- Technical Paper-

APPLICATION OF STRENGTHENING TECHNIQUES USING STEEL PIPE REINFORCEMENT TO POST-INSTALLED OPENINGS OF LARGE-SCALE RC SHEAR WALLS AND EXPERIMENTAL VERIFICATION

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ABSTRACT

To limit reductions in seismic performance caused by post-installed openings in reinforced concrete shear walls, conventional strengthening techniques are used to supply additional reinforcing bars around openings. But in cases of nuclear power plants with thick walls, a large amount of concrete is removed which is costly. To compare conventional techniques with less invasive steel pipe reinforcement methods, four specimens with different reinforcement were tested until failure. Compared with the conventional method, walls with steel pipe reinforcement increased stiffness, strength, and ductility.

Keywords: RC, shear wall, post-installed opening, strengthening technique, seismic performance

1. INTRODUCTION

1.1 Background

Conventional reinforcement methods for strengthening openings in reinforced concrete shear walls consist of the following steps: 1) removing a relatively large amount of concrete around the opening, 2) inserting additional steel reinforcing bars on each side of the opening, and 3) casting new concrete around the opening. This method may be suitable for typical walls, but for structures such as nuclear power plants where wall thickness may range between 0.5m and 1.5 m, the conventional reinforcement method requires excessive concrete removal and is not efficient. Hence, an alternative less invasive type of strengthening technique is preferred to strengthen post-installed openings to achieve the same or better performance as conventional reinforcement methods in a cost-effective manner (Fig.1).

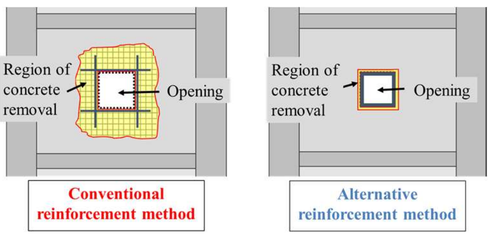
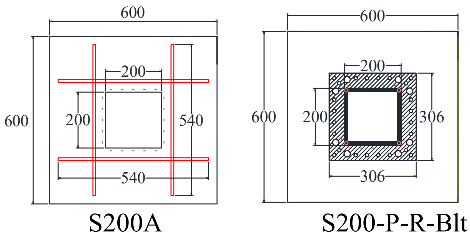


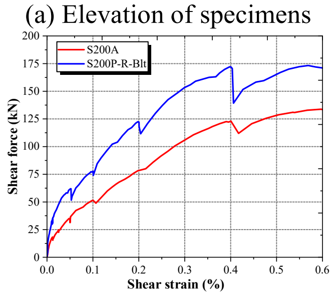
Fig.1 Comparison of conventional and alternative reinforcement methods

1.2 Past Research

Yoshida [1] tested a series of small-scale RC wall panels with openings using five different steel pipe strengthening techniques and observed that each alternative reinforcement performed better than conventional reinforcement up to shear strains of 0.4% and the specimen with steel pipe, flanges (ribs), and bolts (S200-P-R-Blt) performed especially well, reaching an ultimate strength even larger than the solid wall panel (Fig.2). Although this result indicated an effective pipe reinforcement method, the volumetric ratio of steel to concrete is much larger in the small-scale specimen than would be used in an existing shear wall which may have exaggerated the effect of the pipe. Hence, a larger scale test specimen should be tested to verify its effectiveness in existing conditions.



