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# Seismic Retrofit of Deficient RC Sear Walls with FRP Tow Sheets

C. A. Cruz-Noguez[1], A. Hassan[2], D. T. Lau[3], J. Woods[4], and I. Shaheen[5]

## ABSTRACT

This paper presents the results of a comprehensive study on the repair and strengthening of seismically deficient, reinforced-concrete (RC) shear walls using externally bonded fibre-reinforced polymer (FRP) tow sheets. The shear wall specimens had structural deficiencies typically found in buildings designed using older construction codes, such as non-ductile details and insufficient shear reinforcement. The study comprises both analytical and experimental components. In the experimental component, sixteen shear wall specimens with different height-to-length aspect ratios (varying between 1.20 and 0.68) are subjected to in-plane, cyclic loading until failure, and externally bonded FRP sheets oriented in the vertical and horizontal directions are used to enhance the seismic response of the walls. In the analytical component, pre- and post-test finite-element simulations are conducted to predict and simulate, respectively, key parameters of the structural response of the FRP-reinforced walls (such as nonlinear force-displacement relationships and modes of failure). The test show that the FRP system is effective in preventing premature shear failure in the wall specimens, significantly increasing their energy dissipation capacity and enhancing their stiffness and flexural strength. Satisfactory correlation was found between the analytical prediction and the actual response observed during the tests, satisfactorily capturing and modelling the nonlinear response of repaired and strengthened walls, failure modes, debonding progression and strain profile distributions. The study shows that the FRP system is an attractive option to retrofit shear wall structures that might exhibit seismic vulnerabilities.

[1] Assistant Professor of Civil Engineering, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada.
[2,4,5] Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Carleton University, Ottawa, Canada.
[3] Professor of Civil Engineering, Dept. of Civil and Environmental Engineering, Carleton University, Ottawa, Canada.

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## ABSTRACT

This paper presents the results of a comprehensive study on the repair and strengthening of seismically deficient, reinforced-concrete (RC) shear walls using externally bonded fibre-reinforced polymer (FRP) tow sheets. The shear wall specimens had structural deficiencies typically found in buildings designed using older construction codes, such as non-ductile details and insufficient shear reinforcement. The study comprises both analytical and experimental components. In the experimental component, sixteen shear wall specimens with different height-to-length aspect ratios (varying between 1.20 and 0.68) are subjected to in-plane, cyclic loading until failure, and externally bonded FRP sheets oriented in the vertical and horizontal directions are used to enhance the seismic response of the walls. In the analytical component, pre- and post-test finite-element simulations are conducted to predict and simulate, respectively, key parameters of the structural response of the FRP-reinforced walls (such as nonlinear force-displacement relationships and modes of failure). The test show that the FRP system is effective in preventing premature shear failure in the wall specimens, significantly increasing their energy dissipation capacity and enhancing their stiffness and flexural strength. Satisfactory correlation was found between the analytical prediction and the actual response observed during the tests, satisfactorily capturing and modelling the nonlinear response of repaired and strengthened walls, failure modes, debonding progression and strain profile distributions. The study shows that the FRP system is an attractive option to retrofit shear wall structures that might exhibit seismic vulnerabilities.

## Introduction

Reinforced concrete (RC) shear walls are an efficient lateral-load resisting system often used in structures located in seismically active regions. Although performance of shear wall buildings that meet current construction code requirements has shown an overall satisfactory seismic behavior [1,2], many older structures are still at risk of suffering severe damage during moderate or large earthquakes because of insufficient in-plane stiffness, flexural and shear strengths and/or ductility [3]. Among the retrofit and repair options available, an attractive, minimally disruptive option for the repair and strengthening of shear walls is the use of externally bonded fibre-

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[1] Assistant Professor of Civil Engineering, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada.
[2,4,5]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Carleton University, Ottawa, Canada.
[3] Professor of Civil Engineering, Dept. of Civil and Environmental Engineering, Carleton University, Ottawa, Canada.

