SEISMIC STRENGTHENING OF REINFORCED CONCRETE SQUAT WALLS USING EXTERNALLY BONDED CFRP SHEETS

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Abstract: This paper presents experimental results on a minimally disruptive retrofitting scheme consisting of externally bonded carbon fibre-reinforced polymer (CFRP) sheets. The test specimens are 2/3 scale reinforced concrete squat walls with a height-to-length aspect ratio of 0.85 tested to failure under reversed cyclic lateral load. The wall specimens are detailed with the structural deficiencies commonly found in walls designed according to older design standards. The retrofitting scheme consists of a combination of vertical and horizontal CFRP sheets designed to eliminate premature shear failure and enhance the flexural load carrying capacity of the wall specimens. Results on two different anchor systems are presented including FRP anchors, and a mechanical tube anchor system developed at Carleton University. Results demonstrate the ability of using CFRP sheets as a viable retrofitting alternative to improve the seismic performance of deficient RC squat walls.

1. INTRODUCTION

The use of reinforced concrete (RC) shear walls to resist lateral forces induced by wind loads began in midrise construction during the 1950s and 60s. During this time, very little emphasis was placed on seismic design and the potential forces induced on a structure by an earthquake. As a result, there are a significant number of shear wall structures constructed prior to 1970 that pose a significant seismic risk due to a lack of ductility and energy dissipation capacity. The poor seismic performance of these structures is attributed to inadequate seismic detailing, which typically included insufficient shear reinforcement and a lack of confinement of the boundary elements. To address these deficiencies, there are a number of available retrofitting techniques aimed at improving the performance of older shear wall structures. However, in the current state of seismic-resistant structural design, engineers are seeking innovative techniques in the form of advanced materials and structural systems to not only meet the life-safety objectives present in most seismic design standards around the world, but to also meet the multiple objectives associated with performance based seismic design. One such innovative retrofitting solution is the use of externally bonded carbon fibre-reinforced polymer (CFRP) sheets. CFRP is an advanced composite material, which is lightweight, resistant to environmental degradation and can be applied to a structural member without causing a significant disruption to the everyday operation of the building. Numerous studies have demonstrated that using CFRP in retrofitting applications can improve the strength, ductility, energy dissipation capacity of RC shear walls (Antoniades et al. 2003; Patterson and Mitchell 2003; Khalil and Ghobarah 2005; Elnady, 2008). However, there has been limited research into its use in walls with poor seismic detailing, particularly shear dominant squat walls.

The goal of this study is to evaluate the effectiveness of using externally bonded CFRP sheets to improve the performance of older, deficient RC squat shear walls. Three 2/3 scale squat RC shear wall specimens are cyclically tested to failure. Due to the shear dominant nature of these wall specimens and the deficiencies in their design, the wall specimens are expected to fail in a sudden and brittle manner. The study focuses on the ability of the CFRP retrofitting system to improve the seismic performance of shear walls with and without pre-existing damage. In contrast to previous studies, the CFRP sheets are not wrapped around the wall specimens to ensure the practicality of the retrofitting system. The study compares the performance of two different anchor systems used to transfer the forces carried by the CFRP to the supporting structural elements. The two anchor systems include FRP fan anchors, and a mechanical tube anchor system developed at Carleton University. The ability of each anchor system to transfer the force in the CFRP sheets to the supporting structural elements and prevent premature failure of the retrofitting system is evaluated.

2. DESIGN METHODOLOGY

The wall specimens described in this study are 2/3 scale RC shear walls designed according to older design standards (ACI 318-68; CSA 23.3-77). The wall specimens measure 2.1m in length (l_w), 1.8m in height (h_w) and 0.14m thick resulting in an overall aspect ratio (h_w/l_w) of 0.85. Shear walls with an aspect ratio less than 1.5 are typically considered shear dominant walls, and referred to as squat walls. The wall specimens are detailed with several common deficiencies associated with older design standards, including insufficient shear reinforcement, a lack of confinement in the boundary elements, and a lower concrete strength typically used in construction during the 1960s. During this time, both the Canadian Standard for the Design of RC Structures (CSA A23.3-77) and the American Concrete Institutes Building Code Requirements for Structural Concrete (ACI 318-68) had no explicit requirement for the concentration of vertical reinforcement or confinement in the boundary elements of a shear wall. The minimum vertical and horizontal steel reinforcement ratios were 0.15% and 0.25% respectively for both design standards. Figure 1 shows the dimensions and steel reinforcing scheme for a typical shear wall specimen in this study. The walls are detailed with a vertical steel reinforcement ratio of 3.0% and a horizontal steel reinforcement ratio of 0.25%. These reinforcement ratios meet the minimum prescribed requirements of both design standards while ensuring that shear is the controlling mode of failure for the wall specimens in their unstrengthened state. The wall specimens have no concentration of vertical reinforcing steel or confinement within the boundary elements. Material properties for the steel and concrete are shown in Table 1.

