Comprehensive Experimental Testing Program of Limited Ductile Reinforced Concrete Walls

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Abstract

This paper outlines the comprehensive experimental testing program the authors have recently completed into the seismic performance of limited ductile reinforced concrete (RC) walls in Australia. This experimental wall testing was performed as part of the most recent phase of a long-term Australian Research Council (ARC) funded research program to assess and reduce the seismic risk in Australia. The experimental testing program consisted of both large-scale system level wall tests and component level tests of wall connections and boundary elements. The system level testing consisted of one monolithic cast in-situ rectangular wall specimen, one monolithic cast in-situ box shaped building core specimen and three jointed precast box shaped building core specimens. The component level testing consisted of seventeen boundary element prism tests and three precast building core connections. The testing was performed in the Smart Structures Laboratory at Swinburne University of Technology. The large-scale wall specimens were tested using the state-of-the-art MAST System. The paper concludes with some findings and observations from the experimental program.

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

1 Introduction

The authors have been undertaking a long-term Australian Research Council (ARC) funded research program to assess and reduce the seismic risk and rationalise the seismic design procedures and practices in Australia. While the primary focus is Australia, the research outcomes and findings are relevant to most regions of lower seismicity around the world. This has included research studies that have: led to the development of the Component Attenuation Model (CAM) (Lam et al. 2000a; Lam et al. 2000b), which led to the development and implementation of a new response spectrum for Australia (Wilson and Lam 2003); assessed the seismic performance of unreinforced masonry structures (Griffith, Lam and Wilson 2006; Griffith et al. 2004); and assessed the seismic performance and drift capacity of soft-storey RC buildings with non-ductile RC columns (Wibowo et al. 2014; Wibowo et al. 2011; Wilson et al. 2015). The experimental testing program outlined in this paper forms part of the most recent phase of this research program to assess the seismic performance of RC wall buildings in regions of lower seismicity.

RC walls form the primary lateral load resisting system for the majority of low, mid and high-rise buildings in Australia (Menegon et al. 2017c). 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), however this would be considered as simply ‘non-ductile’ construction in many regions of higher seismicity. RC walls were traditionally constructed as monolithic cast in-situ RC elements and generally have rectangular cross sections or form box shaped building cores around lift shafts or stairwells. In recent times, cast in-situ walls have started to be substituted for precast walls, particularly in low and mid-rise construction in south-eastern Australian states. Jointed precast building cores are commonly utilised and typically consist of individual rectangular panels, with or without openings, which are cast in an offsite factory and erected and joined together on-site accordingly. The panels are typically joined vertically using grouted dowel connections and joined horizontally to adjacent panels using welded stitch plate connections. The grouted dowel connections connect the panel to the panels above or below and the welded stitch plate connections allow for composite action to be developed between the panels.

The experimental testing program was primarily designed to best match standard design and construction practices for RC walls in Australia, however the testing and associated outcomes are relevant to RC wall design in most regions of lower seismicity around the world. This meant the specimens were detailed using limited ductile or non-ductile detailing practices, which generally consisted of two layers of vertical and horizontal reinforcement (one per face), no confinement reinforcement in the end regions of the wall and lap splices of the vertical reinforcement at the base of the wall in the plastic hinge region. Common detailing practices, which are widely adopted across Australia, were identified in a desktop study by the authors (Menegon et al. 2017c) and adopted when designing the test specimens in this study to ensure they best represented ‘industry standard’ construction practices in Australia.

2 Experimental Testing Program

The experimental program consisted of three phases of testing, which comprised: five large scale RC wall tests; seventeen boundary element prism tests; and three precast building core connection tests. Each phrase of testing is outlined in the subsequent three subsections respectively.

2.1 Wall Testing

The system level wall testing consisted of five test specimens. The specimens were tested using the Multi-Axis Substructure Testing (MAST) System at Swinburne University of Technology. The MAST System is a state-of-the-art testing machine capable of applying full six degree-of-freedom (DOF) loading in mixed-mode, switched-mode, hybrid simulation or a combination therein (Al-Mahaidi et al. 2018; Hashemi et al. 2015). The specimens were tested under unidirectional quasi-static cyclic test conditions.

