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Applicability of Grade 550 MPa Shear Bars in RC Walls with Aspect Ratio of 2.0

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***Abstract*—In the construction of nuclear power plants using massive walls, the use of high-strength reinforcing bars for shear design is necessary, to enhance the constructability and economy. In this study, heavily reinforced walls with aspect ratio of 2.0 were tested, to investigate the shear capacity under cyclic loading. The major test parameters were the grade of shear reinforcement (Grade 550 / 420 MPa), web bar ratio (half / full of permissible maximum bar ratio. According to the direct comparison between the walls with 550 and 420 MPa bars, they had negligible difference in the failure modes, peak shear strength, and lateral stiffness. Particularly, for the walls with Grade 550 MPa bars, the safety margin predicted by ACI 349 was significant. The test result indicates that Grade 550 MPa bars can be applicable to RC walls with aspect ratio less than or equal to 2.0.**

***Keywords*— walls with aspect ratio of 2.0, heavily reinforced walls, high-strength reinforcement, nuclear power plant walls, shear strength,.**

I. Introduction

Currently, high-performance material has been utilized to enhance the constructability and economy in the field of civil and building construction. In particular, high-strength reinforcement has been adopted by Eurocode 2[1]. In design of nuclear power plants abided by ACI 349[2] (or ACI 318[3]), however, the use of reinforcing bars whose yield strength greater than Grade 420 MPa is not permitted because of the conservatism of shear design (Chapter 11 of ACI 349). Thus, to apply the high-strength bars to nuclear power plants, experimental investigations are required for low-rise walls with aspect ratio less than or equal to 2.0, which are the major structural components in nuclear power plants.

Unfortunately, such experimental studies of walls with 1) large shear reinforcement ratio (the typical reinforcing bar condition in nuclear power plant walls), 2) high-strength shear bars [bar yield strength $f_y \geq 550$ MPa], and 3) shear failure mode before flexural yielding are rare. In the present study, cyclic lateral loading tests were performed for low-rise walls (aspect ratio of 2.0) with Grade 550 MPa bars, to investigate the shear capacity under cyclic loading, before flexural yielding. In addition, the tests of identical counterparts with conventional Grade 420 MPa shear bars were also performed, to compare the structural performances and identify differences between Grade 550 and 420 MPa bars in low-rise walls.

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II. Experimental Program

A. Design of Specimens

In nuclear power plant walls, the shear reinforcement ratio is close to the permissible maximum shear reinforcement ratio specified by current design codes. Thus, the specimens described in the paper were designed with the permissible maximum shear reinforcement ratio, focusing on the behavior of walls with high shear reinforcement ratio.

Four wall specimens with aspect ratio of 2.0 were prepared for testing (Fig. 1(a)). The dimensions of the specimens were 1500 mm (length) x 3000 mm (height) x 200 mm (thickness). The design parameters included the grade of shear reinforcement (Grade 420/550 MPa bars), web bar ratio (half/full of permissible maximum horizontal bar ratio). The properties of the walls are summarized in Table 1.

B. Instrumentation

Axial compressive loading and lateral cyclic loading were applied using the test set-up shown in Fig. 1(b). An axial load of approximately $0.07A_cf_c'$ (756 kN for 36 MPa concrete) was applied at the top of the wall by two displacement-controlled actuators. The level of the axial compressive force was maintained during cyclic lateral loading, by manually controlling the vertical displacement.

The lateral loading protocol followed the "Acceptance Criteria for Special Structural Walls"[4]. Fig. 1(b) shows the LVDT(Linear Variable Differential Transformer)s for the measurement of lateral displacements, sliding at the base, and shear deformations. Fig. 1(a) shows the location of the strain gauges, to measure the strains of the flexural bars, web vertical bars, and horizontal bars.

