LATERAL INSTABILITY OF DUCTILE STRUCTURAL WALLS: STATE-OF-THE-ART

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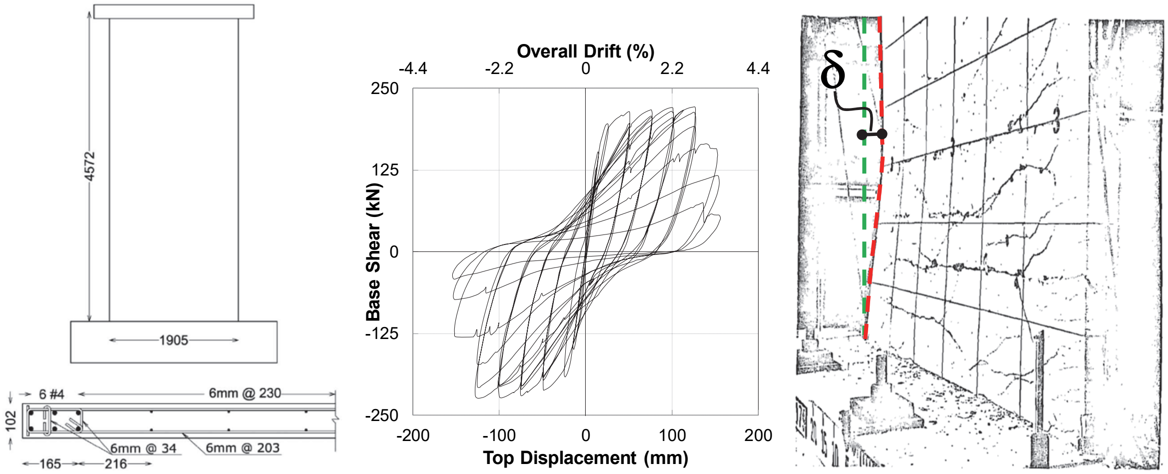
Abstract
Following observations of out-of-plane instability in slender ductile structural walls in some recent earthquakes, this mode of wall failure has been and is being investigated by several research groups. Analytical, numerical and experimental investigations have been conducted to study this failure mechanism as well as its controlling parameters. Both singly reinforced and doubly reinforced concrete walls have been studied under uni-directional and bi-directional loading. A simplified approach making use of concrete columns representing boundary zones of rectangular walls has also been used to reduce the computational and experimental costs of the research programs. This paper provides a state-of-the-art on the research conducted on this failure mechanism and the corresponding findings.

Introduction

According to the observations made in recent earthquakes in Chile and New Zealand, lateral instability (also referred to as out-of-plane buckling) of a large portion of rectangular walls was one of the failure patterns that raised concerns about the performance of shear wall buildings designed using modern codes (Sritharan et al. 2014). Prior to the Chile earthquake, this failure mechanism had only been primarily observed in laboratory tests (Oesterle et al. (1976), Goodsir (1985), Thomsen IV and Wallace (1995), Beattie (2004), Johnson (2010)). Out-of-plane buckling or instability due to in-plane loads refers to buckling of an end region of a wall section, where development of large tensile strains followed by a load reversal can result in exertion of large compressive actions on reinforcing bars of a cracked section, thus providing a critical situation for instability of the section. This failure mode (i.e. instability) can be exacerbated by any inherent eccentricities in the load application in addition to non-uniformity of material response (e.g., reinforcement yielding) along the wall thickness. Observations of this mode of failure in two wall experiments, which were not designed to investigate this mode of behavior are summarized as below.

