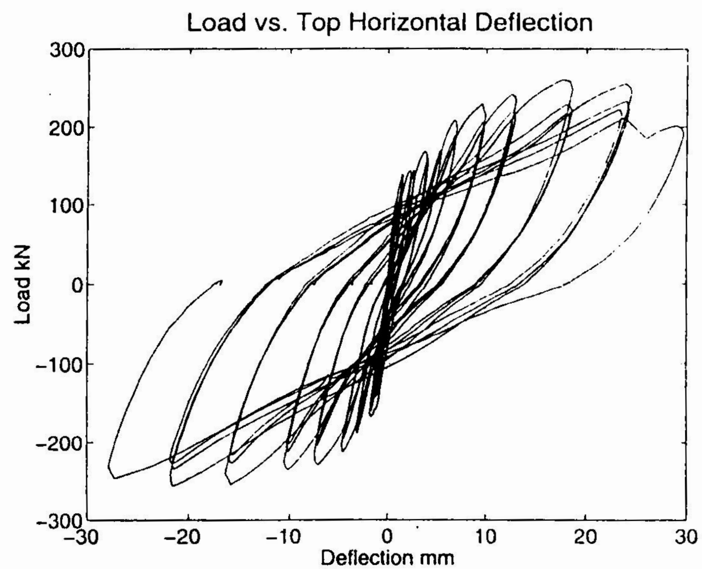

Figure 5.0 Load versus top horizontal deflection for strengthened wall #1