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CYCLIC LOADING TEST FOR CYLINDRICAL WALL WITH POST-TENSIONING

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Abstract: *In the case of containment building of nuclear power plant, the shape of wall is cylindrical shape to induce the internal pressure. However, most of specimens of RC walls were planar shaped. Therefore, to investigate the effect of cylindrical shape on shear strength, the cyclic loading test with semi-cylindrical and cylindrical walls were conducted. In addition, to investigate the effect of vertical and horizontal post-tensioning on shear strength of cylindrical wall, the post-tensioned concrete walls were tested. The major test parameters were direction of post-tensioning and cross-tie. The test results showed that the shear strengths of cylindrical walls were greater than the nominal shear strength specified in ACI 359 and EPRI. The effect of post-tensioning on web crushing strength was not significant. However, in the case of specimens with horizontal post-tensioning, the delamination cracks in the direction of circumferential were occurred. Thus, the test specimen with cross-tie was prepared and tested. The cross-tie prevented the delamination cracks due to post-tensioning. The maximum strength of concrete wall retrofitted by cross-tie was observed to increase in direct proportion to the ratio of the thickness of the concrete cover.*

1. Introduction

The nuclear power plant is a building that contains the radioactive materials. If the radioactive materials are leaked, huge economic and environmental damages are expected. To prevent these accidents, nuclear power plant structures were designed with maximum reinforcing bar ratio. The earthquake loading is the most important external loading in accident scenario. Therefore, nuclear power plants were required high seismic performance. Thus, the thickness of wall was designed with 1.2m.

To investigate the shear strength of reinforced concrete walls, various experimental researches have been performed. However, the most of them were considered the planar walls with and without boundary elements and the case of the test with consideration of post-tensioning was rare. The researches of the shear strength of cylindrical walls are relatively rare. To verify the shear strength and ductility and seismic capacity of cylindrical wall, structural tests using reinforced concrete cylindrical vessel were conducted and reported by Uchida et al (1979) and Ogaki et al. (1981).

In this study, to investigate the shear strength of cylindrical wall, cylindrical and planar reinforced and post-tensioned concrete wall specimens were tested under cyclic lateral loading. All test specimens were designed based on the reinforcing bar and tendon ratios of actual containment building of nuclear power plants in Korea.

2. Previous researches of cylindrical wall test

In this chapter, the results of cyclic test for cylindrical wall is modified version of the published paper of Yang and Park (Accepted, 2023) and has been reproduced here.

2.1 Test plan

In a nuclear power plant containment building, due to high seismic demand and integrity capacity, the building was designed with high horizontal reinforcing bar ratio and post-tensioning. The reinforcing bar ratio was close to 1.0 % which is the maximum allowable reinforcing bar ratio as specified in ACI 349. The post-tensioning bar ratios are 1.0% and 0.6% for horizontal and vertical directions, respectively (Lee and Song (1999)). Based on these design parameters, the test specimens were designed with the maximum reinforcing bar ratio.

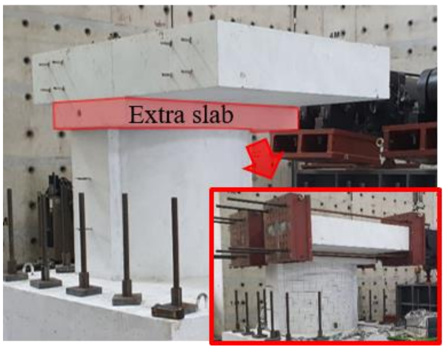
The shapes of test specimens were semi-cylindrical and barbell shaped. **Table 1** shows the design parameters of test specimens. The name of the specimens represents the test parameters. The first letter S, and I represent the shapes of specimens, which are semi-cylindrical, and barbell shapes. The second letter, S refers to low- loading rates of 1 mm/s. The following number 1.0 indicates the aspect ratio of specimens. The fourth letters M, refers the 0.96 % of horizontal reinforcing bar ratio. The last letters VH indicates vertical + horizontal post-tensioning. To investigate the effect of cylindrical shape, the barbell shaped walls with same reinforcing bar and flange detail were prepared.

