Effect of Strengthening Techniques Applied to RC Walls with Post-installed Openings on Shear Resistance

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ABSTRACT

Shear walls increase stiffness and strength of reinforced concrete buildings improving their capacity to resist earthquake damage. Nevertheless, it is common for shear walls to contain openings for a variety of purposes including doors, windows, and elevator shafts. Openings reduce initial stiffness and shear strength of walls. To limit reductions in seismic performance, strengthening techniques are applied around critical locations. In cases where openings are made in existing structures, an efficient strengthening method should minimize the amount of concrete to be removed for accommodating the strengthening device in order to reduce installation cost and operational downtime.

To compare the effects of a range of strengthening methods on the stiffness and strength of wall panels, six specimens were tested. Three specimens serve as references - one solid wall, one wall with opening, and one wall with opening and standard additional reinforcement. The other three specimens were built using different strengthening techniques, and include steel pipe with rough surface, steel pipe with smooth surface and flanged ends, and steel pipe with rough surface and flanged ends.

Based on the experimental results, strengthening techniques increased the shear resistance of specimens with openings for shear strains up until 0.2% relative to specimens with standard additional reinforcement. This suggests an increase in seismic performance from standard practice without expensive fabrication costs. The specimen with steel pipe, rough surface, and flanged ends reached a shear strength larger than that of the specimen with standard additional reinforcement indicating an effective strengthening technique.

1 INTRODUCTION

In Japan, when designing openings in RC shear walls, it is common practice to strengthen the region around the opening with reinforcing bars (Architectural Institute of Japan, 2018). For existing buildings, the construction of new openings requires that surrounding concrete be removed so that supplemental reinforcement can be added to wall (Fig. 1). Past research has focused on the effects of openings with standard additional internal reinforcement on stiffness and strength of shear walls (Alwashali 2021, Alwashali 2022, Tsurugai 2023). Other studies have proposed the use of steel pipes to be used as reinforcement to reduce the amount of concrete removal (Tanabe, 2020). In this study, a reinforcement method using steel pipe reinforcement is designed to reach similar strength and stiffness as the conventional opening reinforcement (Yoshida, 2024). In addition to the pipe, a rough surface to improve the adhesion mechanism between steel and concrete, and a flange welded to pipe to increase stiffness of wall are proposed and tested.

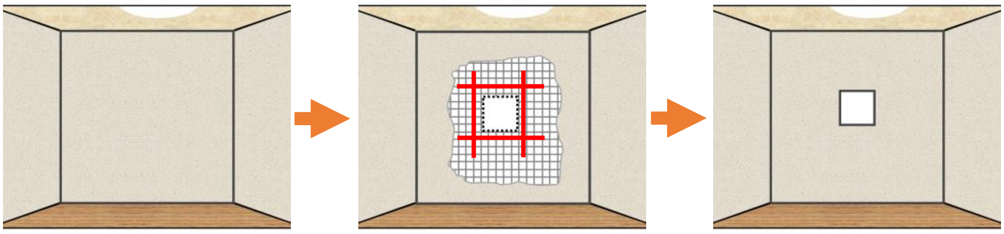


Figure 1: Standard procedure for adding reinforcement around opening in existing shear wall

2 PROPOSED REINFORCEMENT METHODS

2.1 Shear resistance mechanism of shear walls

Figure 2 shows plausible shear transfer by compressive struts for walls with and without openings. For a solid wall, shear force is transmitted by a 45-degree compressive strut. But for a wall with an opening, the shear resistance is lower than that of a solid wall because the compressive struts are more inclined to avoid the opening. In this study, the shear resistance mechanism of a shear wall with an opening is investigated, and the effectiveness of reinforcement bars compared with alternative reinforcement methods are studied and verified by wall panel experiments.

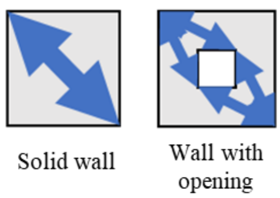


Figure 2: Shear transfer by compressive strut

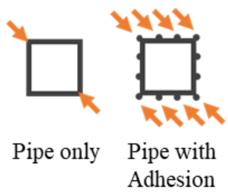


Figure 3: Effect of adding adhesion to pipe

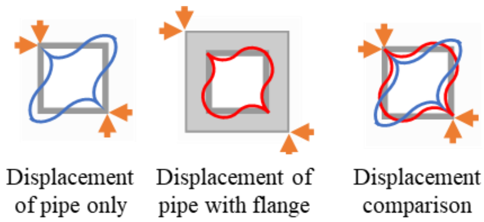


Figure 4: Effect of adding flange to pipe on displacement

2.2 Proposal of strengthening techniques using steel pipes

In this study, there are three components of the strengthening technique: (1) a steel pipe, (2) a mechanism to ensure adhesion (referred to as bond) between the steel pipes and concrete, and (3) a mechanism to ensure bending rigidity (flanges) of the steel pipes. The steel pipe (Fig. 3) is expected to replace the standard additional reinforcing bars (Fig. 2) The adhesion between the steel pipe and concrete (Fig. 3) is expected to effectively transfer compressive forces from concrete to steel pipe. The flanges (Fig. 4) welded to the steel pipe are expected to increase the bending stiffness of the plates on the four sides of the steel pipe and contribute to the load transfer of the diagonal compression strut. The effects of the strengthening techniques on strength and stiffness were evaluated as follows:

2.2.1 Effect of strengthening technique on stiffness

The compression strut generated in wall is transmitted through center region (Fig. 5) near opening producing shear forces and bending moments in steel pipe (Fig. 6) The horizontal stiffness K_{sp} assuming pipe is a frame structure with lateral load applied at top is obtained using Equation (1).

