12TH CANADIAN CONFERENCE ON EARTHQUAKE ENGINEERING
JUNE 17-20, 2019
CHÂTEAU FRONTENAC
QUÉBEC, QC.

12ÈME CONFÉRENCE CANADIENNE DU GÉNIE PARASISMIQUE
17-20 JUIN 2019

CCEE 2019

Non-linear cyclic response of concrete walls with different transverse reinforcement detailing

Mayank Tripathi[1], Rajesh P. Dhakal[2], Farhad Dashti[3]

[1] Ph.D. Student, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand.
[2] Professor, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand.
[3] Research Engineer, UC Quake Centre, University of Canterbury, Christchurch, New Zealand.

ABSTRACT

This paper summarizes the results of an experimental campaign carried out to investigate the buckling performance of reinforcing bars in reinforced concrete (RC) structural walls. The post-buckling response of reinforcing bars in concrete structures is known to depend on the effective lateral restraint offered by transverse reinforcement against buckling. Therefore, the test matrix comprised three RC wall specimens designed according to the New Zealand Concrete Standard (NZS3101:2006) with different transverse reinforcement detailing. The parameters considered in this study are the spacing and arrangement of transverse reinforcement. The test specimens were half-scale, representing the first story of a four-story prototype wall. Therefore, in addition to the in-plane lateral load, the bending moment arising from the upper stories was applied at the top of the specimen. Failure of the tested specimens was initiated by buckling of the longitudinal bars at the boundary regions, followed by bar fracture, concrete crushing and development of lateral instability localized at the base of the boundary regions. Even though all the three tested specimens showed similar failure mechanisms, the lateral drifts corresponding to the initiation and propagation of individual failure modes were different. Variation of the transverse reinforcement detailing did significantly affect the performance of the designed walls. The hysteretic responses of the tested specimens are compared and the effect of boundary zone detailing on buckling of longitudinal bars as well as deformation capacity of the tested walls are discussed in light of the experimental observations.

Keywords: Reinforced concrete, structural walls, bar buckling, boundary zone detailing

INTRODUCTION

Reinforced concrete (RC) structural walls offer relatively high in-plane stiffness and are therefore considered as the primary lateral load resisting system in RC structures. However, the performance of wall structures during the past earthquakes in New Zealand and Chile highlighted the inability of the modern design standards to prevent premature progression of several failure patterns in RC walls including buckling of the longitudinal reinforcing bars. This failure pattern and its effect on acceleration of other mechanisms, such as bar fracture and concrete crushing has been observed during the laboratory tests on flexurally-dominated RC walls, as well. Figure 1 shows observation of bar buckling during the past earthquakes and wall experiments.

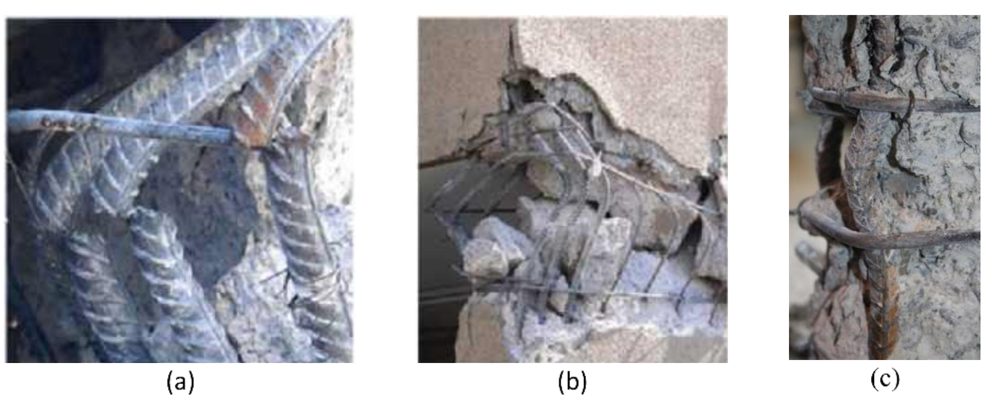


Figure 1: Damage observed in RC walls during the past earthquakes and wall tests (a) Fracture [1], (b) Buckling [1], (c) Buckling [2]