Table 1. Design parameters of test specimens

Name	f_c' (MPa)	Load. rate (mm/s)	Reinforcing bar ratios			Prestressing bar ratios			Design strength prediction			
			ρ_h, %	ρ_v, %	ρ_f, %	ρ_{pv}, %	ρ_{ph}, %	F_{ph}, (MPa)	V_f	$V_{n,A}$	V_{sf}	$V_{n,E}$
SS1.0M	36	1	0.96	1.86	5.74	-	-	-	3775	425	3121	1081
SS1.0M-VH	36	1	0.96	1.86	5.74	0.64	1.00	1300	4972	983	3121	1758
IS1.0M	36	1	0.96	1.86	5.74	-	-	-	2575	1434	2305	1380
IS1.0M-VH	36	1	0.96	1.86	5.74	0.64	1.00	1300	3263	1434	2305	1981

Note: f_c' is a concrete compressive strength; ρ_h, ρ_v, and ρ_f, are horizontal, vertical reinforcing bar ratios in the web area, and vertical reinforcing bar ratio in the flange area, respectively; ρ_{ph} and ρ_{pv}, are horizontal, vertical prestressing bar ratios in the web area, respectively; V_f is a flexural strength prediction; $V_{n,A}$ is a shear strength predicted based on ACI 359; V_{sf} is a shear-friction strength prediction; and $V_{n,E}$ is a shear strength prediction predicted based on EPRI report.

Figure 1 shows the test set-up. Due to asymmetrical shape of semi-cylindrical wall, torsional force was expected, two actuators were used to apply lateral force without torsional force. To measure the torsional displacement, the linear variable displacement transducers (LVDTs) to out-of-plane direction were installed at the head. **Figure 2** shows detail of test semi-cylindrical and barbell wall specimens. Because of high expected capacity of wall, the specimens with maximum horizontal reinforcing bar ratio (0.92%) were designed as semi-cylindrical shape. The dimensions of semi-cylindrical wall specimens were 1,860 mm (external diameter) × 1,200 (height) × 180 mm (thickness). To prevent premature failure at the anchorage, the vertical reinforcing bars were added at the flanged area.



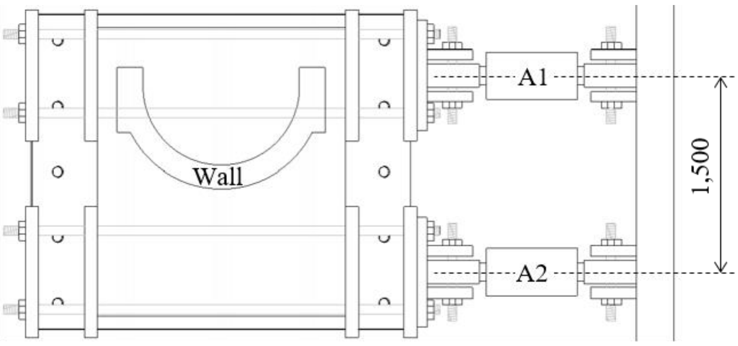
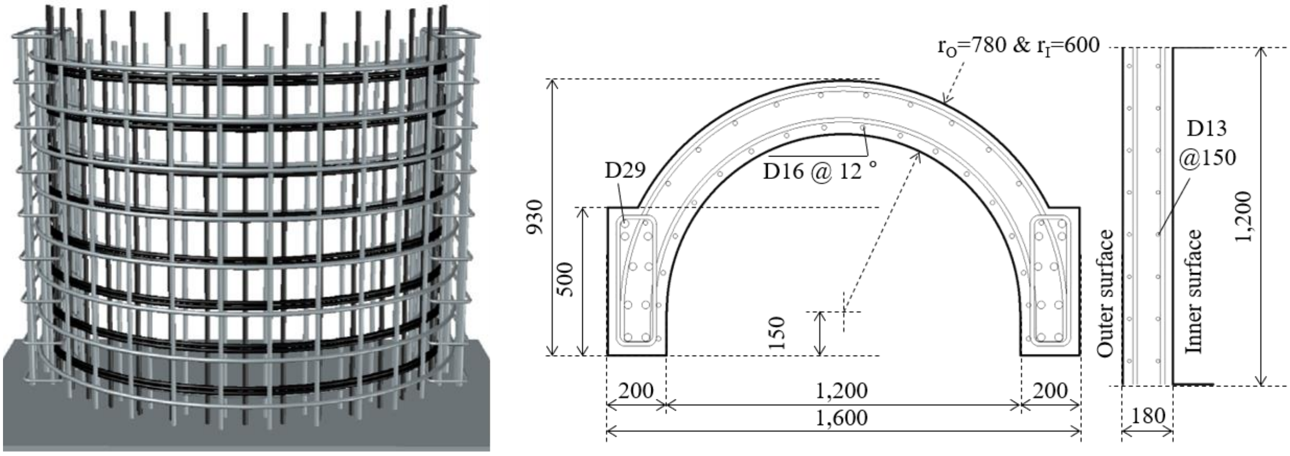
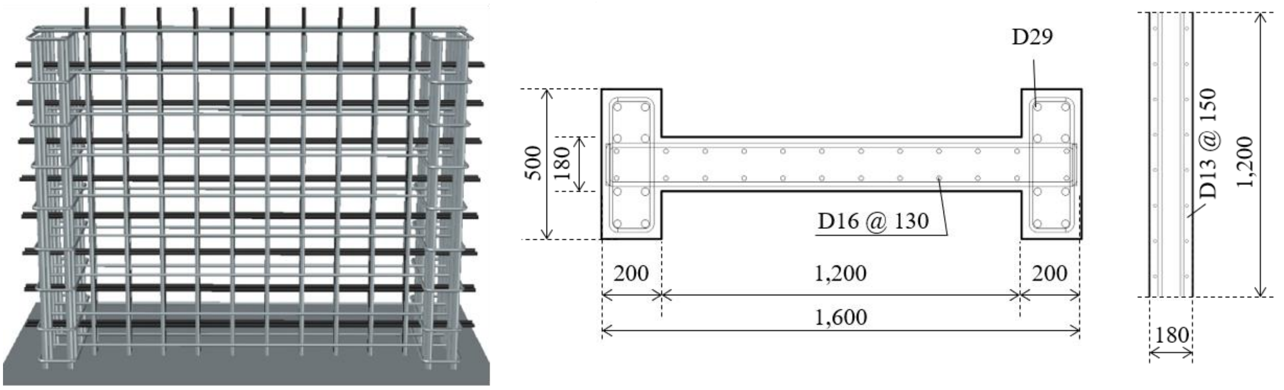


