Australian Earthquake Engineering Society 2016 Conference, Nov 25-27, Melbourne, Vic

Plastic Hinge Development in Limited Ductile Rectangular Reinforced Concrete Walls

Scott J. Menegon[1], John L. Wilson[2], Nelson T. K. Lam[3] and Emad F. Gad[4]

1. Corresponding Author. PhD Candidate, Centre for Sustainable Infrastructure, Swinburne University of Technology, Melbourne, VIC, Australia. Email: smenegon@swin.edu.au

2. Professor and Executive Dean, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Melbourne, VIC, Australia. Email: jwilson@swin.edu.au

3. Associate Professor and Reader, Department of Infrastructure Engineering, The University of Melbourne, Melbourne, VIC, Australia. Email: ntkl@unimelb.edu.au

4. Professor and Chair of Department, Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, VIC, Australia. Email: egad@swin.edu.au

Abstract

This paper provides a brief overview of a recently completed experimental testing program consisting of limited ductile reinforced concrete (RC) walls. The experimental program included one monolithic cast in-situ rectangular wall specimen, one monolithic cast in-situ box shaped building core specimen and two jointed precast box shaped building core specimens. The specimens were tested using the MAST system at Swinburne University of Technology. They were tested under cyclic in-plane unidirectional lateral load with a shear-span ratio of 6.5. The specimens were detailed to best match typical RC construction practices in Australia, which generally results in limited ductile structures to AS 1170.4. This reinforcement detailing consisted of a continuous mat of constant-spaced horizontal and vertical reinforcement with a lap splice at the base of the wall. A preliminary set of results for the cast in-situ rectangular wall specimen have been summarised within the paper. The lap splice at the base of the rectangular wall resulted in it having a somewhat different post yield displacement response than what is typically seen in RC wall tests performed elsewhere in literature. Instead of a typical plastic hinge with distributed cracks being developed, a 'two crack' plastic hinge was formed. This consisted of one major crack at the base of the wall and another at the top of the lap splice, with only hairline cracks developing between these two major cracks. The majority of the plastic rotation was concentrated in each of these two major cracks.

Keywords: RC walls, wall testing, building cores, rectangular walls, plastic hinge.

1 Introduction

The authors are currently undertaking a long term experimental testing program into reinforced concrete (RC) limited ductile walls in Australia. The majority of RC construction in Australia is considered ‘limited ductile’ in accordance with the Australian Standard for earthquake actions, AS 1170.4 (Standards Australia 2007). As such this experimental testing program is focused towards limited ductile RC walls, as opposed to moderate or full ductile RC walls which have had much research attention in recent times (Menegon et al. 2016). The experimental program has included boundary element prism tests (Menegon et al. 2015a; Menegon, Wilson and Lam 2015b) and near-full scale RC wall tests. This paper will present a brief overview of the near-full scale RC wall experimental test program and the preliminary results of the first specimen in that test program; a rectangular limited ductile RC wall.

Due to the different detailing techniques used in limited ductile RC construction typical in Australia, which was reflected in the reinforcement detailing used in this experimental study, the rectangular wall developed a somewhat different curvature distribution at the base of the wall (i.e. plastic hinge) compared to what is typically seen in RC wall testing. The plastic hinge development in rectangular limited ductile RC walls, as seen in the experimental testing, will be the discussion point of this paper.

2 Experimental Testing Program

The experimental program of large scale RC wall tests initially consisted of four specimens, with an additional two more specimens proposed in the planning phase. The four specimens tested to date, denoted S01 to S04, consisted of one rectangular wall (S01), one cast in-situ box shaped building core (S02) and two jointed precast box shaped building cores (S03 and S04). The test specimen details of S01 and S02 are summarised in Table 1 and illustrated in Figure 1 and Figure 2. Specimens S03 and S04 were essentially replicates of specimen S02 except using jointed precast construction.

The test specimens represent the ground storey component of a taller four storey RC wall and were constructed at a scale of approximately 60 to 70 per cent. They were tested using the state-of-the-art Multi-Axis Substructure Testing (MAST) system at Swinburne University of Technology (Hashemi et al. 2015), which was programed to apply cyclic unidirectional in-plane lateral displacements and a corresponding moment to simulate the moment and shear force response of the taller four storey wall, in the ground storey component test specimen. Further details relating to the test program and loading regime can be found in Menegon, Wilson and Lam (2016) and Menegon, Wilson and Lam (2016).

