DO AXIAL CYCLIC TESTS ON BOUNDARY ZONE PRISMS REPRESENT RC WALLS RESPONSE?

M. Tripathi(1), R. P. Dhakal(2), F. Dashti(3)

(1) *Research Associate, Quake Centre, University of Canterbury, New Zealand, mayank.tripathi@canterbury.ac.nz*
(2) *Professor, University of Canterbury, New Zealand, rajesh.dhakal@canterbury.ac.nz*
(3) *Research Associate, Quake Centre, University of Canterbury, New Zealand, farhad.dashti@canterbury.ac.nz*

Abstract

RC structural walls are efficient and preferred structural system for building to resist lateral-loads during seismic excitations. Numerous analytical, numerical and experimental investigations have been conducted to study the behavior of RC wall systems under seismic loading, and to develop and modify design guidelines for RC walls. A simplified approach of investigating concrete columns representing boundary zones of walls has also been used extensively to reduce the computational and experimental costs of research programs looking into seismic performance of RC shear walls. However, in most of the reported literature, the representativeness of testing boundary zone prisms to predict the failure modes of RC walls has not been evaluated. In this study, the limitation of axial tests on boundary zone prisms to capture likely failure modes of RC walls is investigated. To evaluate this, tests on three slender RC walls under in-plane cyclic loading and the corresponding RC prisms under axial cyclic loading were conducted. In this paper, details of this experimental campaign are presented and the failure modes observed in the wall units are compared with those of the RC prisms representing their boundary zones. The test matrix comprised three slender RC wall specimens with different transverse reinforcement detailing designed according to NZS3101:2006, and three RC prisms representing their boundary elements. Comparative evaluation of the responses from the tests on RC walls and RC prisms is carried out and the efficacy of this simplified method (i.e. axial testing of boundary zone prisms) to predict the failure modes of RC walls is evaluated. Comparison of the experimental responses suggests that testing the boundary elements as isolated elements makes them susceptible to out-of-plane buckling, and therefore cannot completely represent the failure modes observed in RC walls. In all the tested RC prism specimens, failure due to out-of-plane instability was observed as compared to the failure due to bar buckling, concrete crushing and bar fracture observed during the tests of their prototype RC walls.

Keywords: boundary elements; shear walls; reinforced concrete; bar buckling; out-of-plane buckling

1. Introduction

Reinforced Concrete (RC) walls are commonly used as lateral load-resisting systems in buildings located in seismically active regions. Structural walls resist lateral load by undergoing flexure and shear deformations in their critical regions i.e. *plastic hinges*. Walls with high shear span ratio are expected to respond flexurally with inelastic deformations being concentrated in the plastic hinge regions, and the overall response of the wall being governed by the axial behavior of confined end regions of the wall known as boundary zones. Therefore, to ensure that RC walls respond in a ductile manner at ultimate limit state, the boundary elements of flexure-dominated walls are designed and detailed to sustain large axial strain demands. The performance of RC walls during the past earthquakes in Chile (2010) and New Zealand (2010-11) has raised few concerns about the susceptibility of flexural walls to non-ductile compression controlled failure modes such as bar buckling, concrete crushing and out-of-plane instability [1-5]. Therefore, following the observations from these earthquakes, several experimental studies have investigated the seismic performance of this type of RC walls [6-15]. Fig. 1 shows the typical failure mode observed in the boundary regions of walls.

(a) Earthquake observations [1-5]

(b) Experimental observations [13]

Fig. 1: Bar buckling observed during the past earthquakes and experimental tests

Testing full-scale or scaled wall specimens to estimate their performance under lateral loading can provide detailed insights about the response of wall system under lateral loads. However, testing wall specimens is a resource-intensive task and requires significant experimental and financial resources. Therefore, often the seismic performance of flexure-dominated RC walls is evaluated by a simplified approach of testing rectangular RC prisms idealized as the wall boundary elements under axial cyclic loading. In this approach, the rectangular RC columns (or prisms) are subjected to axial cyclic loading (cyclic tensile and compressive strain loading) expected at the wall boundaries during seismic excitation. This type of research was first conducted by Goodsir [16] to investigate the effect of tensile strain loading on out-of-plane response of RC walls. Similarly, Chai and Elayer [17] investigated the progression of out-of-plane instability in slender walls by testing prism specimens with pinned end conditions subjected to axial strain loading. Following the earthquakes in Chile (2010) and New Zealand (2010-11), several research studies have investigated the effect of different design parameters (detailing, thickness, loading history and prism slenderness) on axial and out-of-plane response of wall boundary zones by testing idealized prisms under axial loading[1, 18-22].

Although idealized, testing prisms to characterize the response of wall boundary elements is well accepted by the research community and is often undertaken to understand the behavior of flexural walls under seismic loading. However, the efficacy of testing prisms to represent failure mechanisms expected at the boundary elements of slender RC walls has not been evaluated. Therefore, this study aims at investigating the effectiveness of testing RC prisms under axial loading to simulate failure mechanisms expected at the wall boundaries. To achieve this objective, experimental tests on three RC walls and three rectangular RC prisms representing their boundary elements were carried out. The test results are summarized in this paper along with detailed comparison of the experimental measurements. The advantages and disadvantages of this simplification are discussed in light of the experimental observations.