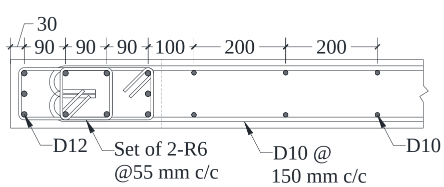
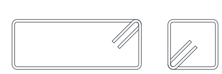
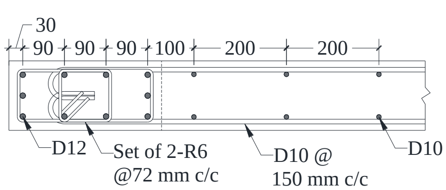
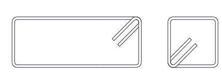
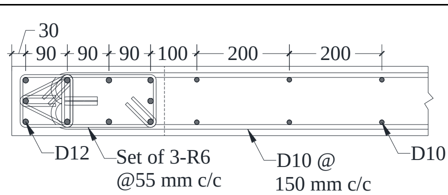
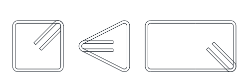
Although a significant amount of research has been conducted on the seismic performance of RC walls, most of the reported work revolves around investigating the effects of key design parameters (e.g. wall thickness, axial load ratio, shear span ratio, reinforcement ratio, etc.) on their global response, and limited research has been reported that aimed at investigating the influence of transverse reinforcement detailing on local and global response of walls. Also, the reported research has mostly focused on the effect of confinement reinforcement on global response of RC walls with no emphasis on controlling reinforcement buckling in RC structural walls [3-6]. In addition to this, limited guidelines are available for design of anti-buckling transverse reinforcement and most of the design codes emphasize only on confinement reinforcement as a measure to restrain reinforcement buckling in RC structures. This study investigates the influence of transverse reinforcement detailing (that includes both the spacing and arrangement) on buckling performance of the longitudinal bars and the corresponding effects on the global behavior of RC structural walls.

DESCRIPTION OF THE TEST PROGRAMME

Test specimens

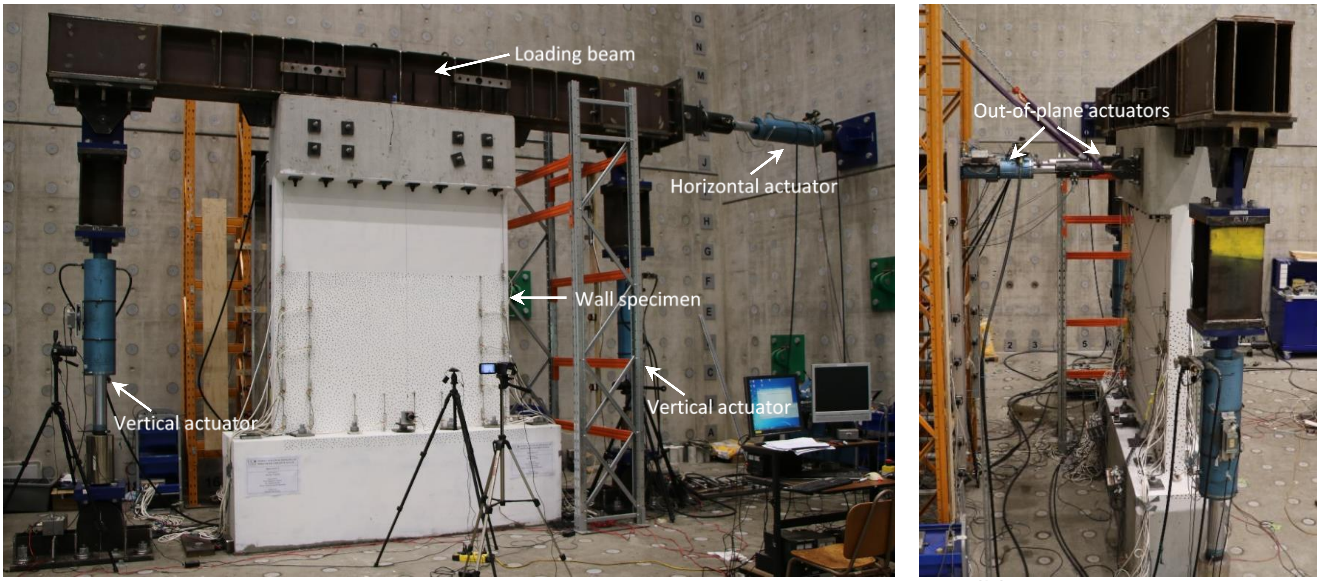
Table 1 summarizes the three specimen test matrix that was designed to achieve the outlined objectives of this research. The wall specimens were half-scale models of a prototype wall designed according to the NZS3101:2006 [7]. All the specimens had identical dimensions (length, height and thickness) as well as longitudinal and shear reinforcement but had different transverse reinforcement detailing. Transverse reinforcement was carefully designed to achieve the desired bar buckling performance, as the buckling resistance of longitudinal reinforcing bars is known depend on the effective axial stiffness of ties [8]. SWD-1 was the benchmark specimen that consisted of transverse reinforcement spaced at 55 mm c/c. SWD-2 was identical to the benchmark specimen in all aspects except that the spacing of transverse reinforcement was increased to 72 mm c/c keeping the arrangement and area constant. The spacing of transverse reinforcement in SWD-2 was increased to reduce the buckling induced axial demands on the ties, thereby ensuring that the available tie stiffness is sufficient to restrict the buckling of longitudinal bars to within single tie spacing. The third wall specimen (SWD-3) consisted of improved transverse reinforcement detailing designed with an aim to restrict buckling of reinforcing bars to single tie spacing. This was achieved by reducing the length of tie legs that restrained the longitudinal bars against buckling (thereby increasing the axial stiffness of the ties and hence better buckling resistance).