The specimens were designed as a one-storey element that represented the ground floor component of a taller four-storey wall. The geometry of the test specimens was constrained by the test machine and as such they were designed to represent a 60% to 70% full scale component. The specimens were tested under in-plane cyclically increasing lateral displacement. To simulate the response of the equivalent taller four-storey wall, an in-plane moment was applied, which was coupled to the in-plane force capacity of the specimen. This allowed the resulting bending moment and shear force diagrams of the one-storey test specimens to match the equivalent response of a taller four-storey wall. The in-plane moment was equal to the lateral force response of the specimen multiplied by a constant k. The constant k is dependent on the number of stories, the height of the stories and the lateral load distribution across the height of the stories. For a four-storey element with an inter-storey height of 2600 mm and a triangular lateral load distribution the constant k equals 5.2. This means the applied moment was equal to $5.2F_x$ (as shown in Figure 1). This results in the test specimens having a shear-span ratio of 6.5. The reader is directed to Menegon et al. (2017b) for further details of the test setup and loading protocol used for the wall testing.

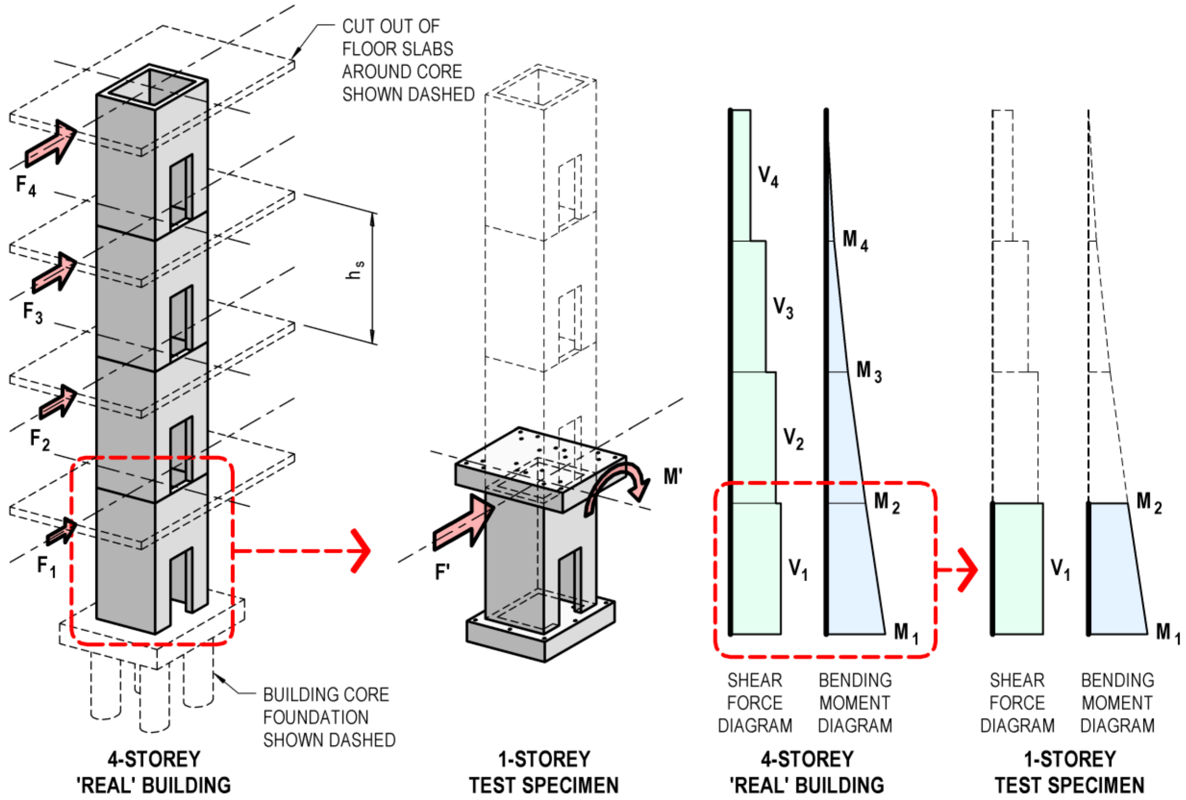


Figure 1. Four-storey 'real' building versus one-storey test specimen.