The test walls were designed and detailed such that they ‘best matched’ typical construction practices used in Australia, as identified by the authors (Menegon et al. 2016). The test specimens were constructed using grade N40 concrete. The walls had large aspect ratios and were very slender with a shear-span ratio of 6.5. The reinforcement detailing consisted of a constant-spaced continuous mat of horizontal and vertical bars on each face of the wall with ‘U’ bars at the end regions of the wall (i.e. specimen S01, refer Figure 1) and corner intersections (i.e. specimen S02, refer Figure 1). The percentage of horizontal reinforcement was quite modest at 0.5 per cent for specimens S01 and S02. The percentage of vertical reinforcement was somewhat higher at 1.8 and 1.4 per cent respectively for specimens S01 and S02. The cast in-situ test specimens (i.e. specimen S01 and S02) were detailed using a lap splice at the base of the wall, in line with construction practices in Australia (Figure 4).

Table 1. Test specimen S01 and S02 details.

Specimen	Depth (mm)	Test wall height (mm)	Real wall height (mm)	Shear span ratio	Vertical reinf. ratio	Horizontal reinf. ratio
S01	1200	2600	10400	6.5	0.018	0.005
S02	1200	2600	10400	6.5	0.014	0.005

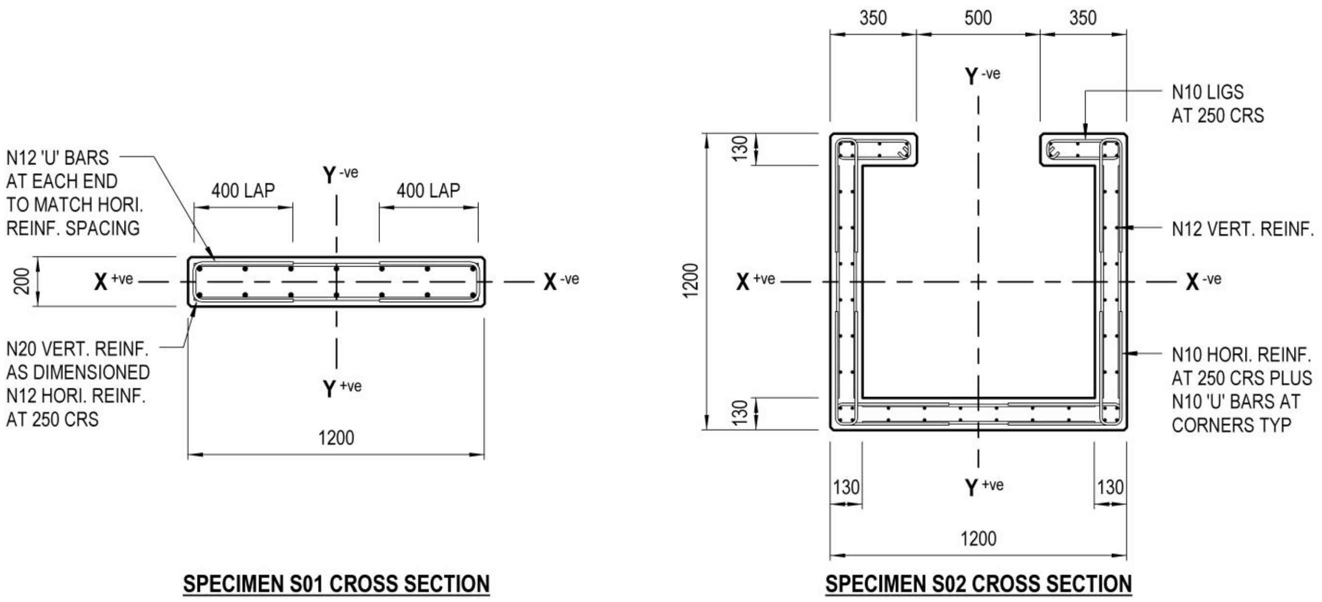


Figure 1. Test specimen S01 and S02 details.

