Numerical analysis of out-of-plane deformation of shear wall

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Abstract. An important factor in slender reinforced concrete shear wall design is the out-of-plane instability, identified as one of the main failure modes. Previous experimental researches had observed this failure in T-shape slender walls as well as rectangular walls. This paper describes the development of out-of-plane instability of slender shear walls with different end configuration which subjected to in-plane quasi-static lateral loading. Experimental results of a T-shape thin wall specimen which failed in out-of-plane mode were used for verification of the modelling, using finite element nonlinear static analysis. The numerical analysis results were in good agreement with the experimental results and the overall global response of shear wall can be predicted using finite element analysis. Series of models were developed to scrutinize the major sources governing the out-of-plane instability. Based on the investigation, shear to span ratio, axial load ratio, wall thickness, and different end configurations of the boundary element are identified as the main parameters governing the wall instability.

1. Introduction
Shear wall clearly able to resist combinations of shear, moment and axial load induced by lateral and gravity loads transferred from other members as a structural vertical member. Reinforced Concrete walls instability is commonly correlate with out-of-plane unsteadiness which result to failure modes of reinforced concrete (RC) walls. Previously, such failures detected in a trial and error studies with use of rectangular walls and has drawn tons of consideration to the following failure mechanisms of several walls in the recent earthquakes in Chile and Christchurch [1]. A limited number of major works have been issued on out-of-plane stability of RC walls with respect to in-plane loading [2, 3]. Such studies describe the basic mechanics of the phenomenon, identify some of the fundamental features triggering a potentially unstable wall behavior, and propose simple models.

Lateral stability of walls are merely depends on out-of-plane buckling of thin walls which leading supreme inelastic tensile strain on the vertical wall edge regions [2, 3] claimed that large tensile strains, developed as a result of significant yielding in the wall due to earthquake will cause consequences on the wall stability with respect to the magnitude of the tensile strain imposed. A critical condition exists where excessive out-of-plane displacement may occur upon load reversal prior to crack closure causing the wall to buckle. They studied the minimum wall thickness required to ensure that the in-plane lateral strength can be fully developed in the reversed direction to overcome the instability of walls.
Recently, many experimental works have been conducted to investigate the out-of-plane behavior of RC shear walls [4, 5, 6, 7, 8, 9]. This is due to the occurrence of 2010 Chile and 2011 New Zealand earthquakes, where many walls were found to fail in out-of-plane. In general, the studies revealed that significant out-of-plane displacement occurred with the use of one layer of longitudinal reinforcement, and the buckling zone covers roughly the entire storey height and is not limited to the predicted plastic hinge region. Walls with boundary element (flanges) were found to perform better compared to rectangular walls in terms of ductility. The axial load ratio plays a very important role in the displacement capacity, where the capacity of the walls was reduced almost by half when the axial load ratio increases from 0.15 to 0.35. When the thickness of the wall is reduced, the deformation capacity and ductility decrease, and walls are more susceptible to brittle compressive failure.

Very limited finite element models have been developed to investigate this phenomenon. [10] investigated the ability of finite element analysis to predict nonlinear behavior and failure patterns of RC structural walls using shell element with embedded bar. They found that the model predictions were in reasonably good agreement with the experimental measurements for all specimens. The study discovered that the primary parameters governing the wall instability are wall length, slenderness ratio and axial load ratio. Simultaneously, elasticity of material properties have direct effect on axial load ratio.

Due to the high cost, time consuming and complexity of the experimental setup for these types of researches, the numerical simulation of finite elements is the best alternative to investigate the behavior of the RC wall and its damage mechanism. Nevertheless, there is not many papers reported on the out-of-plane of the reinforced concrete shear wall using the finite element modelling. In this study, the out-of-plane failure mechanism of the RC wall is investigated numerically using finite element analysis based on existing experimental result from [9]. Next, parametric study is conducted to investigate the factors effecting the out-of-plane failure on a wall panel and a 5-story RC wall.

