



Investigating the load paths of RC shear wall with openings under reversed cyclic loadings

Hui Wu & Bing Li

Nanyang Technological University, Sch. of Civil & Env. Eng., Singapore 639798

ABSTRACT: Ten models of structural walls were analyzed using a reliable non-linear finite element program. Six models walls with low aspect ratios, including one solid wall, three walls with irregular openings and two walls with regular openings, were identical with the specimens tested by Yanez in the University of Canterbury. The other four slender walls, including one solid wall and three walls with stagger openings, were tested by Ali in the University of Michigan. The models were analyzed under reversed cyclic loading to simulate the behavior of the walls subjected to earthquake. Based on the principal compressive stress flows obtained from the finite element analysis, the load paths in the walls with irregular openings were proposed to understand the force transfer mechanisms in these walls. The load paths showed a good correlation with the strut-and-tie models proposed to design these walls. The typical principal stress distributions and the internal forces of the sections in some critical zones at each ductility level were studied to verify the load paths. Similar force transfer mechanisms were found in the walls with regular openings. A cyclic strut-and-tie model for walls with openings proposed based on the analytical results was also analyzed.

1 INTRODUCTION

Reinforced concrete structural walls play a very important role in carrying lateral loading and resisting drift in tall buildings. Piercing a wall with openings may significantly influence its behaviours, such as changing its force transfer mechanism, deducting its strength and stiffness, and decreasing its ductility level. So if openings are demanded, the careful detailing and proper distribution of these openings are required by common codes. Currently only small openings are allowed in a wall or the opening should be aligned along the vertical direction of the wall so that the wall can be treated as a solid wall or a coupled wall. The application of the walls with irregularly distributed openings is still limited though these kinds of walls have shown satisfactory performances in the severe seismic regions, such as Chile and some research (Yanez 1991, Ali 1991) also has shown that these kinds of walls could achieve satisfactory strengths and ductility levels. Paulay (1992) has proposed a design method using strut-and-tie models for these kinds of walls, which has been used by Yanez (1991) to design the specimens with irregular openings. However because the presence of openings causes a complex stress state in the wall when it is subjected to the external loading, there is still a lack of enough materials to prove that a strut-and-tie model could represent the necessary complex stress state. Therefore, in this paper, an analytical study of these kinds of walls using the non-linear finite element method (FEM) was firstly performed. Then the load paths obtain from the analytical results of stress distributions were discussed and compared with the strut-and-tie models proposed by previous researchers. At last a cyclic strut-and-tie model proposed based on the analytical results was analysed.

2 PREVIOUS RESEARCH

In Yanez's experiment (Yanez 1993), six three-storey reinforced concrete model walls, scaled to about one third, were tested under reversed cyclic lateral loading. One of the walls had no opening (S1), three had irregular openings (S2-S4) and two had regular openings (S5 and S6). The walls were 2000 mm wide, 2300 mm high and 120 mm thick. Specimens S2, S3 and S5 had 600×600 mm openings and specimen S4 and S6 had 400×400 mm openings. Figures 1a-c show the distribution of the openings of S2, S3 and S4 respectively. S2 was similar to S3 but the horizontal stagger between two openings was 400 mm unlike 200 mm in the S3. The openings of S5 and S6 were in the same levels as S3 and S4 respectively but they were aligned in the middle of the walls. The vertical and horizontal reinforcing ratio for all walls were approximately 0.5% and 0.4% respectively. It was found that the size and arrangement of the openings did not have a significant effect on the behaviours of the walls under cyclic lateral loading and the strut-and-tie models were valid for the seismic design of the reinforced concrete walls with irregular openings.

In Ali's experiment (Ali 1991), four five-storey walls were tested under reversed cyclic lateral loading while an axial load of 270 kN was applied. One specimen had a solid web (W-1) and the other three (W-2 ~W-4) had staggered openings. Each wall was 3.56 m high and 1.22 m wide, resulting in an aspect ratio of 2.9. The cross-section was barbell shaped. The web was reinforced with a ratio of 0.3%. Figure 1d shows the configuration of the specimen W-2 that had a horizontal stagger of 380 mm between the door openings. W-3 and W-4 were similar to W-2 but they had a stagger of 200 mm and 130 mm respectively. It was found that these walls could experience a 1.0% lateral storey drift without significant damage and higher drifts may be obtained with greater confinement, but door openings located too close to the boundary element could trigger an early shear compression failure.