Table 1: Details of the tested wall specimens [9]

Specimen	Cross-sectional details	Transverse reinforcement detailing	Length, mm	Thickness, mm	Shear span ratio	Axial load ratio (%)
SWD-1			2000	150	3	5.5
SWD-2			2000	150	3	5.5
SWD-3			2000	150	3	5.5

Test setup

The test setup was designed to apply the lateral load as well as the bending moment coming from the upper stories. Figure 2 displays the configuration of horizontal and vertical actuators producing this loading pattern. The lateral load was applied through the horizontal actuator, whereas the combination of axial load and bending moment arising from upper stories was applied using the two vertical actuators. The specimens were subjected to unidirectional quasi-static reversed cyclic loading and a constant axial load ratio of 5.5%. The specimens were fixed to the strong floor and loading beam through high strength threaded rods. The story level restraint in out-of-plane direction was provided through two out-of-plane actuators as shown in Figure 2b.

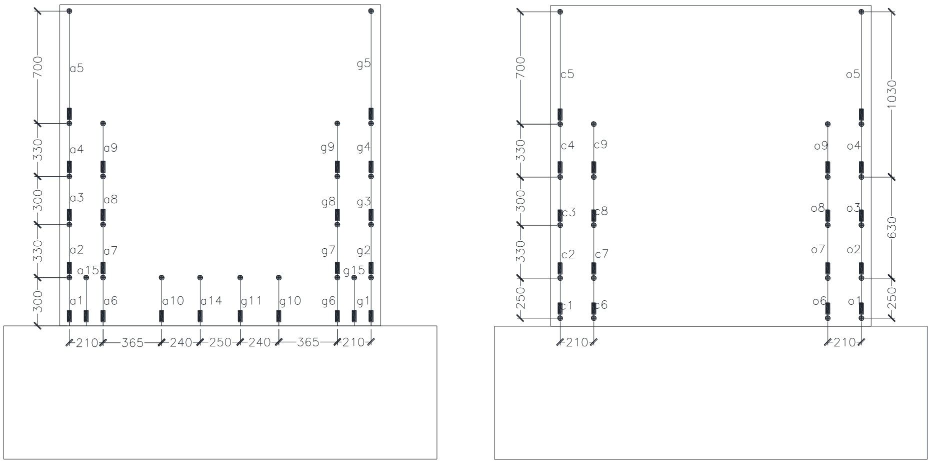


(a) Test setup: Front view (b) Test setup: Side view

Figure 2: Test setup [9]

Instrumentation

The wall specimens were instrumented with linear potentiometers and draw-wire potentiometers to measure and record the important aspects of wall behavior throughout the test. Figure 3 shows the linear potentiometers provided on both faces of the specimens to measure vertical deformation of the specimens. These potentiometers with a measuring range of 50 mm were provided along the height of the boundary regions to measure the local deformation of the specimens and along the base to measure the strain gradient along the wall length.



(a) West face (b) East face

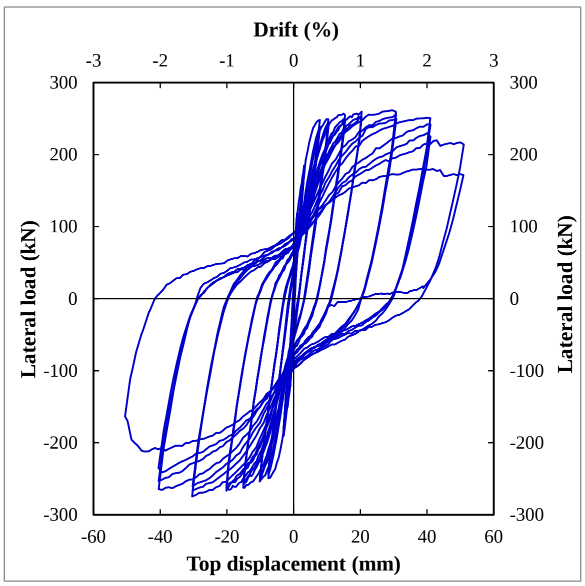
Figure 3: Instrumentation: Linear potentiometer provided on wall specimens