III. Test Results

A. Damages and Failure modes

Fig. 2 shows the damage modes of specimens at the end of test. In Specimen **NS2** with Grade 420 MPa bars (f_{yh}=470 MPa, ρ_h=0.99 %, ρ_v =1.10 %), the first horizontal cracks initiated along the wall ends at the drift ratio of 0.2 %. At 0.35 %, the

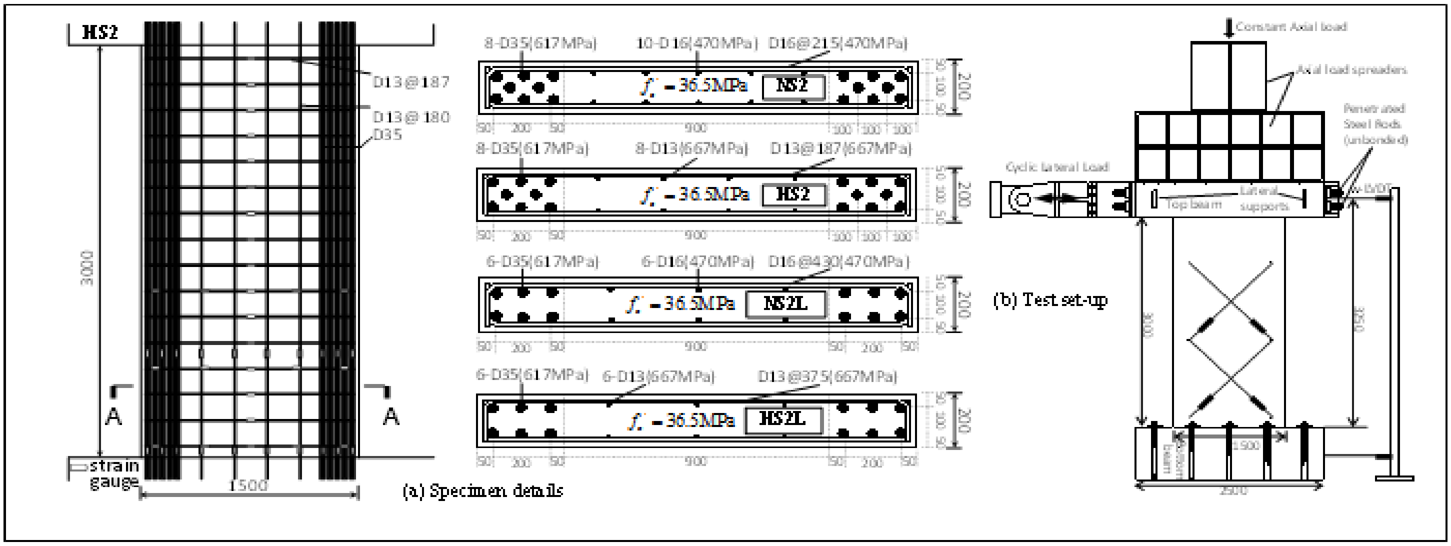

Figure 1. Test Set-up

Tabel 1. Design parameters of test specimens

Specimen	Failure mode	Concrete strength f_c' MPa	Wall web region						Wall boundary region			V_f / V_n
			Horizontal				Vertical		Horizontal boundary hoop spacing	Vertical		
			$V_s / V_{s\,max}$	f_{yh} MPa	ρ_h (%)	$\rho_h f_{yh}$ MPa	f_{yv} MPa	ρ_v (%)		f_{yf} MPa	ρ_f (%)	
NS2	shear	36.5	1.16	470	0.99	4.67	470	1.10	-	617	12.7	1.40
HS2		36.5	1.12	667	0.68	4.50	667	0.70	-	617	12.7	1.41
NS2L		36.5	0.54	470	0.99	2.17	470	0.66	-	617	12.7	1.93
HS2L		36.5	0.56	667	0.68	2.25	667	0.42	-	617	12.7	1.88

