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Parametric study of reinforced concrete walls with irregular openings

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ABSTRACT: A parametric study was conducted on the walls with irregular openings to investigate the influence of critical parameters on the behaviors of these walls subjected to earthquake loadings. The parameters included the flanges, the axial load, the sizes and the positions of openings. The parameters were added to the specimens tested by the previous researchers. The study was conducted using a reliable non-linear finite element program. The load paths indicated by the principal compressive stress flows obtained from the finite element analysis were studied to understand the influence of these parameters on the force transfer mechanisms of these walls. Analytical results show that the flange and axial load increased the load carrying capacity of the walls but decrease the structural ductility. The sizes and positions of openings can decrease the strength, stiffness and ductility level of walls with opening. However, the walls could perform satisfactorily if the opening areas were limited within certain levels and the walls were well detailed to ensure the force-transferred mechanisms in the walls could function.

1 INTRODUCTION

The research on the solid walls has shown that some critical parameters, including the boundary elements, the aspect ratio, and the strength of concrete etc, can influence the behaviours of solid walls significantly. It is reasonable to think that these parameters could also impose some effects on the walls with irregular openings. However, it is difficult to consider all parameters through the ways of experimentation. With the development of the nonlinear finite element (NLFE) analysis skill, many programs have been compiled and proved that could predict accurately the behaviours of walls such as their strengths, stiffness, ductility and crack patterns. Therefore an extensive parametric study based on the reliable nonlinear finite element analysis program may give great help in the recognition of the influence of these parameters. Parametric investigation on the RC structural wall under monotonic loading performed by Lefas (1990) using the NLFE analysis program showed that the axial loading and the strength of concrete etc could increase the shear resistance capacity of solid wall while the horizontal reinforcement could give slight influence. Analysis conducted by Sittipunt (1995) on the solid walls showed that reinforced concrete walls subjected to the cyclic lateral loads exhibited types of responses that were different with those under monotonic loads. Some undesirable modes of failure might occur in this case. In this study, the program UC-WIN/MESH & UC-WIN/WCOMD (Okamura 1991) was used to investigate the influence of some critical parameters on walls with irregular openings subjected to cyclic loading. The corresponding load paths were analysed and the strut-and-tie method, which has been significantly advanced by researchers such as Collins (1986), Schlaich (1987), and Foster and Gilbert (1996) since the mid 1980's, was applied to explain the effects of the parameters. The effects of flanges, axial load and the size and arrangement of openings were focused upon in this study.

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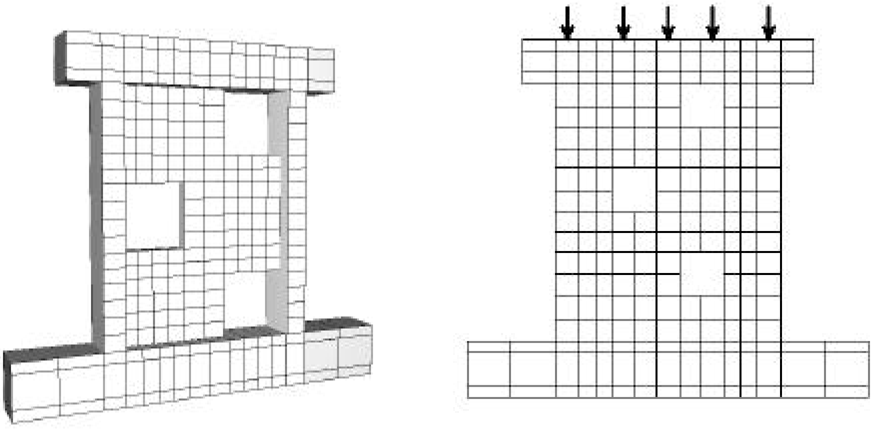
2 ANALYSIS LAYOUT

In order to investigate the influence of flanges, a $200 \times 400\,mm$ flange was added to each side of Yanez's specimens with irregular openings (S2~S4) (Yanez 1991). The same load history was applied to each wall with flanges respectively. The results were compared with the walls without flanges. Figure 1a shows the specimen S2 with flanges. A series of axial loads of between $0.05 \sim 0.2 f_c' A_g$ were added to the top of each of Yanez's and Ali's specimens (Ali 1991) with irregular openings then the same lateral loading history was applied to investigate the influence of axial loads. Figure 1b shows the application of axial loading to S4. Based on the analysis result, the effect of the size and the arrangement of the openings was discussed. The load paths showed by the principal compressive stress flows were analysed to understand the force-transferred mechanisms of these walls.