3 ANALYTICAL PROGRAM

Ten models of structural walls, including six walls (S1~S6) with low aspect ratios identical to those tested by Yanez (1991) in the University of Canterbury and the other four slender wall models (W-1~W-4) identical to the walls tested by Ali (1991) in the University of Michigan, were analysed with a non-linear finite element program named UC-WIN/MESH & UC-WIN/WCOMD.

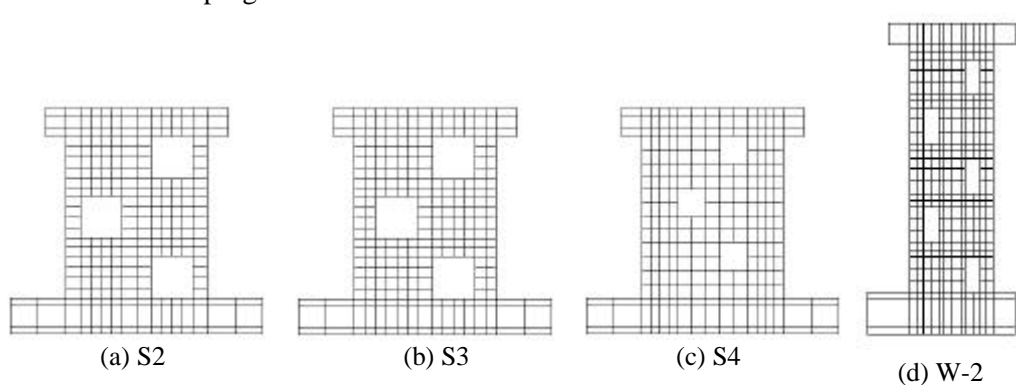


Figure 1. Meshes of specimens

The program UC-WIN/MESH & UC-WIN/WCOMD (Version 1.01.02), a product of the FORUM8 company, consists of two sections: the analysis solver section, UC-WIN/WCOMD, and the interface section, UC-WIN/MESH. The former has been developed at the University of Tokyo and mainly deals with the two-dimensional non-linear dynamic/static analysis of reinforced concrete structures. The latter is produced by FORUM8 as a tool for creating mesh data used by UC-WIN/WCOMD. The smeared crack model and the joint element model developed by the University of Tokyo for cracked reinforced concrete are used in this program. A smear crack model, in which the generation and propagation of an individual crack is considered in average within a finite region, is used in the regions where the members with distributed two-directional reinforcement. A joint element model, one

of discrete crack models, which can deal directly with the discontinuities, is used in the regions where the effects of local discontinuities are larger. This program combining the advantages of two types of elements can predict the behaviours of reinforced concrete structures subjected to reversed cyclic loadings satisfactorily, especially for reinforced concrete walls (Okamura 1991).

Figure 1 shows the meshes of S2, S3, S4 and W-2. The meshes of other specimens were similar to these specimens. The details of the ten walls were referred to references (Yanez 1993, Ali 1991) respectively. The material properties and the load histories were defined according to those provided by the researchers. The load history of Yanez's experiment was begun with three load-controlled cycles followed by the displacement-controlled cycles, including one cycle at the ductility factor of ± 1 (DF= ± 1) and two cycles at each successive ductility factor. A displacement-controlled mode was applied in Ali's experiment, in which displacement was increased according to the average drift ratios.

4 ANALYTICAL RESULTS OF WALLS WITH LOW ASPECT RATIOS

4.1 Load-displacement response

The comparisons between the finite element analysis (FEA) results and the experimental results of load-displacement responses of all specimens were first carried out. Figure 2 shows the comparison of the specimen S2. It can be seen that the FEA result was close to the experimental one. This convincing match was also observed in the other specimen. The results show that the program UC-WIN/MESH & UC-WIN/WCOMD can predict the behaviours of these kinds of walls satisfactorily.