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reinforced polymers (FRP) sheets [4]. FRP has been traditionally used to enhance the shear strength and energy dissipation capacity in structural components [5-7], although in comparison, the number of studies that address the use of FRP to increase (in strengthening applications) or restore (in repair uses) the flexural strength of RC shear walls is limited. The work presented in this paper discusses the experimental and analytical results obtained during a 13-year study on the effectiveness of using externally-bonded carbon FRP (CFRP) sheets to enhance the flexural and shear strength in seismically deficient RC shear walls. The developed FRP system was designed to promote a ductile behavior of the walls while preventing premature failures in shear. The objectives of the study are 1) to obtain experimental evidence on the effectiveness of the FRP system in enhancing the flexural/shear strength, stiffness and ductility of RC shear walls under moderate and severe damage scenarios, 2) to develop innovative FRP-concrete anchoring systems to prevent premature debonding failures [8], 3) to obtain insight on the response behavior and failure modes of FRP-reinforced shear walls, and 4) to develop analysis models to capture the nonlinear response of RC walls reinforced with FRP sheets, including concrete-debonding mechanisms and brittle details (such as lap splices at the plastic hinge zone).

## Shear wall experimental program

The first series of experiments were conducted to investigate the ability of the FRP system to enhance the strength and stiffness in flexurally dominated walls and comprise seven slender walls (with a height-to-length, *h/l* aspect ratio of 1.20) tested up to failure. The second series of experiments are intended to investigate the ability of the FRP system in enhancing the flexural/shear strength and ductility of nine seismically deficient walls, designed as per older specifications [9, 10]. The structural deficiencies in the walls tested in the second series of experiments include insufficient shear reinforcement, poor confinement at the boundary zones, and lap splices at the plastic hinge region. This phase includes slender and squat wall specimens, with three different aspect ratios, that account for a total of nine walls.

### Flexurally dominated walls

The walls tested in this phase comprise seven cantilevered wall specimens (Fig. 1) subjected to quasi-static, cyclic in-plane lateral load applied at the top [3, 11]. All walls are designed according to the CSA A23.3 [12] specifications in their un-repaired/ un-strengthened state to ensure that they would exhibit ductile failure before their calculated shear strength is reached. The flexural strength in walls with vertical FRP reinforcement was determined assuming perfect bond between FRP and the concrete. Since it is well known that in FRP-reinforced structures FRP-concrete debonding occurs before rupture of the FRP material and/or concrete crushing [13], the design flexural strength, determined with the perfect bond assumption, was intended to represent a theoretical upper bound for the flexural capacity of the walls.

The test walls include two control walls (CW), two repaired walls (RW), and five strengthened walls (SW). The control walls have no FRP reinforcement and no previous damage. They are tested in their original state to serve as a baseline for the evaluation of the repair and strengthening techniques of conventional RC walls which have suffered repairable damage from moderate to large earthquakes. After being subjected to cyclic loading, the CW specimens are repaired with one vertical layer of CFRP sheet on each side of the wall. The designation of these walls is then changed from CW to RW and the specimens are tested again to failure. Specimens SW are strengthened with CFRP sheets applied in the vertical direction prior to testing. To avoid brittle shear failure, some of the walls are also reinforced with an additional layer of CFRP in the horizontal direction (specimens SW2-1 and SW3-2) to increase their shear strength. A summary of the repair/strengthening schemes used for each wall is given in Table 1.

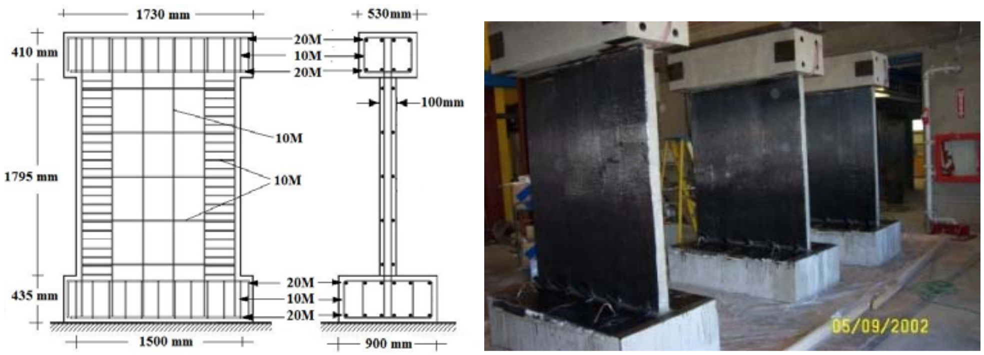

Figure 1: Flexurally dominated wall design details

Table 1: Repair/Strengthening schemes for flexurally dominated walls [3,11]

| Anchor type | Type of Specimen | Repair/ Strengthening Scheme* | Code |
|---|---|---|---|
| Angle | Control | --- | CW-1 |
| | Repaired | 1V | RW-1 |
| | Strengthened | 1V | SW1-1 |
| | Strengthened | 2V + 1H | SW2-1 |
| Tube | Control | --- | CW-2 |
| | Repaired | 1V | RW-2 |
| | Strengthened | 1V | SW1-2 |
| | Strengthened | 2V | SW2-2 |
| | Strengthened | 3V + 1H | SW3-2 |