Figure 1. Test set-up



(a) Semi-cylindrical shape wall



(b) Barbell shaped wall

Figure 2. Dimensions of specimens

2.2 Test results

Table 2 shows the summary of test results. **Figure 3** shows the lateral displacement and reaction force curve. The maximum strengths of all specimens were greater than the design strength of ACI 359. On the other hand, in the case of EPRI code for nuclear power plant evaluation, the expected strengths were close to the maximum test strengths. The drift ratio when the maximum strength was occurred was closed to 1.0 %, which is twice greater than the drift ratio limit of 0.5 % (EPRI and ASCE).

Table 2. Summary of test results

Name	Load. rate (mm/s)	Test results				
		$V_{test,+}$	$V_{test,-}$	V_{test}	Drift ratio at V_{test} (%)	Failure mode
SS1.0M	1	2,014	1,931	1,973	+1.02 / -0.90	Shear
SS1.0M-VH	1	2,347	2,193	2,270	+1.03 / -1.04	Shear
IS1.0M	1	2,154	2,202	2,178	+1.19 / -1.17	Shear
IS1.0M-VH	1	2,200	2,198	2,199	+0.74 / -0.72	Shear

Figure 4 shows the failure mode of specimens. The failure modes of all specimens were shear failure. In the case of cylindrical wall with 0.52 % of horizontal reinforcing bar ratio, the shear failure with horizontal bar yielding and large diagonal crack was occurred. After the diagonal crack, huge area of concrete cover was

dropped. On the other hand, the semi-cylindrical wall with 0.92 % of horizontal reinforcing bar ratio, the concrete crushing was occurred at the web area. Due to thick wall and doubled layered reinforcing bar, the cover concrete failure was not occurred.