2. Case Study
The capability of finite element analysis to model the out-of-plane deformation of shear walls is verified using the result of experimental study by [9] as shown in Figure 1. This structure failed in out-of-plane buckling with its maximum displacement of 44mm. The wall dimensions were 2000mm height, with thickness of 80mm and length of 2700mm. The longitudinal reinforcement consists of a single layer of T16 at 100mm spacing and T6 at 200mm spacing, while the horizontal reinforcement consists of T6 bars with spacing of 200mm.

![Figure 1. Geometrical characterization and detailing of test unit TW1 [9]](image_url)
2.1. Material properties
In this study, material nonlinearity of concrete and steel reinforcement property are modelled to ensure accurate structural behavior could be observed. Isotropic material properties will be set to the concrete and the reinforcement bars to stimulate the nonlinear behavior of the concrete and the steel bars. Steel was assumed to behave as an elastic-plastic material in both tension and compression with equal yield conditions. The yield stress, $f_y$, is taken as 550MPa and modulus of elasticity, $E_s$ is 200GPa.

The response of a wall under load depends on the stress-strain relation of the constitutive model of the materials and the magnitude of stress. Since concrete is used mostly in compression, the stress-strain relation in compression is of primary interest. The concrete stress-strain relation exhibits nearly linear elastic response up to about 30% of the ultimate compressive strength. This is followed by gradual softening up to the concrete compressive strength, when the material stiffness drops to zero. Beyond the compressive strength, the concrete stress-strain relation exhibits strain softening until failure takes place by crushing. Table 1 shows the mechanical properties of the concrete used in all the models. The stress-strain behavior for both confined and unconfined concretes were modelled based on constitutive model by [11].

| Properties                | Values   |
|---------------------------|----------|
| Compressive strength      | 31.2 MPa |
| Density                   | 2,400 kg/m³ |
| Modulus of elasticity     | 26.3 GPa |
| Poisson’s ratio           | 0.2      |
| Tensile strength          | 2.07 MPa |
| Fracture energy/ unit area| 73.6 N/m |
| Strain at peak compressive stress | 0.0022 |

2.2. Element modelling
Embedded bars with combination of nonlinear shell elements were used to simulate the RC walls. The shell elements can be used for capturing buckling and post-buckling responses based on isoperimetric degenerated solid approach. Six degrees of freedom are defined in every element node: three translations and three rotations. Three types of section area with different material properties and reinforcement arrangements were used in the shell. Confined concrete shell element represents the boundary of the web and the flange wall, while unconfined concrete shell element to represents the mid-part of the web of the wall. The quadratic elements were meshed with uniform size of 50mm×50mm in order to get accurate results.

2.3. Loading and boundary conditions
An axial load was applied to the top of the shell element as shown in Figure 2, where the wall carries an axial load ratio of 0.05. Beside the gravity nonlinear static load case which represent the dead load and axial load, a new load case was defined as nonlinear static load case to stimulate the lateral quasi-static load at the top right side of the wall. Nonlinear pushover analysis was used to determine the overall behaviour of the shear walls. In the pushover analysis, the lateral forces were applied up to failure of the structure. Member forces were calculated for each step and the stiffness of the members were recalculated accordingly. This process ends when the structure becomes unstable. In this study, displacement control was used for the pushover analysis. Geometric nonlinearity effects were included in this analysis.
The bottom nodes were restrained against translation and rotation in all directions (fixed support), while the top nodes were constrained against translation in the out-of-plane direction (y-plane) as shown in Figure 2.

**Figure 2.** Loadings and boundary conditions of shear wall in case study

### 3. Parametric Study

Several parameters were investigated in this study. Different geometry, height, thickness, axial load ratio and arrangement of reinforcement were modelled to investigate the major sources of out of plane deformation in shear walls. The summary of walls used in this study is summarized in Table 2.