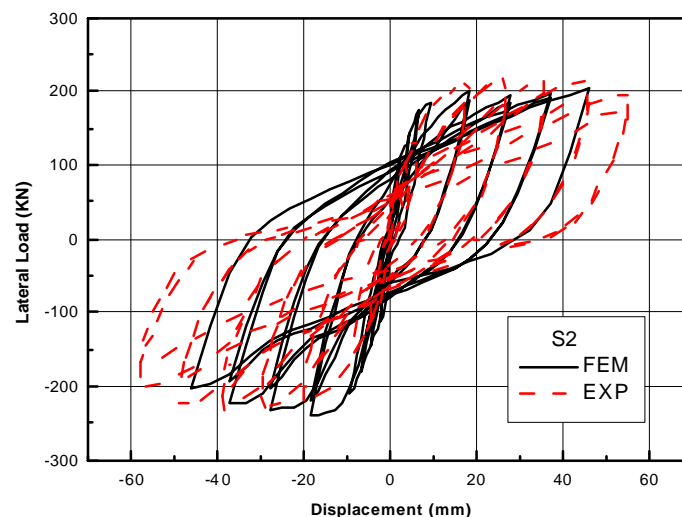


Figure 2. Comparison of analytical and experimental load-displacement responses of specimen S2

4.2 Load paths of the walls with irregular openings (S2-S4)

According to Schlaich (1987), the load path method is an underlying element in developing strut-and-tie model and the load path can be achieved in accordance with the mean direction of the principal compressive stresses. Therefore those compressive stress flows of specimen S2, S3 and S4, which were designed using strut-and-tie models, were analysed in this study. Figure 3 shows the principal compressive stress flows of the specimen S2 at the ductility factor equal to ± 1 (DF= ± 1). As shown in these figures, the principal compressive stress concentrated in the diagonal directions of the “panel” or “column” zones of the walls. “Columns” took part in transferring a part of the shear through the diagonal struts in them. Similar principal compressive stress flows were observed in the specimen S3 and S4. Figure 4 shows the load paths of specimen S2 developed according to the principal compressive stress flows. A strut-and-tie model could be developed based on this load path, in which the column contribution for resisting shear was considered. The model showed a good correlation with

the strut-and-tie model used by Yanez (1991,1993) to design and analyse the specimens. Similar strut-and-tie models could be built for S3 and S4.

According to the characteristics of the stress distribution shown in the specimens (Fig. 3), the wall with irregular openings could be divided into four zones, namely the beam zones, the column zones, the panel zones and the nodal zones (Fig. 4b). The beam zones are the horizontal parts of the wall between the openings. The column zones are the vertical parts of the wall between the openings, including the boundary elements. The left solid parts of the wall are the panel zones. The nodal zone is located in the intersectional part of the beam and column zones. A diagonal principal compressive stress flow often occurs in the panel zone, while a tensile stress field often occurs in the beam or column zone. The nodes of the strut-and-tie model often lie in the nodal zones.

