Out-of-plane buckling of limited ductile reinforced concrete walls under cyclic loads

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ABSTRACT: Out-of-plane buckling of reinforced concrete walls under cyclic axial tension-compression has been a frequently observed phenomenon, with many cases reported following the recent 2010 Chile and 2011 Christchurch earthquakes. However, little research effort has been directed towards this area. This behaviour can result in the sudden and almost complete loss of the walls axial load carrying capacity, potentially triggering the progressive collapse of the building. This paper presents the first findings of a current and ongoing research program investigating the collapse behaviour of limited ductile reinforced concrete walls under cyclic axial tension-compression loading. For this purpose an experimental laboratory regime has been undertaken, involving the testing of a series of limited ductile RC walls under cyclic axial loading.

The preliminary results show that cyclic axial tension-compression loading of a wall results in a bifurcation effect; if the wall undergoes moderate tension strains, in the reversed axial compression cycle the initial axial stiffness of the wall can be recovered and the wall can be loaded to near its uncracked compressive capacity. However, when subject to higher tensile strains, the wall fails in out-of-plane buckling at a compressive load 10 to 20 per cent of its uncracked compressive capacity. Furthermore, in the lightly reinforced wall specimen, local buckling of the vertical reinforcement occurred prior to the wall being able to develop sufficient tensile strains to trigger out-of-plane buckling.

1 INTRODUCTION

Out-of-plane buckling of reinforced concrete (RC) walls under cyclic axial tension-compression loading was widely observed and well documented following the recent 2010 Chile and 2011 Christchurch earthquakes (Wallace 2012; Elwood 2013; Sritharan et al. 2014). While this phenomenon was first observed and presented some 20 years ago by Paulay and Priestley (1993), little attention has been directed towards this area since. The majority of studies undertaken have been focused on ductile RC walls. This paper outlines the first findings of a current research program aimed at documenting and predicting the aforementioned behaviour in limited ductile RC walls.

In areas of low to moderate seismicity, such as Australia, the vast majority of the building stock consists of RC buildings where the lateral load resisting system comprises limited ductile RC walls. This paper will show that limited ductile RC walls subjected to cyclic axial tension-compression loading could result in sudden and catastrophic failure, which in turn, could potential trigger complete structural collapse of a building, in certain circumstances.

The cyclic axial loading of RC walls occurs when they are subjected to cyclic lateral loads, such as during an earthquake. Depending on the wall configuration within the building, the level of lateral loading in question and the number of stories, the boundary elements of RC walls resisting lateral load will undergo cyclic axial tension-compression or cyclic axial compression-compression loading. Walls which have a neutral axis relatively close to the extreme compression fibre of the wall during bending and have a low pre-compression force (i.e. ‘T’, ‘L’ or box cross section walls in mid-rise buildings) will generate large tensile strains in their respective boundary elements. Alternatively, walls which do not have a large compression flange and have a high pre-compression force (i.e. rectangular walls in high-rise buildings) may only generate small or in some situations zero tensile strains in their respective boundary elements. This is illustrated in Figure 1.