2. Experimental Test Program

The experimental investigation conducted in this study included testing three flexure-dominated RC walls and their boundary elements under lateral and axial cyclic loading, respectively. Experimental investigation on RC walls aimed at scrutinizing the effect of transverse reinforcement detailing on the buckling performance of boundary zone reinforcing bars and deformation capacity of walls. Therefore, the wall test matrix (presented in Table 1) comprised three RC wall specimens with different transverse reinforcement detailing. The wall specimens were designed according to NZS3101:2006 [23] and represented the first-story of a four-story prototype wall. Fig. 2 shows the test setup and typical cross-sectional details of the wall specimens tested in this study. Wall SWD-1 was the benchmark wall with transverse reinforcement spaced 55 mm apart. Walls SWD-2 and SWD-3 were tested to evaluate the effect of spacing and arrangement of transverse reinforcement on hysteretic response of RC walls, respectively. The test setup employed a horizontal actuator for the application of in-plane drift loading and was connected to the wall specimens through a stiff loading beam (as shown in Fig. 2). In addition, two vertical actuators were provided for the application of constant axial load throughout the test. As only the first-story of the wall was tested, bending moment arising from the upper stories was also applied using these vertical actuators to maintain a constant shear span at the base. The details about the design objectives of wall specimens and the test setup are outside the scope of this paper and are reported elsewhere [13-15].

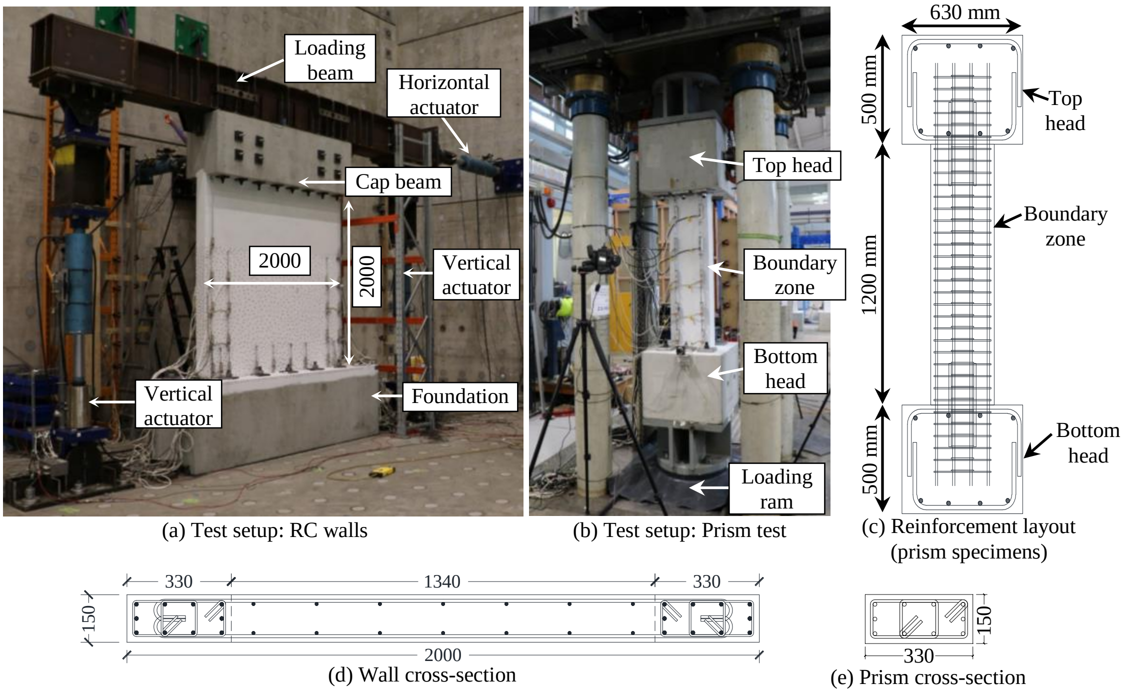
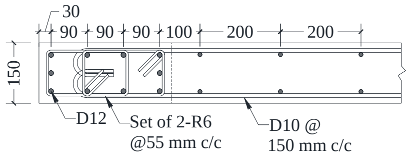
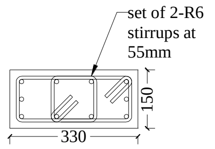
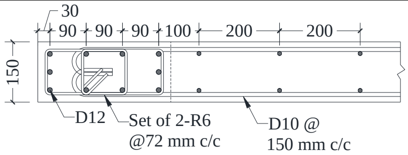
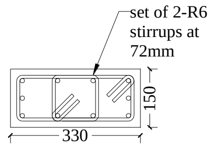
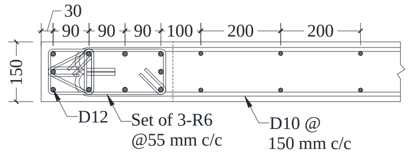
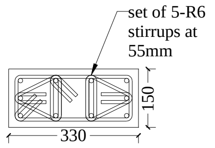
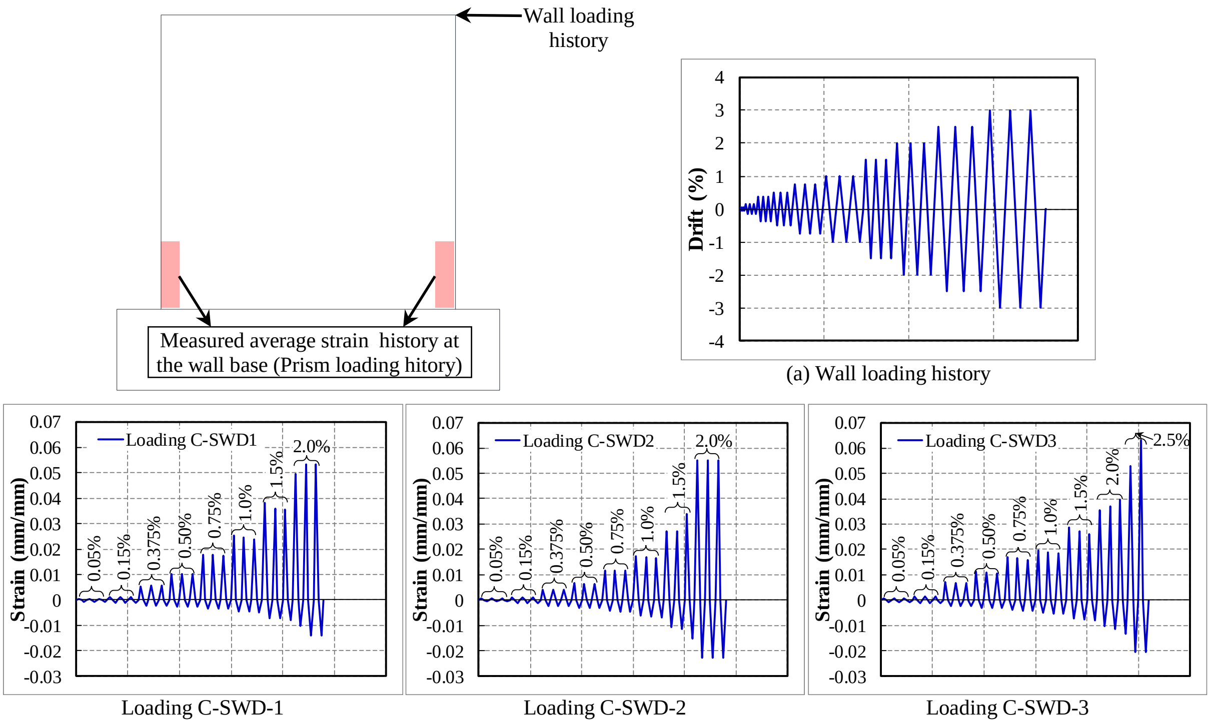