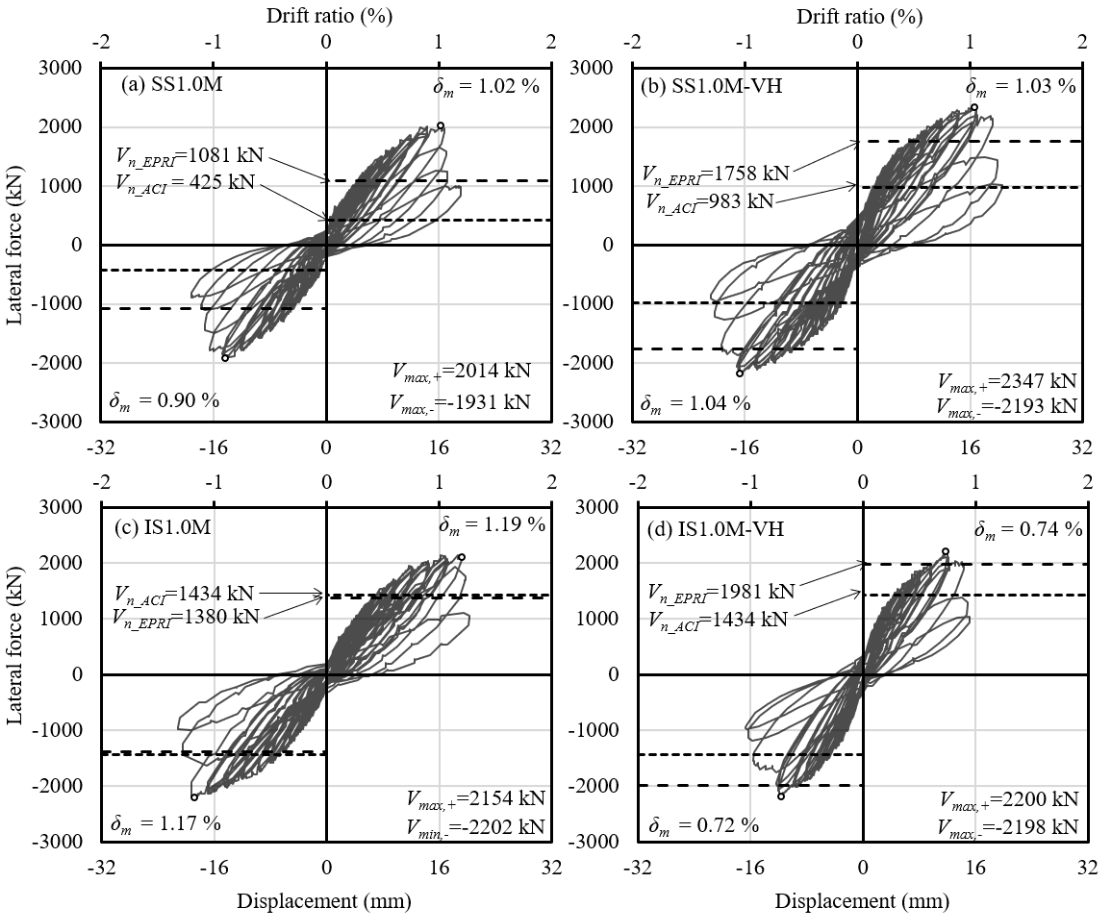


Figure 3. Lateral load-displacement relationships

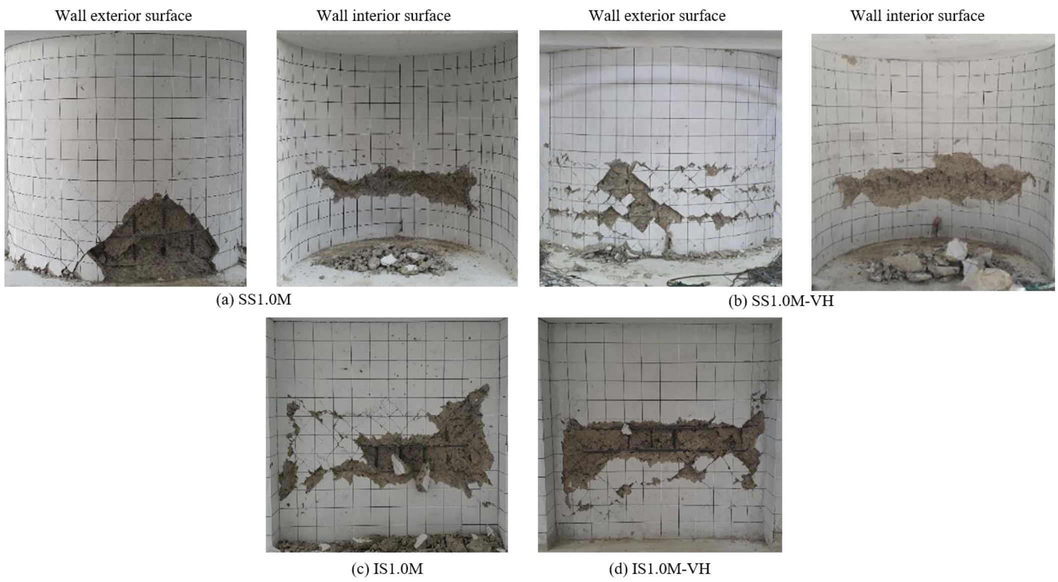


Figure 4. Failure mode of specimens

After the end of tests, to check the delamination cracks due to the horizontal post-tensioning, the concrete core boring was performed (**Figure 5**). The location of boring was at the top of wall, because the damage from lateral loading was minimized. The internal cracks occurred along the horizontal post-tensioning layer. On the other hand, in the case of SS1.0M-VHC with the cross tie, the internal cracks were not observed although the horizontal post-tensioning was applied.