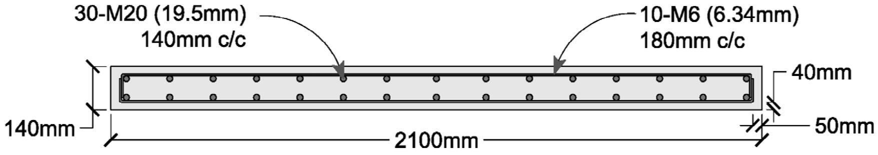


Figure 1: Shear wall dimensions and reinforcing details

The three wall specimens include a control wall, denoted CW, which is cyclically tested up to failure and then repaired, changing its denomination to RW. The ability of the retrofitting scheme to restore the initial stiffness of the wall and increase the shear strength, ductility, in-plane strength and energy dissipation capacity is evaluated after the repair procedure. This part of the investigation provides insight on using the CFRP retrofitting system in repair application for walls that have experienced some seismic damage during an earthquake and must be repaired to restore the safety of the structure. The other two wall specimens are strengthened with CFRP sheets prior to testing, with no previous damage (denoted SW1/SW2). The performance of these wall specimens are compared with the control wall to evaluate the effectiveness of externally bonded CFRP sheets as a retrofitting scheme in deficient shear wall structures.

Table 1: Concrete, steel, and FRP material properties

Concrete		Steel Rebar		CFRP (Gross Laminate)		GFRP (Gross Laminate)	
Material Property	Test Value	Material Property	Test Value	Material Property	Test Value	Material Property	Test Value
f'_c	19.1 MPa	f_y	415 MPa	$f_{CFRP,u}$	931 MPa	$f_{GFRP,u}$	575 MPa
ε'_c	0.0018	ε_y	0.00218	$\varepsilon'_{CFRP,u}$	0.01	$\varepsilon'_{GFRP,u}$	0.022
E_c	20.7 GPa	E_s	200.1 GPa	E_{CFRP}	91.9 GPa	E_{GFRP}	72.4 GPa

2.1 Design of CFRP Reinforcing Scheme

One of the main objective of this study is to investigate the ability of the retrofitting system to increase the in-plane flexural strength of RC shear walls designed according to older design standards. The properties of the cured CFRP laminates used in this study are determined by performing tension tests on CFRP coupons. Table 2 shows the results from the CFRP coupon tests and the number of CFRP layers applied to each wall specimen. To improve the flexural strength of the wall specimens, two sheets of vertically oriented CFRP composite are applied to each wall. To ensure the wall specimens fail in a flexural manner, the capacity of the wall against diagonal tension shear failure must be increased beyond its flexural capacity by applying horizontally oriented CFRP layers. Because of the shear dominant nature of the wall specimens, six layers of horizontal CFRP reinforcement are required to ensure that the capacity against diagonal tension shear failure is sufficiently higher than the walls flexural capacity. Wall specimen SW1 is retrofitted with the CFRP layers evenly distributed on each side of the wall, and the second strengthened wall specimen (SW2) is tested with all of the CFRP sheets on a single side. This will allow for comparison between the strengthening schemes and determine the influence the distribution of the CFRP sheets has on the seismic performance of the wall.

Table 2: FRP reinforcing scheme and anchor system

Wall I.D.	Number of CFRP Sheets	Distribution of CFRP Sheets	Vertical CFRP Anchor System	Horizontal CFRP Anchor System
CW	-	-	-	-
RW	1V+3H*	Each Side	Tube Anchor	-
SW1	1V+3H*	Each Side	Tube Anchor	-
SW2	2V+6H*	Single Side	CFRP Anchors	GFRP Anchors

* V – vertically oriented CFRP fibres; H – horizontally oriented CFRP fibres.

2.2 Experimental Test Setup and Instrumentation

To simulate the drift demand and damage effects on a RC shear wall during a major seismic event, the wall specimens are tested under a pre-determined cyclic lateral load sequence up to failure. Figure 2 shows the test setup for a typical shear wall. The test specimen is secured to the laboratory strong floor, and a hydraulic actuator applies the lateral load to the top of the wall. Due to limitations on the experimental test setup, axial load is not applied to the walls. Out-of-plane deformation of the test specimen is minimized by using a lateral restraint frame. Each wall specimen is first tested in load control, applying two successive cycles at 25%, 50%, 75% and 100% of the estimated yield strength. The yield strength of the wall specimens are based on finite element simulations conducted by Shaheen (2014). The test is then continued in displacement control by increasing the target displacement ductility level for two successive cycles up to failure. Strain gauges are used to monitor steel strains at the base, middle, and top of the vertical and horizontal reinforcing bars. Strains in the reinforcing steel assist in determining the flexural capacity of the wall specimen and monitor the inelastic behavior of the wall.

