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Cyclic Test on Squat RC Shear Walls with Thick Flanges

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ABSTRACT

RC flanged walls with aspect ratio of 0.5 were tested under cyclic loading to investigate the effect of the thick flanges on shear strength of squat walls. The over-strength ratio of tested shear strength to nominal shear strength specified in ACI 349 was greater than 2.0 due to the vertical reinforcing bars in flanges. On the other hand, horizontal reinforcement rarely affected the shear strength of flanged walls due to the low height to length ratio of test specimens.

1. INTRODUCTION

In designing nuclear power plants (NPPs), structural walls were designed to remain elastic under design basis earthquakes (DBE). However, due to the increasing seismic demands on NPPs there is an increasing interest in evaluating the marginal capacities of the safety-related structural walls which were designed decades ago based on the seismic demand at the time.

Structural walls in NPPs can be characterized by low aspect ratio (height to length ratio) less than 1.0, high reinforcement ratio, and thick flanges due to the complex arrangement of walls. Accordingly, the walls in NPPs can show distinct failure modes and peak strengths different from typical RC shear walls.

The present study focused on the failure mode and marginal capacity of highly reinforced squat RC walls with flanges. Three reversed cyclic load tests were performed and the measured peak shear strength were compared to the design code equations as well as equations proposed by other researchers.

2. EXPERIMENTAL PROGRAM

Three low aspect ratio (wall height to length ratio) RC shear wall specimens were tested. Test parameters and reinforcement details are summarized in **Table 1**. Test parameters were: 1) vertical reinforcement ratio in flanges and 2) horizontal

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reinforcement ratio in webs. Wall geometry was determined considering the maximum capacity of the actuator used in the test (+5,000 kN, -3600 kN). The length, height, and thickness of the wall specimens were 2080mm, 800mm, and 160mm, respectively. Wall aspect ratios were 0.50. No axial loads were imposed to the specimens. The specimen names indicate the design parameters. The first three letters H08 and H04 refer to the horizontal reinforcement ratio 0.8% and 0.4%, respectively. The last three letters V10 and V20 indicates the vertical reinforcement ratio of 1.0% and 2.0%, respectively. Accordingly, horizontal reinforcement ratio of specimen H08V10 was two times greater than that of H04V10 and vertical reinforcement of H08V10 was only a half of that of H08V20.

Due to the large uncertainties of the peak strength of squat walls with flanges, shear force corresponding to the nominal bending moment capacity $V@M_n$ was designed at least two times greater than the nominal shear strength V_n to make specimens fail in shear. $V@M_n$ was determined by the sectional analysis and V_n was calculated based on ACI 349code provisions (ACI 2013).

As presented in Fig. 1, reversed cyclic loadings were imposed to the test specimens laterally. Loading protocol was developed following ACI 374.2R-13: Guide for testing reinforced concrete structural elements under slowly applied simulated seismic loads. 19 LVDTs were installed to measure wall deformations including flexural deformation, shear deformation, sliding at the wall-base interface as well as base rocking and slip (Hiraishi 1984). 40 strain gauges were attached to the horizontal and vertical reinforcing bars to measure strain fields at each loading step.

3. TEST RESULTS

All specimens failed in shear. Specimen H08V10 showed a combination of diagonal tension and web concrete crushing. Specimen H08V20 and H04V10 failed in diagonal tension cracking which penetrated the middle flange. Flange walls in compression zone was also failed in shear at the end of the test due to the loss of load resistance of web walls. However, the diagonal shear cracking in flanges were not observed at peak strength. For all specimens, flange horizontal cracks were observed in common due to the flexural deformation.