(a) Elevation of specimens



(b) Backbone curves

Fig.2 Results of small-scale wall panel tests

1.3 Research Objectives

The experiments described in this paper have two main objectives. The first objective is to verify the

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effectiveness of steel pipe reinforcement methods on larger scale RC shear walls with double-layer reinforcement, a significant increase from previous 60mm single-layer specimens. This scale was chosen to accommodate double-layer reinforcement within laboratory testing limits, aiming to bridge the gap between small-scale tests and full-scale power plant walls. While the steel pipes' impact on reinforcement effectiveness is uncertain, they were deemed suitable for comparing 1/3-scale and full-scale wall behavior. This research focuses on a new steel pipe reinforcement method for shear walls with openings, aiming to match or exceed the performance of traditional rebar reinforcement around openings. It does not aim to achieve the performance of unreinforced shear walls, thus no target performance was set for them. The second objective is to evaluate the effects of two strengthening parameters, length of rib and length of pipe, on overall seismic performance. The steel pipe reinforcement is designed based on the strongest type tested by Yoshida [1] and consists of a steel pipe, outside flanges welded to edges of pipe, and bolts with threads anchored approximately one-third of wall thickness (Fig.3).

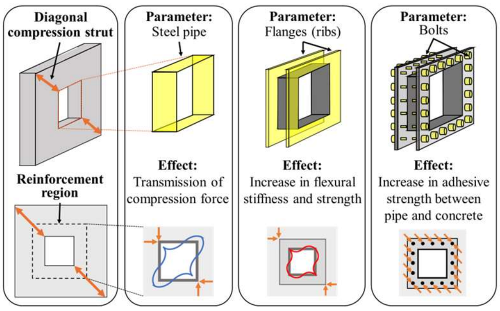


Fig.3 Components of steel pipe reinforcement

2. METHODOLOGY

2.1 Test Specimen

Four 1/3-scale reinforced concrete frame-wall specimens were constructed and tested, one with conventional reinforcement and three with steel pipe reinforcement. Wall length and height are 1750 mm, wall thickness is 200 mm, and wall reinforcement ratio was 1.2% consisting of double layer D10 rebars spaced at 60 mm (Fig.4).

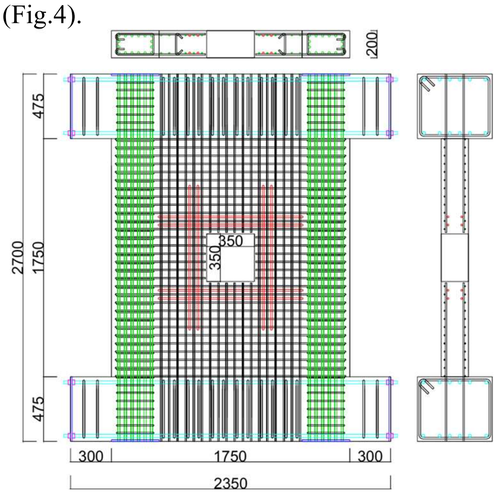


Fig.4 Elevation of test specimen

2.2 Strengthening Techniques

Three steel pipes were designed varying two parameters, length of rib, and length of pipe. Two pipes were designed with a rib length of 170 mm assuming wall with pipe reinforcement would reach the same initial stiffness of solid wall. Of the two mentioned pipes, one had a pipe fully penetrating the thickness of wall (Fig 5-c), and one had a partial pipe penetrating approximately 1/3 of wall thickness on each side (Fig 5-b). The third pipe had a rib length of 130 mm and a partial pipe on each side of wall (Fig 5-a). The flexural stiffness of the pipe with shorter ribs is approximately half of the two pipes with longer ribs. The motivation for testing one pipe with a shorter rib is to confirm to what extent a weaker system can increase seismic performance. The bolts are post-installed anchors and have the role of transmitting the force from the concrete to the reinforcement part, but in this specimen the additional reinforcement and the opening were made together from the beginning. The conventional reinforcing method consisted of double layer reinforcement (D13) placed around opening (Fig 5-d). The amount of additional steel was designed to equal the amount of steel removed from the opening in accordance with AIJ Standard [2].