*: *n*V = Wall reinforced with *n* layers of unidirectional FRP on each side in the vertical direction
*: *m*H = Wall reinforced with *m* layers of unidirectional FRP on each side in the horizontal direction

## Seismically Deficient Walls

This series of experiments comprises nine shear wall specimens. The structural deficiencies in the walls are intended to represent typical design details in older construction codes [9,10], and include poor confinement, insufficient shear reinforcement, and non-ductile details (lap splices) at the plastic hinge region. The experimental setup includes testing of two wall specimens with $h/l$=1.2, three walls with $h/l$=0.85, and four walls with $h/l$=0.65 (Table 2). Two of the four walls with $h/l$=0.65 have lap splices at the plastic hinge region. All wall specimens are designed to exhibit a brittle shear failure response before their flexural capacity is reached. Design details for these walls are shown in Fig. 2.

The externally-bonded CFRP sheets are applied in both the vertical and horizontal directions. The retrofitting scheme is designed to achieve ductile flexural behaviour and prevent premature shear failures from occurring, as well as improving the confinement of the concrete by wrapping the horizontal sheets around the wall. Both repair and strengthening applications were investigated, with some specimens having no FRP reinforcement being tested as a reference (control walls). The nine seismically deficient shear wall specimens are analyzed numerically using finite-element models. Fig. 3 shows the experimental setup and schematics for Squat Wall 2.

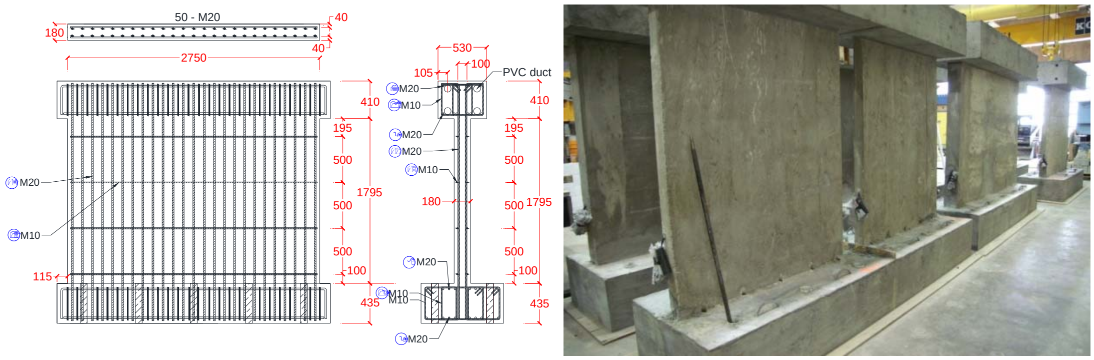


Figure 2: Left: Squat wall-2 specimen details; Right: seismically deficient squat walls

Table 2: Repair/Strengthening schemes for seismically deficient walls

| Wall Type | Aspect Ratio (h/l) | Vertical sheets* | Horizontal sheets* | CFRP sheets per side |
|---|---|---|---|---|
| 2x Slender wall | 1.2 | 1V | 3H | 1V+3H |
| 3 x Squat wall-1 | 0.85 | 1V | 3H | 1V+3H |
| 2 x Squat wall-2-1 | 0.65 | - | 4H | 4H |
| 2 x Squat wall-2-2 | 0.65 | 3V | 4H | 3V+4H |

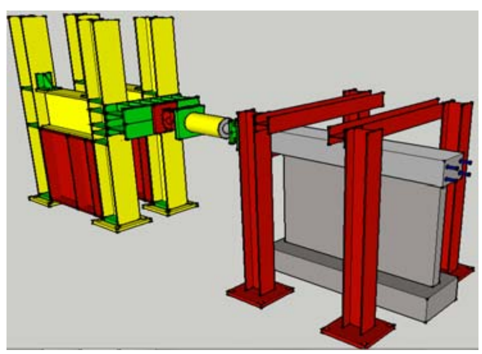

Figure 3: Experimental setup

## Enhancement of flexural strength and stiffness

Envelopes of the hysteretic base shear – top deflection response measured during the testing of the flexurally dominated walls is presented in Fig. 4. Detailed results for Phase 1 tests are discussed elsewhere [3, 14].