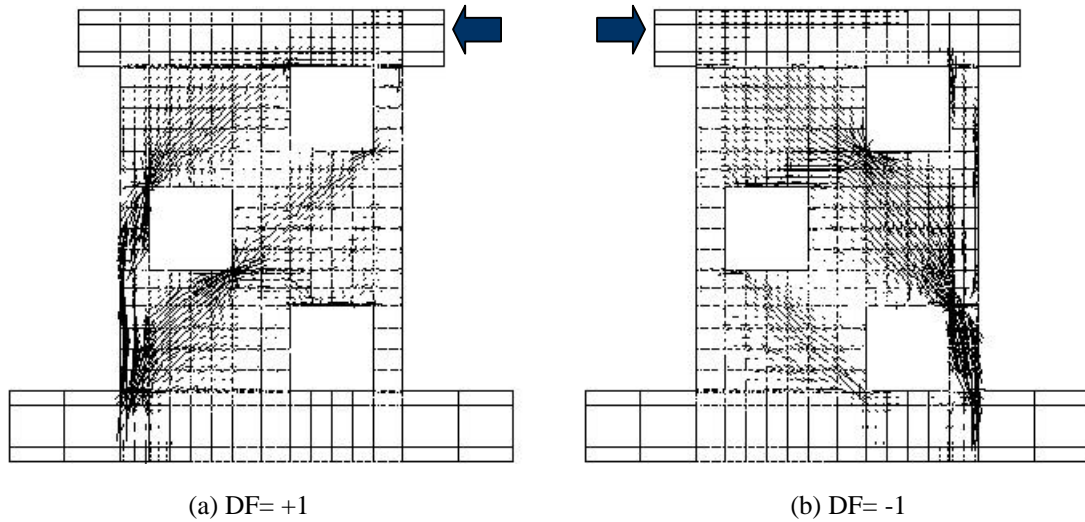


Figure 3. Principal compressive stress flows of specimen S2

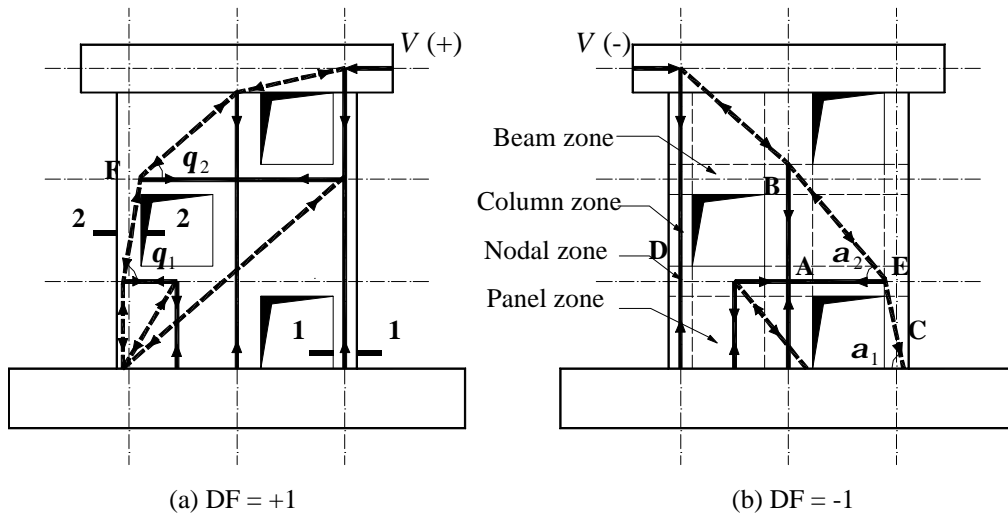


Figure 4. Load paths of specimen S2

The load path can also be supported by the typical principal stress states in the nodal and column zones. The stress magnitudes and the orientations of four typical points (A-D) shown in Figure 4b were studied. The analysis results showed that the principal stresses including s_1 and s_2 at point A in the lower nodal zone were positive and the orientations of the principal stresses varied between $-7.5^\circ \sim 5^\circ$ and $82.5^\circ \sim 95^\circ$ respectively through each negative ductility factor ($-1 \sim -5$) when the wall was subjected to negative lateral loading (Fig 4b), whereas the principal stresses s_1 and s_2 at point B were also positive and the angles were within $-4.5^\circ \sim -11^\circ$ and within $-79^\circ \sim -85.5^\circ$ respectively through each positive ductility factor (1~6) when the wall was subjected to positive lateral

loading (Fig. 4a). It meant that the nodal zone was under tensions when corresponding lateral loading was applied like the prediction by the load path (Fig. 4). The stress states at point C and D showed that when the column zone was under tension, the orientation of the principal tensile stress was about 90° , which meant that axial tensions occurred in those zones. However when they were under compression, the orientations of the principal compressive stresses at points C or D changed from a sloping angle to 90° with the cycle number increased, indicating that the compressive column zones could transfer a part of the shear force at the beginning but after the concrete cracked and crushed, they could only support axial loading and could not longer transfer the shear force.

In order to find out the proportions of the shear forced carried out by the column zones, the shear forces in the sections 1-1 and 2-2 (Fig. 4a) were analysed. Figure 5 shows the proportions (P) of shear forces transferred by column zones (V_c) of specimens S2 ~ S4 to the total forces (V) in each cycle. According to the load history, cycle 4 was corresponding to the ductility factor (DF) ± 1 , followed by the 2 cycles of at each successive ductility factor. It can be seen that the proportion reached its maximum at cycle 4 or cycle 5 then decreased with the cycles increasing. After cycle 9 (DF= ± 4), the section 1-1 in the lower column zone of specimen S2 or S3 beside the openings, carried almost no shear force because at this ductility level the concrete was cracked or crushed and the diagonal strut could not form, whereas the section of specimen S4, due to its larger area, continued sustaining a large proportion of shear force thus enabling the diagonal strut in this zone to be retained. The maximum proportion of shear force carried by the section 1-1 (P_1) or section 2-2 (P_2) could be approximated by the force equilibrium condition in the node E or node F (Fig. 4) respectively. It needed to satisfy the following equation:

$$P_1 = \frac{V_c}{V} = \frac{\tan \mathbf{a}_2}{\tan \mathbf{a}_1} \quad \text{or} \quad P_2 = \frac{V_c}{V} = \frac{\tan \mathbf{q}_2}{\tan \mathbf{q}_1} \quad (1)$$

where \mathbf{a}_1 , \mathbf{a}_2 , \mathbf{q}_1 and \mathbf{q}_2 were the angles shown in Figure 4.

Table 1. Maximum proportions of shear forces carried by column zones

Specimen	\mathbf{a}_1	\mathbf{a}_2	\mathbf{q}_1	\mathbf{q}_2	P_1	P_{Max1}	P_2	P_{Max2}
S2	76.1°	50.6°	78°	47.6°	0.30	0.31	0.23	0.25
S3	68.9°	52.9°	71.8°	51.3°	0.51	0.51	0.41	0.45
S4	63.8°	50.6°	57.4°	49°	0.60	0.64	0.74	0.51

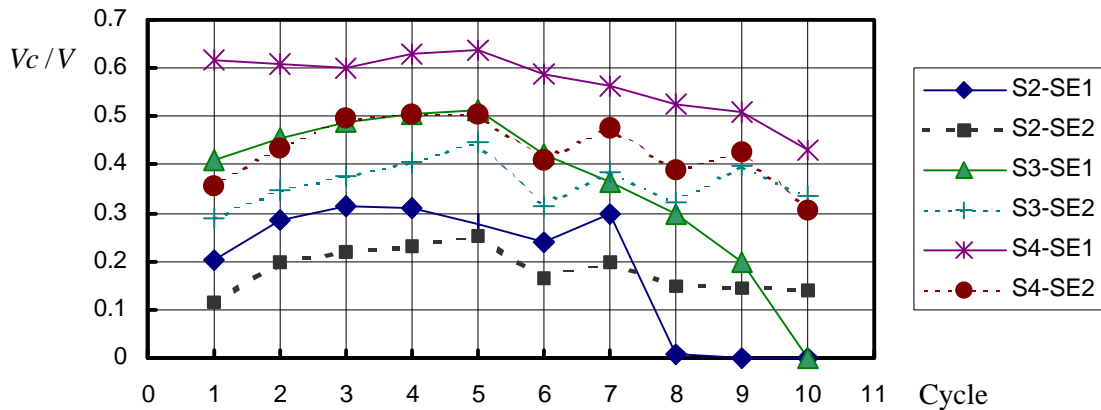


Figure 5. Proportions of shear force carried by column zones

Table 1 shows the comparison between the proportions estimated by the equations and the maximum proportions P_{Max1} and P_{Max2} obtained from FEA of the specimen S2 ~S4. It can be seen that the proportion estimated by equation (1) shows a convincing match with the FEA results except for the P_2 of S4. The finite element result showed that the uppermost column zone of specimen S4 kept on transferring approximate 20% of the shear force in every cycle due to its relatively larger area.

Both the stress state analysis and the section analysis showed that the column zones beside the openings could sustain a proportion of the shear force through the diagonal struts, so a strut-and-tie model developed based on the load path shown in Figure 4 could be used to estimate the maximum shear strength of the wall. However the function of the column zone for carrying shear would decrease with the cycle increasing due to the cracking and crushing of the concrete in the column zones under the action of cyclic lateral loading. Hence, at a high ductility level, the strut-and-tie developed by Yanez (1991), in which the column zone could only sustain axial loading, would be more accurate to evaluate its behaviour.

4.3 The force transfer mechanisms of the walls with regular openings (S5-S6)

Specimens S5 and S6 contained similar shear force transfer mechanisms. Figure 6 shows the principal compressive stress flow in specimen S5. It can be seen that diagonal struts formed in the beam zones and panel zones to transfer the shear force. The bottom section analysis results showed that one of the sidewalls was almost under tension whereas the other sidewall was almost under compression and that most of the shear force was transferred through the compressive sidewall to the foundation when the wall was subjected to lateral loading.