(a) Specimen S2 with flanges (b) Application of axial load to S4

Figure 1. Typical specimen and application of axial load

3 ANALYSIS RESULTS

3.1 Effect of reinforcement ratio and effect of flanges

Figure 2 shows the backbone envelopes of the loops of the load-displacement responses of specimens S2, S3, and S4 with flanges. Two groups of models with the vertical reinforcement ratios of $r_v = 0.5\%$ and $r_v = 0.8\%$ respectively in the flanges were analysed. The envelopes were compared with the experimental results (Yanez 1991), which were obtained from the specimens with vertical reinforcement ratios of about $r_v = 0.5\%$. It can be seen that the presence of flanges may increase the lateral load resistance capacity significantly. When the reinforcement ratio in the flange was correct, the walls with flanges and openings could achieve good ductility, such as $r_v = 0.5\%$ in the flange. However a little increase in the reinforcement ratio in the flange to $r_v = 0.8\%$ might increase the lateral force dramatically and changed the failure mode from the compression of concrete in the boundary element to the tension failure in the beam zones which meant shear failure became critical. In order to obtain the necessary ductility level as shown in Figure 2, the reinforcement in the beam zone was increased from 6 high strength deformed bars with diameter of 8 *mm* (6HD8) to 6 bars with diameter of 10 *mm* (6HD10). Like the observation in Yanez's experiment (Yanez 1991), the size and arrangement of the openings did not have a significant effect on the behaviours of the walls with irregular openings and flanges. As shown in Figure 2 the three specimens (S2, S3, and S4) showed the similar strength capacities and ductility levels.

Figure 3 shows the principal compressive stress flow under each lateral loading direction. The load path indicated by the stress flow was similar to that found in the wall without flange. This means the shear force was also transferred to the foundation through a strut-and-tie model considering the contribution of column zones. According to this model, about 70% and 40% of the shear force were transferred through the beam zones in the specimens S2 and S3 respectively. The maximum lateral load of these two walls then can be estimated by the reinforcement capacity (6HD10) in these zones. They were 320 kN and 373 kN, close to the finite element analysis results. The shear forces in the sections of the column zones obtained from NLFE analysis also supported the idea that the strut-and-tie model could evaluate the behaviour of wall with flanges.

The following reasons may explained why the flanges could improve the lateral load carrying capacity and keep satisfactory ductility levels in the well detailed walls with irregular openings. Firstly, the existence of flanges helps to form the strut-and-tie mechanism in the walls. This is achieved by mobilizing more concrete to participate in carrying shear force, by improving the end conditions of diagonal strut, and by changing the strut angle to sustain more shear force due to flanges providing anchorage for the reinforcement in the beam zones of shear wall with openings. Secondly, the large boundary area can sustain more normal force and can help the diagonal strut to endure more loading cycles. However, it is important to ensure that the enough reinforcement was provided in the critical part of the load path, such as in the beam zones.