The first two specimens were monolithically constructed cast in-situ elements. The first cast in-situ specimen (i.e. S01) was a rectangular wall. The second cast in-situ specimen (i.e. S02) was a box shaped building core specimen. The remaining three specimens were jointed precast building cores. The first precast building core specimen (i.e. S03) was a replica of the cast in-situ building core specimen. The second (i.e. S04) had the same geometry of S03, however it had a higher percentage of vertical reinforcement. The third (i.e. S05) generally had the same geometry as S03 and S04 except it was constructed using 150 mm thick panels, as opposed to 130 mm thick panels that were used for S03 and S04. S05 was also constructed using low ductility reinforcement. Each specimen was constructed using standard N40 grade concrete, which has a minimum characteristic 28-day compressive cylinder strength of 40 MPa. The walls were tested with an axial load ratio of approximately 5%. The geometry and reinforcement details of each specimen are presented in Table 1 and Figure 2. A photo of test specimen S02 in the MAST System is shown in Figure 3(b).

Table 1. Wall specimen details.

Specimen	Wall type	Wall length (mm)	Test wall height (mm)	Real wall height (mm)	Effective height (mm)	Shear-span ratio*
S01	Cast in-situ	1200	2600	10400	7800	6.5
S02	Cast in-situ	1200	2600	10400	7800	6.5
S03	Precast	1200	2600	10400	7800	6.5
S04	Precast	1200	2600	10400	7800	6.5
S05	Precast	1200	2600	10400	7800	6.5

* Shear-span ratio is equal to the moment at the base of the wall divided by the product of the shear force and wall length. Alternatively put, the shear-span ratio is equal to the aspect ratio of the equivalent single degree-of-freedom system.