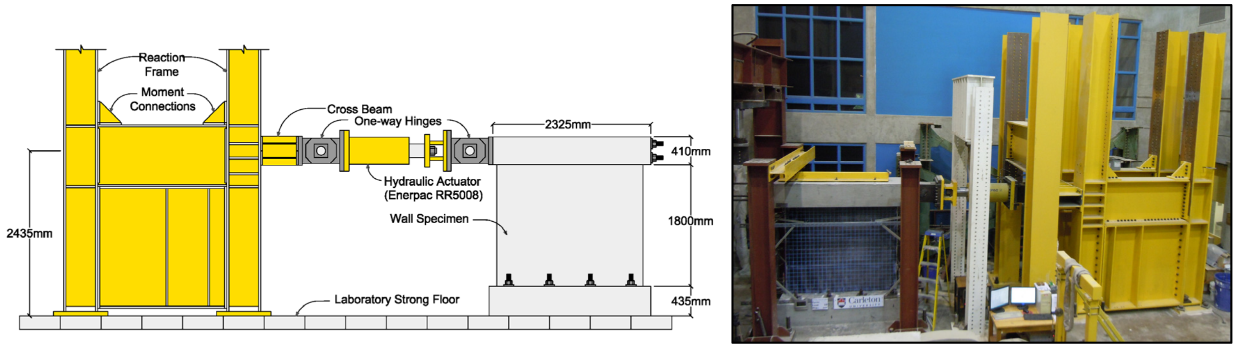


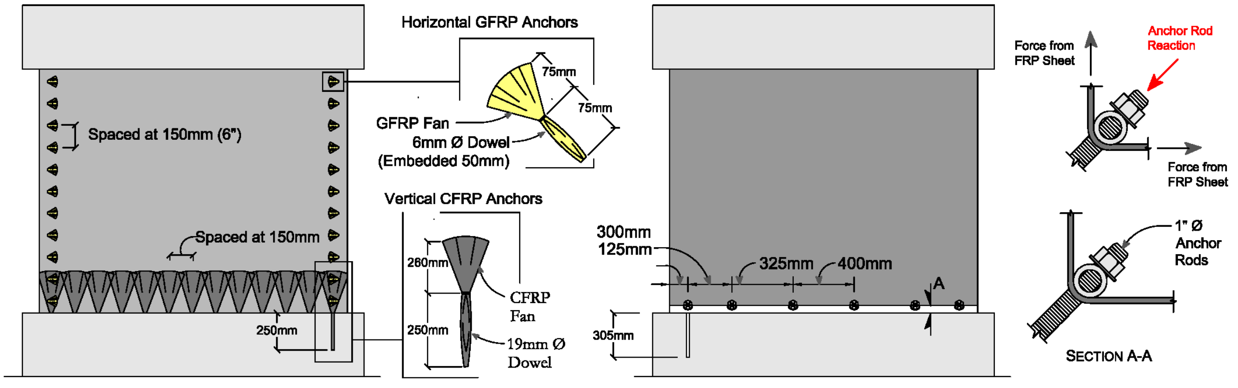
Figure 2: Experimental test setup

2.3 Anchor Systems

A crucial component of any retrofitting scheme requiring termination of a CFRP sheet at the boundary between two structural elements is an effective anchor system. The anchor system is designed to maximize the utilization of the high strength capacity of the CFRP composite before the ultimate failure of the retrofitted member. By providing a load transfer mechanism between the CFRP sheet and the supporting structural element, the anchor system allows the CFRP sheet to approach its ultimate tensile capacity, maximizing the efficiency of the retrofitting system. In this study, two different anchor systems are used to transfer the force carried by the CFRP sheets into the adjacent supporting structural element, which in this case is the foundation of the wall.

The first anchor system used in wall specimens RW and SW1 is an innovative tube anchor system fabricated from a cylindrical steel tube. The design of the tube anchor system is shown in Figure 3b. The CFRP sheet is wrapped around a steel tube that is placed along the base of the wall and bolted to the foundation at several locations along its length. As shown in Figure 3b, the anchor rods are installed at a 45-degree angle to concentrically transfer the load carried by the CFRP to the foundation of the wall. The design of the tube anchor system is based on an optimized designed procedure developed by Woods (2014). This procedure uses detailed finite element simulations to select the optimal tube dimensions and anchor bolt spacing to ensure effective performance of the anchor system while maintaining cost-efficiency.

The second strengthened wall specimen (SW2) uses anchors fabricated from bundles of high strength fibres, commonly referred to as fan or spike anchors. The fibres are bundled together at one end to form a dowel and inserted into a predrilled hole in the concrete. The fibres at the opposite end are splayed over the CFRP sheet and bonded to the CFRP using epoxy resin. The force carried by the CFRP sheet is transferred through the fan anchor to the supporting structural element. Figure 3a shows the dimensions and layout of the fan anchors for the wall specimen. CFRP anchors, measuring 510mm in length are embedded into the foundation of the wall specimen to transfer the load carried by the vertical CFRP sheets to the concrete foundation. Smaller 150mm GFRP anchors placed along the edges of the wall prevent premature debonding of the horizontal CFRP sheets. Results on the performance of the anchor systems are presented in Section 3.5. Material properties for the CFRP and GFRP anchors are shown in Table 1.