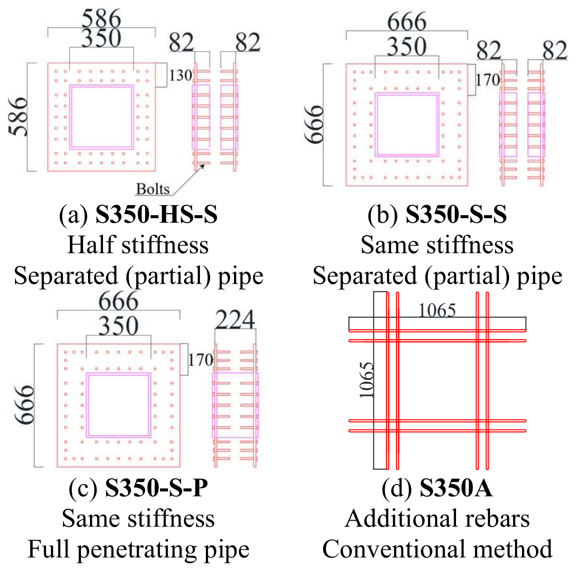


Fig.5 Strengthening techniques

2.3 Material Properties

Material tests conducted on concrete cylinders resulted in an average compressive strength of 40.2 N/mm². Material tests on D10 wall reinforcement resulted in a yield stress of 356 N/mm². Mill sheets of steel pipe and rib materials indicated a yield stress of 382 N/mm², and yield strain and Young's modulus were assumed as tabulated in Table 1.

Table 1 Material properties

Concrete	Ec [N/mm^2]	2.74 x 10^4
	σB [N/mm^2]	40.2
Wall reinforcement D10 (SD295)	Es [N/mm^2]	1.80 x 10^5
	σy [N/mm^2]	356
Opening reinforcement D13 (SD295)	Es [N/mm^2]	1.74 x 10^5
	σy [N/mm^2]	374

Column reinforcement D16 (SD345)	Es [N/mm^2]	1.88 x 10^5
	σy [N/mm^2]	380
Steel pipe 350x350x12 (BCR295)	Es [N/mm^2]	2.05 x 10^5
	σy [N/mm^2]	382
Steel rib t=12mm (SS400)	εs [μ]	2000

2.4 Test Setup

Specimens were tested uniaxially under combined axial and lateral loads using the loading apparatus shown in Fig.6. The setup comprised a strong floor, steel beams, steel columns, and hydraulic jacks. Vertical loads were applied to specimens to simulate gravity loads in wall elements in existing structures. Horizontal jacks were attached to a reaction frame and a reaction wall to ensure effective load transfer to specimen with minimal slip. A pantograph assembly reduced out-of-plane displacement. Loading was applied at mid-height of wall producing an inflection point at center of opening to increase flexural strength and the likelihood of shear failure.

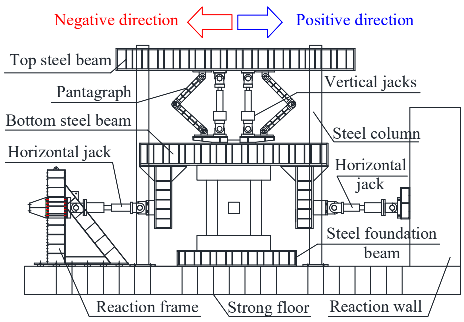


Fig.6 Experimental setup

2.5 Loading Protocol

A constant axial stress of 0.5 N/mm^2 was applied to wall specimens as lateral loading was cycled in positive and negative directions. Two cycles each at story drift ratios of ±0.0125%, ±0.025%, ±0.05%, ±0.1%, ±0.2%, ±0.4%, ±0.6%, ±0.8%, ±1.0%, ±1.5% were conducted. If failure did not occur by a story drift ratio of 1.5%, load was applied monotonically until a 20% decrease in load from ultimate strength was observed.

2.6 Instrumentation

Load cells, displacement transducers, and strain gauges were attached to specimens. Thirty-six transducers attached to backsides of specimens were measured local shear strains as well as compressive and tensile strain (Fig.7). Strain gauges were attached to wall rebar and on pipe reinforcement (Fig.8).