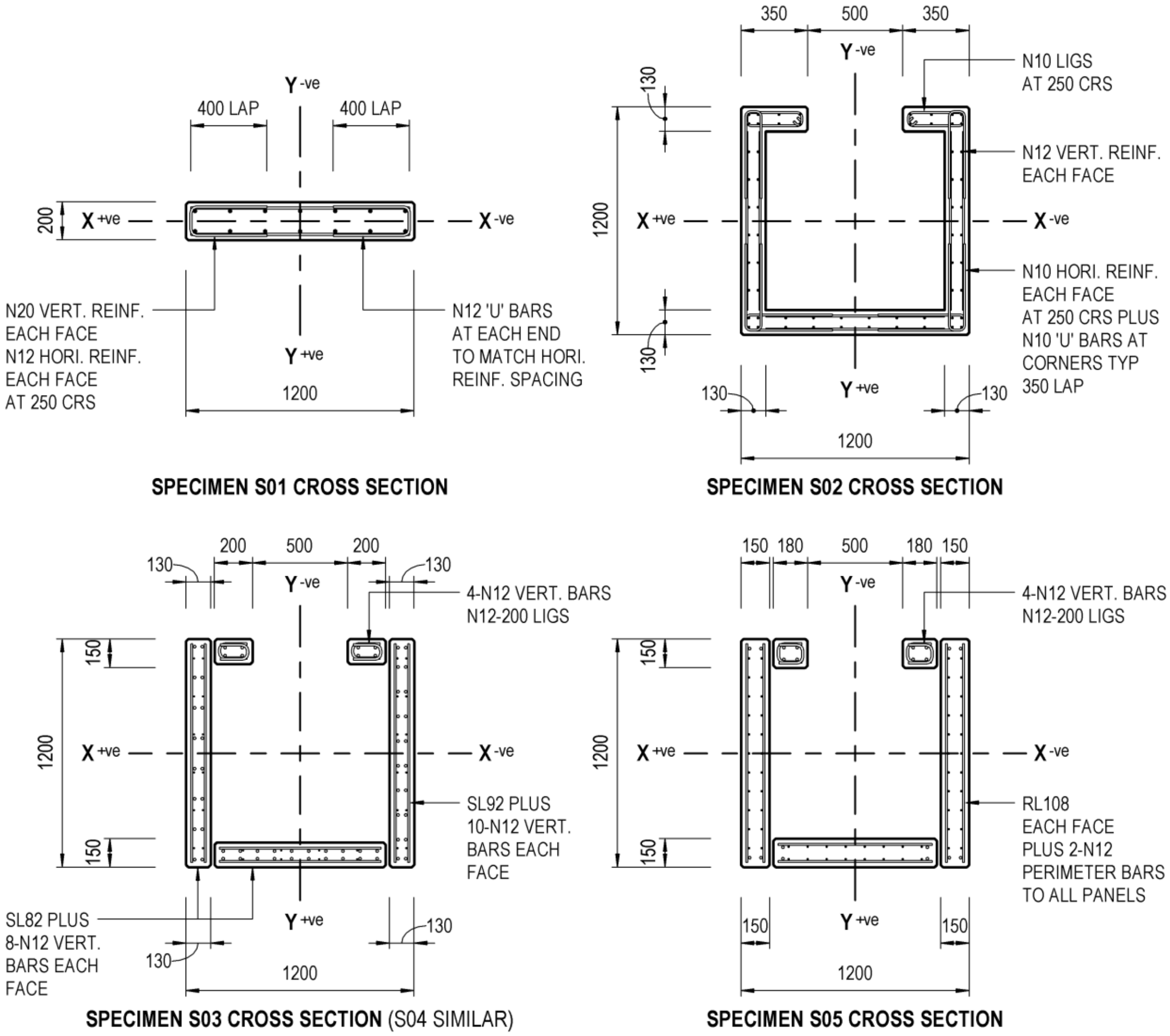
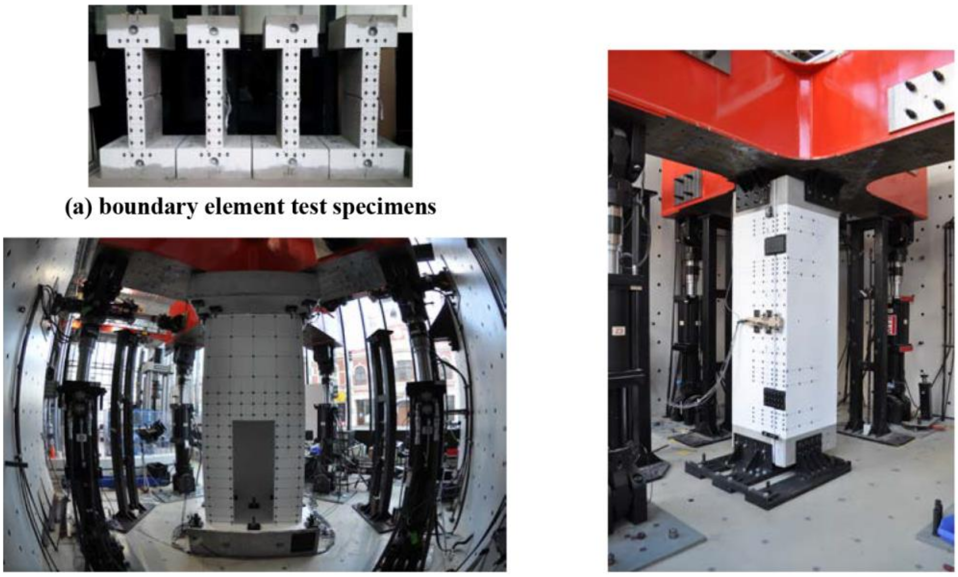


Figure 2. Wall specimen cross sections.



(a) boundary element test specimens

(b) cast in-situ building core test specimen

(c) building core connection specimen

Figure 3. Test specimen photos.