(a) (b)

Figure 3: (a) CFRP and GFRP fan anchor system; (b) Steel tube anchor system

3. EXPERIMENTAL RESULTS

3.1 Performance of Control Wall (CW)

As anticipated, the failure of the control wall specimen occurs in sudden and brittle diagonal tension shear failure at a lateral drift of 0.63%. The distinct diagonal tension failure plane shown in Figure 4 occurs after rupture of the horizontal steel stirrups at a lateral load of 1030kN. Table 3 shows important structural parameters for the response of each wall specimen. Figure 5a and 5b show the strain profiles in the vertical and horizontal reinforcing steel at increasing levels of lateral. Results show that yielding only occurs in the bars located closest to the edges of the wall prior to failure. The horizontal strain profile in Figure 5b also shows that the transverse reinforcing steel reaches its rupture strain in the centre of the wall. Results reveal the brittle nature of shear wall specimens with poor seismic detailing and emphasize the need to retrofit these walls to protect the safety of a structure.

Following the initial test, the control wall specimen is repaired using a combination of epoxy resin, patching mortar and CFRP composite sheets. In contrast to previous studies (Antoniades et al. 2003; Paterson and Mitchell, 2003; Khalil and Ghobarah, 2005; and Elnady, 2008) the CFRP sheets are not wrapped around the wall to account for the fact that in a typical retrofitting scenario, the sides of a RC shear wall are not exposed. By not wrapping the CFRP sheet around the wall, the retrofitting scheme becomes more practical, reducing the application time and level of disruption to the operation of the facility.

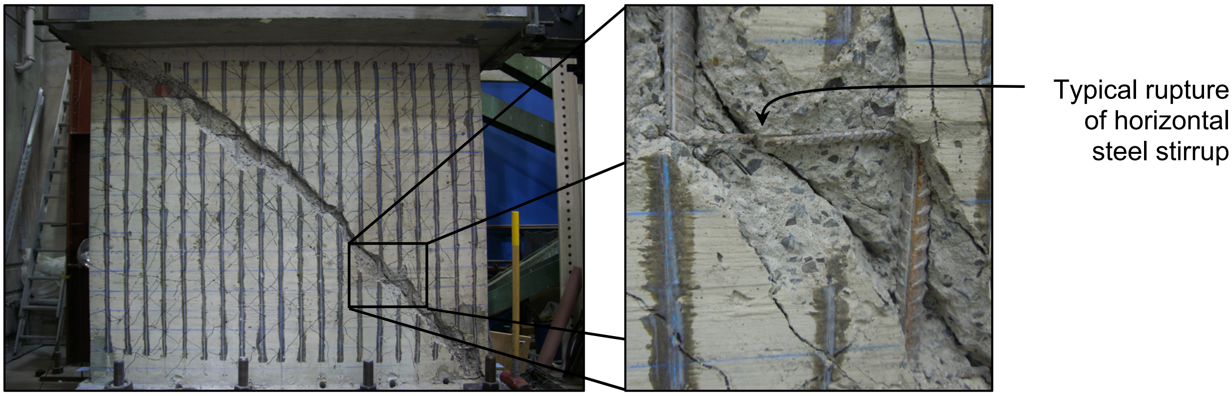
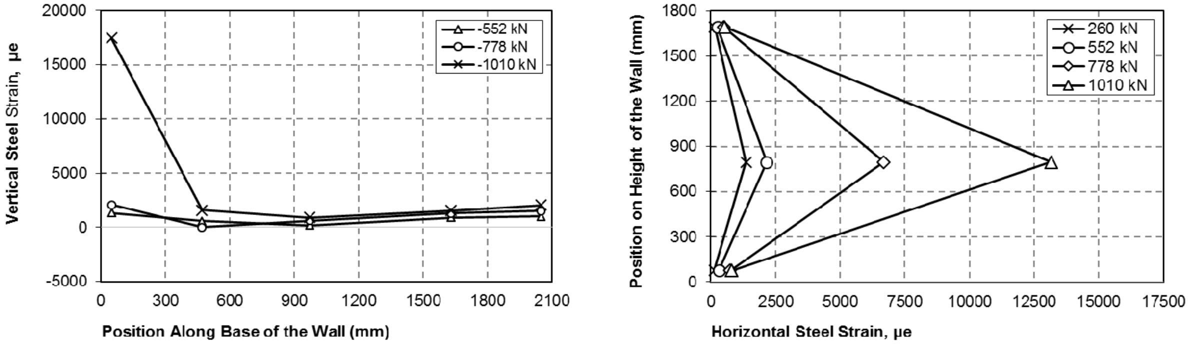