#### Table 2. Summary of shear wall models

| Model | Geometry   | Layers of renf. | Length (mm) | Height (mm) | Thickness (mm) | Axial load ratio (%) |
|-------|------------|-----------------|-------------|-------------|-----------------|----------------------|
| T1    | T-shape    | 1               | 2700        | 2000        | 80              | 0.05                 |
| T2    | T-shape    | 1               | 2700        | 2000        | 80              | 0                    |
| T3    | T-shape    | 1               | 2700        | 2000        | 80              | 0.1                  |
| T4    | T-shape    | 2               | 2700        | 2000        | 150             | 0.05                 |
| T5    | T-shape    | 1               | 2700        | 4000        | 80              | 0.05                 |
| R1    | Rectangular| 1               | 2700        | 2000        | 80              | 0.05                 |
| R2    | Rectangular| 2               | 2700        | 2000        | 150             | 0.05                 |

#### 3.1. Effect of the top moment to the out-of-plane instability

All the previous models were one story walls under lateral load (Figure 2) without any effect of top-wall moment. In a multi storey building, the walls will have to resist not only shear force, but also the cumulative moment from the floors above, as shown in Figure 3(a). To capture the effect of the additional bending, a five story wall were developed to study the behaviour of the wall at the bottom. This lateral load was stimulated as a pushover load case concentrated at the top left node of story number five. The wall is of 10m height and 2.7m in length. All material properties, dimensions, loadings and boundary conditions were similar to the TW1 model by [9]. In each story level, the wall was constrained against the out-of-plane displacement as shown in Figure 3(b).
4. Results and Discussions

4.1. Finite element model verification

In wall T1, significant out-of-plane displacement was observed and shown in Figure 4. Based on the experiment by [9], the maximum out-of-plane displacement ($\delta_{opp}$) for T1 is 44mm, occurring around mid-height of the wall at 755mm from the base. The maximum out-of-plane displacement obtained from the numerical analysis is 40.1mm occurred at the height of 800mm from the base, as illustrated in Figure 4. The findings indicate good agreement between the experimental and the numerical results.

Figure 4. Out-of-plane displacement at different wall heights for wall T1

An important input key for the evaluation of the out-of-plane stability of walls is the height where the out-of-plane displacement develops ($l_0$). It was suggested by [2] and [12] that $l_0$ should be taken as the equivalent plastic hinge length, $l_p$, where large tensile strains developed over the lower part of the wall. It is suggested that $l_0$ should be less than 80% of the clear unsupported height of the shear wall.
(which is typically equal to the story height \( h_w \)). However, as observed from the results of T1, the out-of-plane deformation extends through the entire wall height \( (l_0 = h_w) \).

### 4.2. Out-of-plane instability parameter

According to the repeated tests of rectangular and T-shape structural walls, tensile strain of the boundary zone found to be the main source out-of-plane instability under in-plane loading of RC structural walls. Other parameters are the wall height, length, thickness, axial load ratio, number of reinforcement layers and wall geometry.

1. Axial load ratio

   The axial load ratio (ALR) is one of the key constraints that involves in failure modes of reinforced concrete shear walls. To examine the consequences of this constraint on the out-of-plane instability, 0, 0.05 and 0.1 percent of ALR were assigned to three models (T2, T1 and T3 respectively) having the same mechanical properties and geometry (Table 2). Figure 5 shows the out-of-plane displacement throughout the wall height at different ARL based on finite element analysis.

   The out-of-plane displacement of wall with 0 percent ARL is 17.8mm, corresponding to the normalized out-of-plane displacement \( (\zeta_{oop}) \) of 0.22% of the wall thickness. As the ALR increases to 0.05 and 0.1 percent, the out-of-plane displacement increases by 56% and 68%, indicating its significant effect to the structure. The maximum capacity of the wall to resist any out-of-plane displacement decreased with the increase in ALR.