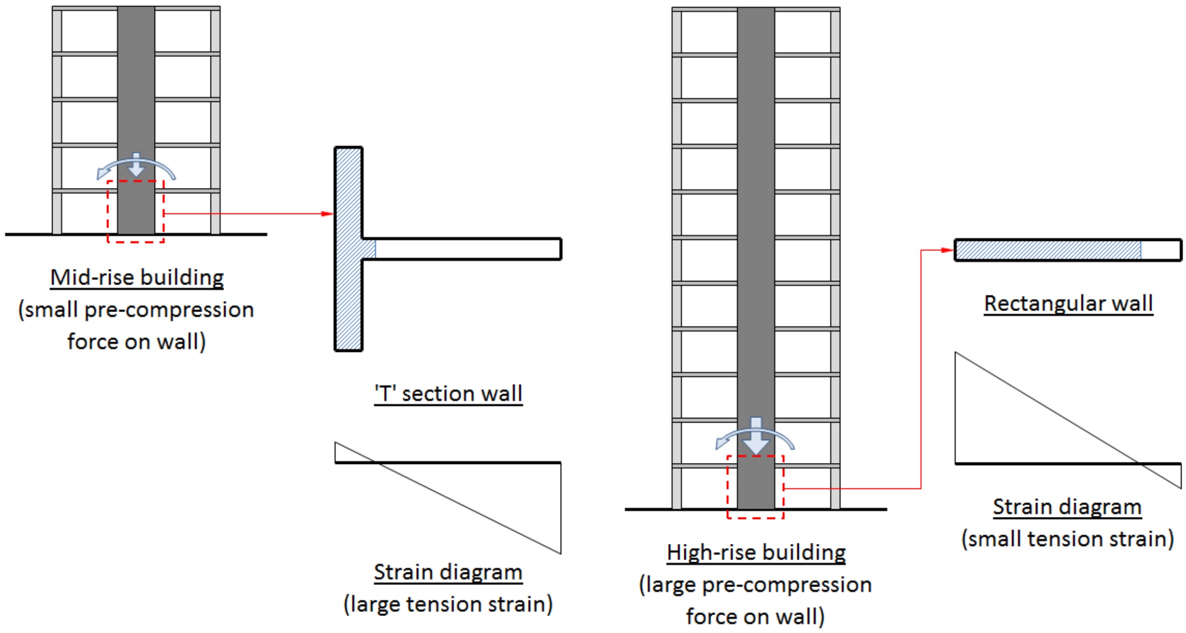


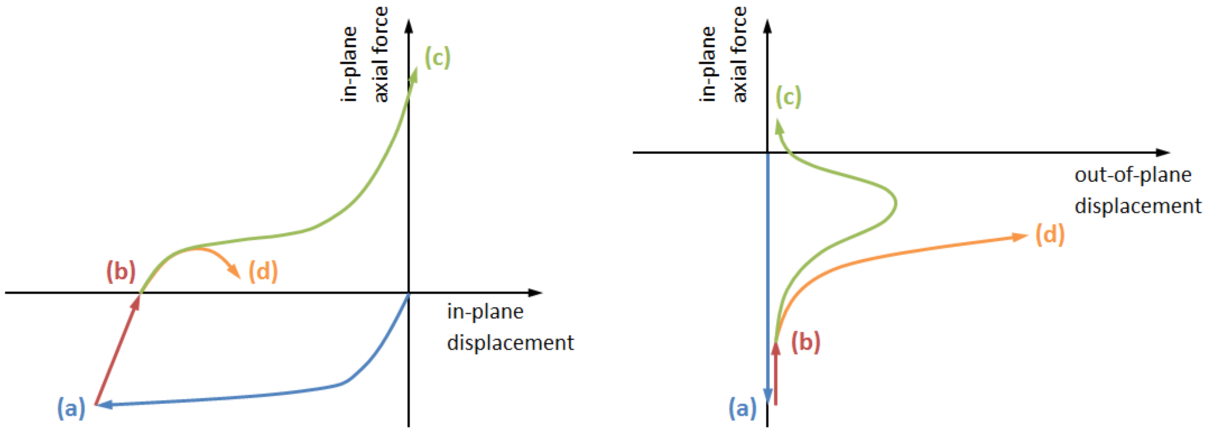
Figure 1. LEFT: RC wall subjected to large tensile strains. RIGHT: RC wall subject to low tensile strains.

2 OUT-OF-PLANE BUCKLING BEHAVIOUR OF WALLS

Out-of-plane buckling of RC walls occurs when the boundary element of the wall undergoes plastic tensile strains, such that after load reversal the residual crack widths along the height of the wall prevent the wall from regaining its initial uncracked axial stiffness. This phenomenon is presented in Figure 2, where pathway a-b-c represents the boundary element of a squat wall (i.e. low height-to-thickness ratio) which has been loaded in axial tension, followed by load reversal (i.e. axial compression) and the regaining of its initial uncracked axial stiffness. Pathway a-b-d represents the boundary element of slender wall (i.e. high height-to-thickness ratio), which after load reversal, is unable to regain its initial uncracked axial stiffness, resulting in out-of-plane buckling.