Fig. 4 clearly illustrates the efficiency of the CFRP flexural reinforcement system to increase the load capacity and ductility in both repaired and strengthened walls. The initial stiffness of strengthened specimens is significantly increased. For repaired walls, the CFRP system is successful in restoring the initial stiffness.

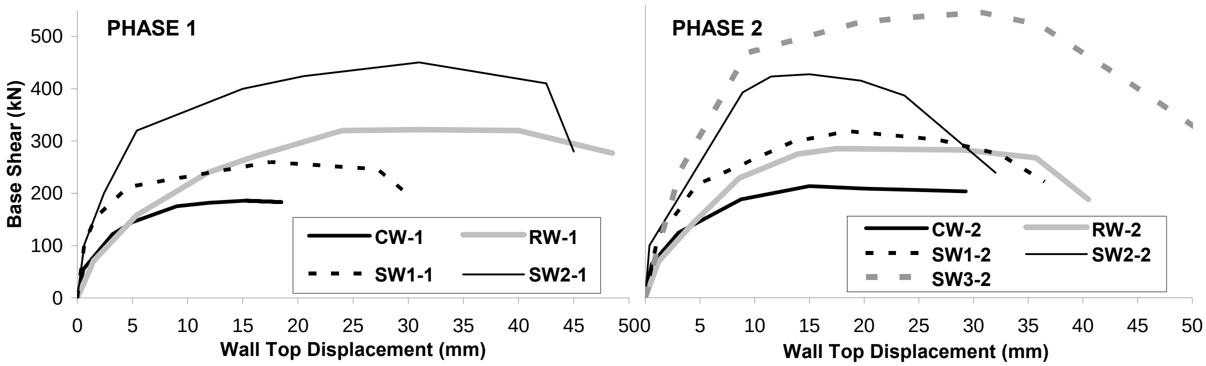


Figure 4: Envelopes of load-deformation hysteretic response: flexurally dominated walls

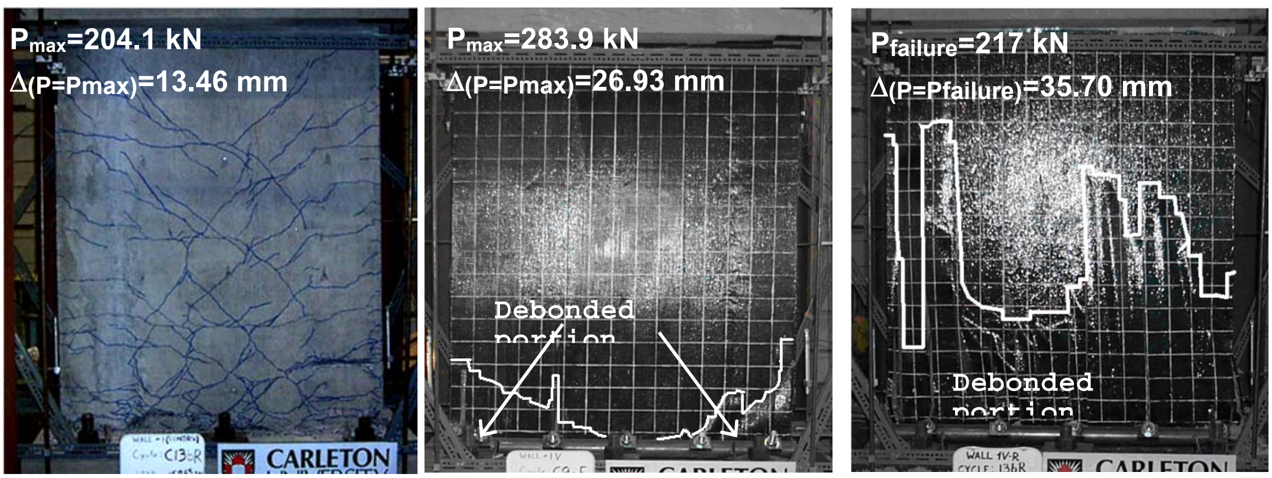


Figure 5: Left to right: crack pattern in specimen CW-2; RW-2 specimen at maximum load; RW-2 specimen at failure load.