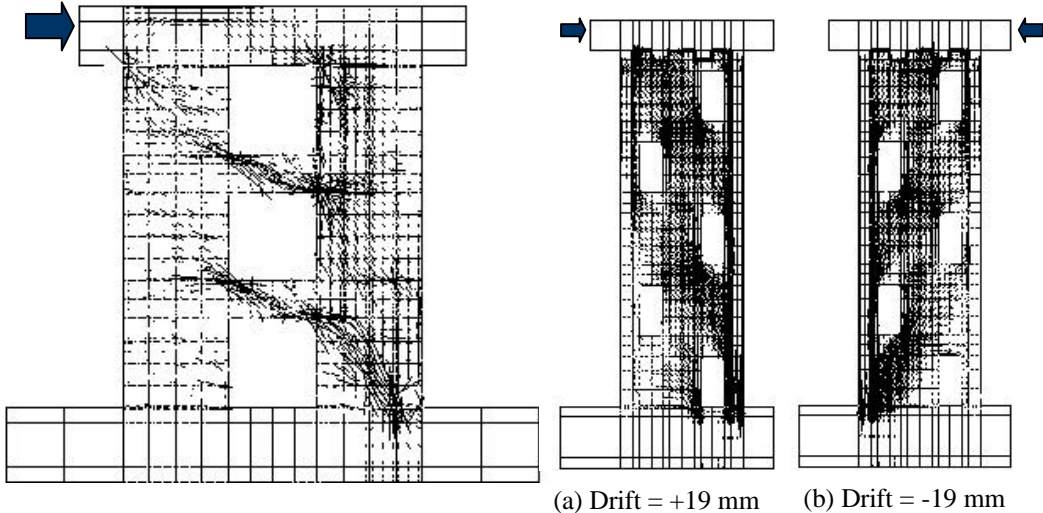


Figure 6. Principal compressive stress flow of S5 (DF = -6)

Figure 7. Principal compressive stress flows of specimen W-2

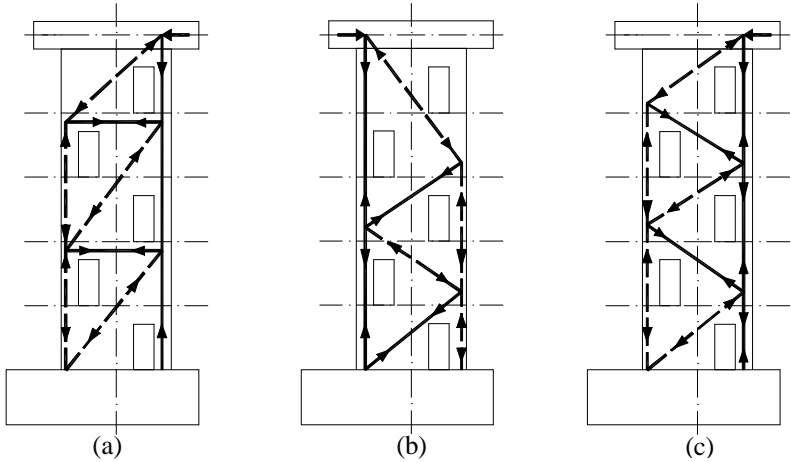


Figure 8. Load paths in specimen W-2

5 ANALYSIS RESULTS OF SLENDER SHEAR WALLS

In this study, a comparison of load-displacement responses of the FEA results and Ali's experimental results (Ali 1991) was also made. A good correlation was found as that in the walls with low aspect ratios. Figure 7 shows the principal compressive stress flows in specimen W-2. Similar stress flows were observed in the other specimens. It can be seen that the wall could also be divided into beam, column and panel zones. Clear diagonal struts were also observed in the panel zones. Figure 8a shows a load path developed in a similar way as that in the wall with low aspect. However this load path was not supported by the FEA results. According to this model, the maximum shear capacity was determined by the horizontal reinforcement in the beam zones, in which 3 No. 2 bars could only sustain a shear force of about 54 kN. This was only about 1/3 of the capacity obtained from the FEA or experiment. The analysis showed that the column zones beside openings sustained very little shear force unlike that experienced in the walls with low aspect ratios, whereas the panel zones transferred most of the shear force through the slender walls due to that the large compression or tension which occurred in the boundary elements resulted in these zones sustaining only the axial load. Therefore the load paths shown in Figures 8b-c were more suitable for this slender wall. According to these load paths, the reinforcement in the panel zones could also be motivated to transfer shear force.