The two critical parameters controlling the out-of-plane buckling behaviour of walls are the height-to-thickness ratio of the wall (where the height is the unrestrained floor-to-floor height of the wall) and the maximum tensile strain the wall undergoes prior to the subsequent reversed compressive load cycle. Building codes in areas of high seismicity typically set upper limits for the height-to-thickness ratio of walls; for example the Uniform Building Code imposed a slenderness ratio (i.e. height-to-thickness ratio) limit of 16 (Wallace 2012). However, Wallace (2012) goes further to recommend a slenderness ratio limit of 10, for the web element in ‘T’ and ‘L’ cross section walls, until further more conclusive research on the subject is undertaken. Alternatively in areas of lower seismicity, such as Australia, no consideration is given to restricting the slenderness ratio of walls to prevent out-of-plane buckling, where AS 3600 (Standards Australia 2009) only has a nominal slenderness ratio limit of 30.

Priestley, Calvi and Kowalsky (2007) proposes limiting the tensile strain of the vertical reinforcement in the boundary element of a wall to 60 per cent of the ultimate strain of the reinforcement, i.e. 0.03 and 0.06 for Class N and Class E reinforcement respectively. This tensile strain limit recommendation is widely known and adopted by many as a *rule-of-thumb* value. It was selected to prevent low-cycle fatigue failure of the vertical reinforcement and does not take into consideration out-of-plane buckling. It should be noted that this *rule-of-thumb* is strictly only applicable to ductile RC walls and requires confinement reinforcement at a spacing not exceeding three or four bar diameters (depending on the class of reinforcement), to ensure local buckling of the vertical reinforcement does not occur.



a) The boundary element of the wall undergoes axial tension, resulting in the yielding of the vertical reinforcement and the development of significant plastic tensile strains.
b) Lateral load reversal occurs, allowing for elastic recovery of the vertical reinforcement.
c) The boundary element of the wall undergoes axial compression with an initial loss in axial stiffness, followed by crack closure and recovery of axial stiffness (e.g. a squat wall).
d) The boundary element of the wall is unable to regain its axial stiffness and out-of-plane buckling of the wall occurs (e.g. a slender wall).

Figure 2. LEFT: Typical in-plane force vs. in-plane displacement graph.
RIGHT: Typical in-plane force vs. out-of-plane displacement graph.

Paulay and Priestley (1993), using an experimental study comprising four ductile RC walls and the fundamentals of reinforced concrete behaviour, developed a formula to calculate the maximum tensile strain a boundary element of a wall can undergo prior to out-of-plane buckling occurring in the subsequent reversed load cycle. Following this, Chai and Elayer (1999) performed an experimental study where they tested 14 ductile RC columns meant to represent the boundary elements of ductile RC walls. Using the results of their experimental study they further refined the formula presented by Paulay and Priestley (1993). The derived formulae by (Paulay and Priestley 1993) and (Chai and Elayer 1999) are expressed below by Equation 1 and 2 respectively. The formulae presented are a function of the thickness to buckling length ratio of the wall. The buckling length of the wall is assumed to be equal to the plastic hinge length but no greater than 80 per cent of the unrestrained floor-to-floor height of the wall (Paulay and Priestley 1993).

$$\varepsilon_{sm} = 8\beta\left(\frac{t_w}{L_o}\right)^2 \xi_c \quad (1)$$

Where: t_w = wall thickness; L_o = buckling length; β = the ratio of the distance to the outer layer of vertical reinforcement to the thickness of the wall (i.e. $d = \beta t_w$); ξ_c = the critical normalised out-of-plane displacement.

$$\varepsilon_{sm} = \frac{\pi^2}{2}\left(\frac{t_w}{L_o}\right)^2 \xi_c + 3\varepsilon_{sy} \quad (2)$$

Where: t_w = wall thickness; L_o = buckling length; ε_{sy} = yield strain of reinforcement; ξ_c = the critical normalised out-of-plane displacement.

$$\xi_c = 0.5\left(1 + 2.35m - \sqrt{5.53m^2 + 4.70m}\right) \quad (3)$$

Where: $m = pf_{sy} / f_c^{'}$ (i.e. the mechanical reinforcement ratio of the boundary element).