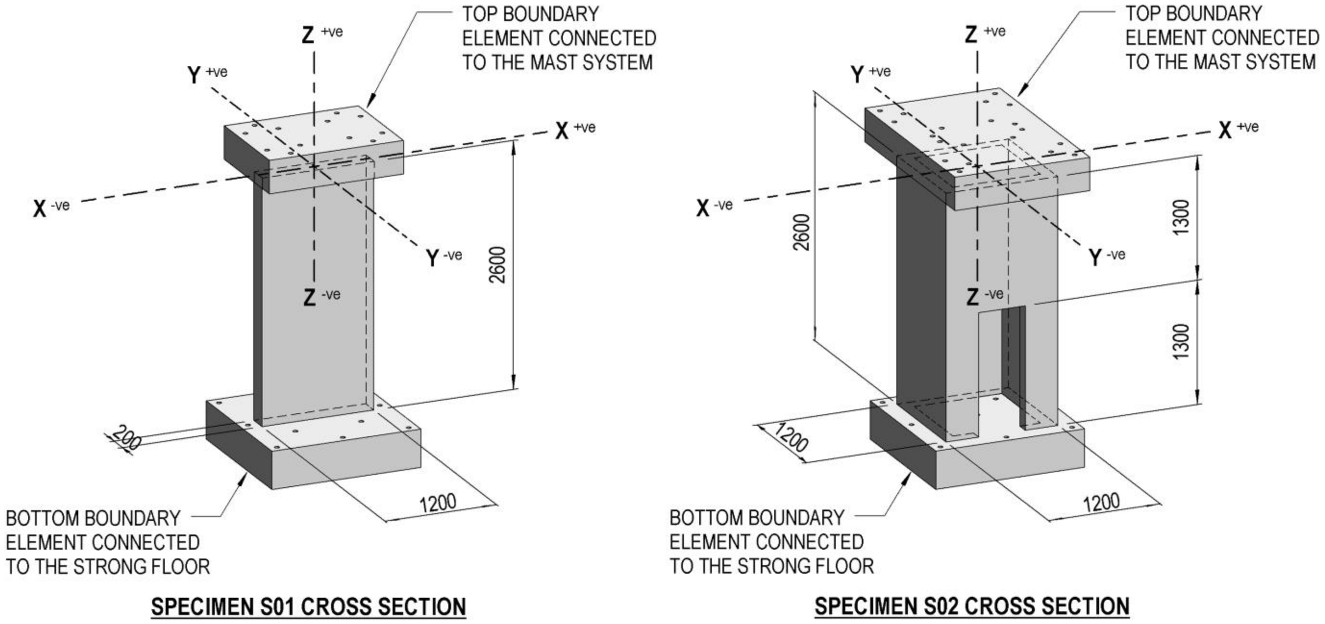


Figure 2. 3D view of test specimens.

3 Instrumentation

A combination of physical instrumentation attached to the test specimens (i.e. LVDTs, string potentiometers and laser displacement sensors) and a contactless photogrammetry system was used to measure the response of the test specimens. The photogrammetry system used was the V-STARS S Mode by Geodetic Systems and was the primary method for quantifying the different types of deformations (e.g. flexure and shear deformation) and sectional responses (e.g. strain and curvature profiles) of the specimens. An overview of the photogrammetry targets for test specimen S01, where individual displacement measurements can be determined throughout the test, is shown in Figure 3. A series of string potentiometers and laser displacement sensors were used to measure the overall global displacements and rotations of the test specimen (Figure 4). Finally, a series of LVDTs were used to verify the strain and curvature profiles determined from the photogrammetry system (Figure 4).