Fig. 2: Test setups and cross-sectional details of the wall and boundary zone specimens

The performance of wall boundaries as isolated prism elements is evaluated by testing rectangular RC prisms representing the boundary zones of RC walls. For this purpose, three rectangular prisms with cross-sectional detailing identical to the detailing of boundary elements of tested walls were tested under axial cyclic loading (as shown in Table 1). The prisms were thus 150 mm thick, 330 mm wide and had a height of 1200 mm (as shown in Table 1). The prisms were tested under axial cyclic loading using a Dartec 10 MN universal testing machine capable of applying both tensile and compressive loading. To facilitate the assembly of prisms in the test setup, prisms were cast monolithically with enlarged ends that were connected to the Dartec using specially designed steel fittings. Fig. 2 shows the typical layout of test specimens and the setup used for prism testing.

Table 1: Test matrix for wall and prism tests

Detailing	Wall		Prism	
Type-1	SWD-1		BZ-1-C-SWD1	
Type-2	SWD-2		BZ-2-C-SWD2	
Type-3	SWD-3		BZ-3-C-SWD3	



(b) Prism loading histories

Fig. 3: Loading history: (a) Wall tests and (b) Prism tests

To reasonably compare the experimental response of wall boundaries and RC prisms, prism specimens were tested under axial strain history measured at the wall boundaries. For this purpose, the axial strain histories measured at boundary zones of the three wall specimens during in-plane cyclic loading were evaluated, and the average axial strain histories for the corresponding prism specimens were derived (as shown in Fig. 3). As the strain demand at wall boundaries is a function of the loading history, wall capacity, and the type of damage in these regions, the prism specimens with detailing type-1, -2 and -3 were tested under three different loading histories C-SWD1, C-SWD2 and C-SWD3, respectively. The wall drift corresponding to each strain level is also shown in Fig. 3. It should be noted that the prism testing ignores the strain gradient that is developed along the wall height and a uniform strain distribution along the prism height is assumed in this approach. In this paper, the wall and prism responses are evaluated by comparing the damage state in prisms with the damage state in wall boundaries when the strains at the wall base are similar to the average axial strain applied to the prism specimen.