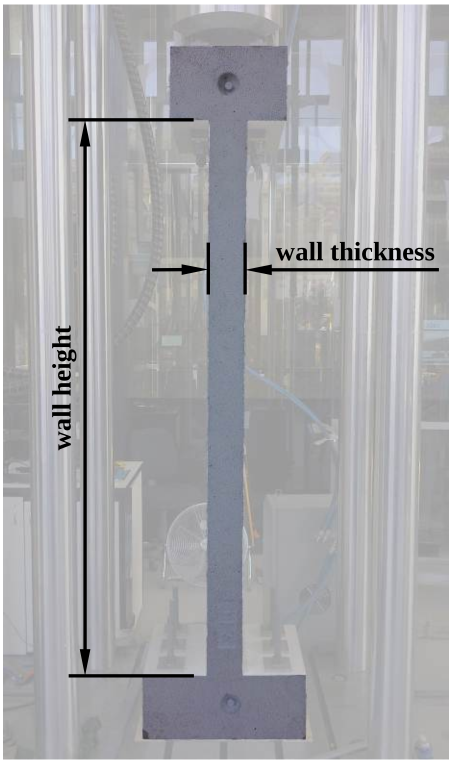
3 EXPERIMENTAL STUDY

The experimental study consisted of three types of wall specimens with different reinforcement ratios and configurations but the same height, thickness and length. Wall types 1 and 2 had a high and moderate reinforcement ratio respectively, with two layers of vertical bars. Wall type 3 had a low reinforcement ratio with one central layer of vertical bars. The reinforcement for the three wall types was selected to represent typical reinforcement ratios and layouts used in Australia. The wall types are further illustrated and summarised in Figure 3 and Table 1.

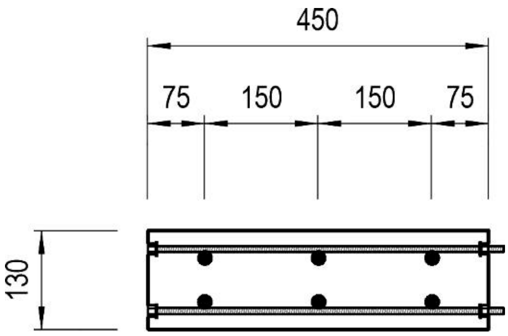
The wall segment tested was designed to simulate the boundary element in the web of an 'L' or 'T' section wall or a segment of the flange element in a box shape or 'C' section wall. In both of these applications the horizontal reinforcement would generally be fully developed, either by the continuous section of wall adjacent to the 'test specimen' or by reinforcement cogs or 'U' bars at the ends of the wall. As the test specimen was not long enough to ensure the horizontal reinforcement is sufficiently developed, the horizontal reinforcement was substituted for threaded rod with a nut and washer at each end. The nut and washer ensures the threaded rod is fully developed, hence providing the equivalent amount of unidirectional confinement that would be present in a 'real world' version of the wall.

For each wall type, two specimens were produced. The first was tested in axial compression to determine the 'baseline' axial compressive capacity of that wall type. The second was tested in axial tension-compression to determine its performance with regards to out-of-plane buckling. After observing the failure mode of wall types 1 and 3 under axial compression, it was deemed satisfactory to estimate the axial compressive capacity of wall type 2 by taking the ratio of the cylinder strength of wall type 2 to wall type 1 and multiplying it by the compressive capacity of wall type 1.

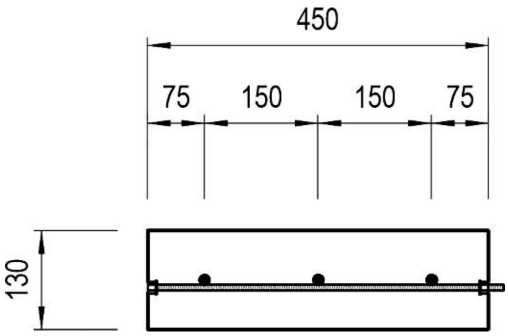
It is noted the test setup in the experimental study results in a constant strain gradient across the height of the wall. However in a typical building, due to the overturning moments developed, the strain gradient would not be constant and in fact would vary along the height of the wall. In the case of a ground floor wall in a building greater than four stories, the difference between an approximated constant strain gradient versus the actual strain profile would be minimal.