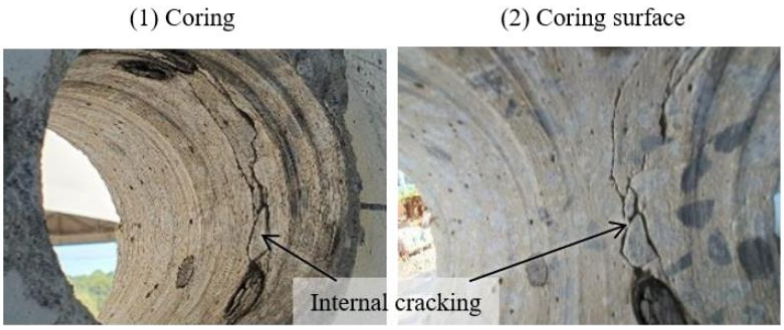


Figure 5. Internal cracks due to horizontal post-tensioning in semi-cylindrical specimens

3. Effect of cylindrical shape

To investigate the effect of structural shape of wall on shear strength, the test results of I-shaped and semi-cylindrical walls were compared. The thickness of wall, detail of boundary element of vertical and horizontal reinforcing bar and post-tensioning force were the same for I-shaped and semi-cylindrical specimens. In the case of specimens without post-tensioning force, the test results of semi-cylindrical specimen SS1.0M were compared to those of IS1.0M. On the other hand, in the case of post-tensioning specimens, the I-shaped specimen IS1.0M-VH was compared to SS1.0M-VHC. All details of SS1.0M-VH were the same as IS1.0M-VHC, however, the crosstie was not installed. Thus, the test results of SS1.0M-VH were different from SS1.0M-VHC with delamination cracks.

Figure 6 shows the comparison results of envelop curves of reinforced and post-tensioning concrete specimens. The difference of stiffness from two comparison results was small. Because the contribution of stiffness was mainly from the cross-section detail of web area. The maximum tested strengths of specimens without post-tensioning forces were 6 %, 12 % and 9 % less at the semi-cylindrical specimen in positive and negative directions and average, respectively (**Figure 6(a)**). The failure mode of interior surface of semi-cylindrical wall was similar to the failure mode of I-shaped. However, the failure mode of exterior surface with large diagonal cracks was different with I-shaped one.

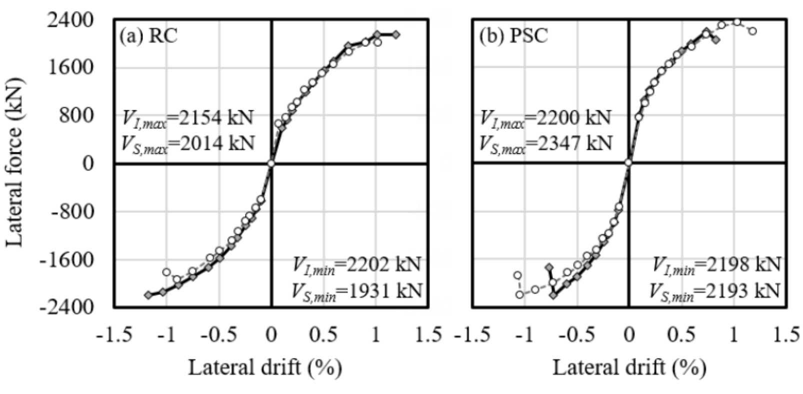


Figure 6. Comparison of envelop curves of I-shaped and semi-cylindrical walls

In the **figure 7**, the comparison results of strain distributions of horizontal reinforcing bars were presented. In the case of reinforced concrete walls (**Figure 7(a)**), the strain of horizontal reinforcing bars of semi-cylindrical specimen when the maximum strength was occurred were 46 % greater than those of I-shaped specimen. Especially, the strain of horizontal reinforcing bar in the middle height was 192 % greater in the semi-cylindrical specimen. In the case of specimens with post-tensioning force (**Figure 7(b)**), the strains at the maximum tested strength of horizontal reinforcing bars of semi-cylindrical specimens were 46 % greater than those of I-shaped specimen. The difference ratio of strains was 1.10 to 1.87.