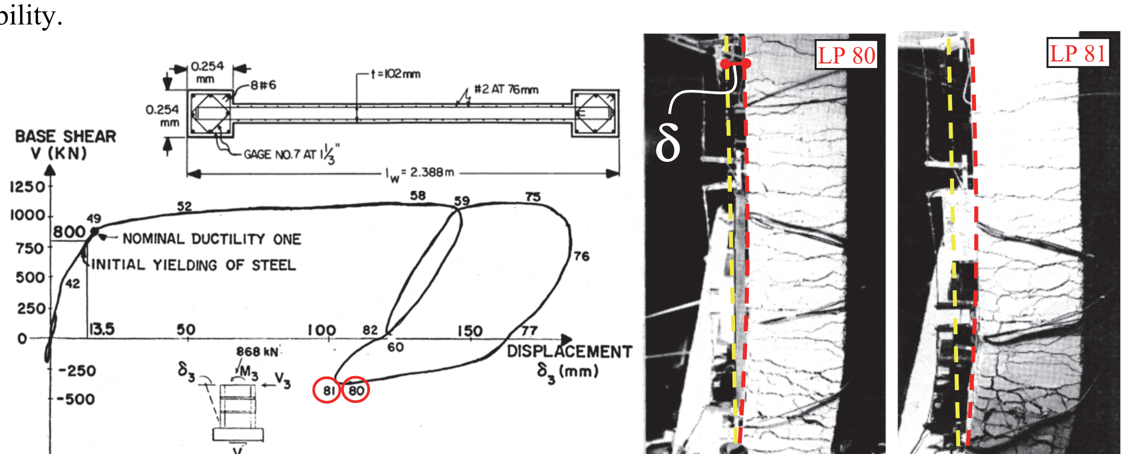
PCA Wall Experiments (Oesterle et al. 1976). Specimen R2 (Oesterle et al. 1976), was a relatively slender RC wall with an aspect (height-to-length) ratio of 2.4 and no axial load, subjected to a low shear stress demand. The dimensions and reinforcement detailing of this specimen are illustrated in Figure 1a. This specimen started to exhibit out-of-plan deformation after being exposed to three cycles at 1.7% drift. The maximum value of this initial out-of-plane displacement, which was measured at a point 1.1 m above the base, was 6.4 mm. Although this out-of-plane deformation progressed further with each cycle, the load carrying capacity of the wall remained stable. Figure 1b displays the base shear versus top displacement response of the specimen. The test was stopped after the 2nd cycle at 2.2% drift, during which the maximum out-of-plane movement reached 76.2 mm (as shown in Figure 1c), and a lateral support was provided at the level of 1.1 m. A large out-of-plane deformation was observed within the lower 1.1 m during the 2nd cycle at 2.8% drift accompanied by about 20% reduction in the load carrying capacity. Several bars fractured during the 1st cycle at 3.3% drift and the out-of-plane displacement progressed further. The load carrying capacity continued to decrease during the 2nd and 3rd cycles at 3.3% drift along with considerable crushing and loss of concrete.



(a) (b) (c)

Figure 1. Response of Specimen R2: (a) dimensions and reinforcement detailing; (b) load-displacement response; (c) out-of-plane displacement during the 2nd 2.0% drift

EERC Wall Experiments (Vallenas et al. 1979). Vallenas et al. (1979) observed instability of the boundary zones in three of the tested wall specimens (Specimens 3, 5 and 6). Specimen 3 was an I-shaped specimen with the boundary zone thickness more than two times of the panel thickness (as shown in Figure 2a). The instability developed after unloading the specimen from a monotonic displacement equivalent to about 6.0% drift and during reloading in the opposite direction. The quantity of the average tensile strain developed in the bottom 700 mm (25% of the height) of the boundary region at the peak displacement (6.0% drift) was about 0.1 and the out-of-plane displacement was observable when this strain was reduced to about 0.08. Figure 2a shows the base shear versus top displacement response of the specimen. Load points (LP) are indicated in this figure. Load point 80 is the stage where the instability of the boundary column was observed. The load was able to increase only slightly up to LP 81 when the column completely buckled. This point marked the end of the test and the specimen was unloaded at LP 82. Figure 2b shows the rather abrupt development of out-of-plane instability in the specimen during LPs 80 and 81. No other failure modes (such as bar fracture, bar buckling, concrete crushing) were reported in this boundary column before the initiation of buckling. Therefore, this instability had progressed independently with no interactions with other failure modes and could be considered as the global type of instability.