(a) Typical wall elevation.



(b) Wall type 1 and 2 cross section.



(c) Wall type 3 cross section.

Figure 3. Typical test specimen.

Table 1. Test specimen summary.

Specimen	Thickness (mm)	Length (mm)	Height (mm)	Height-to-thickness ratio	Vertical reinf.	Vertical reinf. ratio
Wall type 1	130	450	2000	15.4	6-N12	0.012
Wall type 2	130	450	2000	15.4	6-N16	0.021
Wall type 3	130	450	2000	15.4	3-N12	0.006

4 RESULTS

A total of five tests were performed; two axial compression tests and three axial tension-compression tests. Figure 4 depicts the failure of all five wall specimens. The wall specimens tested under axial compression failed at a load of 160 and 127 per cent more than the compressive capacity calculated in accordance with the Australian Standard for Concrete Structures AS 3600 (Standards Australia 2009), assuming a material reduction factor of 1.0 (note: generally the material reduction factor for walls in compression is 0.6). AS 3600 was deemed the most appropriate point of reference as the main body of the standard is consistent with limited ductile RC construction. The results of the axial compression tests are summarised in Table 2.

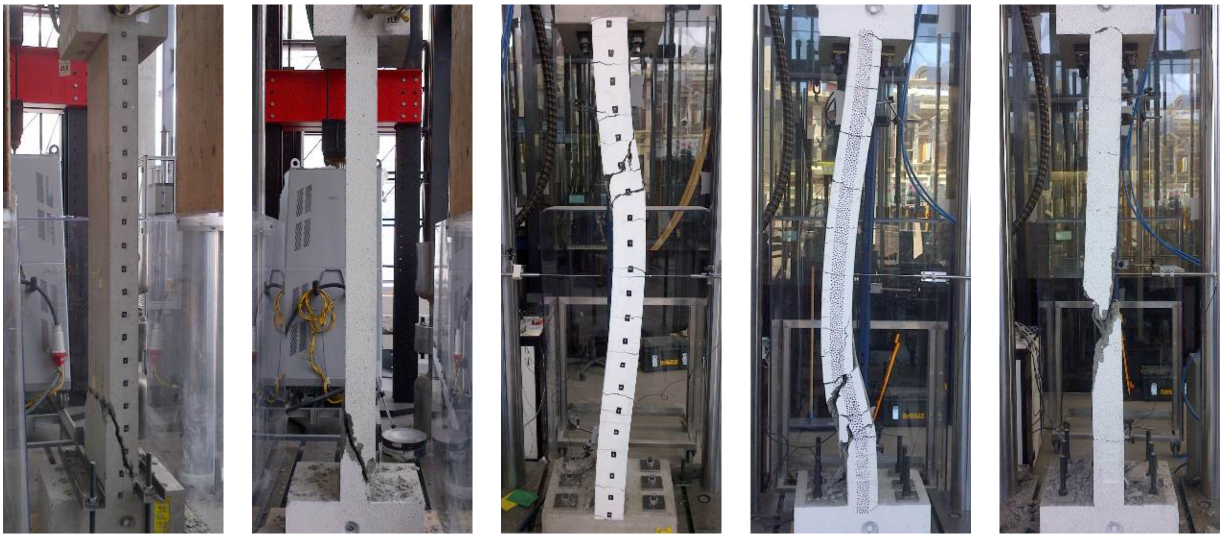
The behaviour of wall type 1 and 2 under cyclic axial tension-compression resulted in a bifurcation effect. When the walls underwent moderate tension strains (i.e. load cycle 1 and 2), in the subsequent reversed axial compressive cycle, the walls were able to recover their initial axial stiffness and be loaded to near their uncracked compressive capacity. However after they underwent higher tension strains (i.e. load cycle 3), in the subsequent reversed axial compressive cycle, the walls were unable to recover their initial axial stiffness and out-of-plane buckling of the wall ensued. Failure occurred at a load of 10 to 20 per cent of its respective uncracked compressive capacity. Refer to Figure 6 for the hysteresis response and out-of-plane displacement of the walls during the different load cycles.