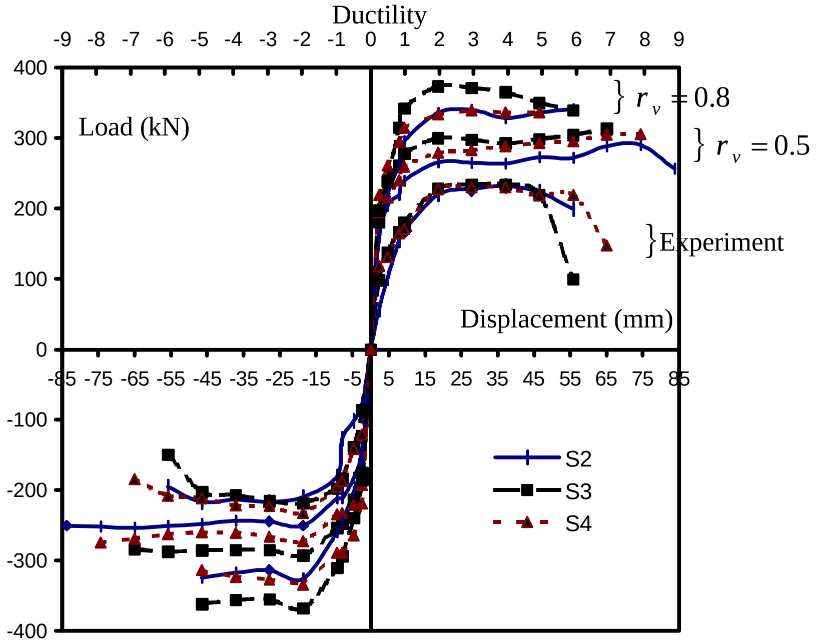
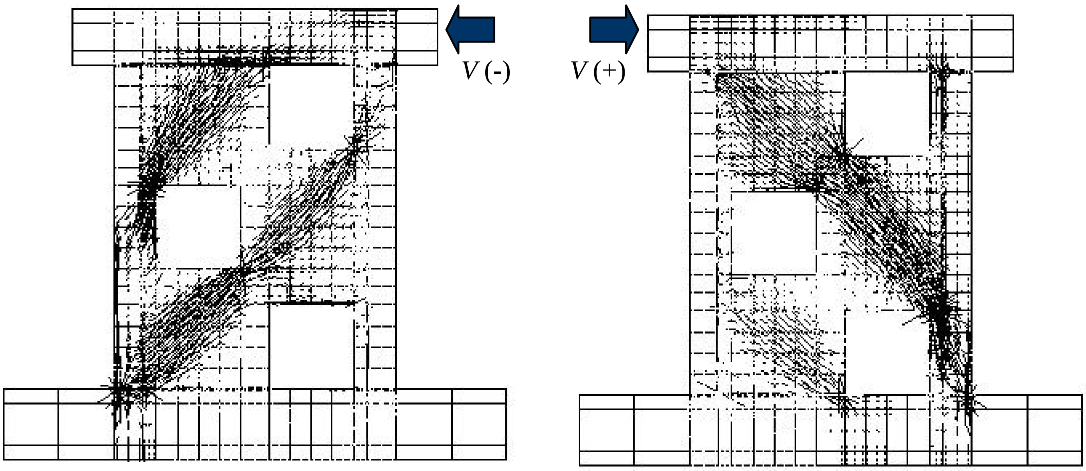


Figure2. Backbone envelopes of load-displacement response loops of S2, S3 and S4 with flanges