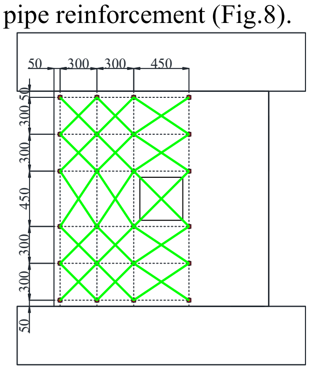


Fig.7 Layout of displacement transducers

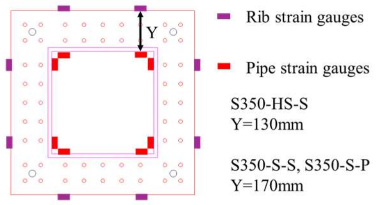
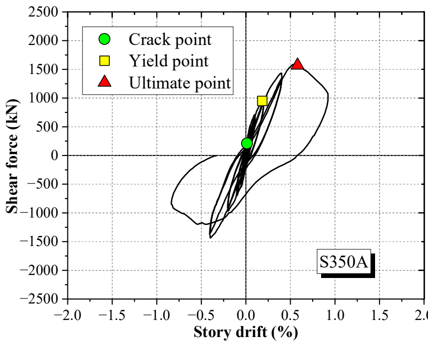


Fig.8 Layout of strain gauges on pipe and rib

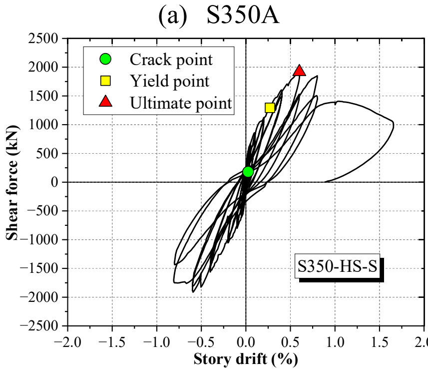
3. EXPERIMENTAL RESULTS

3.1 Hysteresis Curves

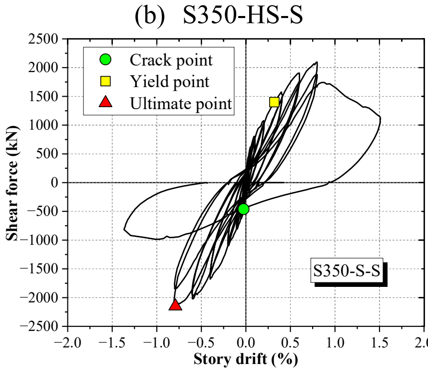
In general, walls with pipe reinforcement had larger initial cracking loads, initial yielding of rebar loads, ultimate strengths, and ductility (Fig.9). The wall with conventional reinforcement (S350A) reached its ultimate strength of 1591 kN at a story drift of 0.55% followed by an abrupt decrease in load caused by large, inclined share cracks. The two specimens with partial pipe reinforcement (S350-HS-S and S350-S-S) had larger ultimate strengths than S350A of 1918 kN and 2151 kN and occurred at story drifts of 0.6% and 0.8%. The specimen with full penetrating pipe (S350-S-P) had the largest ultimate strength of 2261 kN occurring at a story drift of 1.5%.