The failure mechanism of wall type 3 under cyclic axial tension-compression differed from that of wall type 1 and 2. That said, the initial behaviour during load cycle 1 did match that of the other wall types. However during load cycle 2, after the load reversed from axial tension to axial compression and the wall regained its initial axial stiffness, local buckling of the vertical reinforcement occurred. The wall immediately failed following this as illustrated in Figure 5.

The behaviour of wall type 3 was attributed to the irregular and sparse distribution of cracking due to the low percentage of vertical reinforcement. This resulted in the formation of a large crack approximately two thirds from the top of the wall; refer Figure 5(a). During load cycle 2, the axial tension displacement was ~40 mm and the aforementioned crack had a width of ~12 mm, meaning 30 per cent of the axial displacement was concentrated at one location. The average tension strain across the specimen was 2 per cent. However, taking into consideration the models for crack width presented by Ghannoum and Moehle (2012) and Wilson et al. (2015) and back calculating the strain, the local strain of the reinforcement at this location was in the vicinity of 7 to 10 per cent. This much higher local strain was believed to initiate the local buckling of the vertical reinforcement.

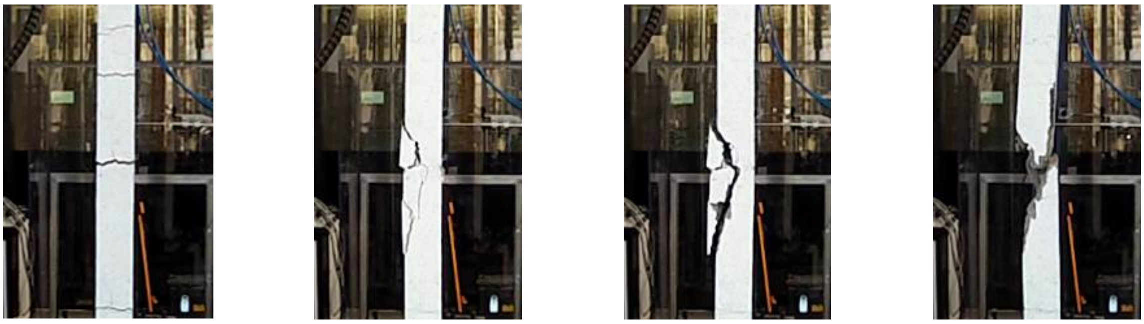
As the percentage of reinforcement increased (i.e. wall type 1 at 1.2 per cent and wall type 2 at 2.1 per cent), the cracking became more regular and consistent. Meaning the local tension strains in the reinforcement at each crack location would have been approximately equal to the average tension strain across the height of the wall. The results suggested the more regular and consistent the cracking is, the more susceptible the wall is to out-of-plane buckling. This is evident in the hysteresis response during load cycle 3 (shown in Figure 6), in which wall type 2 underwent the smallest magnitude of axial displacement yet had the 'most defined' loss of axial stiffness. In contrast wall type 1 appeared to momentarily start to regain axial stiffness prior to buckling.

The results of the experimental study were used to assess the validity of Equation 1 and 2. This study suggests both equations provide very conservative estimates of the maximum tensile strain the boundary element of a wall can undergo prior to out-of-plane buckling in reversed load cycles. This is illustrated by Figure 7. The failure mode of wall type 3, as discussed previously, was not out-of-plane buckling and so is not appropriate for assessing the validity of Equation 1 or 2.



(a) Wall type 1 **(b) Wall type 3** **(c) Wall type 1** **(d) Wall type 2** **(e) Wall type 3**

Figure 4. Left to right: wall type 1 compression test, wall type 3 compression test, wall type 1 tension-compression test, wall type 2 tension-compression test and wall type 3 tension-compression test.