HYSTERETIC RESPONSE OF THE WALL SPECIMENS

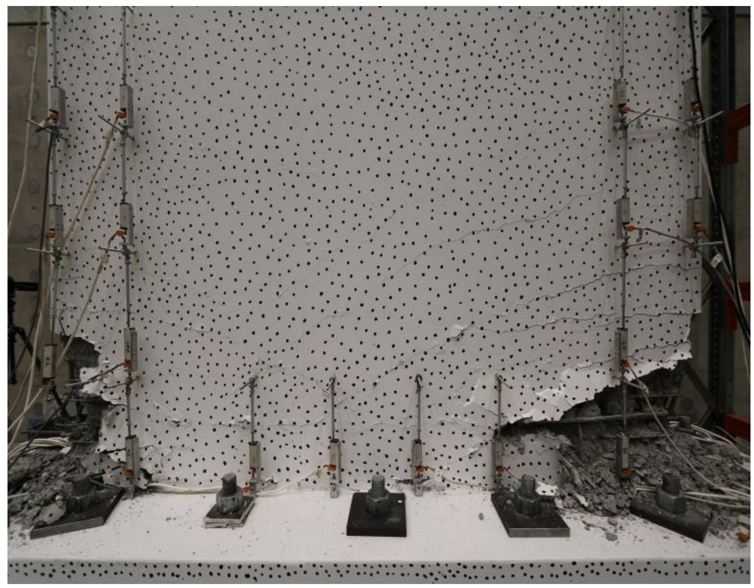
The hysteretic response of the tested walls including the load-displacement response as well as the sequence of events leading to failure of the specimens are summarized in this section. Overall, all three specimens exhibited similar lateral load carrying capacity but with different deformation capacities and with buckling of reinforcing bars being the primary cause of failure.

Wall specimen SWD-1

Specimen SWD-1 was the benchmark specimen with a set of 2-R6 stirrups provided at a c/c spacing of 55 mm as the transverse reinforcement in the boundary regions. Flexure-shear cracks with a crack width of 0.1 mm were developed at 0.15% drift followed by the first yielding of the longitudinal reinforcement at 0.5% drift. The maximum crack width observed during this stage was 1.8 mm. In subsequent loading cycles, the cracks started getting concentrated in the bottom 1000 mm of the wall. The first visible reinforcement buckling, which spanned multiple tie spacings, was observed during 1.5% drift cycle. The buckling mode (i.e. the number of tie spacings the buckled bars spanned) at this stage was 2, 3, 4 and 2, 3 in north and south boundary regions, respectively. The first fracture of buckled reinforcement was observed during the 2.0% drift cycle that resulted in a drop of the lateral load capacity of the specimen. The ultimate failure of the specimen occurred during the first cycle of 2.5% drift as a result of the development of localized out-of-plane instability in the south boundary region. This type of instability is different from the global out-of-plane instability observed in several slender wall experiments and is considered as a secondary failure mode [2, 10]. Figure 4 shows the load-displacement hysteretic response and final failure of specimen SWD-1.



(a) Hysteresis response



(b) Final failure of the specimen

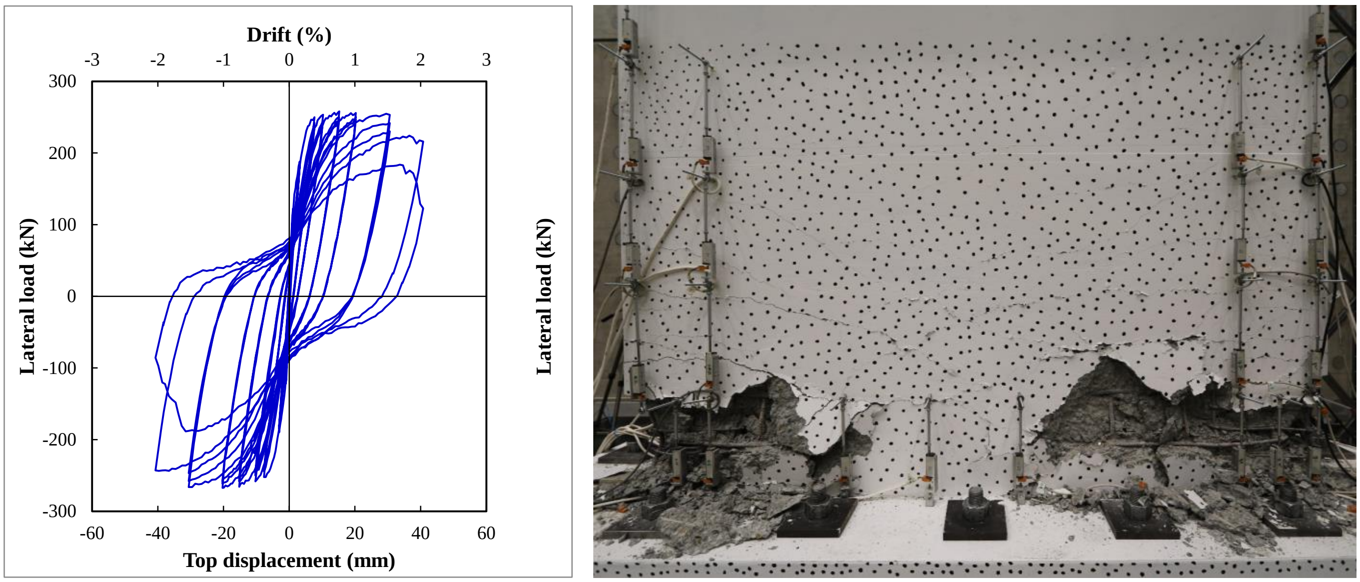
Figure 4: Hysteresis response of wall specimen SWD-1