Table 1 Test parameters

Specimens		H08V10	H08V20	H04V10
Design failure mode		Shear	Shear	Shear
Wall aspect ratio		0.48	0.48	0.48
Concrete strength f_c', MPa		34.7	34.3	34.3
Web reinforcement	f_y, MPa	469	469	469
	ρ_H, %	0.8	0.8	0.4
	ρ_V, %	1.0	1.0	1.0
Flange reinforcement	f_y, MPa	469	469	469
	ρ_H, %	0.8	0.8	0.4
	ρ_V, %	1.0	2.0	1.0
$V@M_n$, kN		3303.3	5348.6	3303.3
V_n, kN		1302.3	1294.8	1214.1
V_{sf}, kN		1835.7	1835.7	1835.7

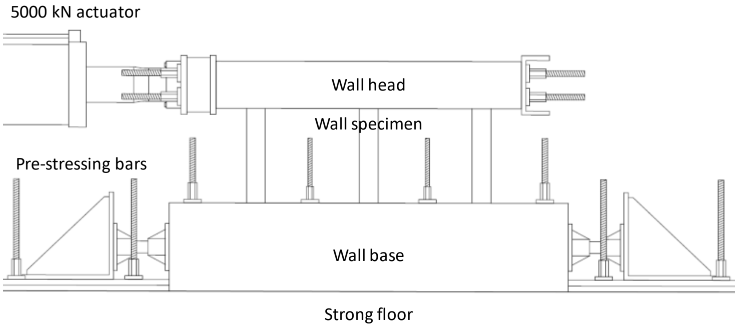

Fig. 1 Testing apparatus

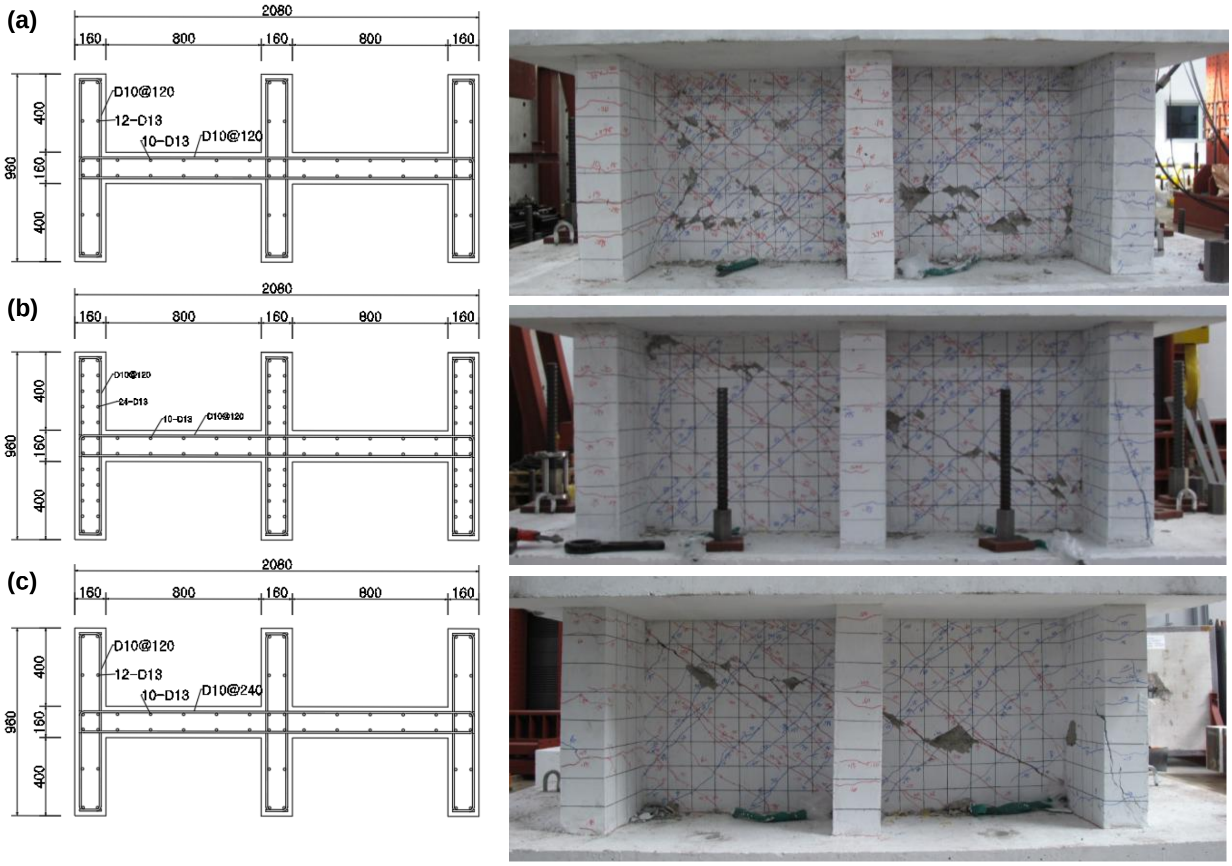

Fig. 2 Damage state at the end of the testing (a) H08V10 (b) H08V20 (c) H04V10

Fig. 3 shows the lateral-drift ratio relationships and the comparison of back-bone curves of test specimens. The drift ratio was calculated by dividing the lateral displacement by the distance between the base and the loading point. For all specimens the peak shear strength was at least two times greater than nominal shear strength V_n. Wall H08V20 (Fig. 3(b)) have the same geometry and horizontal and vertical reinforcement ratios in webs comparing to H08V10 (Fig. 3(a)) but twice as great as the vertical reinforcement ratio in flanges. Wall H04V10(Fig. 6(c)) have about half of horizontal reinforcement ratio compared to H08V10, but everything else was the same as H08V10. Although the horizontal reinforcement ratio decreased by about half in

H04V10, it did not change the peak shear strength much. On the other hand, increase in flange vertical reinforcement ratio significantly increased the peak shear strength as in the case of H08V20 (Fig. 3(d)). The result supports the findings of the previous studies (Barda 1977, Gulec and Whittaker 2011, Moehle 2015, and Luna and Whittaker 2019).