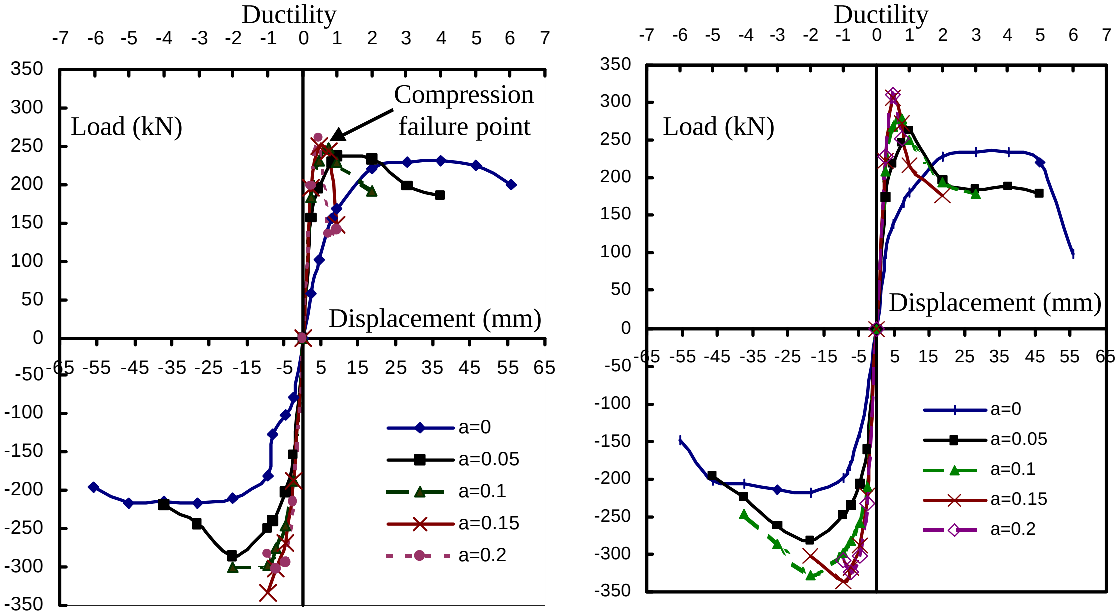


(a) DF=+2 (a) DF=-2

Figure 3. Principal compressive stress flows in specimen S3 with flanges

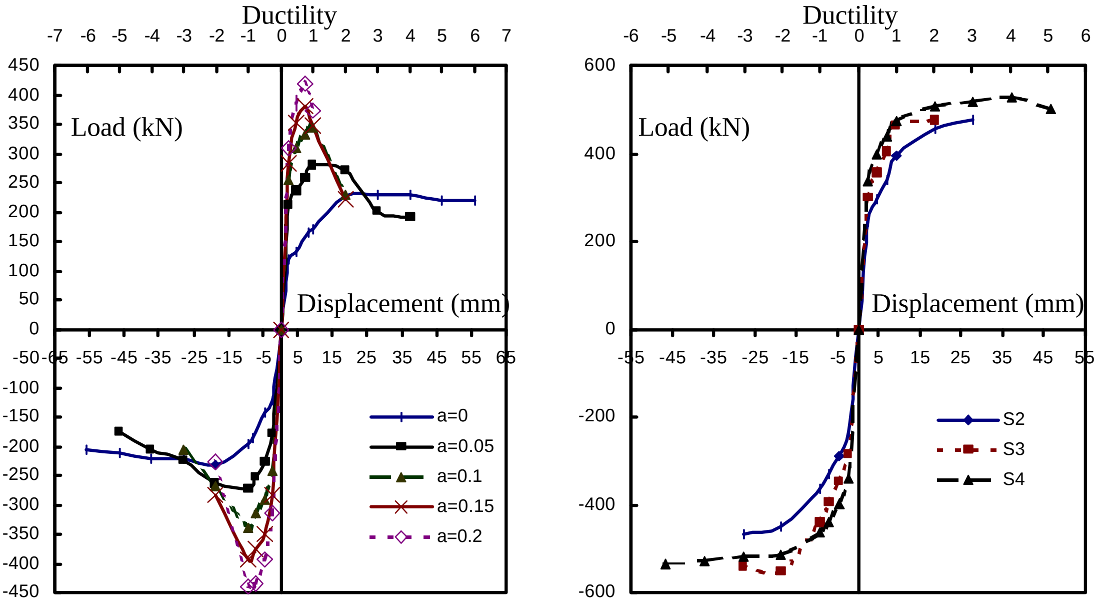
3.2 **Effect of axial loads on walls with low aspect ratios**

Figure 4 shows the backbone envelopes of the load-displacement response loops of Specimen S2, S3, S4, whose configurations could be found from the Figure 1 of the companion paper 123 (Wu & Li 2003), and the specimens with flanges subjected to the axial and lateral loading. Different axial loads $N = af_c'A_g$, where $a = 0.05$, 0.1, 0.15 and 0.2, were applied to walls S2, S3 and S4 respectively and only $N = 0.1 f_c'A_g$ was applied to each wall with flanges. The figures indicate that the presence of the axial load increased the ultimate strength and the stiffness of walls in the early loading stage but decreased the ductility levels dramatically at the same time except for the case with a low axial loading level such as $a = 0.05$, in which the walls could achieve a greater ductility level. When high axial compression was applied, a compression failure occurred at a very early stage, especially in the wall with small boundary column zones such as S2. Specimens with large boundary column zones could achieve higher ductility level in high axial compression condition as shown in Figures 4b-c. Figure 4d shows that the specimens with flanges could resist higher lateral loading and retain stable ductility levels under an axial load of $N = 0.1 f_c'A_g$ compared with the envelopes shown in Figure 2.