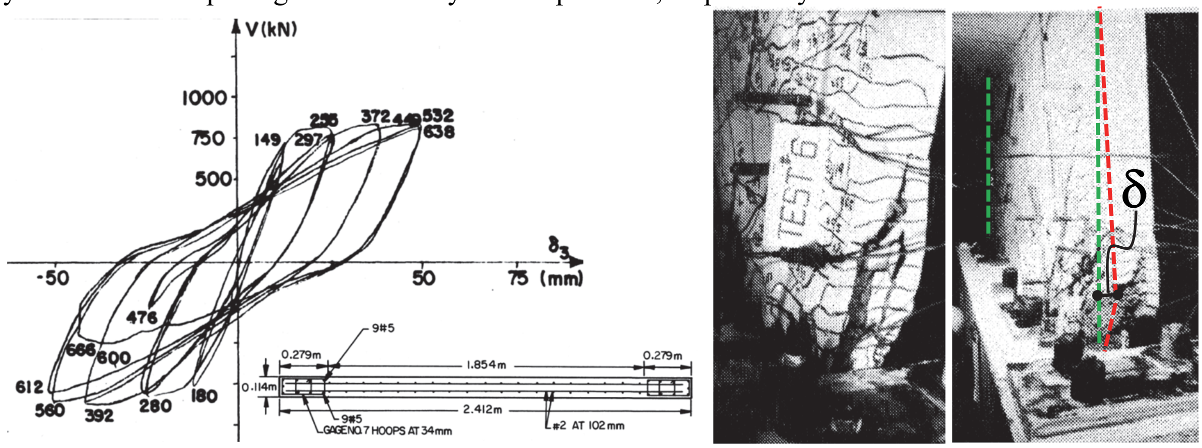


(a) (b)

Figure 2. (a) Cross section detailing and base shear versus top displacement response of Specimen 3 (Vallenas et al. 1979); (b)out-of-plane instability of the specimen

Specimen 5 was a rectangular wall subjected to a monotonic loading protocol. The specimen was loaded up to 2.5% drift level, where a significant drop of strength was observed after rupture of a lateral confinement hoop followed by buckling of longitudinal bars at the base of the compressive column and development of out-of-plane deformation. During unloading and reloading in the opposite direction, compression was introduced in the column that had a large number of residual open tensile cracks, resulting in evolution of out-of-plane deformation in this region. The progression of this out-of-plane deformation was however intervened by a flexural shear crack and the concrete crushing that propagated all the way through the specimen. At this point the load dropped and the specimen failed.

Specimen 6 had the same detailing as Specimen 5 but was subjected to a cyclic lateral loading. During the second cycle at 1.7% drift cover concrete spalled on one side of the compression boundary zone and resulted in its instability, taking part of the wall panel along with it. At this point the lateral load capacity of the specimen dropped and the test was terminated. The cross-section detailing and base shear versus top displacement response of this specimen are displayed Figure 3a. Figure 3b and Figure 3c indicate the asymmetric cover spalling and instability of the specimen, respectively.



(a) (b) (c)

Figure 3. (a) Cross section detailing and base shear versus top displacement response of Specimen 6 (Vallenas et al. 1979); (b) asymmetric cover spalling at the base; (c) instability of the specimen

This paper puts together the methodologies used in recent years for tackling this complex response of structural walls. The research activities conducted in this area can be classified into three groups of analytical, numerical and experimental investigations.

Analytical Predictions

The out-of-plane instability of rectangular walls has generally been addressed using analytical approaches. As there are not many test results on initiation and development of this mode of failure, some assumptions such as the height of the wall involved in formation of the global buckling (buckling length) have been made in these postulations.

Paulay and Priestley (1993) scrutinized the mechanism of out-of-plane instability by idealization of the part of the wall height that has undergone out-of-plane deformation with a circular shape and used the section equilibrium to establish a stability criterion for the section undergoing out-of-plane deformations. According to Paulay and Priestley (1993), in addition to this criterion, out-of-plane instability of the section will occur if the lateral displacement exceeds half of the wall thickness.