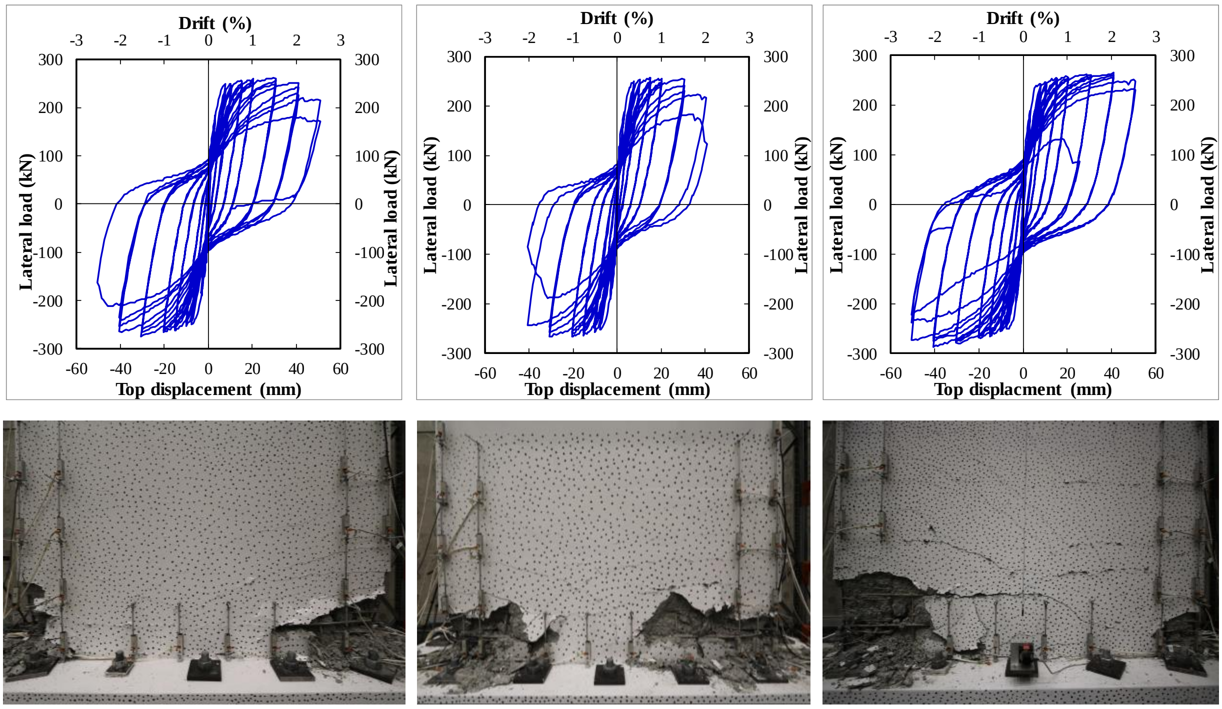
3. Experimental Response of RC Wall and Prism Specimens

Fig. 4 shows the hysteretic response and failure mode of the tested wall specimens. All three walls exhibited flexural response with the observed key milestones as cracking of concrete, yielding of reinforcing bars, spalling, bar buckling, concrete crushing and bar fracture. Bar buckling was the primary failure mode for all the tested walls that resulted in the development of secondary failure modes such as bar fracture, concrete crushing and instability. Change in the boundary zone transverse reinforcement detailing had minimal impact on the lateral-load carrying capacity of the wall (i.e. force carrying capacity), whereas its effect on the deformation capacity of the wall was considerable. Further, the boundary zone detailing influenced the buckling performance of boundary zone longitudinal reinforcing bars. Herein, buckling performance is measured in terms of the buckling mode of reinforcing bars, which is defined as the number of tie spacings the bar buckling spans [24]. Bar buckling with buckling mode ranging between two and four initiated in wall SWD-1 at 1.5% drift loading cycles. During subsequent loading cycles, bar buckling influenced the local response of wall boundary elements causing concrete crushing and bar fracture, resulting in deterioration of stability at the base of boundary regions and development of localized out-of-plane instability. Wall SWD-2 had similar arrangement of transverse reinforcement as wall SWD-1, however, the spacing of transverse reinforcement was increased to 72 mm (as shown in Table 1). Increasing the spacing of transverse reinforcement improved the buckling performance of reinforcing bars during initial loading cycles, and bar buckling was restricted to single tie spacing in this specimen. However, increasing the spacing of transverse reinforcement deteriorated the confinement properties of concrete, and therefore the buckling mode increased to three at later drift levels. Similar to wall SWD-1, wall SWD-2 lost its lateral load-carrying capacity due to the development of localized out-of-plane instability caused due to the combined action of bar buckling, concrete crushing and bar fracture. Wall SWD-3 was an improved version of benchmark wall SWD-1. In this specimen, the spacing of traverse reinforcement was kept the same, however, the arrangement of transverse reinforcement was modified to ensure that buckling remains restricted to single tie spacing. In this specimen, bar buckling with buckling mode one initiated during 1.5% and 2.0% drift loading cycles. Similar to other walls, this specimen failed due to the development of local instability at 2.5% drift loading cycles. Table 2 summarizes the key milestones observed during the test of wall specimens. Fig. 5 shows the buckling mode (at initiation) observed in the three tested wall specimens.

Table 2: Key milestones observed during wall tests [13]

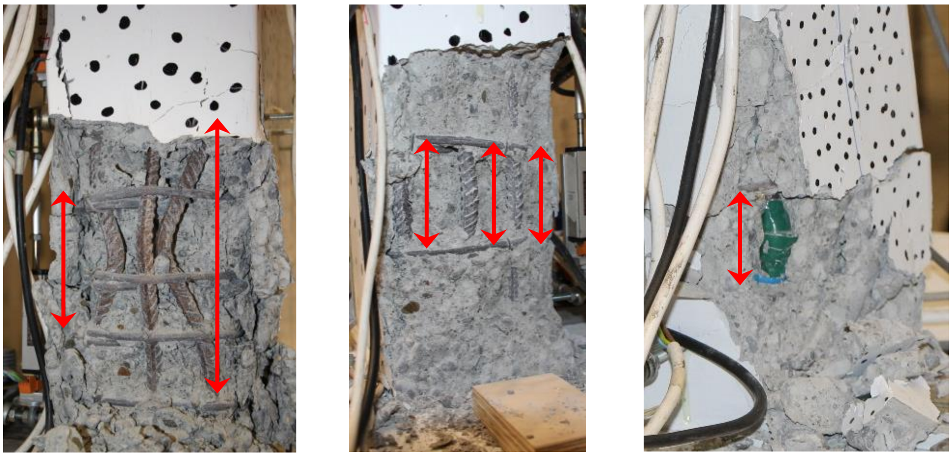
Specimen	**Direction**	**Cracking (%)***	**Yielding (%)**	**Reinforcement buckling (%)**	**Reinforcement fracture (%)**	**Failure (%)**
SWD-1	+	$+0.15^{1}$	$+0.375^{1}$	$+1.5^{3}$	$+2.0^{3}$	$+2.5^{1}$
	-	-0.15^{1}	-0.375^{1}	-1.5^{2}	-2.0^{3}	
SWD-2	+	$+0.15^{1}$	$+0.375^{1}$	$+1.5^{2}$	$+2.0^{1}$	$+2.0^{1}$
	-	-0.15^{1}	-0.375^{1}	-1.0^{3}	-	
SWD-3	+	$+0.15^{1}$	$+0.375^{1}$	$+1.5^{2}$	-	-2.5^{2}
	-	-0.15^{1}	-0.375^{1}	-2.0^{1}	-2.0^{2}	