(a) S2

(b) S3



(c) S4

(d) Specimens with flanges (*a*=0.1)

Figure 4. Backbone envelopes of load-displacement response loops

Figure 5 shows the typical principal compressive stress flow of specimen S3 subjected to an axial load at level a=0.15. Compared with the wall without axial compression loading, a similar load path can be found, indicating that the similar strut-and-tie model could also be applied in this case. However, a difference appeared with the presence of an axial load, which enabled the upper column zone at the side of the opening to transfer a part of the shear force to the lower panel when the wall was subjected to the negative lateral loading as shown in Figure 5. The internal force obtained from NLFE analysis also showed that this part was under compression at the all ductility levels and had resisted a maximum shear force of about 50% of the total force, which could explain why the walls with irregular openings could sustain greater negative lateral loadings and achieve larger ductility in this direction in comparison to the loading in the other direction as shown in Figure 4.

The force equilibrium at the node E was shown in Figure 5. According to the equilibrium conditions, the proportion of the shear force carried by the lower column zone V_c could be estimated by the following equation:

$$\frac{V_c}{V} = \frac{\tan a_2}{\tan a_1} + \frac{xN}{V \tan a_1} \tag{1}$$

where the xN = the axial load applied on the node. This equation indicates that the axial load could increase the proportion of shear force transferred by the column zone while decreasing that force transferred by the horizontal reinforcement in the beam zone at the same time. That is the reason why the wall could reach maximum strength earlier and had greater stiffness compared with the walls that were not subject to the axial loading. However, this mechanism also induced the column zone to reach its ultimate state and thus to begin crushing in an early stage. This in turn meant the column zone could not transfer the shear force and so triggered a compression failure in this zone.

Figure 6 shows the considerably damaged meshes detected by the finite element analysis for the specimen S3 subjected to an axial load of a=0.15 and for S3 with flanges subjected to an axial load of a=0.1. It can be seen that a high axial load leads to serious compressive damage concentrated in the column zones in the wall without flange. This indicates that influenced by the staggered distribution of the walls and the lateral load, the axial load was transferred through these zones. As shown in Figure 5, the axial load was transferred to the middle column zone through the diagonal compressive strut causing the high compressive stress to occur there. The failure damage was observed in that zone. Similar damage occurred in the boundary column zones at the side of the openings in specimen S2.

Flanges can give great benefits to walls in resisting the combined actions of axial loading and lateral loading as shown in Figure 4d. However, once the concrete in the boundary elements reach ultimate strain under the combined action, the shear force would be redistributed, hence the horizontal tie transfers more shear force. In the case where the horizontal reinforcement was not enough to sustain the increased force, damage would occur in the beam zone as shown in Figure 6b. Tensile failure would occur in this zone after several cycles.

3.3 **Effect of axial loads on slender walls**

Figure 7 shows the backbone envelopes of the load-displacement response of the slender walls (W-2, W-3 and W-4). It can be seen that walls with different staggers could achieve similar responses except for the w-2 wall under an axial load of a=0.2, where a decrease in the maximum strength of W-2 wall in the positive direction was detected. Like the observation on the walls with low aspect ratios, the presence of axial loads increased their ultimate strengths but the slender walls showed satisfactory ductility levels because high moments often occurred in the bottom section of these walls, resulting in that the walls failing in the flexural modes before the shear resistance capacity was reached. However, a drop in strength under the cyclic loading was observed in each wall subjected to high compression, because when the boundary concrete reached ultimate strain then crushed under the combined action of moment, compression and shear force, especially in W-2, which had relatively smaller boundary column zones compared with the two others specimens.