   ![Figure 5. Effects of axial load ratio to the out-of-plane displacement](image)

2. Wall thickness and number of steel reinforcement layers

   Two models with different wall thicknesses were developed. T1 and T4 had the same mechanical properties, geometrical shape and ALR (0.05%), but with different wall thickness and steel reinforcement layers. The thickness of wall T1 was 80 mm with one layer of reinforcement, while T4 was 150mm in thickness with two layers of reinforcement. Figure 6 shows the results obtained from the finite element analysis. As shown, when two layers of reinforcement was used with increased thickness, the out-of-plane displacement reduced by 86%, indicating that proper design is necessary to avoid this undesirable failure mode.
Figure 6. Effects of wall thickness and number of steel reinforcement layers to the out-of-plane displacement

As the thickness increase with increasing in the wall’s web boundary section area, multiple smaller cracks developed instead of one big crack. When unloading, these cracks are closed faster than those cracks in a slenderer wall (small thickness). Therefore, the wall thickness is considered one of the key parameters which can control the out-of-plane instability failure as the crack closure will occur more readily for thicker walls compare to thin RC walls for certain out-of-plane displacement.

3. Wall height (shear span ratio)
To investigate the behaviour of wall height in the out-of-plane instability, wall T5 is modelled with properties given in Table 2, and mechanical properties similar with model T1. The wall height of wall T1 is 2000mm and having shear span ratio of 0.741, while wall T5 has height of 4000mm with shear span ratio of 1.48. Figure 7 compares the result of wall T1 and T5 based on finite element analysis. From the figure, the maximum out-of-plane displacement was 40.1 mm at 800 mm height ($\xi_{oop} = 0.502\%$) for T1 model, while the maximum out-of-plane displacement in model T5 increases to 72.8mm at 1400mm height ($\xi_{oop} = 0.91\%$). It is noted that the deformation occurs along the whole height of the wall. [13] confirmed that the instability involved a quite significant height of the wall.

Figure 7. Effect of wall height to the out-of-plane displacement
4. Wall geometry shape (end configuration)

[5] claimed that different end configurations of reinforced concrete shear wall is considered one of the major key parameters that affect the out-of-plane instability. In this study two different models were developed with different geometry shapes. T1 to T5 models were shear walls having T-shape in one of the boundaries as in Figure 1. Walls R1 and R2 are rectangular shear wall with similar properties and dimensions as T1 and T4 respectively. Both walls T1 and R1 have web thickness of 80 mm and 1-layer reinforcement, while walls T4 and R2 have web thicknesses of 150 mm and two layers of reinforcement.

Based on finite element analysis, the result of the out-of-plane displacement throughout the wall height for each wall is shown in Figure 8. The figure shows that the maximum out-of-plane displacement for the walls with web thickness of 80mm increased from 40.1mm (T1) to 43.4mm (R1) when the end configuration is changed from T-shape to rectangular. Similar behaviour is also observed for the wall with web thickness of 150mm (T4 and R2), where the maximum out-of-plane displacement for T4 model increased when the end configuration is changed from flanged wall to rectangular wall.

![Figure 8. Effect of end configuration and wall thickness to the out-of-plane displacement](image)

The results show that the T-shaped wall with boundary element confines the wall and did not experience any out-of-plane deformation, resulting to lesser deformation at its other end. Boundary elements and flanged walls tend to have higher out-of-plane buckling resistance as observed in T1 and T4. When shear walls are subjected to higher lateral load, the larger confining areas (at the boundary element) are able to resist the cumulative increasing compressive forces. T-shape walls experienced a higher tensile strain in the boundary element compared to the rectangular walls. This effect is favorable as it increases the wall capacity to resist the out-of-plane buckling. Moreover, T4 model shows that due to higher amount of the vertical reinforcement (2 layers with 150 mm thickness of the web) at the confined region, the wall could resist higher tensile strain and therefore, a larger out-of-plane buckling resistance. The strength degradation at higher displacement level could be delayed due to the end configurations which, in turn, enhances the out-of-plane stability and improve the seismic performance of the walls. These results are also in good agreement with the experimental results found by [5] and their recommendations of the need to increase the vertical reinforcement ratio and adopt the flanged walls.
5. Lateral load and in-plane moment