# Analysis models for shear walls

## Finite-element modeling

In this study, 2D finite-element analysis models of the walls have been developed using program VecTor2 [15]. Four-node quadrilateral elements are used to model the concrete (Fig. 6). The foundation is not included in the model since it is assumed to be rigid compared to the wall. To model the concrete pre-peak and post-peak response behaviours, the Popovics and the modified Park-Kent models for the concrete materials are used, respectively. The steel rebars and stirrups are modeled as a uniformly-distributed elastic-plastic reinforcing material with strain hardening. The CFRP sheets are modeled by a series of discrete truss elements made of a brittle material with zero compressive strength. The connection between the CFRP truss elements and the concrete at the bottom of the wall is represented using the common-node method since mechanical anchorage between FRP and concrete is provided at the base. For the rest of the wall, zero-length link elements are used to connect the FRP trusses and the concrete elements.

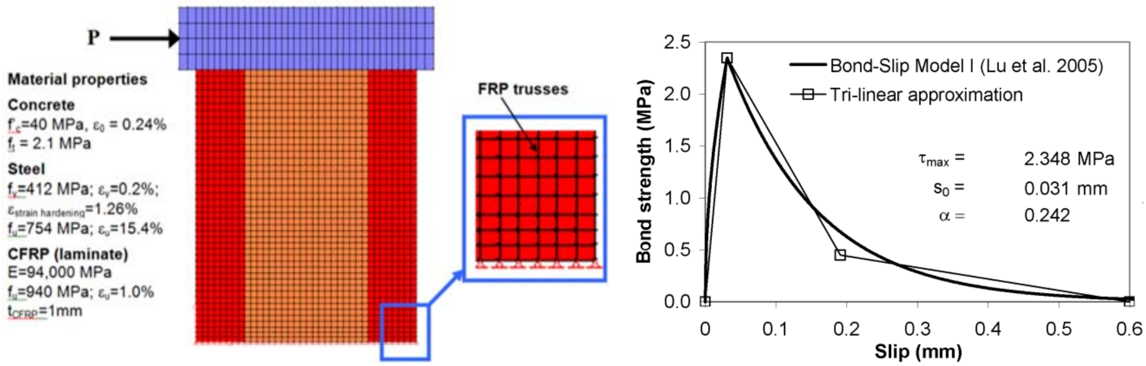


Figure 6: FE shear wall model (left) and tri-linear bond-slip relationship for uncracked interface elements (right)

## Intermediate crack (IC) debonding

Debonding caused by the opening up of flexural cracks in the concrete is referred to as intermediate crack (IC) debonding [13]. In this study, debonding was modelled through the constitutive relationships for FRP-concrete bond-slip interaction developed by Lu et al. [16, 17]. The results from the model were compared to the experimental results. As expected, the model was capable of improving the results obtained from assuming perfect bond (Fig. 7).

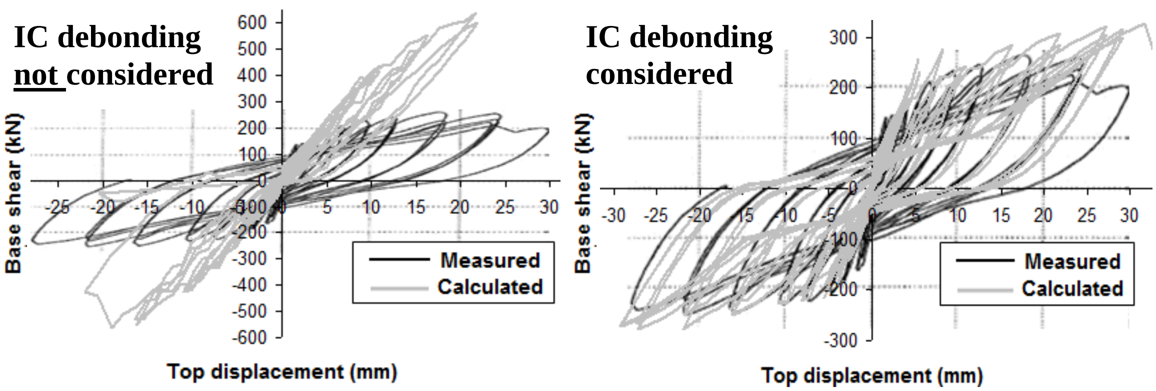


Figure 7: Influence of IC debonding mechanism on the response of specimen SW1-1

## Simplified analysis for strength of FRP-reinforced concrete walls

Although the automatic debonding model is capable of predicting the response of RC shear walls strengthend with FRP, the process is computationally demanding and unpractical for large structures. Alternatively, a pre-debonded model can be used, where the debonded portion of the FRP will correspond to the debonded state of FRP at a certain point. Generally, the instant when the wall reaches its ultimate strength is the most important stage for design and analysis. Therefore, the debonded state of FRP at ultimate strength will be used for the pre-debonded model. During the tests, a “V-shaped” debonding pattern was observed at the instance at which the wall reaches its ultimate flexural capacity. A finite element model of the wall incorporating the FRP truss elements with the debonded pattern observed during tests (Fig. 8) has been developed.