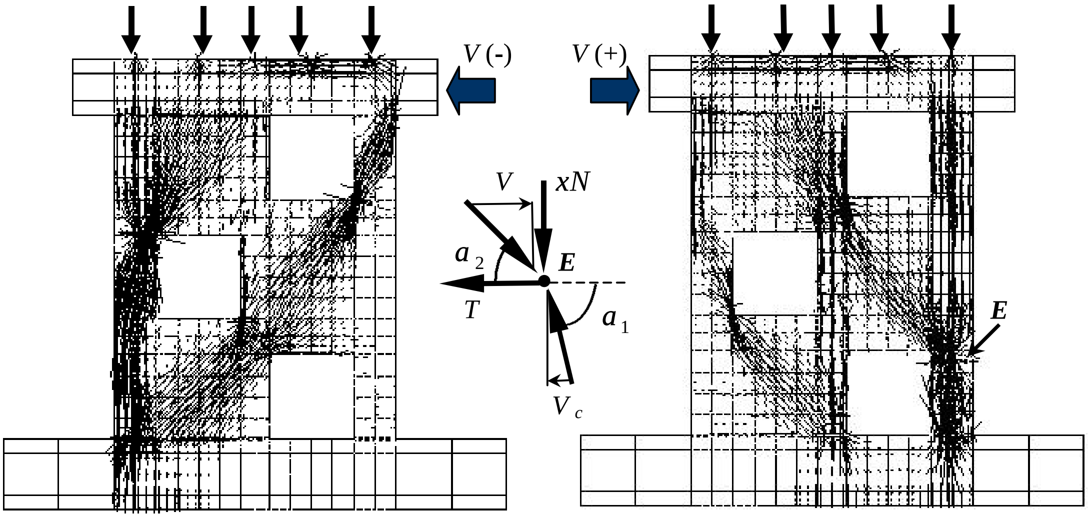
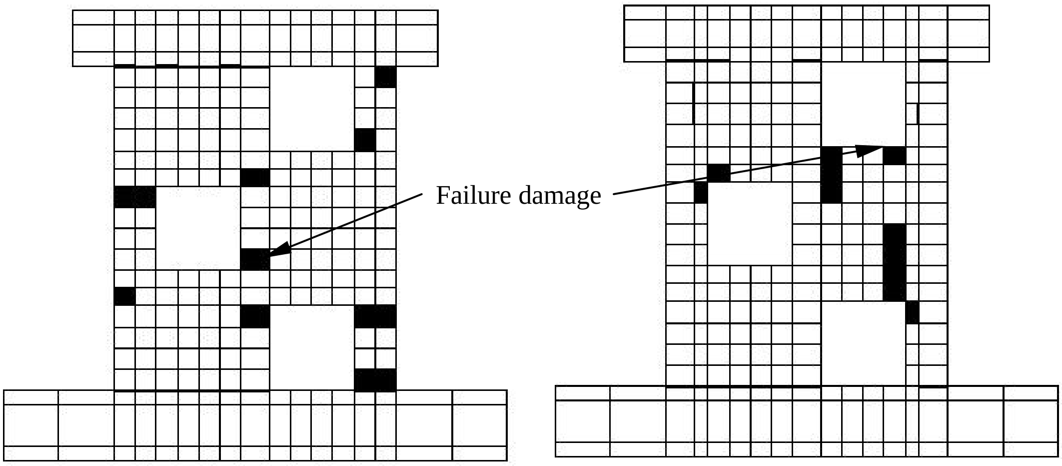


Figure 5 Principal compressive stress flows of S3 ($a=0.15$)



(a) S3 subjected to axial load ($a=0.15$) (b) S3 with flanges subjected to axial load ($a=0.1$)