2.2 Boundary Element Prism Testing

The boundary element prism testing was performed to further investigate localised failure modes in the end regions and boundary elements of RC walls that occur under reversed cyclic lateral load. The failure modes being investigated were local buckling of the vertical reinforcement and global buckling of the entire end region of the wall, both of which occur in the plastic hinge region after plastic tension strains have been developed in the vertical reinforcement. The boundary elements were tested under cyclic axial tension-compression loading, which is essentially what occurs in the end region of a wall, as illustrated in Figure 4. The test specimens mostly comprised cast in-situ elements, with and without lap splices of the vertical reinforcement. The test program also included three specimens that had grout tube connections typical of precast construction. A summary of the boundary element test specimens is presented in Table 2. A photo of test specimens P04 to P07 is shown in Figure 3(a).

Table 2. Boundary element test specimen details.

Specimen	Vertical reinf. spice	Thickness (mm)	Length (mm)	Height (mm)	Height-to-thickness ratio	Vertical reinf.
P01*	No splice	130	450	2000	15.4	6-N12
P02*	No splice	130	450	2000	15.4	6-N16
P03*	No splice	130	450	2000	15.4	3-N12
P04	No splice	130	450	800	6.2	3-N10
P05	No splice	130	450	800	6.2	6-N10
P06	No splice	130	450	800	6.2	3-N16
P07	No splice	130	450	800	6.2	6-N16
P08	Lap splice	150	450	800	2.7†	6-N12
P09	Lap splice	150	450	850	2.8†	6-N16
P10	Lap splice	150	450	800	2.7†	6-N10
P11	Lap splice	150	450	850	2.8†	4-N10
P12	Grout tube	150	450	850	2.8†	8-N12
P13	Grout tube	150	450	850	2.8†	6-N12
P14	Grout tube	150	450	850	2.8†	6-L11.9

* Two identical specimens of P01, P02 and P03 were produced and each respective specimen was tested under a different loading protocol.

† Test specimens P08 to P14 were laterally restrained at mid-height of the specimen, which further reduced the height-to-thickness ratio of the specimen by a factor of two.

2.3 Precast Building Core Connection Testing

The precast building core connection testing was conducted as a joint industry research program. The objective of this testing was to develop alternative precast building core connections to the industry standard welded stitch plate (WSP) connections currently used. Two new prototype connections were developed. The first was developed with ease and speed of construction as the primary objective and the second was developed with strength and performance as the primary objective. The connections were tested in the MAST System as a component level test (i.e. a full building core specimen was not constructed), as illustrated in Figure 5. The new prototype connections are being called a grouted panel pocket (GPP) and post tensioned corbel (PTC) connection respectively. Further details related to this testing are presented in Menegon et al. (2017a). The WSP specimen is shown in Figure 3(c).