Wall specimen SWD-2

Specimen SWD-2 was the second test specimen that was identical to the benchmark specimen SWD-1 in all aspects except that the transverse reinforcement spacing was increased to 72 mm (Table 1). This specimen was tested to investigate the effect of transverse reinforcement spacing on buckling behavior of the longitudinal bars. The overall response of this specimen was similar to that of SWD-1 in terms of damage propagation until buckling of reinforcing bars, which was first observed during the 1.0% drift cycle in the south boundary. Unlike SWD-1, buckling of the longitudinal reinforcement was limited to one tie spacing in SWD-2 (i.e. buckling mode was 1). The north boundary bars exhibited buckling during the 1.5% drift cycle and with a buckling mode of 2. It is noteworthy that the buckling mode generally increased along with the loading cycles due to the increased compression demand on the boundary zone longitudinal bars. The failure of this specimen was observed during the 2.0% drift cycle due to significant buckling and fracture of reinforcing bars, and concrete crushing that resulted in development of localized out-of-plane instability in the wall boundaries. Figure 5 shows the load-displacement hysteretic response and final failure of specimen SWD-2.

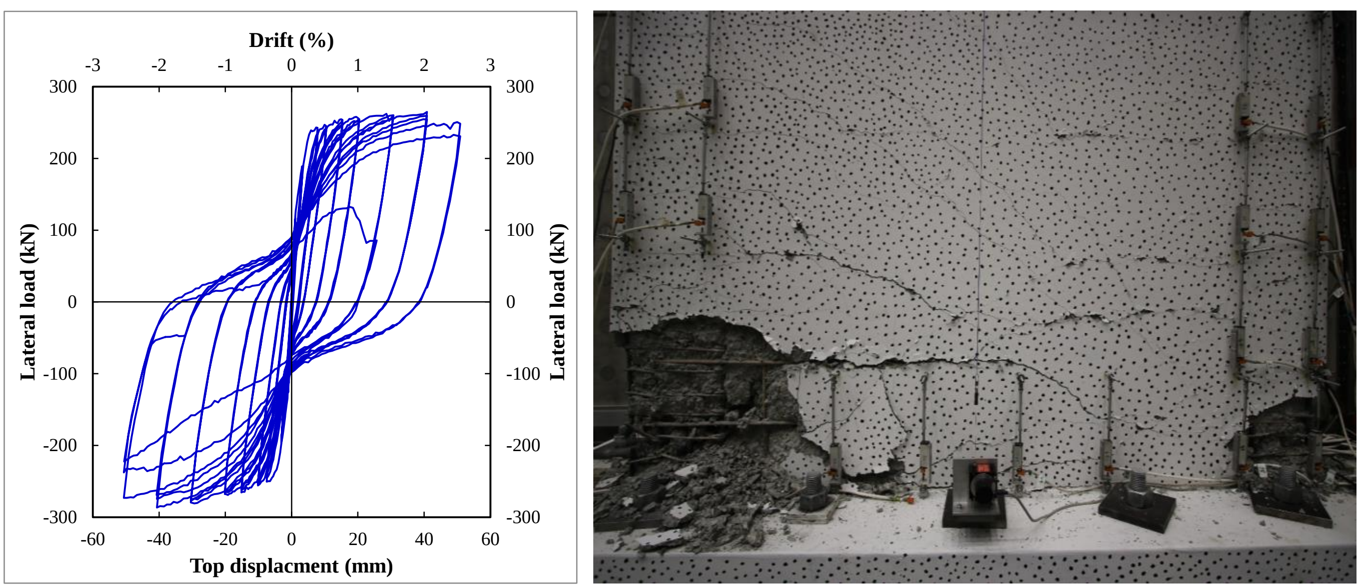
Wall specimen SWD-3

Out of all three wall specimens, specimen SWD-3 was the only one that was provided with an improved transverse reinforcement detailing to restrain reinforcement buckling to single tie spacing. This was achieved by increasing the effective axial stiffness of tie legs by reducing the effective length of ties i.e. the long stirrup provided in the previous specimens was replaced by two smaller stirrups. Further, the unrestrained corner bar (that was exempted from anti-buckling transverse reinforcement) was also restrained using a small triangular stirrup as shown in Table 1. In total, specimen SWD-3 had a set of 3-R6 stirrups spaced at 55 mm c/c (similar to benchmark specimen SWD-1) suitably arranged to restrain buckling to single tie spacing. The overall response of the wall specimen SWD-3 was similar to SWD-1 until one of the corner reinforcing bars in the north boundary buckled at 1.5% drift cycle with buckling spanning single tie spacing. Reinforcement buckling in the south-boundary (with buckling mode-1) was observed during 2.0% drift loading cycle. Reinforcement buckling stayed within single tie spacing in the south boundary throughout the test. The buckling mode of the north boundary reinforcement, however, changed from 1 to 2 once one of the corner reinforcing bars fractured during 2.0% drift. Similar to the other two wall specimens, the failure of this specimen was caused due to the development of localized out-of-plane instability. Figure 6 shows the load-displacement hysteretic response and the final failure of specimen SWD-3.