Typical rupture of horizontal steel stirrup

Figure 4: Diagonal tension shear failure of specimen CW



(a) (b)

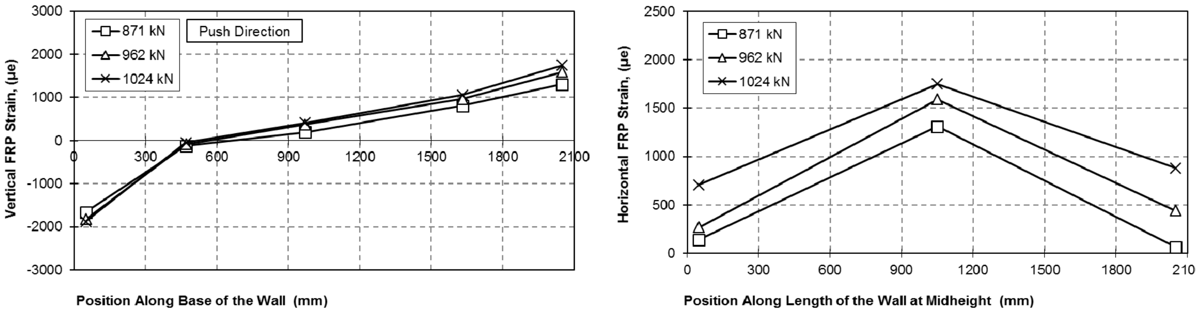
Figure 5: Specimen CW: (a) Vertical and (b) Horizontal steel strain profiles

3.2 Performance of Repaired Wall (RW)

Results from the test of the repaired wall demonstrate that the CFRP retrofitting scheme is successfully capable of restoring the initial stiffness of the shear wall to its original state. Debonding of the CFRP laminate from the concrete substrate first occurs at an average drift ratio of 0.3%. Debonding first occurs in highly damaged regions from the earlier test. At higher levels of lateral drift (0.57-0.88%), debonding initiates at the toes of the wall specimen, which is an indication of flexural cracking and concrete crushing beneath the CFRP. This phenomenon, known as intermediate-crack debonding or IC debonding, is discussed in more detail by Cruz et al. (2014) and is typical in flexurally dominant walls. Because of the additional shear strength provided by the horizontal CFRP sheets, there is a shift in the behaviour of the repaired wall from a shear critical wall specimen to a more flexurally dominant behaviour. Figure 6 shows the vertical and horizontal CFRP strain profiles at increasing levels of lateral load. The strain in the vertical CFRP near the base of the wall remains approximately linear, reaching a maximum strain of approximately 0.2%. The highest strain in the horizontal CFRP occurs in the centre of the wall, a region in which the CFRP is responsible for transferring the shear stress across the diagonal crack formed during the previous test. Ultimately, significant CFRP debonding around the failure plane from the previous test causes reopening of the diagonal crack at 0.72% drift. Although the CFRP retrofitting system is unable to improve the lateral drift capacity of the wall, the retrofitting scheme is able to restore the wall to its original condition. In a severely damaged wall specimen (drop to 15% of ultimate capacity), restoration of the wall to its original state shows the potential for using CFRP sheets as a repair strategy for walls with a lower level of pre-existing seismic damage.

Table 3: Structural response parameters for each wall specimen

Wall I.D.	Initial Stiffness (kN/mm)	Yield Load (*P*$_y$) (kN)	Yield Disp. (mm)	Post-Yield Stiffness (kN/mm)	Max. Load (kN) (Δ_y)	Max. Disp. (mm) (Δ_u)	Ductility (μ_Δ)	Energy Disspation (kN-m)
CW	166	765	6.11	75.0	1020	9.73	1.25	4.9
RW	148	777	7.02	72.8	975	12.9	1.41	11.1
SW1	394	909	4.98	112	1505	21.0	2.91	18.0
SW2	360	835	5.92	133	1405	19.0	2.57	14.8



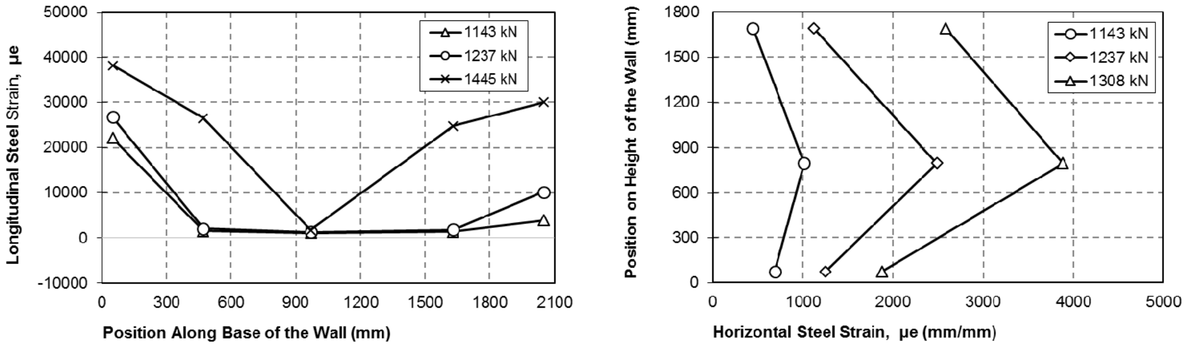
(a) (b)