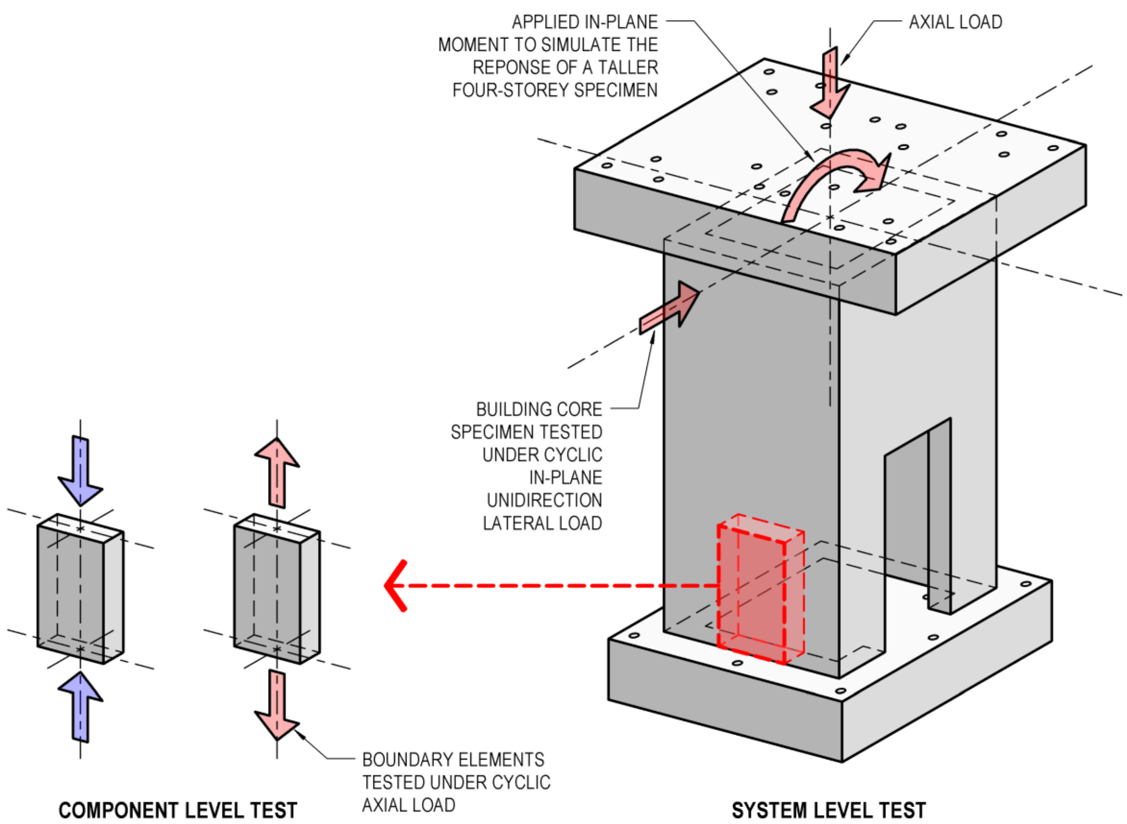


Figure 4. Boundary element prism testing.