*The superscript denotes the cycle number



(a) SWD-1 (b) SWD-2 (c) SWD-3

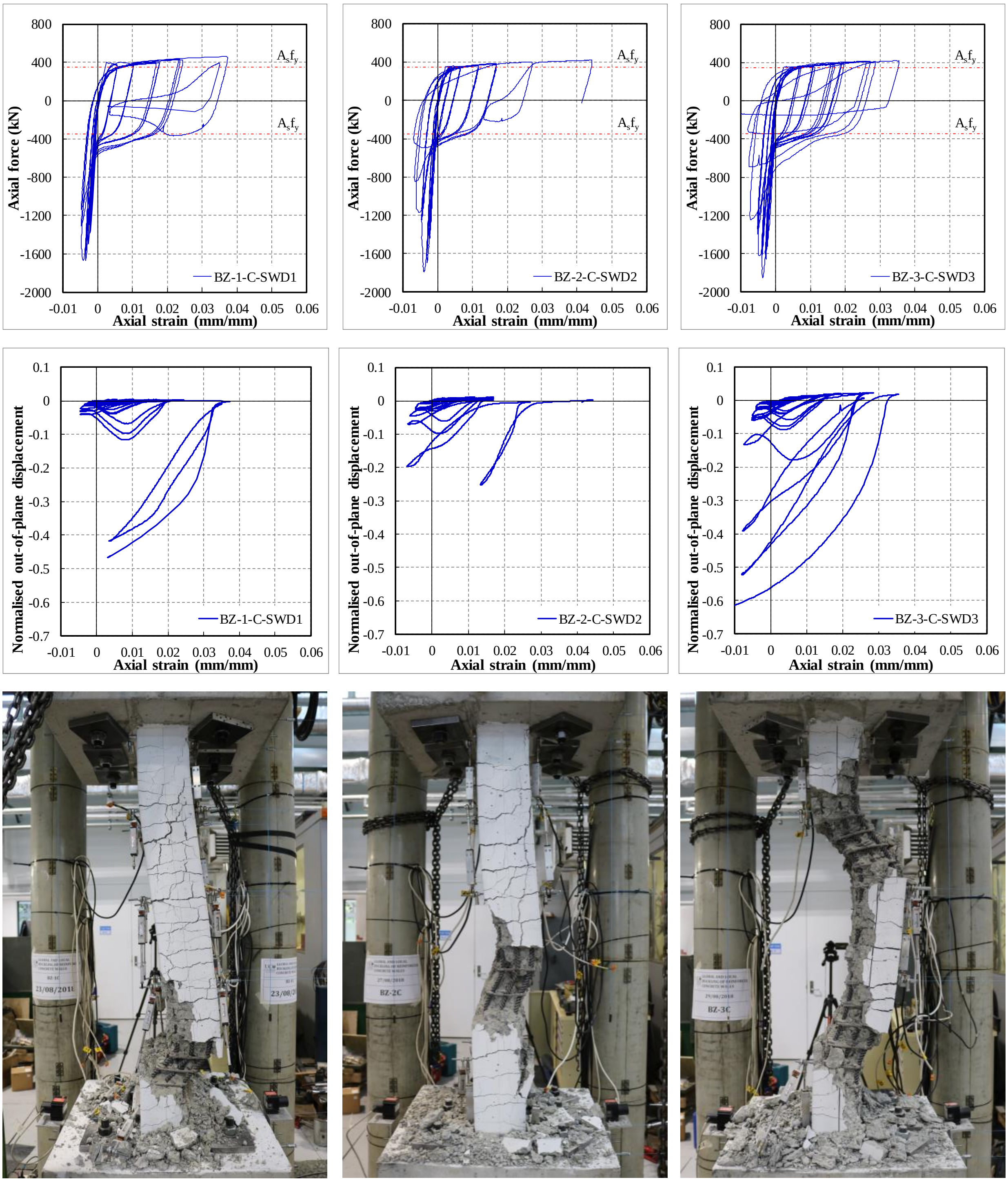
Fig. 4: Hysteretic response of tested wall specimens



(a) Wall SWD-1 (b) Wall SWD-2 (c) Wall SWD-3

Fig. 5: Bar buckling observed in tested wall specimens

Fig. 6 shows the axial cyclic response of the tested prism specimens and their failure modes. The axial cyclic response of prisms was predominantly governed by the uniaxial cyclic response of concrete (confined and unconfined) and reinforcing bars. The axial response of prisms involved development of horizontal cracks distributed along the prism height, yielding of reinforcing bars, development of global out-of-plane deformation, concrete spalling and crushing, bar buckling and development of global out-of-plane instability. Out-of-plane instability with or without bar buckling was the commonly observed failure mode during the test of prism specimens. Horizontal cracks distributed along the prism height initiated during the initial loading cycles followed by the initiation of global out-of-plane deformation. The out-of-plane deformation in prism with detailing type-1, type-2 and type-3 initiated while unloading from 0.01, 0.0117 and 0.0105 average tensile strain, respectively. During subsequent loading cycles, the out-of-plane deformation increased with increasing tensile and compressive strain demands. Concrete crushing occurred in prism with detailing type-1, type-2 and type-3 while unloading from 0.0245, 0.0117 and 0.0169 tensile strain, respectively. Concrete crushing made prisms unstable causing the out-of-plane deformations to increase with increased compressive strain demands. In the subsequent loading cycles, the out-of-plane deformation increased rapidly and caused the development of global out-of-plane instability. This resulted in a rapid strength deterioration while unloading from peak tensile strains (as shown in Fig. 6a). The key milestones observed during the test on prism specimens are summarized in Table 3.