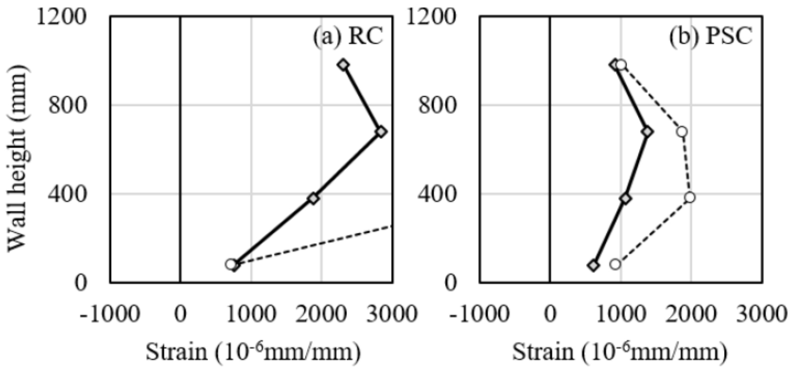


Figure 7. Strain distribution of horizontal reinforcing bars according to wall shapes

The hollow cylindrical wall cannot transfer the lateral force (i.e. seismic load, or wind load) through the centre of the cross section unlike planar, I-shaped, or circular walls (**Figure 8**). Thus, the stress due to the lateral load is transferred along the cross section. In this case, the direction of the load must be continuously changed along the cross section. Therefore, the confining force for lateral force is required.

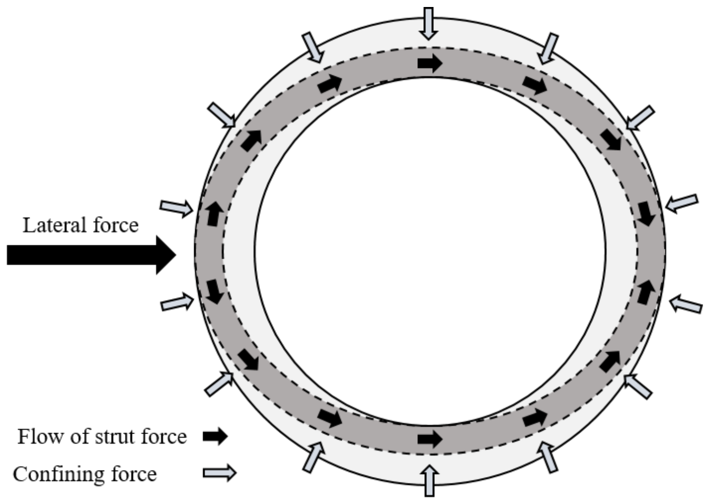


Figure 8. Concept of confining force

The confining force occurs indirectly through the tensile stress of the vertical and horizontal reinforcing bars. The confining force by vertical reinforcing bar was calculated to be very smaller than that by horizontal reinforcing bar. On the other hand, in the case of horizontal reinforcing bars, as shown in **Figure 7**, a higher additional strain appeared in the cylindrical section for the same strength.

In the case of the I-shaped reinforced concrete specimens without post-tensioning test, the maximum tested strength was greater than that of a cylindrical wall. However, the strains of horizontal reinforcing bars were smaller in the case of I-shaped wall as shown in **Figure 7(a)**. This result indicates that additional strain to generate confining forces was appeared. Due to extra strain of horizontal reinforcing bars to generate this confining force, in the case of cylindrical wall, the structural failure was occurred at the lower drift ratio or strength.

On the other hand, in the case of the specimens with horizontal post-tensioning force, the tendencies of maximum strength and strains were different with the results of specimen without post-tensioning. The horizontal post-tensioning force applied to the cylindrical wall generated a radial stress as if to cause delamination. The radial stress was generated the compressive radial stress inside of horizontal tendon layer, and the stress contributes as a confining force on the cylindrical wall. Thus, in the case of cylindrical wall with horizontal post-tensioning like SS1.0M-VHC, the confining force is determined by the sum of effect of horizontal reinforcing bars and radial compressive stress due to horizontal post-tensioning force. Therefore, in the case of specimens with horizontal post-tensioning, the difference of strain distributions at the maximum tested strength was 54 % smaller than that of without horizontal post-tensioning.