horizontal crack extended to the web, forming diagonal cracks. As the drift ratio increased, the diagonal cracks gradually developed toward the upper part of the wall. The higher location of the crack's initiation, the sharper slope of the diagonal crack. At the drift of 2.0 % and peak load, diagonal tension cracking appeared with a diagonal shear crack across the lower part of the wall at an angle of 45 degree (Fig. 2(a)). At the same time, severe concrete damages were accompanied along the diagonal shear cracking (diagonal compression). The flexural and several web (horizontal and vertical) bars were exposed after the sudden failure. The exposed horizontal reinforcing bars were fractured at the location of bending for anchorage hook. The exposed vertical bars showed double curvature at the interface of the diagonal shear cracking, while the flexural bars at wall edges were comparably straight.

In Specimen **HS2** with Grade 550 MPa bars (f_{yh}=667 MPa, ρ_h=0. 68 %, ρ_v=0.70 %), the damage modes were very similar to **HS2** (Fig. 2(b)). The first horizontal crack (0.2 %), diagonal cracks (0.35 %) appeared at the same drift as **HS2**. Eventually, at the drift of 2.0 %, diagonal tension and compression failure were shown, which was the same damage modes and at the same drift ratio as **HS2**. However, the number of diagonal cracks were greater than that of **NS2** at the termination of test.

In Specimen **NS2L**, with Grade 420 MPa bars and a half of maximum horizontal bar ratio (f_{yh} =470 MPa, ρ_h =0.50 %, ρ_v =0.66 %), the first horizontal cracks and formation of diagonal cracks appeared at the drift ratio of 0.15 % and 0.27 %, respectively. As the drift ratio increased, the diagonal cracks gradually developed toward the upper part of the wall, which was the same as **HS2**. At the drift ratio of 1.6 %, the steeper diagonal shear cracking than that of **HS2** or **NS2** covering four fifth of the wall height occurred (Fig. 2(c)). On the other hand, the number of diagonal cracks was much lesser than that of **HS2** or **NS2**.

In Specimen **HS2L**, with Grade 550 MPa bars and a half of maximum horizontal bar ratio (f_{yh}=667 MPa, ρ_h=0.34 %, ρ_h=0.42 %), only few difference compared to **NS2L** was shown: 1) the number of diagonal cracks were greater than **NS2L** [Fig. 2(d)], and 2) one of the horizontal bars exposed due to the diagonal cracking was fractured at the bar center.

B. *Global Responses*

Fig. 3(a) and (b) show the lateral load-displacement (or drift ratio) relationships of Specimen **NS2** and **HS2**, respectively. This figure also shows the shear strength V_n and flexural strength V_f predicted by ACI 349 (ACI 318). In **NS2**, with Grade 420 MPa web bars (f_{yh}=470 MPa, ρ_h=0.99 %, ρ_v=1.10 %) and 36.5 MPa concrete, the load-carrying capacity gradually increased with the lateral displacement. Then, the load suddenly decreased at the drift ratio of 2.1 %. The maximum strength was +2042 and -1989 kN in the positive and negative loading directions, respectively.

The load-displacement relationship of **HS2** with Grade 550 MPa web bars (f_{yh}=667 MPa, ρ_h=0.68 %, ρ_v=0.70 %) was very similar to that of **NS2** with Grade 420 MPa web bars. At the drift ratio of 2.0 %, the load-carrying capacity suddenly decreased. The maximum strength V_{test} was +1917 and -2000 kN, which was on average 3% smaller than that of **NS2**. At the maximum load of both specimens, the flexural bars did not yield, which indicates that the measured maximum lateral load was determined by shear failure, as expected. Fig. 3(c) shows the envelop curves of shear failure mode specimens and flexural yielding specimens, respectively. Likewise, the envelop curves of **NS2L** and **HS2L**, with half of maximum horizontal bar ratio, showed no difference.