Figure 6: Specimen RW: (a) Vertical and (b) Horizontal CFRP strain profiles

3.3 Performance of Strengthened Walls (SW1/SW2)

The application of the CFRP sheets to the strengthened walls follows the same procedure as the repaired wall. Both of the strengthened wall specimens exhibit ductile behaviour up to failure and reach their ultimate flexural capacity. The onset of CFRP-concrete debonding occurs at drift ratios ranging from 0.82-0.88%, which is significantly higher when compared with the repaired wall. This is attributed to the lack of pre-existing damage in the strengthened walls. Debonding in specimen SW1 first occurs in the toes of the wall specimen, which is due to the opening of flexural cracks in the concrete (IC debonding), indicative of flexural behaviour. Specimen SW2 does not experience any visible debonding prior to failure, which is attributed to the GFRP anchors placed along the edges of the wall. Flexural cracking along the height of the wall is observed before the formation of large diagonal cracks in the concrete. This once again indicates a shift in behaviour of the shear wall to a more flexurally dominant behaviour. The strengthened wall specimens (SW1/SW2) reach their ultimate flexural capacity at a lateral load of 1505kN and 1405kN respectively. Figure 7 shows the vertical and horizontal steel strain profiles at increasing levels of lateral load. The increase in shear strength provided by the horizontal CFRP prevents premature shear failure and allows yielding of vertical steel reinforcing bars to spread toward the interior of the wall. The additional shear strength provided by the horizontal CFRP also results in lower strains in the horizontal reinforcing steel when compared to the control wall specimen. At maximum lateral drifts of 1.16% and 1.05% for SW1 and SW2 respectively, both strengthened wall specimens fail in diagonal tension shear, after debonding of the CFRP from the concrete substrate. It is important to note that failure of both wall specimens occurs after achieving their flexural capacity. In specimen SW1, the debonding progression begins along the side of the wall and propagates toward the interior, leading to failure of the wall. Specimen SW2 fails after rupture of the GFRP anchors along the side of the wall. Rupture of the GFRP anchors results in rapid delamination of the CFRP sheets from the concrete substrate and opening of a large diagonal failure plane.

As noted in Table 2, wall specimen SW1 has all of the vertical and horizontal CFRP layers distributed evenly on either side of the wall. Alternatively, wall specimen SW2 has the same number of layers as SW1, but the layers are all on a single side of the wall. This allows for a comparison between the two specimens to get a better understanding of the effect of CFRP sheet distribution on the in-plane behaviour of the wall. Based on test results, the effect of placing all of the CFRP on a single side of the wall specimen did not have a significant impact on the ultimate load carrying capacity or the lateral drift capacity, which differ by only 8 and 10% respectively. However, restraining the out-of-plane deformations of the wall specimens could have influenced the results of the comparison because of the potential torsional sensitivity caused by applying all of the CFRP sheets on a single side of the wall.



(a) (b)