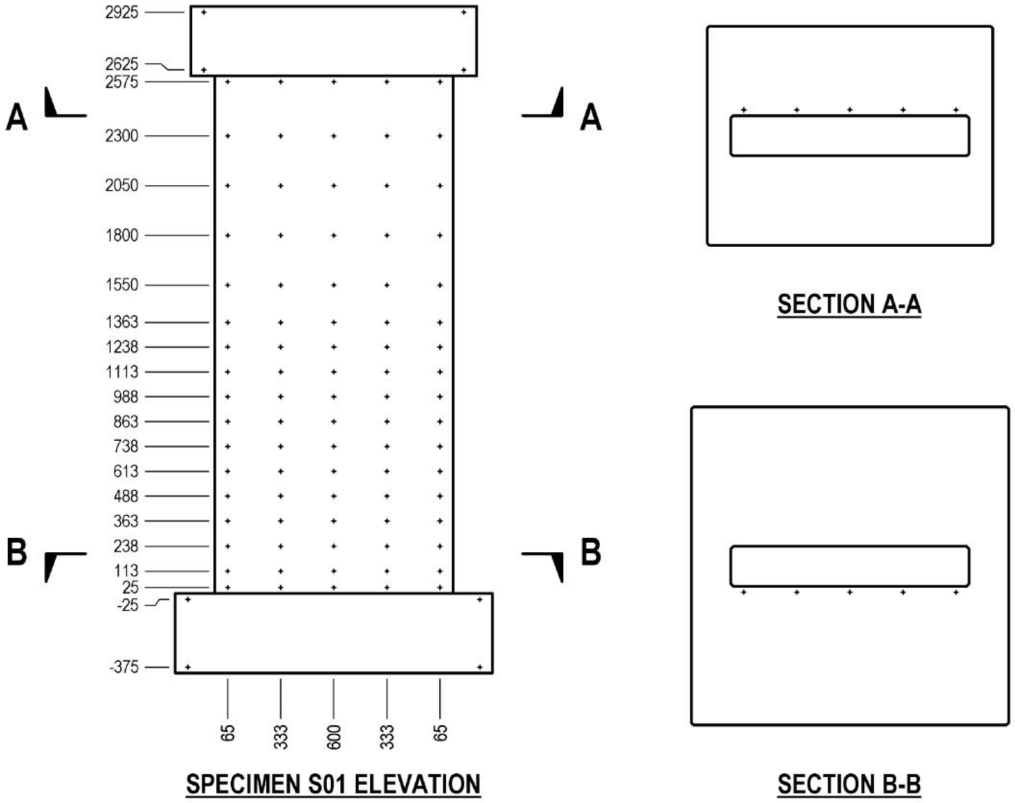


Figure 3. Photogrammetry targets on test specimen S01.

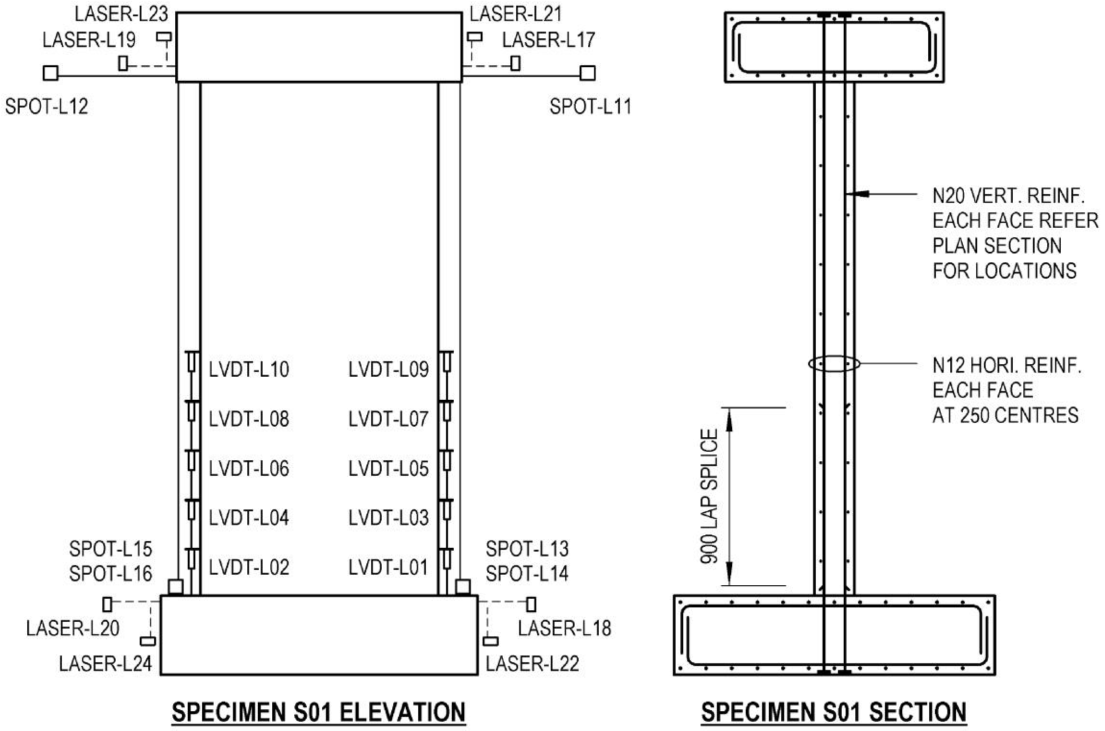


Figure 4. LEFT: physical instrumentation on test specimen S01. RIGHT: wall cross section of test specimen S01.