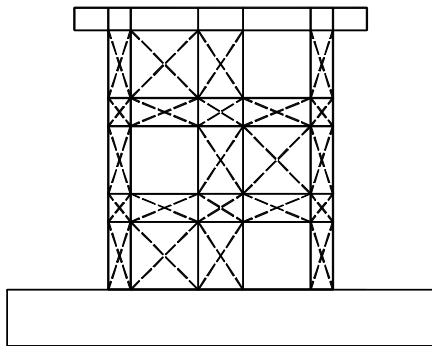


Figure 9. Cyclic strut-and-tie model of S2

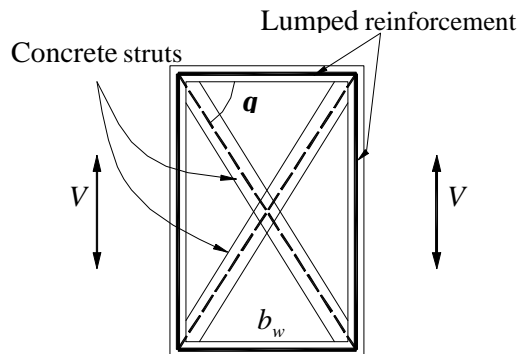


Figure 10. Diagonal strut element

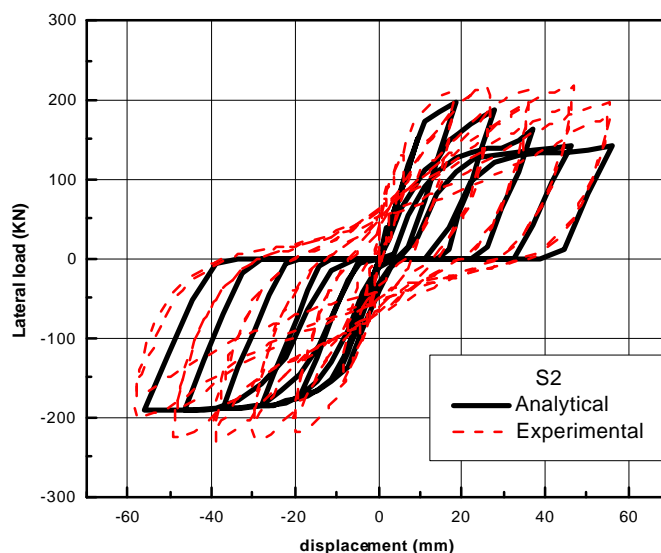


Figure 11. Comparison of the analytical and experimental lateral load-displacement relationship

6 CYCLIC STRUT-AND-TIE MODELS FOR WALLS WITH OPENINGS

Figure 9 shows a cyclic strut-and-tie model proposed for specimen S2. In this model the beam, column, nodal and panel zones were represented by the diagonal strut elements shown in Figure 10. The element consisted of the idealized uniaxial fibre elements developed by To (2000) at the periphery. The reinforcement in the zones was lumped into the uniaxial fibres. The diagonal concrete struts in the middle alternated in tension and compression depending on the direction of the shear force but the diagonal struts could only sustain compression. A gap would develop in them when they were subjected to tension. The strut area was approximated by $b_w / 2 \times \sin \alpha$, where b_w is the length of the short side of the zones and α is the corner-to-corner angle of the zone (Fig.10). The stress-strain curve for concrete confined by rectangular hoops proposed by Kent and Park (Park 1975) was applied but a trilinear curve was used to approximate the curve. Many researches on the effective factor of the concrete compressive strength have been performed since 1980s (Collins 1986, Schlaich 1987, Foster 1996 and Su 2001). In this study, the effective factor of concrete compressive strength in the panel, beam and column zones was taken as 0.68, and the factor of 0.34 was applied in the nodal zones. The model was analysed using the program DRAIN-2DX developed by the University of California, Berkeley (Powell 1993 and Prakash 1993). Figure 11 shows the comparison of the analytical and experimental lateral load-displacement relationship of specimen S2. A satisfactory correlation with the experimental result was observed. The member stiffness and the strength were predicted satisfactorily relative to the experimental curve. However, a slight decrease in strength occurred after several load cycles in the analysis results. High pinching appearing in the unloading branches also indicated the need for developing a more refined model. The cyclic strut-and-tie models were developed for other low walls with openings in the same way and the similar results were obtained.