(a) Hysteresis response (b) Final failure of the specimen

Figure 5: Hysteresis response of wall specimen SWD-2

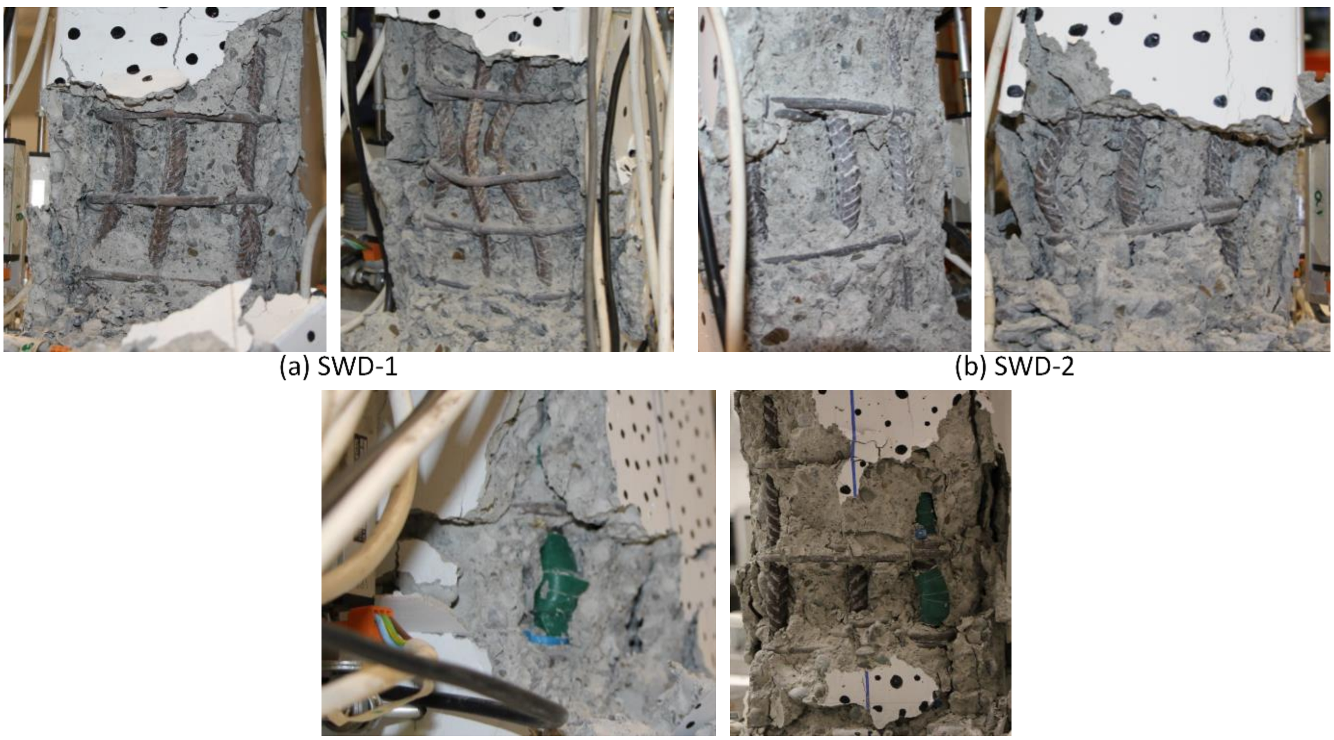


(a) Hysteresis response (b) Final failure of the specimen

Figure 6: Hysteresis response of wall specimen SWD-3

BUCKLING AND FRACTURE OF REINFORCING BARS

All the tested wall specimens exhibited flexural failure due to buckling of corner reinforcing bars with different buckling modes. Modification in transverse reinforcement detailing, i.e. spacing and arrangement of the transverse reinforcement, while keeping the area of tie legs constant altered the effective axial stiffness of the tie legs, thereby improving or degrading buckling performance of the longitudinal reinforcing bars. Figure 7 shows the typical buckling of corner reinforcing bars observed during the tests on RC walls. Out of all the tested wall specimens, specimen SWD-1 showed poor buckling performance as reinforcement buckling initiated with buckling mode greater than one in both the wall boundaries. Increasing the spacing of transverse reinforcement in SWD-2 resulted in an improved buckling performance (during the early stages buckling was limited to single tie spacing) due to the reduced demand on tie legs in lieu of the increased spacing. During the subsequent loading cycles, however, the buckling performance degraded due to the increased axial demands on the longitudinal bars. In specimen SWD-3, reducing the length of tie legs increased the axial stiffness of ties and hence their buckling performance. Throughout the test, buckling was limited to single tie spacing until one of the corner reinforcing bars fractured. This immediate fracture of reinforcing bars after undergoing significant buckling was observed in all the tested wall specimens. Reinforcement buckling expedited the fatigue damage accumulation in bars resulting in their premature fracture. This failure of buckled reinforcing bars due to the accelerated fatigue damage accumulation in bars is in line with the research reported in the literature [11-13].



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

(c) SWD-3

Figure 7: Reinforcement buckling observed during the tests conducted in this study

FLEXURAL DEFORMATION OF THE WALL SPECIMENS

In this section, the flexural deformation of the tested specimens is evaluated. The distribution of curvature along the wall height is calculated and compared. The curvature is estimated using the linear potentiometers provided on the wall surface as shown in Figure 3. Curvature distribution along the height is calculated using the average strain measured at the two extreme ends of the wall assuming a linear strain profile along the wall length. Even though the strain distribution along the wall length is known to be non-linear [14], estimation of curvature assuming a linear strain profile gives a reasonable estimation of the distribution of non-linearity along the wall height. Figure 8 shows the curvature distribution measured along the wall height. As it can be seen in this figure, unlike SWD-3, where improvement in transverse reinforcement detailing (resulting an improved confinement and buckling reinforcement) allowed for better distribution of non-linearity along the wall height, non-linearity was concentrated within the bottom 1000 mm of SWD-1 and SWD-2. This distribution of non-linearity along the height was also in line with visual observation of the crack pattern. In all the tested wall specimens, maximum curvature was concentrated at the wall base resulting in localization of different damage states i.e. buckling, fracture and crushing in bottom 300 mm of the wall. The progression of bar buckling resulted in variation of the strain gradient along the height of the specimens, thereby further localizing the non-linearity at the base.