Chai and Elayer (1999) studied the out-of-plane instability of ductile RC walls by idealizing the end-region of the wall as an axially loaded RC column, and conducted an experimental study to examine the out-of-plane instability of several RC columns designed to represent the end-regions of a ductile planar RC wall under large amplitude reversed cyclic tension and compression. Chai and Elayer (1999) used the same stability criterion as Paulay and Priestley (1993) and considered some different assumptions to calculate the maximum tensile strain corresponding to evolution of this failure pattern. Using the buckling mechanisms described by Paulay and Priestley (1993) and Chai and Elayer (1999), Moyer and Kowalsky (2003) proposed a tension-based buckling model for reinforcement in concrete columns, recognizing the reinforcing bars as the sole source for compression zone stability in a fully cracked section. Chai and Kunnath (2005) investigated the minimum thickness requirements to safeguard against development of out-of-plane instability in ductile RC structural walls. A methodology for assessment of the minimum wall thickness with the parameters that are involved in the current use of structural walls was proposed. For this purpose, the link between wall thickness and a number of parameters including the ground motion intensity, longitudinal reinforcement ratio, floor weight, wall-to-floor area ratio and number of stories was scrutinized.

Parra and Moehle (2014) hypothesized two different mechanisms resulting in instability of slender walls. One hypothesis follows the postulations presented by Paulay and Priestley (1993), recognizing the previously experienced maximum tensile strain as the parameter triggering instability of a cracked wall section subjected to loading in the opposite direction. The second hypothesis postulates that the out-of-plane instability is due to concrete crushing that leaves an irregular/reduced cross section creating ideal circumstances for lateral instability under monotonic loading or under tension and compression cycles. These hypotheses are in line with the two types of buckling first proposed by Vallenas et al. (1979) as described earlier. A theory based on the analytical models proposed by Paulay and Priestley (1993) and Chai and Elayer (1999) was applied by Parra and Moehle (2014) to tests of reinforced concrete prisms and wall units as well as to two Chilean buildings that had some buckled walls after the 2010 Chile earthquake. Herrick and Kowalsky (2016) investigated the parameters that are influential on out-of-plane buckling of ductile walls and re-examined the previously proposed buckling models using the results of prior experimental work as well as time history analyses of buildings subjected to the 2010 and 2011 New Zealand earthquakes.

Numerical Models

Although various models (including both macroscopic and microscopic models) have been proposed for numerical modeling of structural walls, the simulation of out-of-plane instability failure has seldom been attempted because of the challenges related to the nonlinear geometrical and material behaviour, as well as the lack of experimental data for comparison purposes. Attard et al. (1996) derived a model based on plate bending elements for calculating the buckling load of reinforced concrete walls under monotonic loading. The model did not incorporate the instability of the cracked region under the axial compression imposed by cyclic loading and was validated against experimental results of 24 simply-supported reinforced concrete panels under uniform compression.

Simulation of out-of-plane instability using macro models seems rather complicated as its evolution depends on the local material response. The FEM models, however, are able to predict buckling/instability modes of response when a fine mesh across the 3D directions are adopted along with large deflection formulations. An accurate prediction of the 3D response of structural walls can therefore be provided using solid elements in a finite element modeling approach. Mesh discretization along the thickness direction can represent the variation of material properties along this direction due to the effect of confinement in the core region. However, the complexity of generating the model and conducting the analysis associated with this method, particularly with a decent mesh size, would put a limit on practicality of this approach. Models composed of nonlinear shell-type finite elements, which are less computationally demanding, are also able to capture the nonlinear strain profile along the wall length and axial-flexure-shear interaction, thereby enabling them to reliably predict different failure mechanisms of walls. If the mesh density is sufficient and the large deflection formulation is used, overall wall buckling can be captured by this modeling and analysis approach, as well (Maffei et al. 2014).