(a) BZ-1-C-SWD1 (b) BZ-2-C-SWD2 (c) BZ-3-C-SWD3

Fig. 6: Axial cyclic response of boundary zone prisms

Table 3: Key milestones observed during the prism tests

Specimen	Detailing	Corresponding wall	Initiation of out-of-plane deformation*	Concrete crushing*	Out-of-plane instability*	Bar buckling*
BZ-1-C-SWD1	Detailing-1	SWD-1	0.01 (0.5%)	0.0245 (1.0%)	0.0372 (1.5%)	Did not occur
BZ-2-C-SWD2	Detailing-2	SWD-2	0.0117 (0.75%)	0.0117 (0.75%)	0.027 (1.5%)	0.0117 (0.75%)
BZ-3-C-SWD3	Detailing-3	SWD-3	0.0105 (0.5%)	0.0169 (0.75%)	0.0285 (1.5%)	0.027 (1.5%)

*The values in bracket represents the approximate wall drift that the peak tensile strain represent

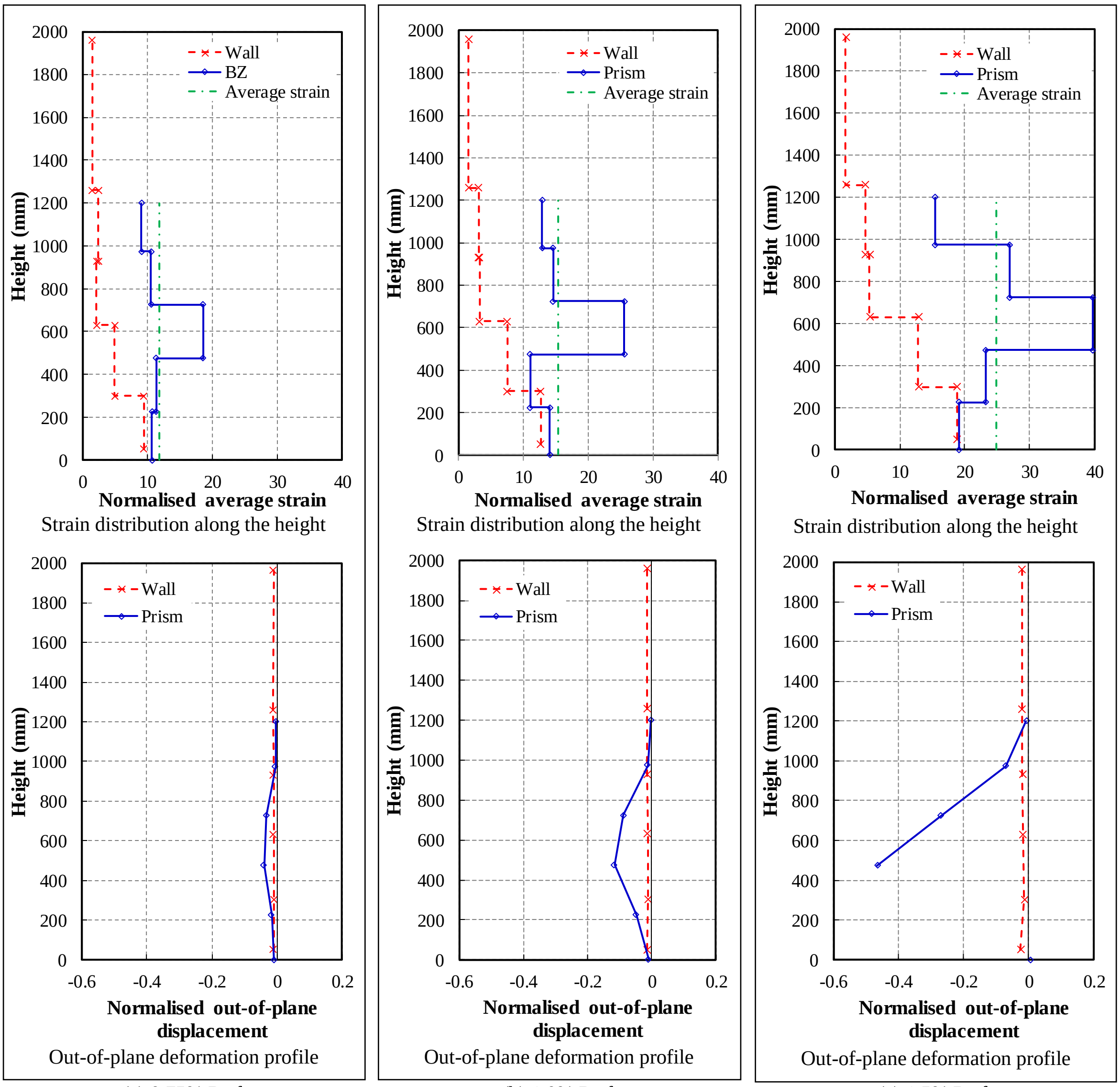
4. Comparative Evaluation of RC Wall and Prism Damage States