Figure 7: Specimen SW1: (a) Vertical and (b) Horizontal steel strain profiles

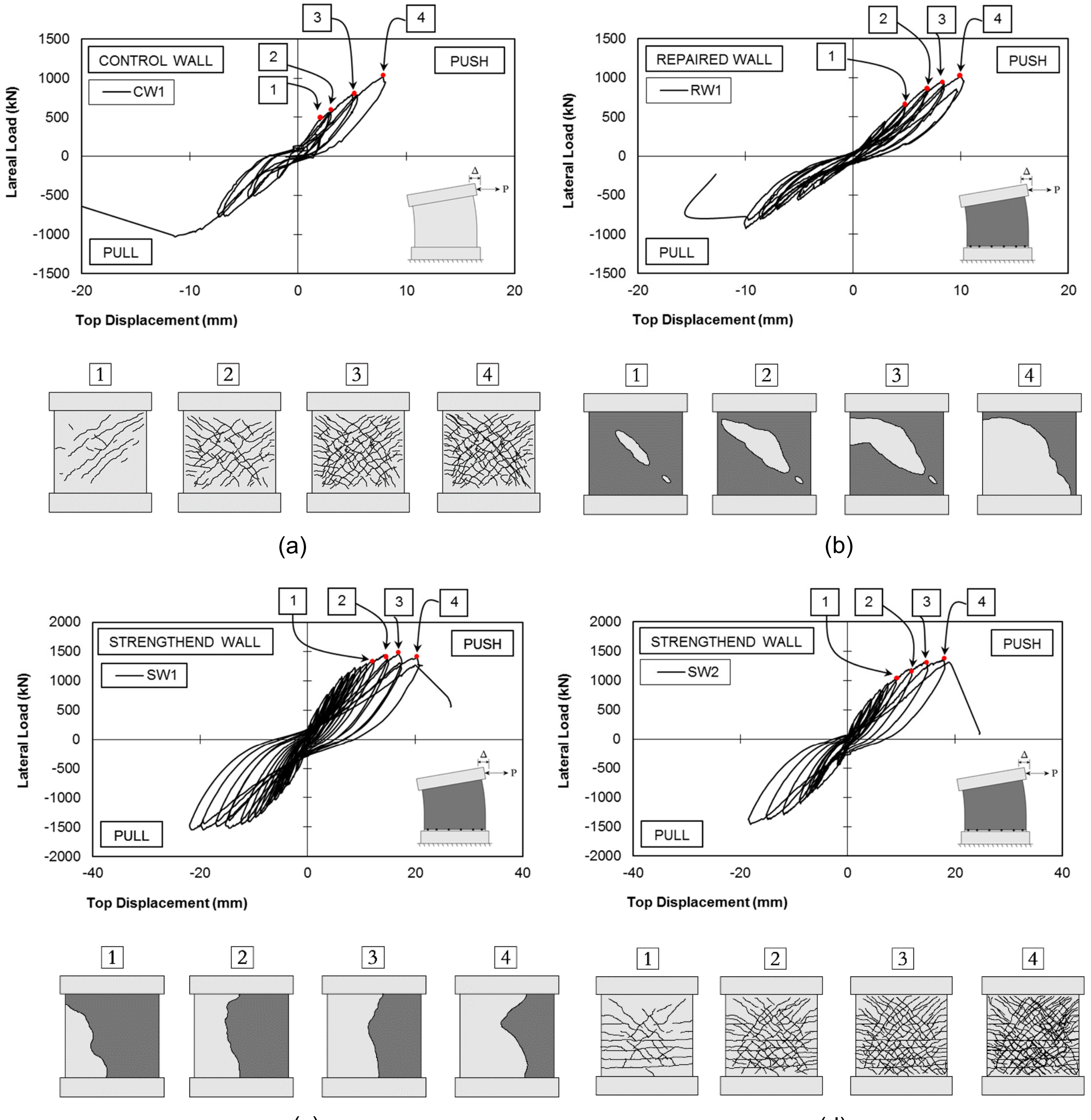
3.4 Comparison of Seismic Performance

The displacement ductility for each wall specimen is computed using a bilinear idealization of the force-displacement envelope to establish the equivalent yield load (P_y) and yield displacement (Δ_y). The maximum displacement (Δ_u) occurs when the load drops to 80% of the ultimate load carrying capacity measured during testing. The displacement ductility (μ_Δ) is then determined by dividing the ultimate displacement by the yield displacement. Table 3 shows the equivalent yield load, yield displacement, ultimate displacement, and displacement ductility for each wall specimen.

The average displacement ductility of the control wall is 1.25, showing the lack of ductility in wall specimens with deficiencies associated with older design standards. The repaired wall specimen has a slightly increased displacement ductility of 1.4, however due to the level of pre-existing damage to the wall during the previous test, it is not significantly higher than the control wall. The strengthened wall specimens attain displacement ductility ratios of 2.91 and 2.57, a significant improvement when compared to the control wall, showing the shift between a brittle shear dominant and ductile flexurally dominant behaviour. The increase in ductility in the strengthened wall specimens is attributed to the increase in yielding of the vertical steel reinforcement throughout the wall specimens prior to failure.

The energy dissipation capacity of each wall specimen shown in Table 3 is calculated by dividing the total work done by the wall (force x displacement) and normalizing it using the maximum force and displacement. Results show that by retrofitting the deficient shear wall specimens with CFRP sheets, the energy dissipation capacity is up to 4 times larger when compared with the control wall. The repaired wall exhibits a higher energy dissipation when compared to the control wall because of the increase in the number of cycles sustained prior to reopening of the diagonal failure plane. Specimen SW2 exhibits slightly less total energy dissipation compared to the SW1 due to the sudden rupture of the horizontal GFRP anchors resulting in failure of the wall.