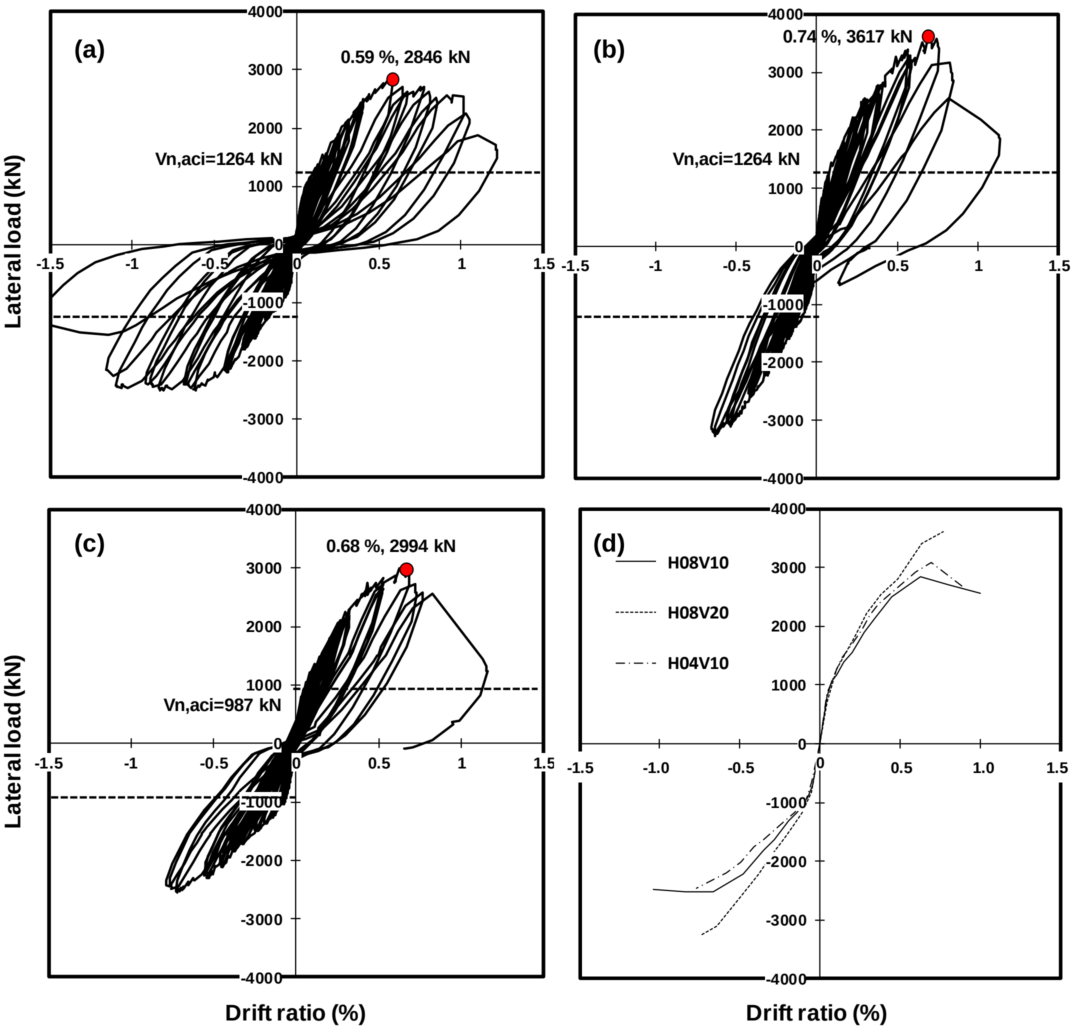

Fig. 3 Global force – drift ratio relationships (a) H08V10 (b) H08V20 (c) H04V10 (d) back-bone curves of the three specimens

Peak shear strength of each specimen was compared to the strength prediction equations proposed by previous researchers. **Table 2** shows the result. As stated in the report NUREG/CR-6926 (USNRC 2007), ASCE43-05 (ASCE 2005) equations generally gave greater value of shear strength than ACI equations. Although shear equations of Gulec and Whittaker, Barda, and Moehle as well as ASCE43-05 explicitly take into account vertical reinforcement ratio in shear strength prediction, the proposed equations still underestimated the peak shear strength of squat flanged walls.

At peak strength, all horizontal reinforcing bars in web walls were remain elastic. The mean tensile strain of horizontal reinforcing bars in H08V10, H08V20, and H04V10 were 0.44ε_y, 0.67 ε_y, and 0.45 ε_y, respectively. The strain data indicates that the horizontal reinforcing bars did not strained to perform its peak strength. Accordingly, the contribution of horizontal reinforcing bars to the shear strength capacity was smaller than what expected in ACI design codes.

Table 2 Comparison of test shear strengths and proposed equations

	V_{peak} (kN)	V_{peak}/V_{Barda}	V_{peak}/V_{Gulec}	V_{peak}/V_{Moehle}	V_{peak}/V_{ACI}	V_{peak}/V_{ASCE}
H08V10	2846	1.63	1.46	1.55	2.19	1.63
H08V20	3617	2.08	1.83	1.83	2.79	2.08
H04V10	2994	1.72	1.54	1.47	2.31	1.72

4. CONCLUSIONS

Reversed cyclic load tests were performed to investigate the effect of flanges and reinforcements on the peak shear strength. The major findings of the present study are summarized as follows:

1) Wall specimens failed in diagonal tension cracking in webs and it can be attributed to the low aspect ratio and flanges at the end of walls which preventing flexure failure mode.
2) Measured peak shear strength was at least two times greater than nominal shear strength specified in ACI design code.
3) Vertical reinforcing bars in flanges increased the peak shear strength while the contribution of horizontal reinforcing bars to the peak shear strength was negligible. At peak shear strength, regardless of the specimens, all horizontal reinforcing bars remained elastic and the mean strain value of the horizontal reinforcing bars were roughly 0.5 ε_y.
4) Although, researchers recognized the influence of flanges and vertical reinforcing bars in webs and flanges and explicitly considered the effect of vertical reinforcing bars to the peak shear strength, the equations still underestimated the peak shear strength of squat walls.

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