In this section, the damage states observed during the tests on wall and prism specimens are compared, and similarities and differences between the experimental responses are highlighted. Although prism specimens had identical detailing as the wall boundary elements, the response of wall and prism specimens were quite distinctive, specially in terms of their overall hysteretic response. All tested wall specimens exhibited failure due to buckling of longitudinal reinforcing bars that resulted in the development of secondary failure modes such as bar fracture, concrete crushing and localized out-of-plane instability. Conversely, prism specimens primarily failed due to the development of global out-of-plane instability with or without bar buckling. Fig. 7 compares the failure mode observed in the boundary region of the wall specimen with detailing type-1 and in the corresponding prism specimen at similar average strain demands. As can be seen in this figure, the visible damage sustained by the prism was significantly more than the damage sustained by the wall boundary. Further, it can also be seen that the prism underwent global out-of-plane deformation at relatively low axial strain demands, followed by development of global out-of-plane instability. However, the wall boundary region underwent the localized out-of-plane instability due to the progression of local compression modes of failure in the preceding loading cycles. Furthermore, the prism specimens failed at relatively low average axial strain demands as compared to the wall specimens with identical boundary zone detailing. For instance, prism BZ-1-C-SWD1 failed at an axial strain level that corresponds to a lateral drift demand of 1.5% as compared to wall SWD-1 that failed during 2.5% drift demand.

This differential damage in wall boundaries and isolated boundary elements could be further explained by comparing the strain distributions at different stages of loading. Fig. 8 shows the strain distribution and out-of-plane deformation profile along the height of the prism and wall boundary region with detailing type-1 at different loading stages. As can be seen from this figure, the prism exhibited larger out-of-plane deformation although it was tested under an average strain history equal to the one measured at the wall boundaries. This inconsistent out-of-plane response could be attributed to the fact that the tensile strain gradient observed in wall boundary regions that results in development of larger strains (i.e. wider cracks) at the wall base is not generated in prism testing. The strain distribution in prism testing leads to generation of wider cracks at about mid-height of the specimen. This type of strain distribution can readily cause progression of yielding in compression during loading reversal at a location far from the fixed boundary condition of the base and result in faster development of out-of-plane deformation and subsequent instability in prism specimens. The effect of vertical strain gradient on progression different types of instability in walls is discussed by Dashti et al. [25]. Conversely, at the wall boundaries, the inelastic strains were localized at the wall base, and therefore most of the nonlinear damage states associated with the inelastic strain demands were concentrated near the wall base. This localization of inelastic strains at the wall base caused concentration of inelastic failure modes such as bar buckling and concrete crushing near the wall base and suppressed the development of global out-of-plane deformation in wall SWD-1, causing the wall to fail due to local failure modes as compared to global failure mode observed in boundary element with identical detailing.

Specimen	0.75%		1.0%		1.5%		2.0%		2.5%	
	Prism	Wall	Prism	Wall	Prism	Wall	Prism	Wall	Prism	Wall
Prism BZ-1-C-SWD1 Wall SWD-1							Prism failed		Prism failed	

Fig. 7: Damage states observed in RC prism and wall boundaries with detailing type-1 at similar average strain demands



(a) 0.75% Drift (b) 1.0% Drift (c) 1.5% Drift

Fig. 8: Strain distribution and out-of-plane deformation profile of wall and prism with detailing type-1

To summarize, the effectiveness of testing RC prisms to investigate the failure mechanisms expected at the wall boundaries is limited by the capability of the test setup to generate a strain gradient identical to that developed along the height of wall boundaries. Assumption of uniform strain gradient along the height accelerates the damage accumulation in the prisms causing them to prematurely fail due to the development of out-of-plane instability. Further, in this testing approach, the strain gradient along the width of the boundary zone and the stiffness imparted by the wall web to the boundary zone in out-of-plane direction is also ignored. Therefore, although axially testing prisms can provide valuable information about the mechanisms of different failure modes (e.g. bar buckling, concrete crushing and out-of-plane deformation) and could be employed for parametric investigations of the failure modes, these tests cannot accurately replicate the response of boundary zones in flexure-dominated RC walls.

5. Conclusions

In this paper, results from an experimental campaign carried out to investigate the efficacy of testing rectangular RC prisms to investigate failure mechanisms observed in boundary zones of flexure-dominated RC walls was presented. A series of RC walls and their corresponding isolated boundary elements were tested under in-plane and axial cyclic loading (respectively). Comparative evaluation of the wall and prism damage states was carried out and limitations of testing rectangular prisms to simulate failure mechanisms in RC walls were highlighted. The key conclusions drawn from this study are:

1. Prism specimens are susceptible to failure due to the development of global out-of-plane instability although their equivalent wall boundary regions may exhibit failure due to buckling of boundary zone longitudinal reinforcing bars.
2. The uniform strain distribution generated along the prism height as a result of the loading protocol results in accumulation of damage at locations that are rather far from the base, causing them to prematurely fail due to global out-of-plane buckling. While the wall boundary zones experience development of large tensile strains at the base and localization of different modes of failure in this region.
3. Axially testing rectangular prisms can provide a conservative estimate regarding the out-of-plane deformation response of structural walls. However, pensive consideration of prism’s unsupported height and boundary condition shall be taken in to account.

6. Acknowledgements

The authors would like to acknowledge the financial assistance provided by the Ministry of Business, Innovation and Employment (MBIE) and the Quake Centre at University of Canterbury for carrying out the research. This project was (partially) supported by QuakeCoRE, a New Zealand Tertiary Education Commission-funded Centre. This is QuakeCoRE publication number 0545.