C. *Shear Strength*

Table 2 presents the flexural strength predictions V_f, maximum test strengths V_{test}, corresponding drift ratios δ_u, failure modes, and shear strength predictions by the general provision (V_n) and the seismic provision (V_{seis}) of ACI 349[2] (or ACI 318[3]), ASCE/SEI 43-05[5] (V_{ASCE}), Wood[6] (V_{Wood}), and Gulec et al.[7] (V_{Gulec}). In all specimens, the test strength V_{test} was greater than the shear strength predictions by the general provision and seismic provision of ACI 349, which are the current design code for nuclear power plant walls. In particular, the ratio of test strength to the shear predictions showed enough safety margin: V_{test}/V_n=1.45~1.85, V_{test}/V_{seis}=1.18~1.46, though the ratio of **HS2**, with Grade 550 MPa shear bars, was slightly smaller than that of **NS2**, with Grade 420 MPa bars.

In all specimens, the test strength V_{test} was also greater than the shear strength predicted by other researchers[5-7]. Among the shear strength predictions given in Table 2, the shear prediction by the seismic provision of ACI 349 was the best estimation.

D. *Lateral Stiffness*

The curves of the stiffness degradation versus the lateral drift ratio are shown in Fig. 4. The stiffness degradation of **NS2L**, **HS2L**, with smaller bar ratio was much faster than that of **NS2**, **HS2**. Throughout the tests, the lateral stiffness with **NS2** and **NS2L**, with 420 MPa shear bars (thus, larger bar ratio), was slightly greater than that of **HS2** and **HS2L**, with 550 MPa shear bars, respectively.

(a) **NS2** (b) **HS2** (c) **NS2L** (d) **HS2L**

Figure 2. Damage modes at the end of tests

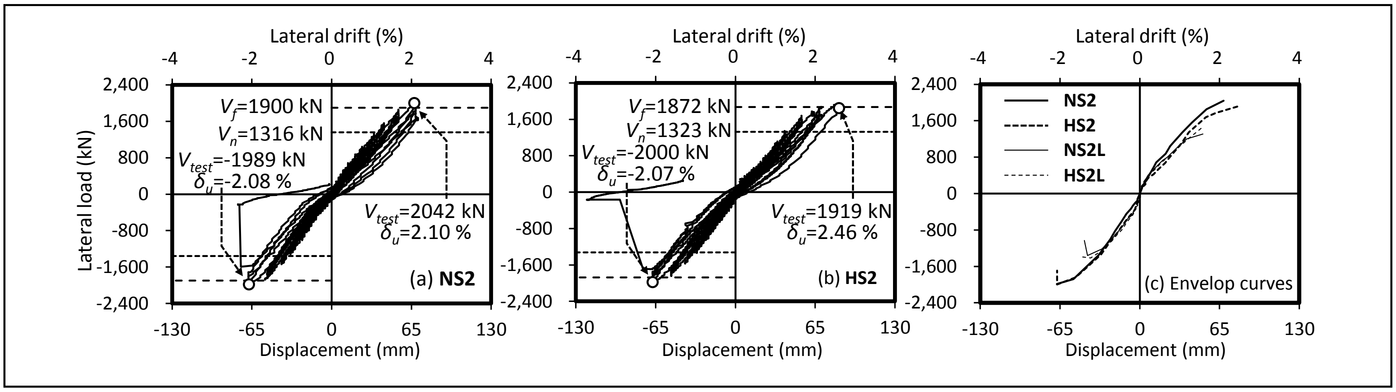

Figure 3. Load-displacement relationships and envelop curves

Tabel 2. Comparison of shear strengths

Specimen	V_f kN	Test results			Ratio of test strength to predictions				
		V_{test} kN	Drift at V_{test} %	Failure mode	ACI 349 Shear provision V_{test}/V_n	ACI 349 Seismic provision V_{test}/V_{seis}	ASCE 2005 V_{test}/V_{ASCE}	Shear prediction by Wood V_{test}/V_{Wood}	Shear prediction by Whittaker V_{test}/V_{Gulec}
NS2	1900	2016	2.10	DT	1.50	1.18	1.62	1.33	1.33
HS2	1872	1959	2.27	DC	1.45	1.18	1.61	1.30	1.30
NS2L	1481	1311	1.45	DT	1.72	1.40	1.34	2.53	1.52
HS2L	1472	1447	1.51		1.85	1.46	1.44	2.65	1.59