In the case of I-shaped wall, the maximum tested strength was similar regardless the post-tensioning force (IS1.0M-VH/ IS1.0M = 1.01). However, in the case of semi-cylindrical test, due to the additional confining force from horizontal post-tensioning, the maximum tested strength ratio of RC and PSC (SS1.0M-VHC/SS1.0M) was increased to 1.15.

In the present test results of specimens with cylindrical section, the failure mode interior surface was huge concrete crushing. According to Timoshenko (1970), in a hollow circular section under radial stress, the in-plane stress increased toward the centre of the cross section. Due to characteristics of the stress distribution of cylindrical section, the concrete crushing was occurred at the interior surface. This is why internal and external failure modes were different each other.

4. Strain increment of cylindrical wall under lateral loading

To investigate the effect of radius on shear strength, FEA analysis was conducted and the horizontal strain was measured from FEA program. Figure 9 shows the concept of horizontal strain of cylindrical wall. Due to the deviation force caused by the radius effect, the radius of wall increases. The horizontal strain of the wall increases due to the increase in radius. Therefore, the horizontal strain of cylindrical wall under lateral loading is summation of strain due to shear deformation and effect of radius.

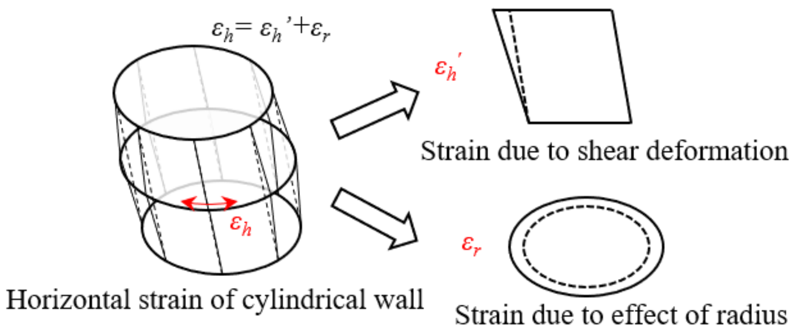


Figure 9. Concept of confining force

Due to the increase in radius of cross section, the horizontal strain of the reinforcement in the cylindrical wall is greater than that in the planar wall. It is believed that the radius effect will affect the degradation of the shear performance of the wall. In particular, the increment of strain of horizontal reinforcing bar is critical to the diagonal tension strength, which is determined by the yield of reinforcing bars. On the other hand, the strength of web crushing failure is affected by the principal tensile stress. However, since the web crushing strength is dominated by the compressive strength of concrete, the effect of the radius is less. In addition, in the previous section, the test results also showed differences in the strain of horizontal reinforcing bars, but the maximum strengths of cylindrical and planar wall were similar each other.

Figure 10 shows the contribution of radius effect on the average horizontal strain based on FEA and test results. The contribution increased as the thickness of the cylindrical wall decreased. The expected contribution based on the analysis results is indicated by a dotted line. The contribution by the radius effect is expected to have significant results from when the thickness of the cylindrical wall becomes half the radius (r_i/r_o = 0.5).

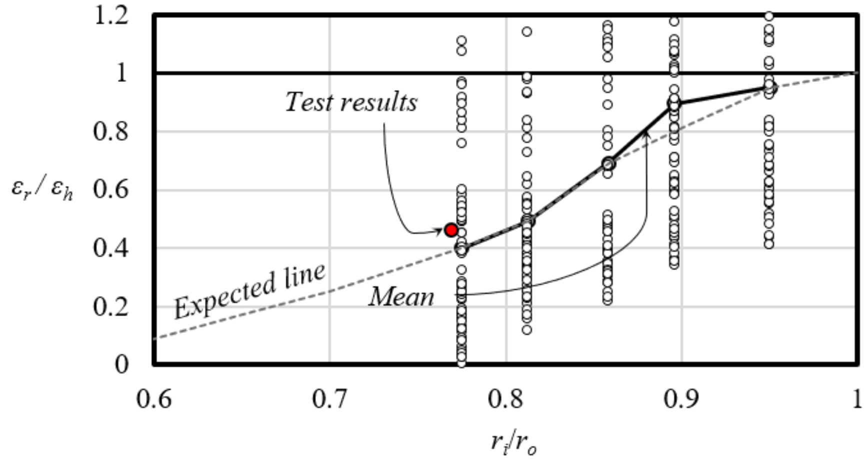


Figure 10. Contribution of effect of radius ($\varepsilon_r/\varepsilon_h$) according to internal and external radius ratio (r_i/r_o)

The thrust line was assumed to investigate the radius effect according to the wall thickness. Figure 11 shows the expected load path in the cylindrical section according to wall thickness. The load path was assumed to have the minimum curvature among the line from the external loading point to the opposite end. The load path determined under above assumption does not have a curvature when the wall thickness is greater than half the radius.