4 Preliminary Results

The rectangular cast in-situ test specimen (i.e. S01) achieved good in-plane lateral response for the associated simplicity in respects to the reinforcement detailing (Figure 5). The wall failed in flexure via crushing of the concrete in the extreme compressive fibre of the section, at the base of the wall.

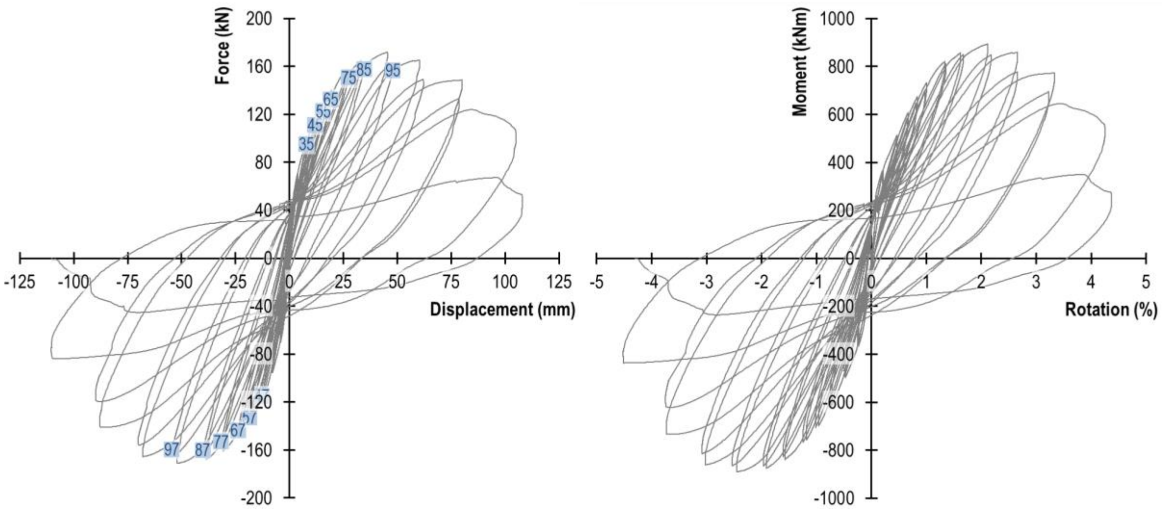


Figure 5. LEFT: force-displacement response at top of test specimen S01. RIGHT: moment-rotation response at top of test specimen S01.

The post yield deformation response was somewhat different to the response commonly seen in rectangular wall testing performed generally in literature. The lap splice at the base of the wall created a region of 'overstrength' which resulted in two dominant cracks forming; one at the interface to the foundation block and the other at the top of the lap splice. The post-yield plastic rotation of the wall was concentrated in these two regions. This is shown in the strain profiles (Figure 6 and Figure 7) and the curvature profiles (Figure 8) of the test specimen.