Notes: V_f = flexural strength predictions, V_{test} = the average value of the measured maximum loads in positive and negative loading directions. Shear strength predictions provided by Chapter 11(V_n) and 21(V_{seis}) of ACI 349, ASCE 2005 code (V_{ASCE}), Sharon Wood (V_{Wood}), and Gulec Cevet (V_{Gulec}), respectively. DC is diagonal compression failure, and DT is diagonal tension failure.

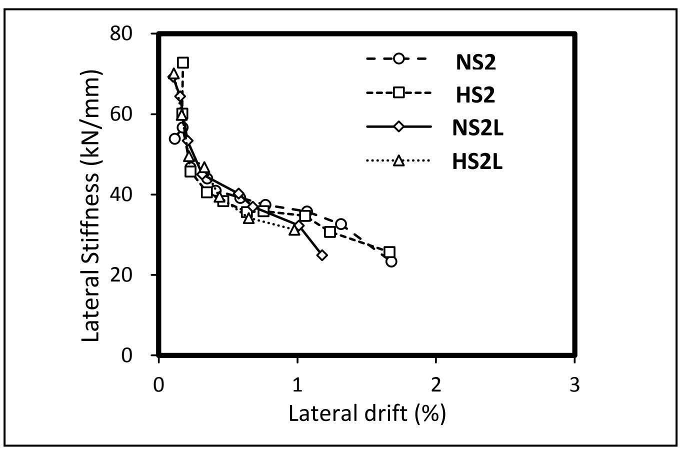

Figure 4. Stiffness degradation curves

IV. Conclusion

To verify the validity of Grade 550 MPa reinforcing bars for shear reinforcement of low-rise walls, four wall specimens with aspect ratio of 2.0 were tested under cyclic lateral loading. Specimens were designed to fail by shear. Using the test results, the validity of the current shear design equations is evaluated for Grade 550 MPa bars. The major findings of the present study are summarized as follows.

- The damage mode of Specimens **NS2**, **HS2** with large shear bar ratio (permissible maximum shear bar ratio in ACI 349) were diagonal tension and compression failure, accompanied by diagonal shear cracking across the lower part of walls. On the other hands, the damage mode of Specimens **NS2L**, **HS2L** with half shear bar ratio of **NS2**, **HS2**, respectively, were diagonal tension failure. The damage mode was not affected by the grade of shear bars.
- The load-displacement of **HS2**, with Grade 550 MPa shear bars was very similar to **NS2**, with 420 MPa shear bars. Likewise, when smaller bar ratio were used (**NS2L**, **HS2L**), the load-displacement were also similar each other.
- In **HS2**, with Grade 550 MPa bars, the ratio of test strength to the shear prediction by ACI 349 was slightly smaller than that of **NS2**, with Grade 420 MPa bars. However, the shear predictions showed enough safety margin: V_{test}/V_n=1.45~1.85 for general provision, and V_{test}/V_{seis}=1.18~1.46 for seismic provision.
- Various shear strength predictions were estimated for the present specimens: the general provision (V_n) and the seismic provision (V_{seis}) of ACI 349, ASCE 2005 code (V_{ASCE}), Wood (V_{Wood}), and Gulec (V_{Gulec}) Equation. The shear prediction by the seismic provision of ACI 349 was the closest to the test results.
- The stiffness degradation of **NS2L**, **HS2L**, with smaller bar ratio was much faster than that of **NS2**, **HS2**. On the other hand, in comparison between **NS2** and **HS2** (or **NS2L** and **HS2L**), the lateral stiffness

was slightly greater in **NS2** (or **NS2L**), due to larger amount of reinforcement.

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