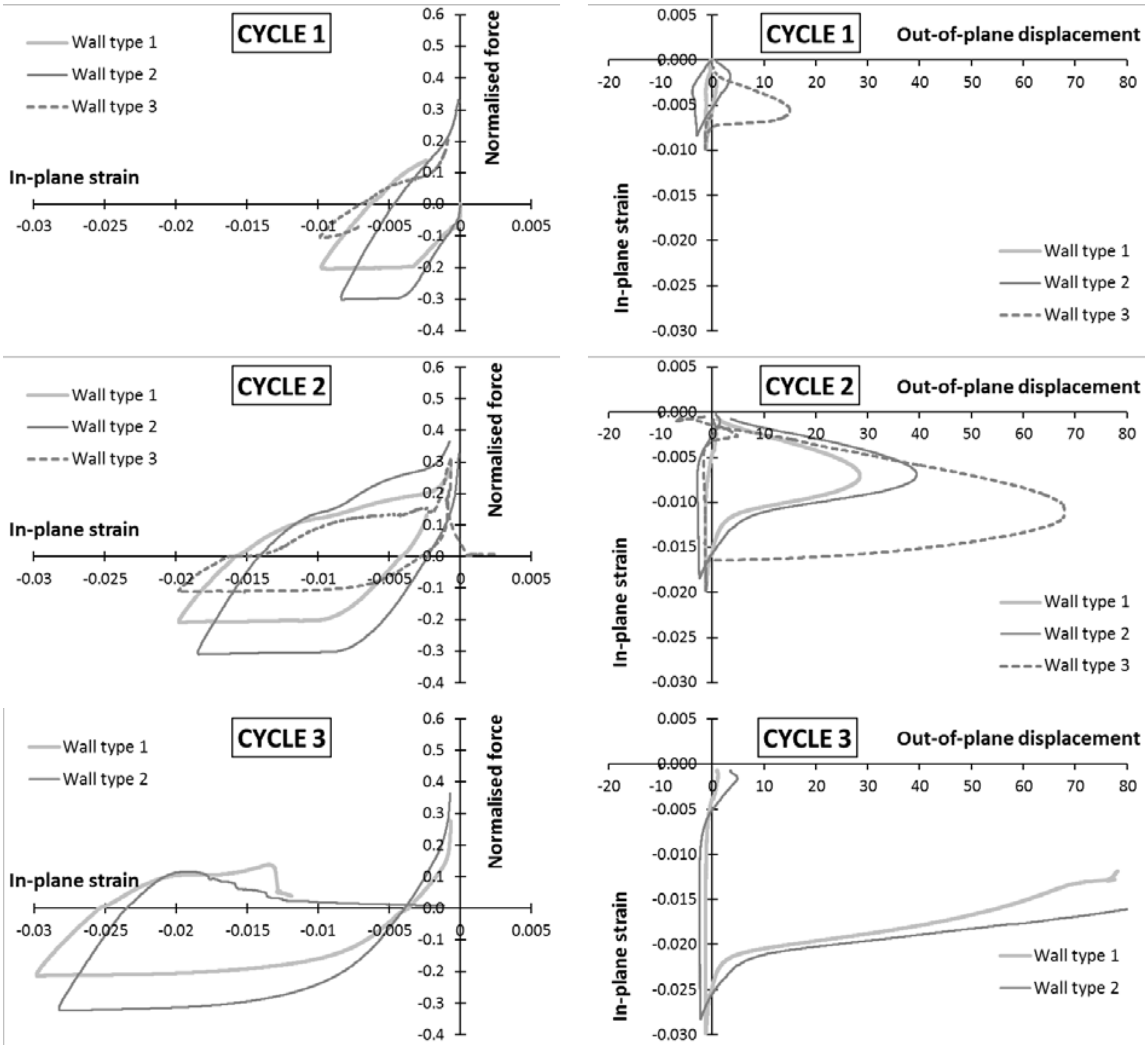
(a) Axial tension **(b) Crack closure** **(c) Local bar buckling** **(d) Wall failure**

Figure 5. Wall type 3 axial tension-compression failure (load cycle 2) showing local bar buckling failure.