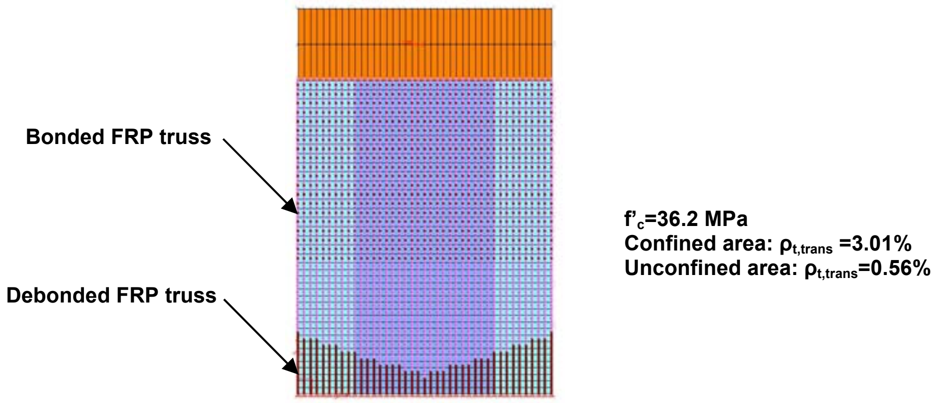

Figure 8: V-shaped debonded pattern of the FRP material in wall SW 1-2

The strain profiles of concrete, steel and FRP obtained at the base of the wall at the instant where the wall reaches its ultimate strength are shown in Fig. 9. The strain in the debonded FRP near the edge of the wall is about 80% to 85% of the adjacent concrete strain. Since the capacity of FRP material to carry compressive forces is neglected in the model, the corresponding FRP stresses in the compressive zone are ignored. Similar results were obtained when the same analysis was run for SW2-2 [18].

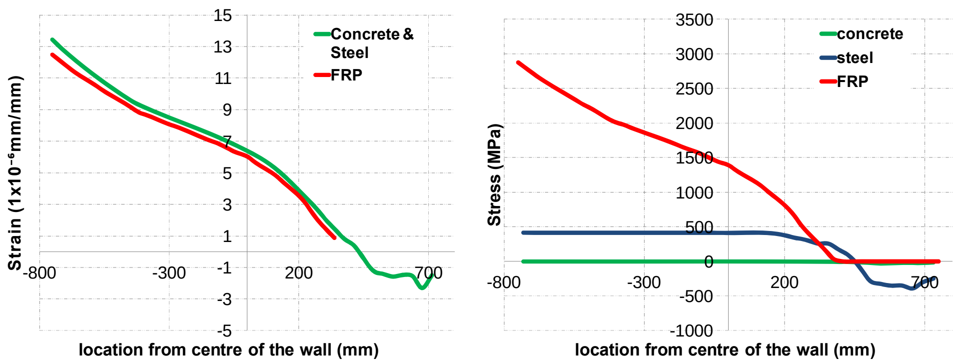

Figure 9: Strain and stress profiles at the base of the SW 1-2 wall

The performance of the simplified analysis model to account for debonding effects can be evaluated by comparing the prediction results with experimental observations. The predicted maximum test load for strengthened wall 1 in phase 2, using the model with pre-debonded FRP illustrated in Fig. 8, was 334 kN (a 6.51% error from the measured value). The predicted load for Strengthened wall 2 in phase 2 was 421 kN (a 1.36% error).

## Performance of seismically deficient RC shear walls

Finite element simulations have been conducted using the finite element program Vector2 to model the second series of experimental tests. The material and element formulations used in the finite element modeling of the nine shear wall specimens are the same as the ones described for flexurally dominated walls. A comparison is conducted between a plain concrete slender wall specimen and its FRP strengthened counterpart (Fig. 10). Results for other walls (whether with or without lap splices) are found to be similar [19].

The hysteresis curves presented in Fig.10 indicate that the contribution of FRP is evident in enhancing the stiffness, ductility, and strength of the wall specimens. The energy dissipation as seen in the models strengthened with FRP is much greater than energy disipated by the control wall specimens. The observed failure modes for all the control walls are characterized in the formation of brittle diagonal shear cracks, which is expected in shear deficient shear wall structures. Premature shear failure is prevented by the contribution from the FRP sheets which facilitate a more ductile flexural type of behaviour. The ultimate failure mechanism is crushing of concrete at the toe of the wall specimens and the ensuing sliding shear failure afterwards.