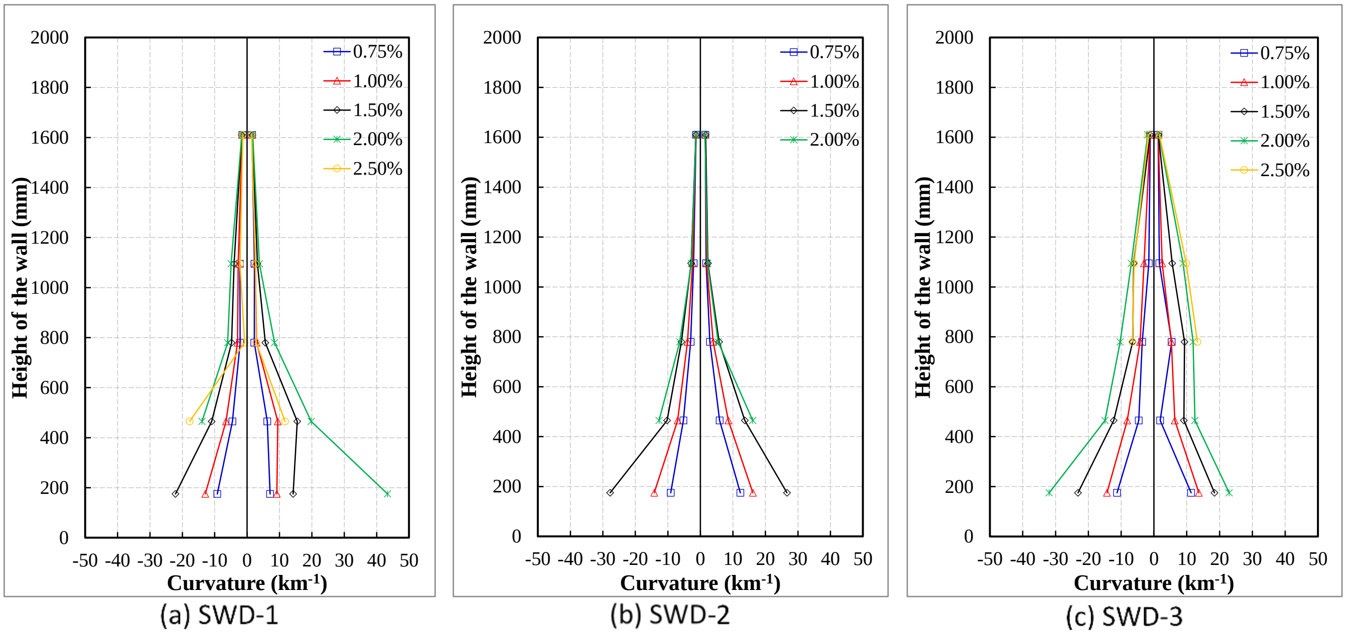


Figure 8: Curvature distribution of the specimens

CONCLUSIONS

In this paper, an experimental test program that was conducted to investigate the effect of transverse reinforcement detailing on reinforcement buckling in RC structural walls was presented. Response of the tested specimens was summarized in light of the buckling mode observed in each wall. The main research findings are listed as below:

1. Buckling of reinforcing bars in RC members depends on the effective stiffness of the ties. Efficient arrangement of stirrups/ties to either increase their effective stiffness (e.g. reducing the length of tie legs or increasing the area of tie legs) or reduce the inelastic demands (e.g. increasing the spacing of transverse reinforcement) can help with restricting the buckling to single tie spacing.
2. Deformation capacity of RC walls can be improved by restricting buckling of reinforcing bars to single tie spacing. Improved transverse reinforcement detailing in specimen SWD-3 resulted a better deformation capacity as compared to specimen SWD-1 and SWD-2.
3. Fracture of reinforcing bars after significant buckling is inevitable. Therefore, the effect of buckling on fracture of reinforcing bars should be appropriately considered.
4. Improvement in transverse reinforcement detailing allows for better distribution of non-linearity along the wall height. Localization of non-linearity in bottom region of the wall may result in accelerated buckling and fracture of the bars due to the increased inelastic strain demands.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial assistance provided by the Ministry of Business, Innovation and Employment (MBIE) and the Quake Centre at the University of Canterbury for carrying out the research. The technical support provided by Russell McConchie and Alan Thirlwell in Structural Engineering Laboratory at the University of Canterbury is greatly appreciated.

REFERENCES

[1] 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.

[2] 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.