7. References

[1] C.W. Hilson, Analytical and experimental studies of the seismic performance of reinforced concrete structural wall boundary elements, Civil Engineering, University of California, Los Angeles, 2014.

[2] L.M. Massone, P. Polanco, P. Herrera, Experimental and analytical response of RC wall boundary elements, Proceedings of the 10th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Alaska, 2014.

[3] J.W. Wallace, L.M. Massone, P. Bonelli, J. Dragovich, R. Lagos, C. Luders, J. Moehle, Damage and implications for seismic design of RC structural wall buildings, Earthquake Spectra 28 (2012) S281-S299.

[4] S. Sritharan, K. Beyer, R.S. Henry, Y.H. Chai, M. Kowalsky, D. Bull, Understanding poor seismic performance of concrete walls and design implications, Earthquake Spectra 30(1) (2014) 307-334.

[5] K.J. Elwood, Performance of concrete buildings in the 22 February 2011 Christchurch earthquake and implications for Canadian codes, Canadian Journal of Civil Engineering 40(3) (2013) 759-776.

[6] C. Alarcon, M.A. Hube, J.C. de la Llera, Effect of axial loads in the seismic behavior of reinforced concrete walls with unconfined wall boundaries, Engineering Structures 73 (2014) 13-23.

[7] M.A. Hube, A. Marihuen, J.C. de la Llera, B. Stojadinovic, Seismic behavior of slender reinforced concrete walls, Engineering Structures 80 (2014) 377-388.

[8] A. Rosso, J.P. Almeida, K. Beyer, Stability of thin reinforced concrete walls under cyclic loads: state-of-the-art and new experimental findings, Bulletin of Earthquake Engineering 14(2) (2016) 455-484.

[9] Y. Lu, R.S. Henry, R. Gultom, Q.T. Ma, Cyclic testing of reinforced concrete walls with distributed minimum vertical reinforcement, Journal of Structural Engineering-ASCE 143(5) (2016) 04016225.

[10] C.L. Segura, Seismic performance limitations of slender reinforced concrete structural walls, Department of Civil Engineering, University of California, Los Angeles, 2017.

[11] F. Dashti, R.P. Dhakal, S. Pampanin, Tests on slender ductile structural walls designed according to New Zealand Standard, Bulletin of the New Zealand Society for Earthquake Engineering 50(4) (2017) 504-516.

[12] A.V. Shegay, C.J. Motter, K.J. Elwood, R.S. Henry, D.E. Lehman, L.N. Lowes, Impact of axial load on the seismic response of rectangular walls, Journal of Structural Engineering 144(8) (2018) 04018124.

[13] M. Tripathi, R.P. Dhakal, F. Dashti, Bar buckling in ductile RC walls with different boundary zone detailing: Experimental investigation, Engineering Structures 198 (2019).

[14] M. Tripathi, R.P. Dhakal, F. Dashti, Nonlinear cyclic behaviour of high-strength ductile RC walls: Experimental and numerical investigations, Engineering Structures (Under Review) (2019).

[15] M. Tripathi, R.P. Dhakal, F. Dashti, Non-linear cyclic response of concrete walls with different transverse reinforcement detailing, 12th Canadian Conference on Earthquake Engineering, Quebec City, Canada, 2019.

[16] W.J. Goodsir, The Design of Coupled Frame-Wall Structures for Seismic Actions, Civil Engineering, University of Canterbury, 1985.

[17] Y. Chai, D. Elayer, Lateral stability of reinforced concrete columns under axial reversed cyclic tension and compression, Structural Journal 96(5) (1999) 780-790.

[18] T.S. Welt, L.M. Massone, J.M. LaFave, D.E. Lehman, S.L. McCabe, P. Polanco, Confinement behavior of rectangular reinforced concrete prisms simulating wall boundary elements, Journal of Structural Engineering (2016).

[19] R. Taleb, M. Tani, S. Kono, Performance of confined boundary regions of RC walls under cyclic reversal loadings, Journal of Advanced Concrete Technology 14(4) (2016) 108-124.

[20] A.G. Haro, M. Kowalsky, Y. Chai, G.W. Lucier, Boundary elements of special reinforced concrete walls tested under different loading paths, Earthquake Spectra 34(3) (2018) 1267-1288.

[21] A. Rosso, L.A. Jiménez-Roa, J.P. De Almeida, A.P.G. Zuniga, C.A. Blandón, R.L. Bonett, K. Beyer, Cyclic tensile-compressive tests on thin concrete boundary elements with a single layer of reinforcement prone to out-of-plane instability, Bulletin of Earthquake Engineering 16(2) (2018) 859-887.

[22] M. Tripathi, R.P. Dhakal, F. Dashti, R. Gokhale, Axial response of rectangular RC prisms representing the boundary elements of ductile concrete walls, Bulletin of Earthquake Engineering (Under Review) (2019).

[23] NZS3101:2006, Concrete Structures Standard- The design of concrete structures, Standards New Zealand, Wellington, 2006.

[24] R.P. Dhakal, K. Maekawa, Reinforcement stability and fracture of cover concrete in reinforced concrete members, Journal of Structural Engineering-ASCE 128(10) (2002) 1253-1262.

[25] F. Dashti, R.P. Dhakal, S. Pampanin, Out-of-plane response of in-plane-loaded ductile structural walls: State-of-the-art and classification of the observed mechanisms, Journal of Earthquake Engineering (2020).