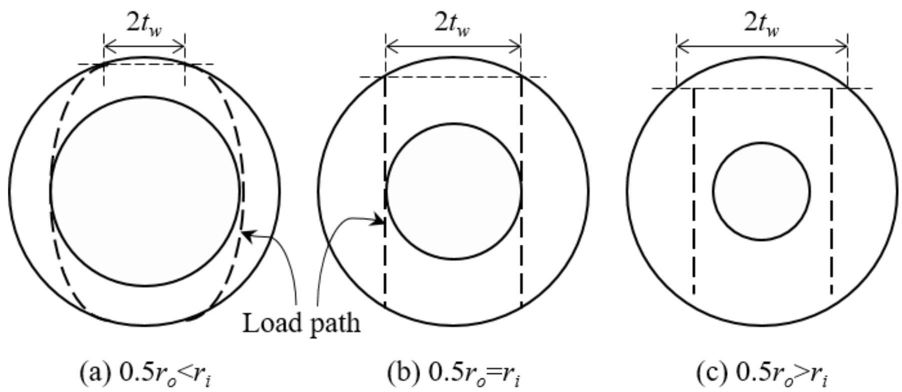


Figure 11. Expected load path in cylindrical section according to internal and external radius ratio (r_i/r_o)

In addition, the load path is affected by the aspect ratio and the cracked angle. Therefore, the loading path does not reach the end of the wall opposite the loading point when the aspect ratio is low. However, in the case of walls with low aspect ratio, the curvature of load path is greater than that of in Figure 11. Thus, when the aspect ratio is low, the radius effect disappears at a lower ratio of t_w/r_o.

If the load path is shown in fig 11, the curvature can be obtained through the following EQ 1. Figure 12 shows the curvature of expected load path according to the ratio of internal and external radius.

$$\kappa_T = \kappa_{R_o} \left[\frac{-1 + 2\left(\frac{r_i}{r_o}\right)}{1 - 2\left(\frac{r_i}{r_o}\right) + 2\left(\frac{r_i}{r_o}\right)^2} \right] \tag{1}$$

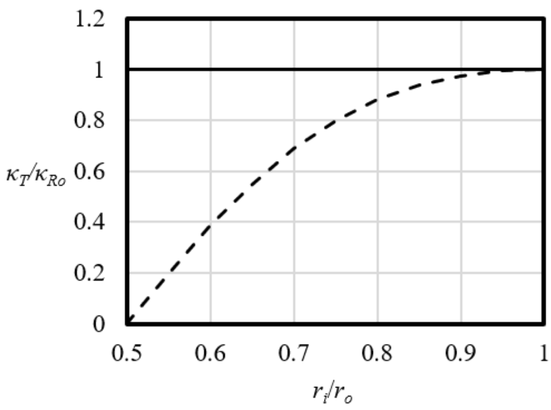


Figure 12. Curvature ratio of cylindrical wall and expected thrust line (κ_R/κ_T) according to internal and external radius ratio (r_i/r_o)

5. Conclusion

In this research, to investigate the effect of radius on shear strength of reinforced concrete wall, structural test and finite element analysis were conducted. The shape of cross-section affects the shear strength of wall. In the case of cylindrical wall, the confining force is needed to resist the lateral forces. The confining force was from the tensile stress of horizontal reinforcing bars mainly. In addition, the radial compressive stress due to horizontal reinforcing bars was contributed to the confining force. Thus, the increment strain of horizontal reinforcing bars due to deviation force should be considered. Also, due to the characteristic of stress distribution in cylindrical section under radial stress, the failure mode of interior and exterior surface was different. Based on the test and analysis results, the increment of strain of horizontal reinforcing bar was suggested. However, the load path is also affected by the aspect ratio, and the crack angle. Therefore, further research is required on when the radius effect disappears or the ratio of the radius effect in the shear deformation.

Acknowledgments

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