[3] J.H. Thomsen, J.W. Wallace, Displacement-based design of reinforced concrete structural walls: An experimental investigation of walls with rectangular and T-shaped cross-sections, Department of Civil and Environmental Engineering, Clarkson University, Potsdan, N.Y., 1995.

[4] Y.H. Oh, S.W. Han, L.H. Lee, Effect of boundary element details on the seismic deformation capacity of structural walls, Earthquake Engineering & Structural Dynamics 31(8) (2002) 1583-1602.

[5] T.S. Welt, Detailing for compression in reinforced concrete wall boundary elements: Experiments, simulations, and design recommendations, University of Illinois at Urbana-Champaign, 2015.

[6] R.K.L. Su, S.M. Wong, Seismic behaviour of slender reinforced concrete shear walls under high axial load ratio, Engineering Structures 29(8) (2007) 1957-1965.

[7] NZS3101:2006, Concrete Structures Standard Part 1- The design of concrete structures, Standards New Zealand, Wellington, 2008.

[8] 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.

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

[10] F. Dashti, R.P. Dhakal, S. Pampanin, Evolution of out-of-plane deformation and subsequent instability in rectangular RC walls under in-plane cyclic loading: Experimental observation, Earthquake Engineering & Structural Dynamics 47(15) (2018) 2944-2964.

[11] M. Tripathi, R.P. Dhakal, F. Dashti, L.M. Massone, Low-cycle fatigue behaviour of reinforcing bars including the effect of inelastic buckling, Construction and Building Materials 190 (2018) 1226-1235.

[12] M. Tripathi, R.P. Dhakal, F. Dashti, L.M. Massone, Evaluation of low-cycle fatigue life of reinforcing bars: Test results, 11th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Los Angeles, CA, 2018.

[13] M. Tripathi, R.P. Dhakal, F. Dashti, L.M. Massone, Experimental investigation on low-cycle fatigue life of reinforcing bars, 7th Asia Conference on Earthquake Engineering, Bangkok, Thailand, 2018.

[14] F. Dashti, R. Dhakal, S. Pampanin, Inelastic strain gradients in reinforced concrete structual walls, Proceedings of the 16th European Conference on Earthquake Engineering, Thessaloniki, Greece, 2018.