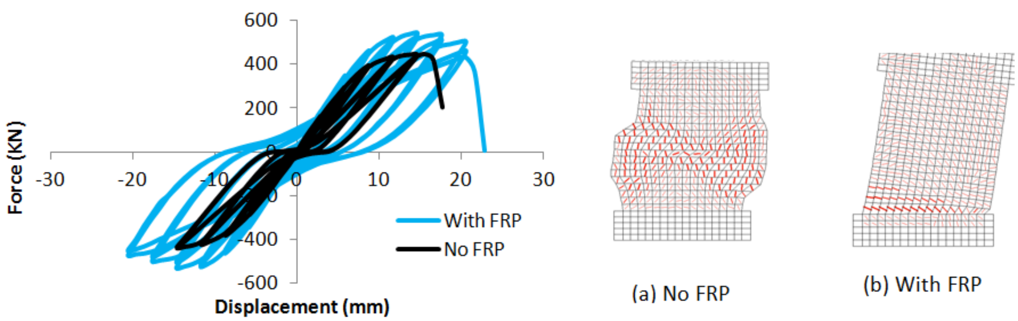


Figure 10: Hysteresis responses of slender walls (with & without FRP)

Fig. 11 shows a view of a seismically deficient slender wall tested to failure. As expected, the wall failed due to diagonal tension due to its insufficient shear reinforcement. The measured ultimate capacity of the wall was 400 kN, which is 11% lower than the model prediction (444.5 kN). Fig. 11 also shows the measured force-displacement relationship of the same wall after being repaired with one layer of vertical FRP and three layers of horizontal FRP per side. Overall, it is seen that the FRP system effectively restored the initial stiffness and significantly increased the strength and ductility of the specimen.

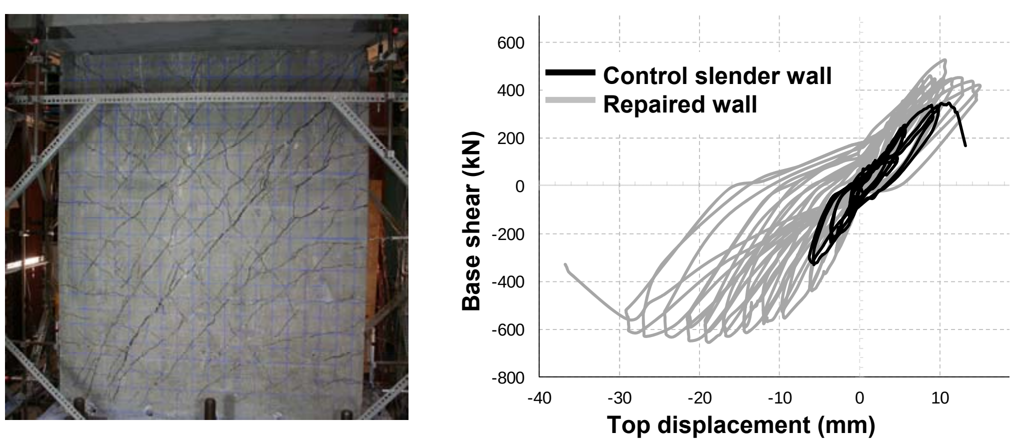


Figure 11: Diagonal tension failure in slender wall with insufficient shear reinforcement (left); performance of the same wall with flexural and shear FRP reinforcement (right)

## Finite Element Modeling of Shear Walls with Lap Splices

Depending on the level of confinement, lap spliced bars can cause premature failure in shear walls due to concrete splitting failures, pullout failures or excessive slips. Therefore, to accurately predict the wall responses it is necessary to account for the influence of the rebar splice. As previously discussed, two of the squat wall specimens have lap splices at plastic hinge region. Lap splices can be modeled by representing the reinforcement as discrete trusses (rather than smeared reinforcement) with an appropriate steel-to-concrete bond strength model. The Harajli bond stress-slip model [20] was used in this study. The performance of the model was compared to experimental results, available in the literature, from three shear walls that included lap splices [6, 21]. The resulting response showed reasonable correlation between numerical and analytical results in terms of prediction of maximum strength (Fig. 12), but shows limitations in predicting the hysteretic capacity. Further work on modeling of shear walls with lap splices is currently underway.