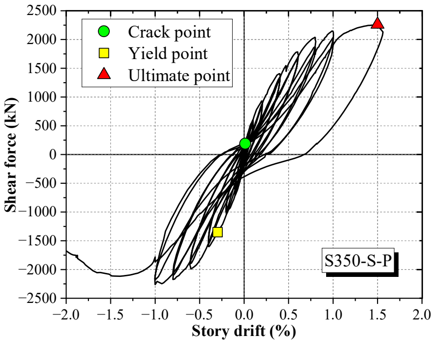
(a) S350A



(b) S350-HS-S



(c) S350-S-S

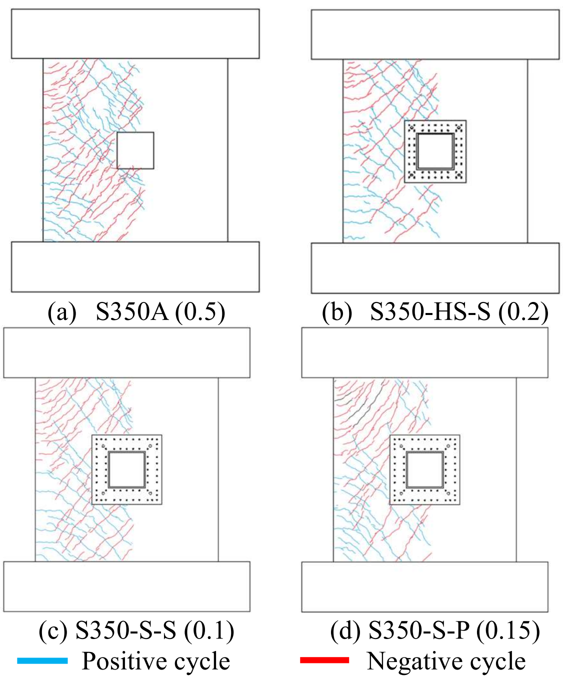


(d) S350-S-P

Fig.9 Hysteresis curves

3.2 Crack Patterns

Crack patterns for walls with conventional and pipe reinforcement at story drift ratios of 0.2% are shown in Fig.10. Specimen S350A had more shear cracks concentrated close to the opening with larger widths than specimens with pipe reinforcement which had fewer shear cracks near opening. Pipe reinforcement with shorter rib produced the most uniform shear crack pattern with nearly equal spacing between cracks near opening and in regions adjacent to opening. But pipe reinforcement with larger ribs produced more cracks in regions adjacent to openings suggesting the stiffness of the pipe strongly influences crack pattern. Initial cracking maps were analyzed and specimen S350-S-P which was tested last had more shrinkage cracks around corners of walls reducing the initial stiffness and stiffness before yielding. The cause of the initial cracks is currently unknown, but it may be due to a problem such as drying shrinkage that occurred during the production of the test specimen or accidental tensile force during setup to fix to the loading steel frame.



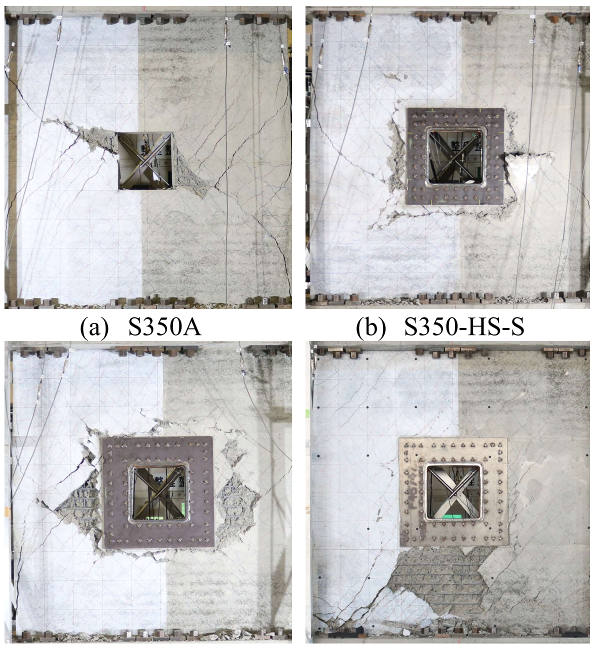
(a) S350A (0.5) (b) S350-HS-S (0.2)

(c) S350-S-S (0.1) (d) S350-S-P (0.15)

Fig.10 Crack patterns at story drift ratios of 0.2% (maximum crack width in mm)