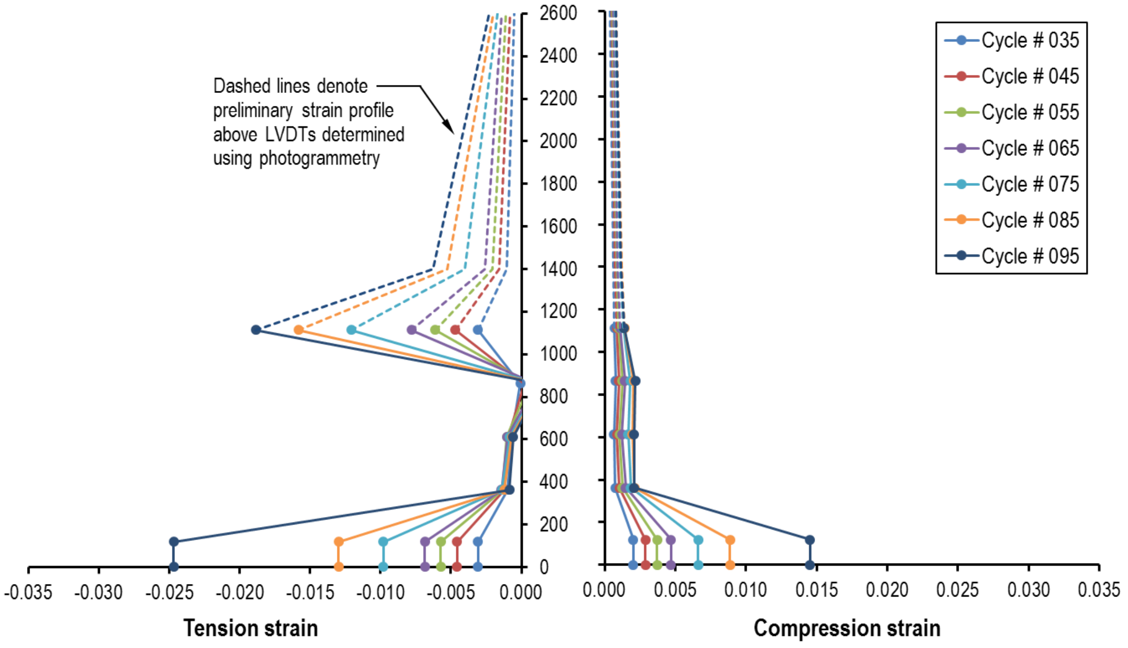

Dashed lines denote preliminary strain profile above LVDTs determined using photogrammetry

Figure 6. Test specimen S01 extreme tension and compression fibre strain profiles – positive cycles.

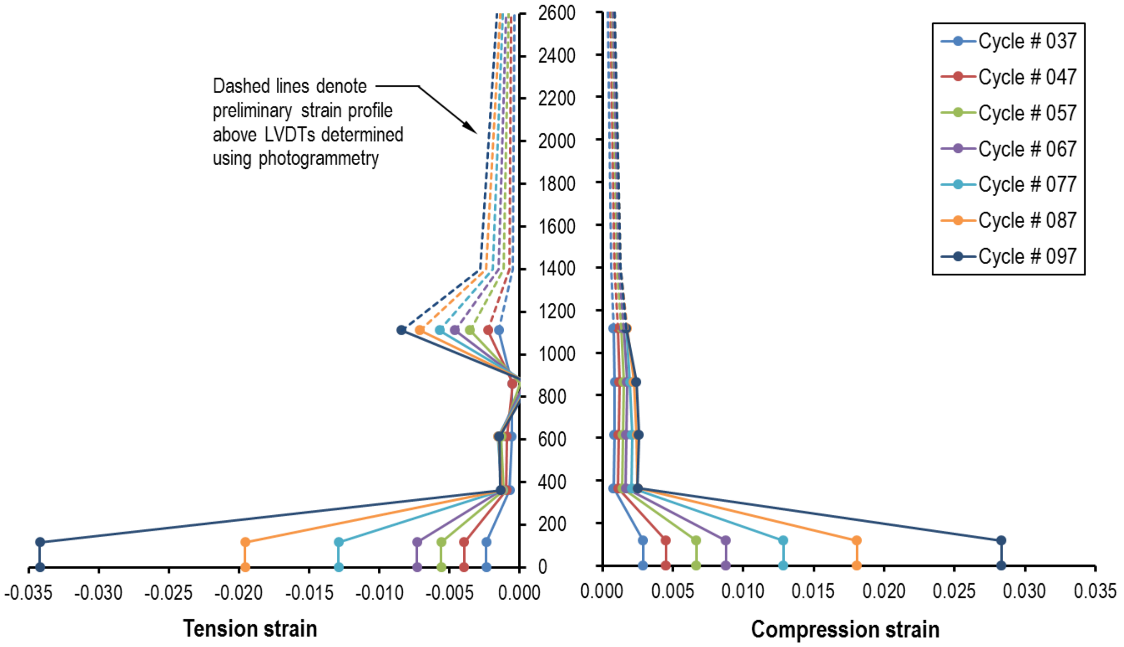


Figure 7. Test specimen S01 extreme tension and compression fibre strain profiles – negative cycles.