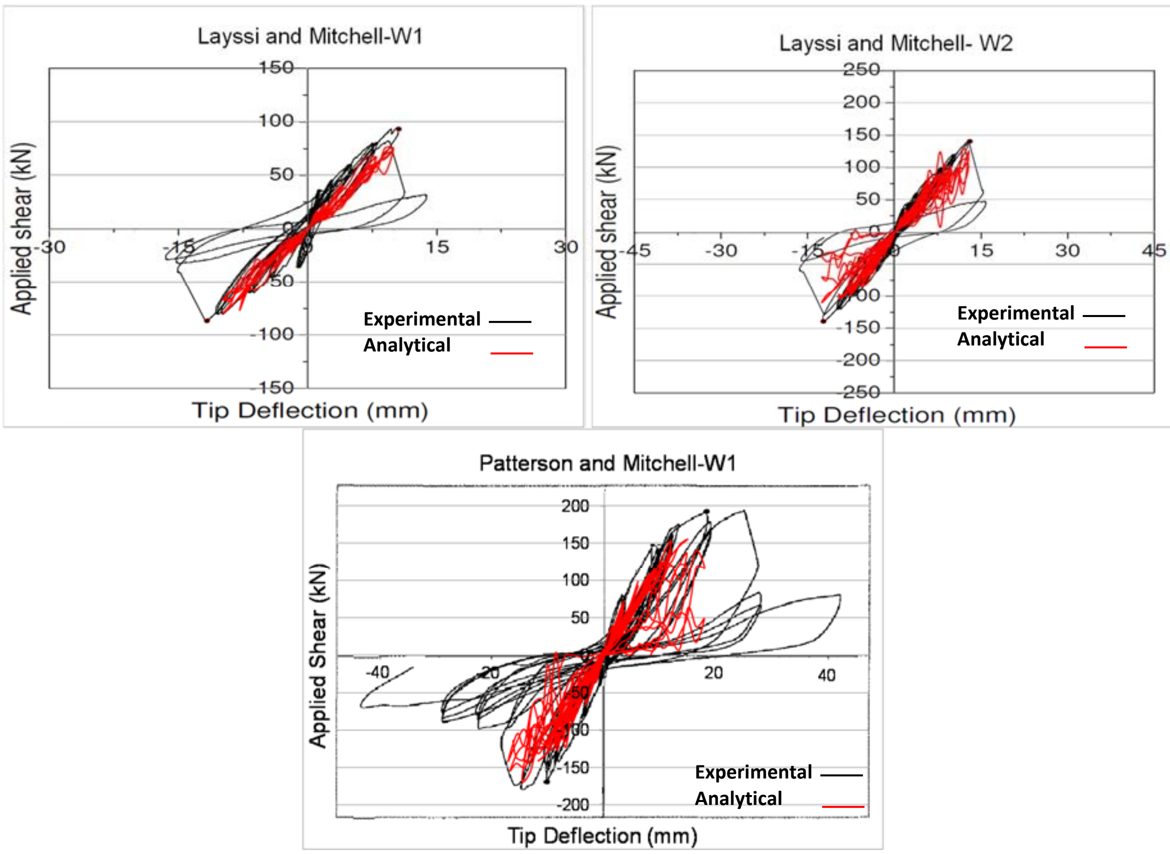


Figure 12: Verification of the Harajli Bond stress-slip model

## Conclusion and final remarks

The paper presents the feasibility of using a reinforcing system consisting of vertical and horizontal FRP sheets to increase the flexural and shear strengths, enhance ductility, and increase energy dissipation ability of shear walls. Experimental results show that the carbon fibre system can be used to recover (in repair applications) or increase (in strengthening applications) the initial elastic stiffness and the maximum flexural capacity of flexurally dominant walls.

The tests showed that FRP-concrete debonding mechanisms play a major role in the response of FRP-reinforced shear walls, limiting the forces carried by the debonded FRP material. FRP-debonding effects are not usually considered when using conventional section analysis. To overcome this, a simplified analytical model has been discussed.

The application of the FRP system in seismically deficient walls has been analytically investigated by finite-element analysis models, and an experimental program that shows promising results in terms of increasing the ultimate strength and ductility of the system is currently underway. Both the experimental results and the analytical models indicate the FRP system is effective in enhancing the ductility as well as the energy dissipation capacity of the reinforced specimens and changing the mechanism of failure from brittle diagonal shear to a ductile one. However, improvements to the current model are warranted, as the model shows limitations in predicting the hysteretic response of shear walls with lap spliced bars.

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