3.3 Failure Mode

Fig.11 shows the final damage condition of the four specimens. The failure mode of wall with conventional reinforcement consisted of tensile splitting cracks near edges of columns combined with inclined shear cracks and concrete crushing concentrated at corners of openings. But walls with pipe reinforcement had more extensive concrete crushing around the perimeter of the ribs suggesting a more uniform compressive force transfer around opening caused by pipe, rib, bolt strengthening technique. Although walls with partial pipes had nearly the same final damage condition with tensile splitting cracks and inclined shear cracks, the wall with full penetrating pipe did not have tensile splitting cracks but instead showed extensive diagonal compression failure.


(a) S350A (b) S350-HS-S

(c) S350-S-S (d) S350-S-P

Fig.11 Final damage condition of specimens

4.COMPARISON OF EFFECTS OF STRENGTHENING TECHNIQUES

4.1 Comparison of Walls with Pipe Reinforcement

To study the increase in shear resistance provided by walls with pipe reinforcement relative to wall with conventional reinforcement, ratios of shear force reached at each story drift were computed and plotted in Fig.12. Shear forces were computed as the average of peak forces reached during first positive and negative cycles. Walls with partial pipe reinforcement (S350-HS-S and S350-S-S) resisted larger shear forces than wall with conventional reinforcement throughout entire test but wall with full penetrating pipe resisted smaller shear forces at drifts before initial yielding of wall rebar (<0.2%) and larger shear forces after initial yielding (Fig.13).

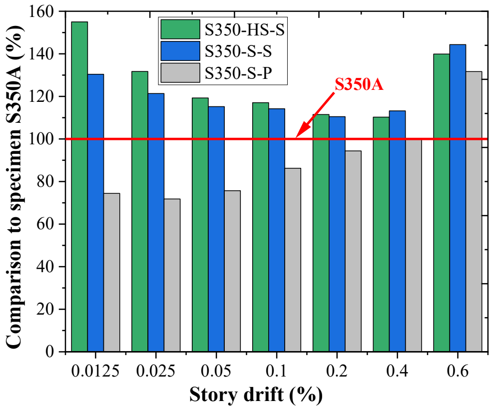


Fig.12 Shear force resisted by pipe reinforcement relative to conventional method

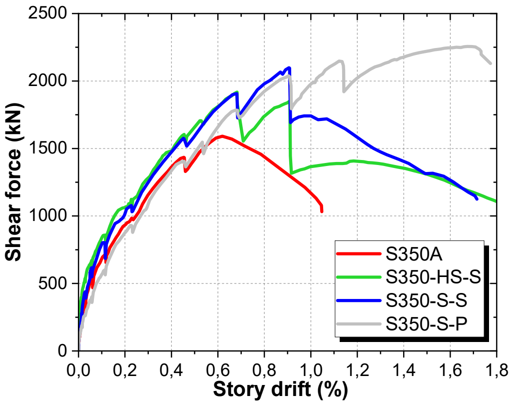


Fig.13 Backbone curves

Table 2 Summary of ultimate strength

Specimen	S350A	S350-HS-S	S350-S-S	S350-S-P
Drift ratio (%)	0.55	0.6	-0.8	1.5
Strength (kN)	1591	1918	-2151	2261

4.2 Contribution of Steel Pipe Reinforcement

Strain gauges attached to the underside of pipe and topside of rib were used to estimate the amount of force resisted by pipe reinforcement. Assuming a linear strain distribution, curvature was estimated using strains measured on pipe and rib (Fig. 14) and related with bending moment and external force acting on pipe reinforcement (Eqs.1-2). Strain gauges were grouped in four groups as shown in Fig.15: two representing ribs (A and B) and two representing pipes (C and D). The average value of each group was calculated and used to estimate force resisted by pipe using Eq.3.