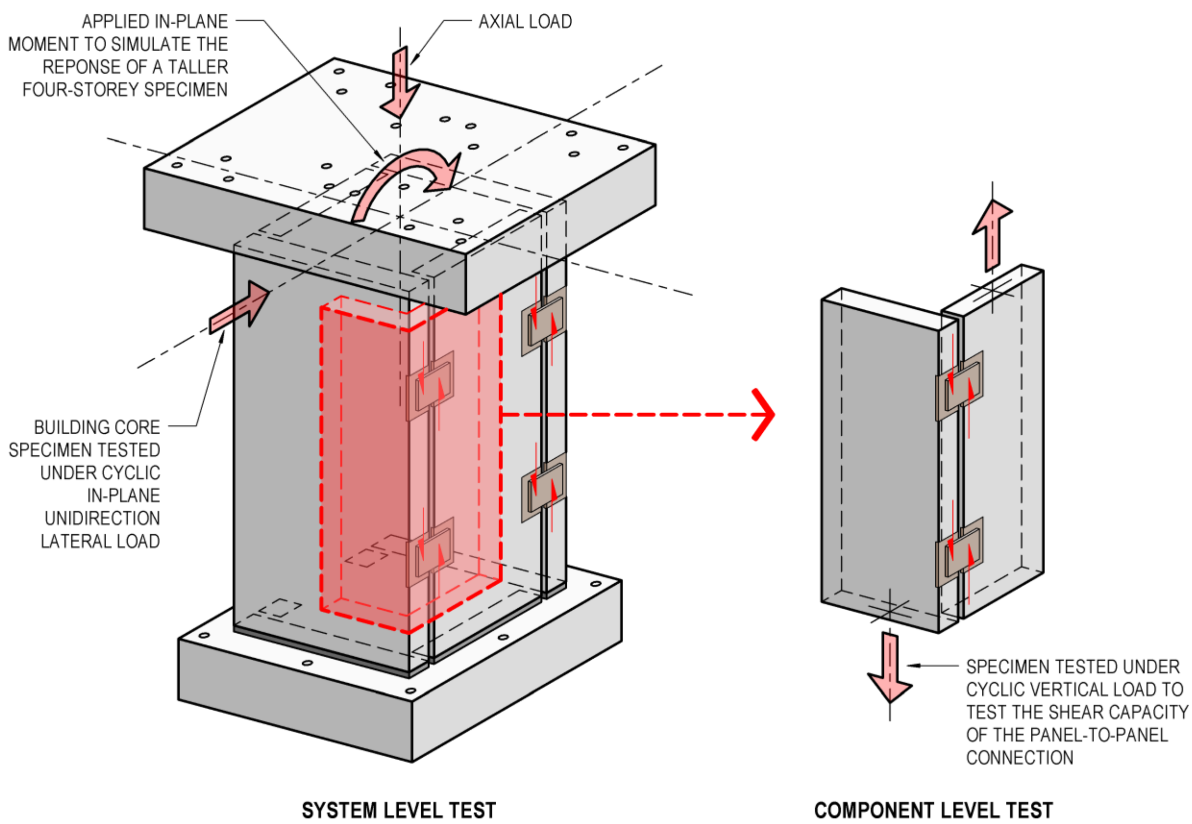


Figure 5. Precast core connection testing (Menegon et al. 2017a).

3 Preliminary Results and Findings

The experimental testing phase of the project has been completed, however the analysis and processing of the results is ongoing. The force-displacement response of test specimens S01, S02 and S05 is presented in Figure 6. Preliminary findings and observations from the testing are:

- The lap splice resulted in an atypical curvature and tension strain distribution. The splicing of reinforcement created a localised region of overstrength and resulted in the majority of the inelastic plastic tension strains being concentrated in two cracks, one at the base of the wall and the other at the top of the splice.
- The precast core was significantly more flexible than the cast in-situ core, with the maximum strength occurring at 0.75% and 1.1% drift for test specimens S02 and S05 respectively.
- Low ductility reinforcement allowed the maximum strength of the section to be developed, but failed quickly thereafter allowing only minimal ductility to be developed.
- Despite the lateral strength decreasing significantly, often below 20% of the maximum response, the walls could withstand very large in-plane lateral drifts prior to axial load failure occurring (i.e. complete structural collapse). Test specimens S01 and S02 reached 4.2% and 4.5% respectively before axial load failure occurred, whereas test specimens S03, S04 and S05 reached 6.5%, 8.0% and 4.9% respectively without axial load failure occurring, at which point the test was terminated.

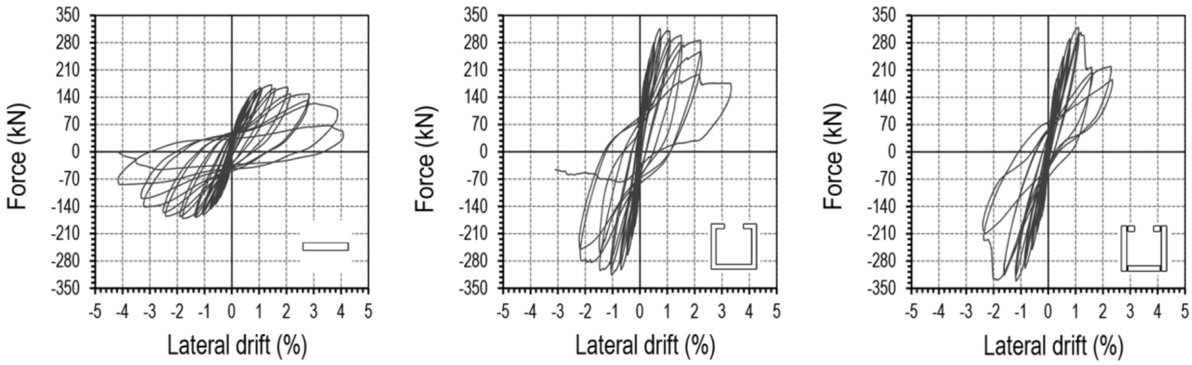


Figure 6. Force-displacement response for test specimens S01 (left), S02 (middle) and S05 (right).

4 Conclusions

This paper has presented an overview of a recent experimental testing program performed by the authors looking at the displacement behaviour of RC walls in Australia. The study included one cast in-situ rectangular RC wall specimen, one cast in-situ box shaped building core specimen, three jointed precast box shaped building core specimens, seventeen boundary element test specimens and three precast building core connection specimens. While all the experimental work has been completed, the study is still ongoing and some preliminary results are presented within. The testing has shown that despite the limited ductile detailing, which is widely adopted in RC walls in Australia, due to the relative low percentages of axial load, the walls can withstand very large in-plane lateral drifts prior to axial load failure occurring (i.e. complete structural collapse).

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