7 CONCLUSIONS

Six walls with low aspect ratios and four slender walls were analysed using the non-linear finite element program UC-WIN/MESH & UC-WIN/WCOMD. The results obtained from the analysis were compared with the experimental results. Good agreement was obtained through the comparison.

The principal compressive stress flow obtained from FEA was studied to understand the load paths in the walls subjected to reversed cyclic lateral loading. It can be seen that lateral force was transferred to the foundation by diagonal struts in the column and panel zones. The load paths show a good relation with the strut-and-tie models proposed by previous researchers. The analysis on the shear force in the certain sections of the column zones shows that these zones of walls with low aspect ratios transferred a proportion of the shear force. A strut-and-tie model considering the column contribution could estimate the maximum shear strength of the walls with irregular openings. The strut-and-tie model neglecting the contribution of column zones could be applied to evaluate the shear capacity of the wall at high ductility levels. In the slender walls with staggered openings, the zones in the web transferred most of the shear force. A strut-and-tie model with diagonal struts and ties in the web was more suitable to be applied.

A cyclic strut-and-tie model was developed based on the force-transferred mechanism of walls with openings. Good correlation between the analysis and experimental result was observed.

REFERENCES

- Ali, A. & Wight, J. K. 1991. RC Structural Walls with Staggered Door Openings, *Journal of Structural Engineering*, ASCE, Vol 117(5): 1514-1531.
- Collins M. P. & Mitchell D. 1986. A Rational Approach to Shear Design – the 1984 Canadian Code Provisions, *ACI Structural Journal*, Vol 83(6): 925-933.
- Foster S. J. & Gilbert R. I. 1996. The Design of Nonflexural Members with Normal and High-strength Concretes, *ACI Structural Journal*, Vol 93(1): 3-10.
- Okamura, H. & Maekawa, K. 1991. *Nonlinear Analysis and Constitutive Models of Reinforced Concrete*, Japan: Gifoudo-Shuppan.

- Park, R. & Paulay, T. 1975. *Reinforced Concrete Structures*, New York: John Wiley and Sons.
- Paulay, T. & Priestley, M. J. N. 1992. *Seismic Design of Reinforced Concrete and Masonry Buildings*, New York: John Wiley.
- Powell, G. H. 1993. *DRAIN-2DX Element Description and User Guide For Element Type01, Type02, Type04, Type06, Type 09, and Type15 Version1.10*, Department of Civil Engineering, University of California, Berkeley, California. Report No. UCB/SEMM-93/18.
- Prakash, V., Powell, G. H., & Campbell. S. 1993. *DRAIN-2DX Base Program Description and User Guide Version 1.01*, Department of Civil Engineering, University of California, Berkeley, California. Report No. UCB/SEMM-93/17.
- Schlaich, J., Schäfer, K. & Jennewein, M. 1987. Toward a Consistent Design of Structural Concrete, *PCI Journal*, Vol 32(3): 74-150.
- Su R. K. L. & Chandler A. M. 2001. Design Criteria for Unified Strut and Tie Models, *Progress of structural Engineering*, Vol 3: 288-298.
- To, N. H. T., Ingham, J. M. & Sritharan, S. 2000. Cyclic Strut & Tie Modeling of Simple Reinforced Concrete Structures, *Proceedings of 12WCEE*.
- Yanez, F. V., Park, R. & Paulay, T. 1991. Seismic Behaviour of Reinforced Concrete Structural Walls with Irregular Openings, *Pacific Conference on Earthquake Engineering*, New Zealand.
- Yanez, F. V. 1993. *Seismic Behaviour of Reinforced Concrete Walls with Irregular Openings*, PhD dissertation, University of Canterbury, Christchurch, New Zealand.