The variation of force resisted by pipe reinforcement with story drift shows a nearly linear relationship (Fig.16). Expected yielding forces for each pipe reinforcement (Py) were estimated using expected yielding stress of steel plates and pipe dimensions. The pipe reinforcement with shorter rib reached initial yielding of rib at a story drift of 0.6% coinciding with ultimate strength of specimen. Because not all gauges on ribs yielded, the average force in pipe reached only 80% of the theoretical yielding force. The two pipe reinforcements with longer ribs did not reach their yield force.

The contribution of the pipe reinforcement relative to overall shear resistance of wall ranges from nearly 5% at small strains to 30% at a story drift of 1.0% (Fig.17). The pipe reinforcement with partial length pipe and long rib (S350-S-S) consistently had the highest contribution to the load carried by wall. This may suggest good adhesion of to the concrete wall by anchor bolts and good balance of flexural stiffness of steel pipe and surrounding concrete wall.

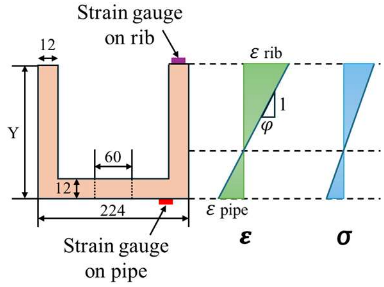


Fig.14 Strain and stress profile of pipe reinforcement (units: mm)

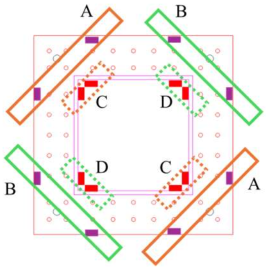


Fig.15 Strain gauge grouping on pipe and rib

$$P = \frac{4M}{H} \quad (1)$$

$$\varphi = \frac{\Delta\varepsilon}{\Delta Y} = \frac{M}{EI} \quad (2)$$

$$P = \frac{4 * Es * (\varepsilon_{pipe} + \varepsilon_{rib}) * I}{H * Y} \quad (3)$$

ε: strain measured on pipe, rib;
Es: Young's modulus of steel;
I: second moment of inertia;
H: length of side of opening;
Y: distance between strain gauges on pipe and rib;
M: bending moment resisted by pipe reinforcement.

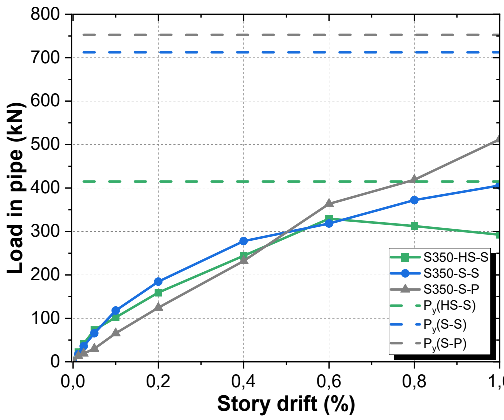


Fig.16 Force resisted by pipe reinforcement

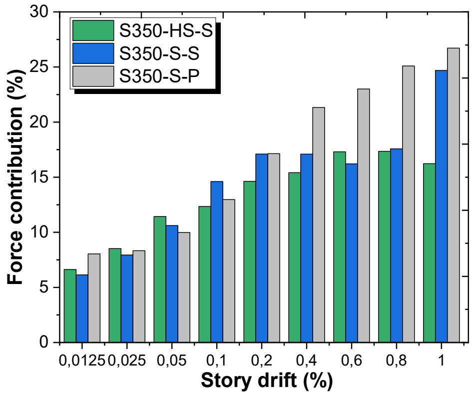


Fig.17 Contribution of pipe reinforcement on overall shear resistance of wall

4.3 Local Deformation of Wall Segments

To study the effects of pipe reinforcement on local deformations of wall segments, compressive strains of concrete and opening regions were computed using the transducers shown in Fig.7. In general, openings have larger compressive strains than surrounding concrete likely caused by compressive stress concentration at corners of openings (Fig.18). For wall with conventional reinforcement, the compressive strain of opening is approximately 5 times larger than surrounding concrete but for walls with pipe reinforcement, compressive strain of opening is between 1 and 2 times larger than that of surrounding concrete.