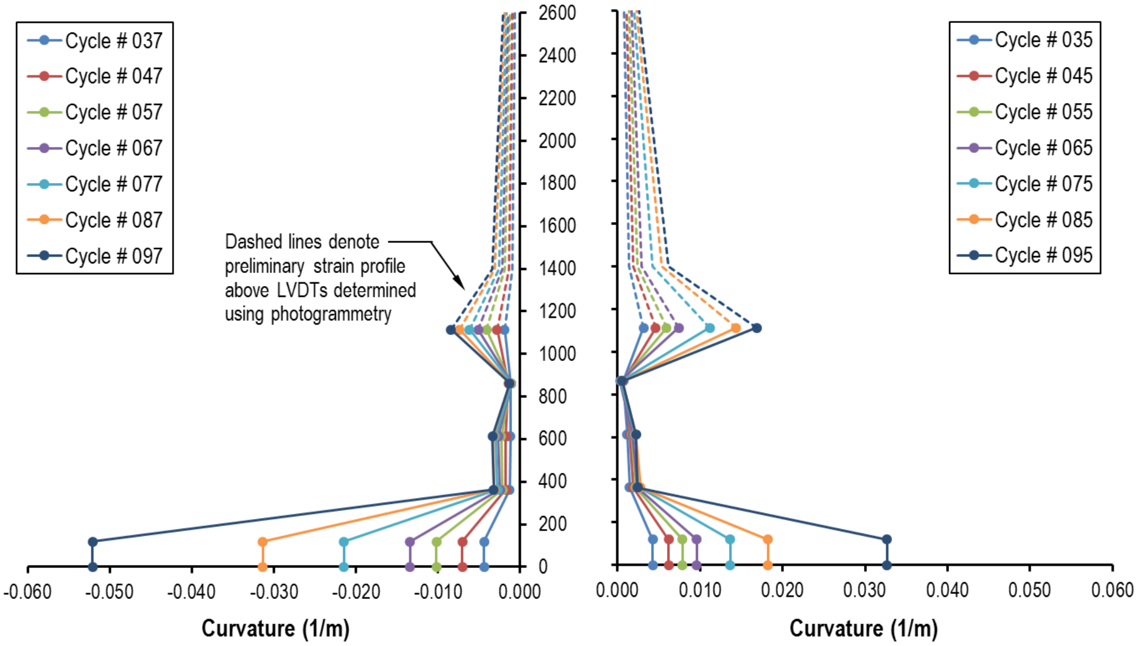


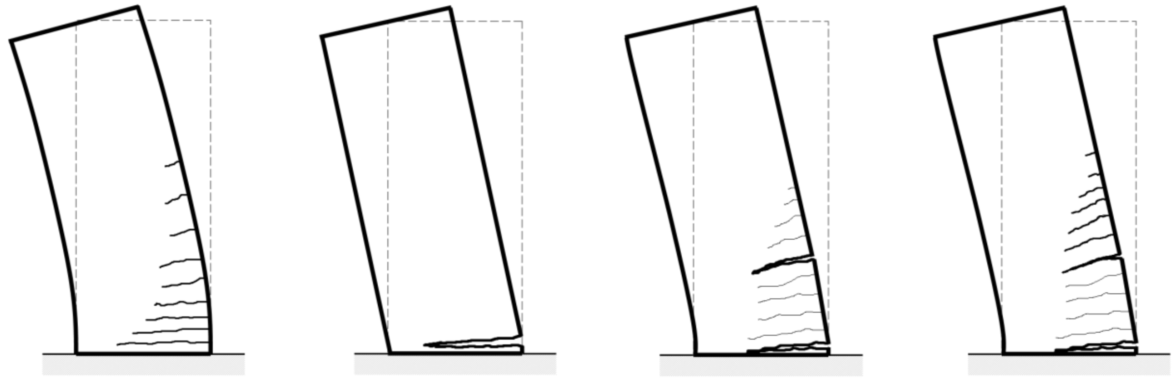
Figure 8. Test specimen 01 curvature profiles (negative cycles left and positive cycles right).

Note: the cycle numbers in Figure 6, Figure 7 and Figure 8 relate to the associated performance points shown on the force-displacement response curve shown in Figure 5. The solid line data is from the LVDT measurements and the dashed line data is preliminary output data from the photogrammetry system.

5 Plastic Hinge Development in Limited Ductile RC Walls

The lap splice at the base of the wall created a different post-yield deformation response to what is usually seen in RC wall testing. Typically – when no lap splice is present at the base of the wall – the wall either develops a traditional plastic hinge with distributed cracking at the base of the wall, where the inelastic plastic behaviour is ‘spread’ across multiple cracks, or when the percentage of vertical reinforcement is not sufficient to initiate distributing cracking, a single crack forms with a concentration of the inelastic plastic behaviour in one location. The latter of these two scenarios obviously has a significantly reduced inelastic displacement capacity compared to the former and is generally associated with the scenario where the cracking moment capacity of the wall is greater than the ultimate moment capacity of the wall. These two plastic hinge models are shown in Figure 9(a) and Figure 9(b) respectively.