Figure 6 Considerably damaged meshes in S3

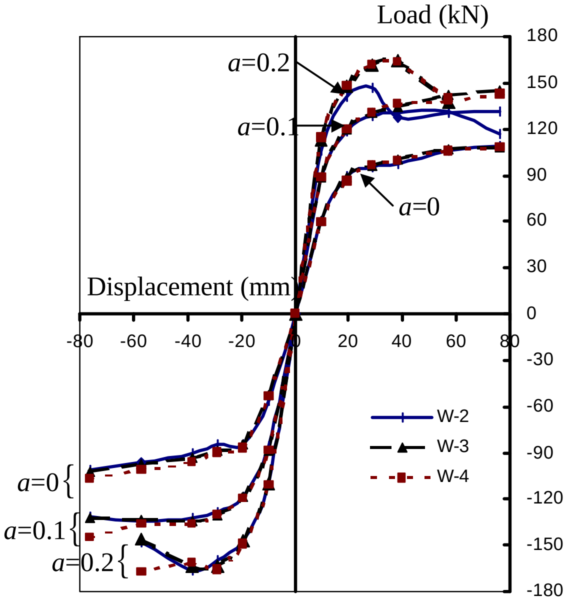


Figure 7. Backbone envelopes of load-displacement response loops of slender walls with axial loadings

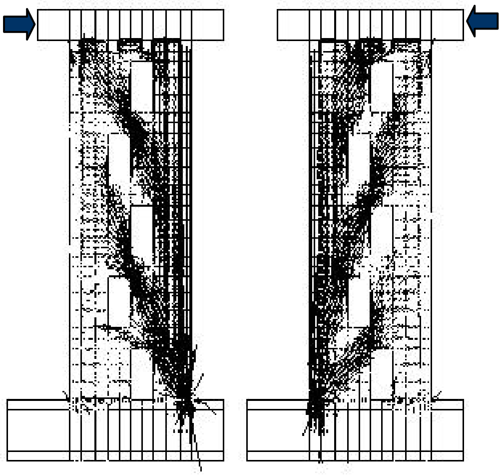


Figure 8. Principal compressive stress flows of slender wall with zero horizontal stagger

3.4 Effect of the size and arrangement of openings

According to the experimental research of Yanez (1991), the size and arrangement of the openings did not have a significant effect on the behaviours of the walls subjected to cyclic lateral loading. However, the influence of axial loading was not considered in his research. As shown in Figure 4, the arrangement and size of openings may exert influence on the strength and ductility of walls when they were subjected to the combined action of axial and lateral loading. Table 1 shows the maximum strength V_u of each wall with a different opening size and arrangement subjected to different axial loading level. The maximum strength of the solid wall (S1) at each axial loading level was also provided to act as a controlled specimen. This table indicates that the difference between the maximum strengths of the solid wall and the wall with staggered openings increased with the increase of axial loading, and the wall S4 which had relatively small openings of $400 \times 400\,mm$ showed a closer correlation to the solid wall when under middle and low compression. Wall S2 with $600 \times 600\,mm$ openings and relatively small column zones ($200\,mm$) at the boundary showed the largest difference when it was subjected to positive lateral loading due to the small compressive column zone reaching ultimate compressive state under the combined action. Wall S3 with the same openings as S2 but with a relatively larger column zones ($300\,mm$) demonstrated a better response than S2. It could be concluded therefore that in the case of walls with low aspect ratios and staggered openings subjected to the combined action of axial compression and lateral loading, a certain total width of column zones should be retained to ensure the transfer of axial loading and that the opening should not be arranged too near to the boundary.

Table 1. Maximum strength of the wall with irregular openings

Axial load	P_u (kN)	S1	S2	S3	S4
a=0.05	(+)	295.7	236.4	262.1	281.2
	(-)	-318.3	-285.7	-282.9	-274.9
a=0.1	(+)	370.3	248.1	267.3	333.3
	(-)	-377.1	299.6	-328.4	-340.0
a=0.2	(+)	520.2	259.6	310	418.0
	(-)	-530.0	-302.91	-335	-438.9

The presence of flange may decrease the effect of the size and the arrangement of the opening as shown in Figure 4d. Little difference was found between the walls with flanges when they were subjected to the positive lateral loading. Differences showed however when they were subjected to the negative lateral loading due to the fact that the different proportions of shear force were transferred to the middle panel zones through the upper column zones as indicated by Figure 3.