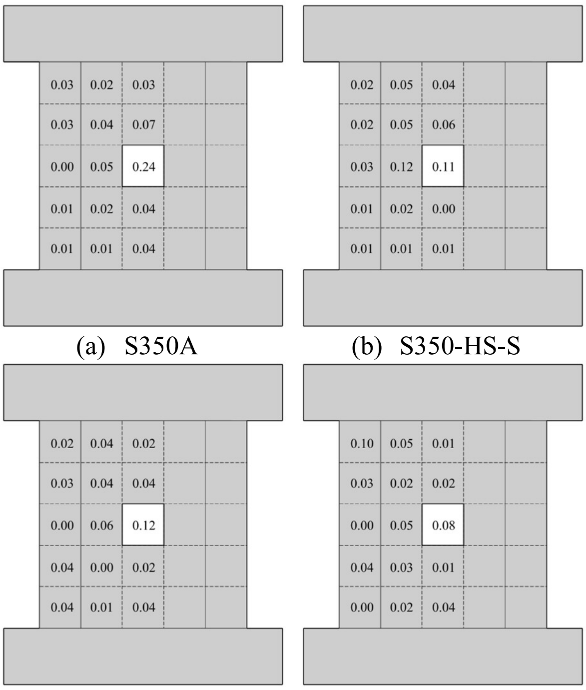


Fig.18 Compression strains of wall segments at story drift ratios of 0.2% (units: %)

To focus on differences in opening deformation between conventional and pipe reinforcement methods, shear strains of opening are calculated using both compressive and tensile strains measured using transducers placed across opening (Fig.7). Variation of shear strain of opening with story drift ratio is plotted in Fig.19 and in general, there is a linear trend. The pipe reduced shear strain by 30-50% for story drift ratios between 0.2-0.4% compared with conventional reinforcement. The full penetrating pipe (S350-S-P) produced the smallest opening shear strains as this reinforcement had the largest flexural stiffness. The conventional reinforcement showed a sudden increase in shear strain of opening after story drift ratio of 0.4% which preceded ultimate strength and shear failure.

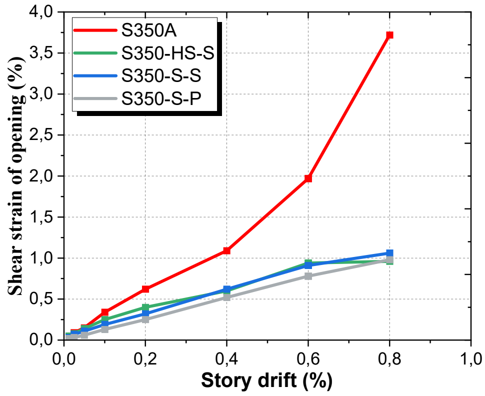


Fig.19 Comparison of deformation of opening

5. CONCLUSIONS

(1) Steel pipe reinforcement increased ultimate strength and ductility of shear walls compared with conventional reinforcing method indicating an effective alternative strengthening technique.

(2) Walls with pipes with longer ribs had smaller initial stiffness, but larger ultimate strength and ductility. Wall with partial length pipes and shorter ribs and had larger initial stiffness suggesting good balance between stiffness of pipe and surrounding concrete.

(3) Pipe reinforcement reduced deformation of opening. Compressive strains of openings of walls with pipe reinforcement were approximately 30% and 50% smaller compared with those of walls with conventional reinforcement at story drift ratios of 0.2% and 0.4%.

(4) Cracks patterns and failure modes indicate that pipe reinforcement produces more uniform compressive force transfer around opening compared with conventional reinforcement.

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