The effect of cumulative moment from stories above is studied using finite element model of a five-story wall as shown in Figure 3(b). The model had the same mechanical and geometry properties, axial load ratio and shear span ratio with the T1 model. Figure 9 illustrates the result of the out-of-plane displacement throughout the building height for the five storey wall, compared to the T1 model. From Figure 9, the maximum out-of-plane displacement was increased by 5%, from 40.1mm to 44.3 mm, when the cumulative moment is considered. The in-plane moment is one of the major key parameters affecting the out-of-plane instability. Its behaviour is similar to the behavior of lateral load, where the increase in the in-plane moment causes decrease in the maximum tensile strain, leading to deformation in the out-of-plane.

![Figure 9. Effect of top moment to the out-of-plane displacement](image)

Due to high moment at the wall base, the boundary region (non-confined boundary) is undergoing high tensile strain before it fails in out-of-plane deformation. This causes the vertical reinforcement to reach the maximum tensile strain and it started to buckle (local buckling). The global buckling is a secondary effect due to the small thickness of the web and small cross section area of the vertical reinforcement (number of reinforcement layers).

Therefore, the wall height and length are the major parameters developing the tensile strain imposed on the confined region reinforcement. The axial load ratio, wall thickness and number of reinforcement layers are parameters that can control the strain profile developed along the wall length. Axial load can be the key role of loading, unloading and reloading in the crack stage as it affects the tensile strain developed in the reinforcement. Furthermore, the increase in out-of-plane instability are sourced from the axial load which also can lead to prevention of its initial displacement depending on its interaction with the other parameters. The wall thickness can control this behaviour as for a given out-of-plane displacement, crack closure will occur sooner for thicker walls. Finally, wall height to thickness ratio, axial load ratio, shear span ratio and end configuration of the boundary element are also found to be the main parameters governing the wall instability.

5. Conclusions

In this study, two-dimensional nonlinear reinforced concrete shear wall was modelled as finite element to investigate the nonlinear behaviour and its out-of-plane instability. This model has been verified against the experimental result obtained by [9] where the wall failed in out-of-plane deformation. Parametric analysis has been performed on eight models to scrutinize the development of out-of-plane instability and the main factors effecting its behavior. The following conclusions can be made:
Based on the numerical investigation, the major parameter governing the wall lateral stability is the tensile strain imposed on a reinforced concrete wall.

- Wall height to thickness ratio, axial load ratio (ALR), shear-span ratio and end configuration of the boundary element were found to effect the wall stability significantly.
- The deformability and failure mechanism of the models were affected by the axial load ratio. The maximum capacity of the wall to resist any out-of-plane displacement decreases with increase in ALR. The maximum normalized out-of-plane displacement was developed when ALR was high. Therefore, the energy dissipation of reinforced concrete shear walls is affected due to the increase of ALR.
- The web region of the wall should be adequately reinforced to increase the out-of-plane buckling resistance by increasing the tensile strain of the reinforcement.
- Boundary elements and flanged walls tend to have higher out-of-plane buckling resistance. These flanged walls have a larger confined area when compared to rectangular walls which can improve the performance in the out-of-plane direction. When the shear wall is subjected to higher in-plane displacement levels or higher lateral loads, larger confined areas (cross section areas at the boundary element) are able to resist the cumulative increasing in the compressive forces.
- The in-plane moment is considered one of the major key parameters affecting the out-of-plane instability. Its behaviour is similar to the behaviour of the in-plane loading. With the increase of the in-plane moment, the maximum tensile strain decrease and thus lead to deformation in the out-of-plane.

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