Dashti et al. (2014a) and Dashti et al. (2014b) proposed a microscopic (FEM) modeling technique using curved shell elements available in DIANA commercial program for numerical modeling of structural walls. The model could reasonably simulate nonlinear response of structural walls and predict the out-of-plane deformation that was observed in several rectangular wall specimens under in-plane loading. The nonlinear response of concrete and rebar elements in the model showed that during unloading and reloading of a cracked wall section, compression was taken by the reinforcement only, until the existing cracks in concrete closed and concrete started contributing to the load-carrying capacity. This phenomenon is mainly controlled by residual strain of the reinforcement and was easily captured by the program using its path-dependent cyclic constitutive models. At this stage, the wall section was more likely to deform in a pattern that requires less energy. In this method, there was no need to make use of an artificial eccentricity that introduces a secondary bending moment, and out-of-plane deformation could be captured under pure in-plane loading through numerical computations based on the energy consumed by different possible modes of deformation. A comprehensive validation of the model was conducted by Dashti (2017), Dashti et al. (2017a), Dashti et al. (2018a) and Dashti et al. (2018b) which mainly focused on verification of the out-of-plane instability simulated by the model using results of several tested wall specimens as well as a blind prediction. To the authors' knowledge, no finite-element models reported in literature were previously verified for simulation of out-of-plane instability in rectangular walls under concentric in-plane cyclic loading. Parra (2016) used the modeling approach proposed by Dashti et al. (2014b) to investigate the out-of-plane response of wall units and the corresponding boundary zones. However, an artificial eccentricity was introduced in the material properties across the wall thickness in this study to trigger this mode of failure. Rosso et al. (2017a) simulated the response of thin RC columns prone to out-of-plane instability using this method. Scolari (2017) compared the out-of-plane response captured by PARC_CL 2.0 crack model with the one predicted by this model.

Experimental Studies

Boundary Zone Testing. The out-of-plane instability of rectangular reinforced concrete walls under in-plane loading has been mainly investigated by idealizing the boundary region of the wall as an axially loaded column. For this purpose, RC prism units were subjected to tension and compression cyclic loading. This type of research on out-of-plane instability failure was first conducted by Goodsir (1985) and the main finding was the effect of the maximum tensile strain reached in the reinforcement on development of out-of-plane deformations. Chai and Elayer (1999) also conducted an experimental study to examine the out-of-plane instability of several RC columns that were designed to represent the end-regions of a ductile planar RC wall under large amplitude reversed cyclic tension and compression. Based on this study, the critical influence of the maximum tensile strain on the lateral instability of slender rectangular walls was confirmed and the basic behaviour of the wall end-regions under an axial tension and compression cycle was described by axial strain versus out-of-plane displacement and axial strain versus axial force plots. Also, based on a kinematic relation between the axial strain and the out-of-plane displacement, and the axial force versus the axial strain response, a model was developed for the prediction of the maximum tensile strain. The effect of the specimen thickness was also studied in this research.

Acevedo et al. (2010) investigated the performance of non-special boundary elements under monotonic axial loading. Creagh et al. (2010) and Chrysanidis and Tegos (2012) subjected concrete prisms to tension and then compression until failure. The results of these experiments confirmed the effect of maximum tensile strain developed during the tensile loading on out-of-plane instability of the specimen during the compressive loading. In another test campaign by Shea et al. (2013), the influence of specimen thickness as well as the maximum tensile strain was investigated. Hilson et al. (2014) investigated the influence of spacing and configuration of transverse reinforcement as well as load history on the response of rectangular columns representative of ordinary boundary elements in thin structural walls. In a similar study by Welt et al. (2016) and Taleb et al. (2016), the influence of reinforcement detailing, cross-section slenderness, and loading pattern on the failure modes of isolated confined boundary zones of rectangular walls was scrutinized. Rosso et al. (2017b) studied the parameters affecting the out-of-plane response of singly reinforced walls using cyclic tensile-compressive tests on the corresponding boundary elements. Haro et al. (2018) included bi-directional loading protocols in the RC prism testing and scrutinized the effect of the longitudinal reinforcement ratio on the onset of out-of-plane instability in planar walls. According to the observations of this study, the axial tensile strains corresponding to buckling are not influenced by application of out-of-plane displacements.