The staggered openings exerted slight influence on the behaviour of slender walls as shown in Figure 7. A deviation was observed in w-2 when it was subjected to an axial load of a=0.2 and positive lateral loading. This may be caused by that the opening being arranged too close to the boundary. A wall of the same opening size as Ali's specimen but of a zero horizontal stagger as shown in Figure 8 was analysed under lateral loading and an axial loading of a=0.1. It was interesting to find that this wall could perform similarly to the other walls. Figure 8 shows the principal compressive stress flow indicating the force-transferred mechanism in this wall. It shows that a diagonal compression strut could also be formed in this wall to transfer the lateral and axial loads.

4 DESIGN IMPLICATIONS

Based on the previous analysis, the following measures could be used to improve the performance of walls with irregular openings when it was subjected to the combined action of axial loading and reversed cyclic lateral loading. First, strengthen the walls with irregular openings along the load paths by the following ways. Provide enough confinement to the column zones to increase their capacities in sustaining compression and shear. Provide enough reinforcement to horizontal beam zones, which were critical to sustain lateral loading in order to ensure that these zones could sustain the increasing part of shear force transferred from column zones due to the concrete crushing in these zones. Also strengthen the bottom panel zones, in which high compression and shear force may occur. Second, add boundary elements to the walls, which can give increased help in sustaining the combined action of the loads as shown in previous analysis. Third, keep the openings at a certain distance from the boundary to avoid compressive failures occurring in the small column zones. Finally, a stricter limit on compressive axial loading could be applied to the walls with irregular openings to avoid this wall being subjected to high compression. Figure 9 shows the load-displacement response of specimens S3-S, which was specimen S3 strengthened along the load path. It can be seen that this wall could perform similarly to that of the solid wall (S1) subjected to an axial load of *a*=0.1 and reversed cyclic lateral loading.

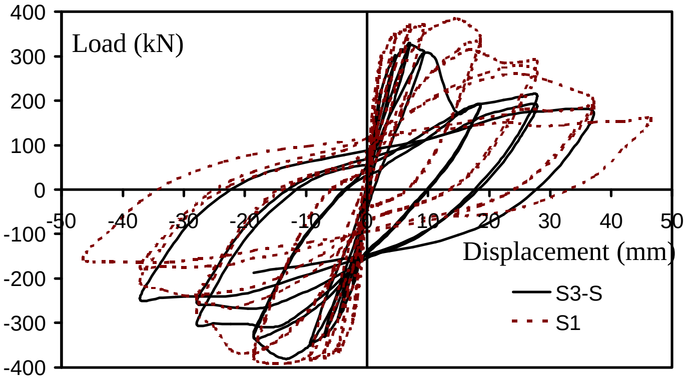


Figure 9. Load-displacement responses of S3-S and S1

5 CONCLUSIONS

The presence of flanges can increase the ultimate strength and improve the ductility level of the walls with irregular openings. A slight increase in the reinforcement in the flange may increase the ultimate strength significantly but may change the failure mode from ductile flexural failure mode to a tensile failure mode caused by the shear force. Therefore an increase in the horizontal reinforcement in the beam zone should be considered at the same time.

A compressive axial loading larger than the middle level may at the same time increase the ultimate strength and decrease the ductility level significantly, or may cause the compression failure in the smaller column zones, especially in the case when these zones were located in the boundary. The presence of axial loading increases the proportion of the shear force carried by the column zone, which in turn results in a higher reinforcement content required of the beam. However it also caused the concrete in the boundary to crush earlier under the action of reversed cyclic lateral loading, resulting in the decrease of wall ductility.

The size and arrangement of openings may exert an influence on the walls with low aspect ratios when it was subjected to the combined actions of axial loading and reversed cyclic lateral loading. Walls with small sized openings can perform better than walls with larger openings. Due to the influence of axial loading, the opening should not be arranged too close to the boundary. Strengthening the walls along the load paths could improve their performances.

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