In this case with the lap splice at the base of the wall, which is common practice in Australia and generally associated with limited ductile RC wall detailing, it has been shown in this testing that neither of the two aforementioned post-yield plastic hinge models are developed. The lap splice creates a region of overstrength at the base of the wall and either results in a ‘two crack’ plastic hinge model or a single crack plus a shifted traditional hinge plastic hinge model, as shown in Figure 9(c) and Figure 9(d) respectively. The former and latter responses will be dictated by the ratio of the applied moment at the base of the wall to the applied moment at the top of the lap splice, which is in turn dependent on the shear-span ratio of the wall (i.e. slenderness).



(a) traditional plastic hinge model with distributed cracking.

(b) single crack plastic hinge model (under-reinforced section).

(c) two crack plastic hinge model (lap splice at base of the wall).

(d) shifted plastic hinge model (lap splice at base of the wall).

Figure 9. Plastic hinge models for RC walls.

6 Conclusions

This paper has presented an overview of a recent experimental testing program performed by the authors looking at the lateral in-plane capacity of limited ductile RC walls in Australia. The study included one cast in-situ rectangular RC wall, one cast in-situ box shaped building core and two jointed precast box shaped building cores. The results of the rectangular cast in-situ test specimen are summarised in the paper and showed that a traditional plastic hinge with distributed cracking and distributed plasticity, as commonly seen in RC wall testing, was not achieved due to the lap splice at the base of the wall. The lap splice created a region of overstrength, over which only hairline cracks formed with major cracks either side, i.e. at the base of the wall and the top of the lap splice. The plastic rotation and curvature of the wall was concentrated within these two locations. Further research is currently being undertaken to better understand this behaviour.

7 Acknowledgements

The authors would like to thank the Brown family for their generous donation in establishing the Dr William Piper Brown AM Scholarship, of which the lead author is the recipient. Financial support from the Australian Research Council (ARC) Discovery Project DP140103350 entitled Collapse Assessment of Reinforced Concrete Buildings in Regions of Lower Seismicity is gratefully acknowledged. The Swinburne Smart Structures Laboratory staff are also thanked for their hard work and expertise provided during the course of the experimental testing program.

8 References

Hashemi, M.J., Al-Mahaidi, R., Kalfat, R. and Burnett, G., 2015. Development and validation of multi-axis substructure testing system for full-scale experiments, *Australian Journal of Structural Engineering*, Vol. 16(4), pp. 302-315.

Menegon, S.J., Wilson, J.L., Gad, E.F. and Lam, N.T.K., 2015a. Out-of-plane buckling of limited ductile reinforced concrete walls under cyclic loads, *Proceedings of the 2015 New Zealand Society of Earthquake Engineering Technical Conference*, Rotorua, New Zealand.

Menegon, S.J., Wilson, J.L. and Lam, N.T.K., 2015b. Local strain of reinforcement and tension stiffening in reinforced concrete walls, *Proceedings of the Tenth Pacific Conference on Earthquake Engineering, Building an Earthquake-Resilient Pacific, 6-8 November 2015*, Sydney, Australia.

Menegon, S.J., Wilson, J.L. and Lam, N.T.K., 2016. Experimental Assessment of the In-Plane Lateral Drift Capacity of Precast Concrete Building Cores, *Proceedings of the Australasian Structural Engineering Conference, 23-25 November 2016*, Brisbane, Australia.

Menegon, S.J., Wilson, J.L. and Lam, N.T.K., 2016. Experimental testing of limited ductile RC walls and building cores, *Proceedings of the 2016 New Zealand Society of Earthquake Engineering Technical Conference*, Christchurch, New Zealand.

Menegon, S.J., Wilson, J.L., Lam, N.T.K. and Gad, E.F., 2016. Reinforced Concrete Walls in Australia: Reconnaissance Survery of Industry and Literature Review of Experimental Testing (unpublished manuscript).

Standards Australia, 2007. *AS 1170.4-2007 Structural design actions, Part 4: Earthquake actions in Australia*, Standards Australia, Sydney.