Wall Unit Testing. The out-of-plane instability failure and the affecting parameters have not been the main research objective in the past experimental research. However, this mode of failure was observed and measured in several experiments. Rosso et al. (2015) provided an inclusive summary of these experiments which were conducted by Oesterle et al. (1976), Goodsir (1985), Thomsen IV and Wallace (1995), Johnson (2010) and Rosso et al. (2014). This data showed that all collected test units had some common features in their response; in particular, reaching the same order of magnitude of maximum tensile strains, and observation of the maximum out-of-plane displacement at approximately 0% in-plane drift.

Rosso et al. (2015) investigated the out-of-plane failure mode of walls by analyzing the response of two singly reinforced walls tested under cyclic loading as part of an experimental campaign on five thin T-shaped walls (Almeida et al. 2017). The specimens were identical but were subjected to two different in-plane and bi-directional loading patterns. One of the issues that was well elaborated in this study was the difference between the effective buckling length assumed in the analytical models and the one observed in the test. Rosso et al. (2015) observed that the application of an out-of-plane displacement at the top of the wall increases the global out-of-plane deformation if it is applied in the opposite direction of the latter and vice versa. The evolution of out-of-plane instability was also observed in several limited ductile walls with tested by Menegon et al. (2015). The specimens had a height-to-thickness ratio of approximately 15 and were designed to be representative of Australian construction practice.

An experimental campaign was recently conducted on the parameters that were identified by numerical simulations to be influential on evolution of out-of-plane instability in doubly-reinforced planar ductile walls (Dashti 2017, Dashti et al. 2017b, Dashti et al. 2017c). Evolution of out-of-plane instability in one of the specimens (Specimen RWL), which was not affected by any other failure modes is described in detail by Dashti et al. (2018c). Two types of instability, namely global (main failure) and local (secondary failure), were observed (Dashti et al. 2018d). Unlike local instability that is developed due to asymmetry generated in the wall cross section by another preceding mode of failure (such as bar fracture, bar buckling or concrete crushing), global instability is identified as an independent mechanism evolving as a result of compression yielding of longitudinal reinforcement along a sufficient height of the wall with residual cracks. Analytical models proposed in the literature for prediction of out-of-plane instability in rectangular walls are developed based on the global instability mechanism, recognizing this mode of response to be evolved due to dependency of the compression load carrying capacity solely on the rebars within a specific height (denoted as buckling length) of the wall. The same philosophy applies when the numerical models exhibit out-of-plane deformation during loading reversal from a lateral displacement that induces a large in-plane curvature demands. The characteristics of the out-of-plane instability observed in several wall buildings after the Chile and New Zealand earthquakes are also more in line with the global mode of failure.

Conclusions

Out-of-plane instability of RC walls has required more attention following observations of this complex mode of behavior in the 2010 Chile and the 2011 New Zealand earthquakes. Analytical, numerical and experimental studies have been conducted on full wall units as well as concrete columns that represent wall boundary zones. The analytical models have generally been developed based on the section equilibrium equations derived by Paulay and Priestley (1993). Out-of-plane instability of ductile structural walls under concentric in-plane cyclic loading was numerically simulated for the first time by Dashti et al. (2014a). This modeling approach, which is based on curved shell finite element formulation, has been extensively used for investigation of this failure mechanism (Parra 2016, Scolari 2017, Daza

Rodríguez 2018). Rosso et al. (2015) and Rosso et al. (2017b) were the first to study the out-of-plane response of singly reinforced walls and the controlling parameters using wall units and boundary zones. An experimental study on out-of-plane response of doubly reinforced walls was conducted by Dashti (2017), based on which the out-of-plane instability of rectangular walls under in-plane loading was classified as global and local (secondary) modes of failure. The characteristics of the global out-of-plane instability observed in this study (Dashti et al. 2018c) are more in line with those of the analytical and numerical predictions as well as post-earthquake observations.

Acknowledgements
The authors wish to acknowledge the financial support provided by the Natural Hazard Research Platform (NHRP), the Ministry of Business, Innovation and Employment (MBIE) and the Quake Centre at University of Canterbury to conduct this research.

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