The poor seismic performance of the control wall is reflected in its hysteretic behaviour shown in Figure 8. The hysteretic response of the control wall shows minimal energy dissipation capacity and ductility prior to failure. The repaired wall specimen does not exhibit the same improvements in seismic performance when compared with the strengthened walls, because of the pre-existing damage from the earlier test. Nonetheless, it is shown that even in a severely damaged wall specimen, the CFRP retrofitting system is capable of restoring the wall to its original state, demonstrating the potential for better performance in walls with less pre-existing damage. The strengthened wall specimens show an increase in energy dissipation capacity, identified by wide hysteretic loops, and an increase in drift capacity when compared to the control wall. By comparing the hysteretic behaviour of the two strengthened walls, the effect on the seismic performance of applying all of the CFRP sheets to a single side of the wall is minimal. The hysteretic behaviour of each wall specimen is very comparable, reaching approximately the same ultimate load and lateral drift capacity. The crack distributions for specimens CW and SW2 are shown in Figure 8a and 8d. Comparing the two, the presence of horizontally oriented flexural cracks in the strengthened wall specimen shows the shift in behaviour from a shear dominant to a flexurally dominant wall specimen. This also demonstrates the ability of the CFRP retrofitting system to prevent premature shear failure, and allow the wall to reach its ultimate flexural capacity, resulting in better seismic performance.



(a)

(b)

(c)

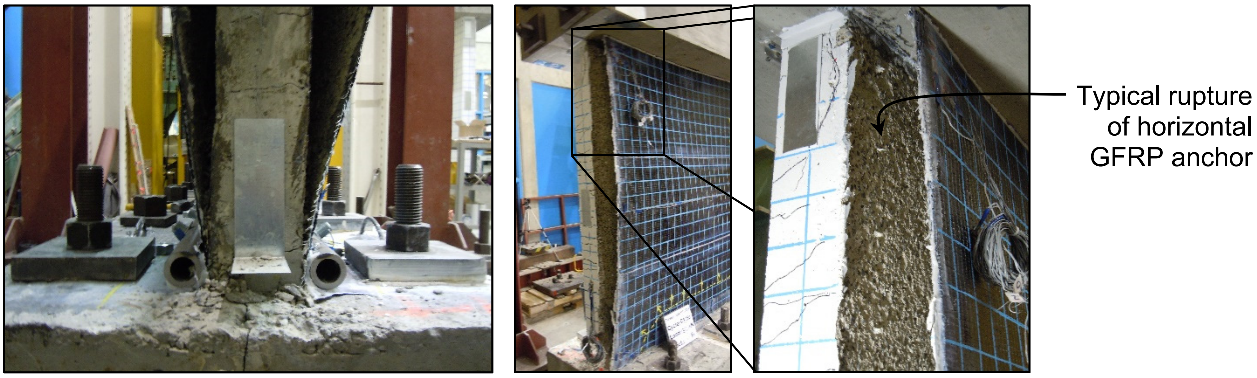
(d)

Figure 8: Hysteretic response: (a) CW; (b) RW; (c) SW1; (d) SW2

3.5 Anchor System Performance

Results from the test show that the tube anchor system performs well in transferring the load carried by the CFRP sheets to the foundation of the wall. The tube anchor system experiences minimal deformation under the force carried by the CFRP sheets, verifying the optimization procedure used in its design. Figure 9a shows an image of the tube anchor system at the end of the strengthened wall test. Even after debonding of the vertical CFRP, the presence of the anchor systems allows the CFRP to sustain further load under multiple load reversals by anchoring the vertical CFRP at the base of the wall.

The FRP fan anchors also perform well in transferring the force from the vertical and horizontal CFRP sheets to adjacent structural elements. The vertical CFRP anchors allow the vertical CFRP sheets to sustain an increase in force, and do not experience pullout prior to failure. Figure 8c and 8d shows the debonding progressions for wall specimens SW1 and SW2. The presence of the GFRP anchors along the sides of the wall delays debonding when compared with specimen SW1, which has no anchorage along the sides of the wall. Specimen SW2 did not experience any debonding until failure of the horizontal GFRP anchors. After failure of the GFRP anchors, a large portion of the CFRP sheets separated from the concrete substrate resulting in failure of the wall (Figure 9b).



(a) (b)

Figure 9: Anchor system performance: (a) Tube anchor; (b) CFRP anchors

4. CONCLUSIONS

This study presents results on the performance of RC shear walls designed according to older design standards, in particular ACI318-68 and CSA23.3-77. Results of the study show that walls designed according to older design standards, particularly those with insufficient shear reinforcement or a lack of confinement in the boundary elements are susceptible to sudden and brittle shear failure with minimal ductility or energy dissipation capacity.

Results show that by applying externally bonded CFRP sheets, the retrofitting system is capable of preventing premature shear failure and promoting a more flexurally dominant mode of failure. The retrofitting system allows the wall specimens to reach their flexural capacity and increases the in-plane strength, ductility and energy dissipation capacity in strengthening applications. In repair applications, the CFRP retrofitting system is capable of restoring the shear wall to its original state, even in severely damaged wall specimens. Experimental results show that the CFRP retrofitting system is capable of increasing the shear strength of the wall specimens without wrapping the CFRP sheets around the wall, improving the practicality of the retrofitting system. An effective anchor system is shown to be a critical factor in the performance of the retrofitting system, allowing the CFRP composite to reach higher levels of stress prior to failure. Both anchor systems perform well in transferring the forces carried by the CFRP sheets to the foundation of the wall.

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