Table 2. Experimental test results for axial compression tests of limited ductile RC walls.

	Wall type 1	**Wall type 2**	**Wall type 3**	**Comments**
$f_{cm} =$	44.7 MPa	54.8 MPa	53.9 MPa	Cylinder strength
$N_{wall} =$	2040.3 kN	~2500 kN	1954.0 kN	Compressive strength
$N_{AS3600} =$	1271.9 kN	1559.3 kN	1533.7 kN	AS 3600 strength*
$N_{gross} =$	2615.0 kN	3205.8 kN	3153.2 kN	$N_{gross} = A_g \times f_{cm}$
$N_{wall} / N_{AS3600} =$	1.60	1.60	1.27	Ratio of actual to code strength
$N_{wall} / N_{gross} =$	0.78	0.78	0.62	Ratio of actual to gross strength

*Axial compressive strength to AS 3600 Clause 11.5 (Standards Australia 2009)



Note:

Normalised force equals the axial force divided by the compressive strength of the wall. In-plane strain is the average axial strain across the height of the wall (i.e. axial displacement divided by the height of the wall). Out-of-plane displacement is the out-of-plane displacement at mid-height of the wall.

Figure 6. Experimental test results for axial tension-compression tests of limited ductile RC walls.

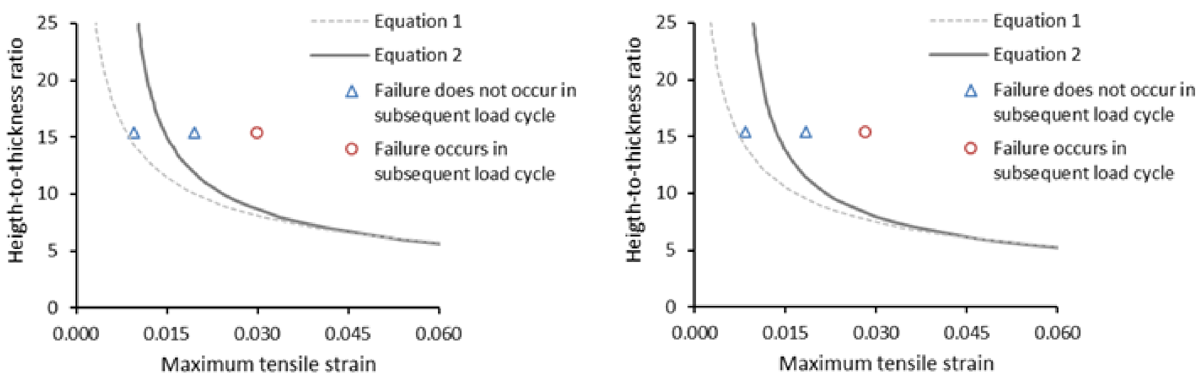


Figure 7. LEFT: wall type 1 comparison. RIGHT: wall type 2 comparison.

5 CONCLUSIONS

This paper has presented the initial findings of a current research program investigating the out-of-plane buckling behaviour of limited ductile RC walls. The experimental study summarised herein showed that slender walls with two layers of vertical reinforcement and a height-to-thickness ratio of approximately 15 can undergo tension strains up to 2 per cent without out-of-plane buckling occurring in subsequent reversed loading cycles. However, after the walls underwent higher tension strains, out-of-plane buckling ensued. In contrast, the lightly reinforced wall with one layer of centrally placed vertical reinforcement could only undergo a significantly lower tension strain of 1 per cent before failure occurred in the subsequent reversed loading cycle. Unlike the heavier reinforced walls, the failure mode in this instance was local buckling of the vertical reinforcement. This suggests lightly reinforced walls, irrespective of the slenderness, with essentially unconfined vertical reinforcement (i.e. typical limited ductile RC construction) are highly susceptible to local bar buckling failure after undergoing very small tension displacements.

Further work is being undertaken to understand and predict local bar buckling failures in limited ductile walls. Continued research efforts are being directed at developing numerical models of the experimental studies to aid in the development of a robust multi-tier design model for preventing the out-of-plane buckling of limited ductile RC walls.

6 ACKNOWLEDGEMENTS

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