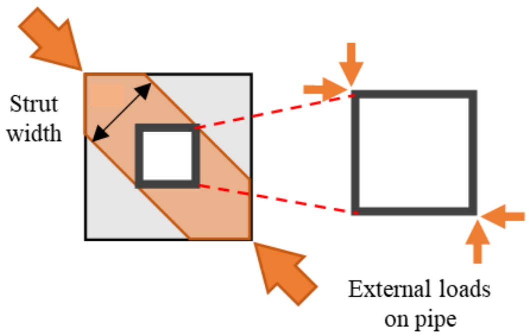


Figure 5: Mechanism of force transmission to steel pipe

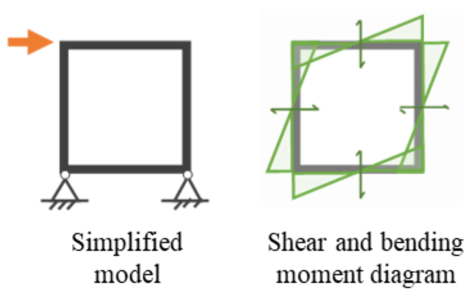


Figure 6: Bending moment of steel pipe

$$K_{sp} = 2 \times \frac{12EI}{L^3} = \frac{24EI}{L^3} \qquad (1)$$

E: Young's modulus of steel, I: Second moment of inertia of steel pipe, L: Height of steel pipe

2.2.2 Effect of strengthening technique on strength

As the compression strut transmits more load to the steel pipe, the bending moment in corners increases until yielding occurs and yielding shear force Q_y is estimated using Equations (2) and (3). The yield moment M_y of the steel pipe is increased by adding flanges to the steel pipe.

$$Q_y = 2 \times \frac{2M_y}{L} = \frac{4M_y}{L} \qquad (2)$$

$$M_y = \sigma_y Z_y \qquad (3)$$

σ_y: yield strength of steel pipe, Z_y: plastic section coefficient of steel pipe plate material.

3 EXPERIMENTAL PROGRAM

3.1 Specimen overview

A total of six specimens were tested and are listed in Table 1. Table 2 shows the details of the reinforcement. The dimensions and reinforcement drawings of the specimens are shown in Figure 7, and the details of the steel pipe reinforcement are shown in Figure 8. Wall panels were 600 mm x 600 mm and openings were 200 mm x 200 mm. Shear forces were transmitted to the specimen by shear studs welded to loading steel plates cast within specimens. The test specimen SS refers to the solid wall specimen (no opening), S200 refers to the specimen with an opening without reinforcement, and S200A refers to the specimen with opening and additional reinforcement around the opening. S200P-R has steel pipe and flanges, and S200P-B has steel pipe and steel rebars for adhesion. Square steel tubes (200 mm x 200 mm x 12 mm) were used as pipe reinforcement. The flanges were welded to steel pipe, and five D10 rebars were welded to each side of the steel pipe to increase adhesion.

The test specimen with steel pipe was designed to resist approximately 10 kN before yielding. Adding flanges to the steel pipe increases the strength by a factor of nearly 20, exceeding a load of 200 kN. The stiffness of the pipe only was estimated to be 5 kN/mm and almost 100 times larger for the pipe with flanges which produces an estimated stiffness of 450 kN/mm.

Table 1: Specimen description

Specimen	Opening	Strengthening technique	Adhesion
SS	None	-	-
S200	200x200	None	-
S200A		Add. rebars	-
S200P-B		Steel pipe	Included
S200P-R		Pipe + flanges	None
S200P-R-B		Pipe + flanges	Included

Table 2: Details of strengthening techniques

	S200A	S200P-R	S200P-B	S200P-R-B
Strengthening technique	Additional reinforcement	Pipe with flanges	Pipe with adhesion	Pipe with flanges and adhesion
Details	2-D10 (SD295)	Pipe: 12 x 200 x 200 Flange: 9 x 306 x 306	Pipe: 12 x 200 x 200 Adhesion: D10 rebars	Pipe: 12 x 200 x 200 Flange: 9 x 306 x 306 Adhesion: D10 rebars

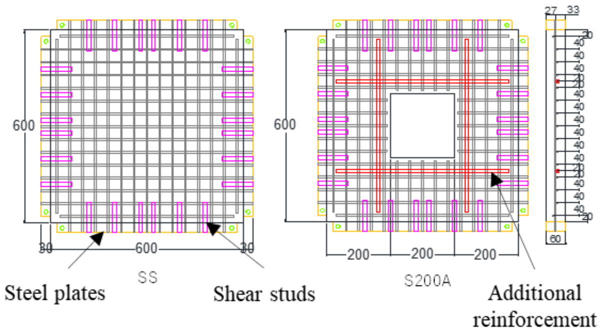


Figure 7: Reinforcing bar layout of wall specimens

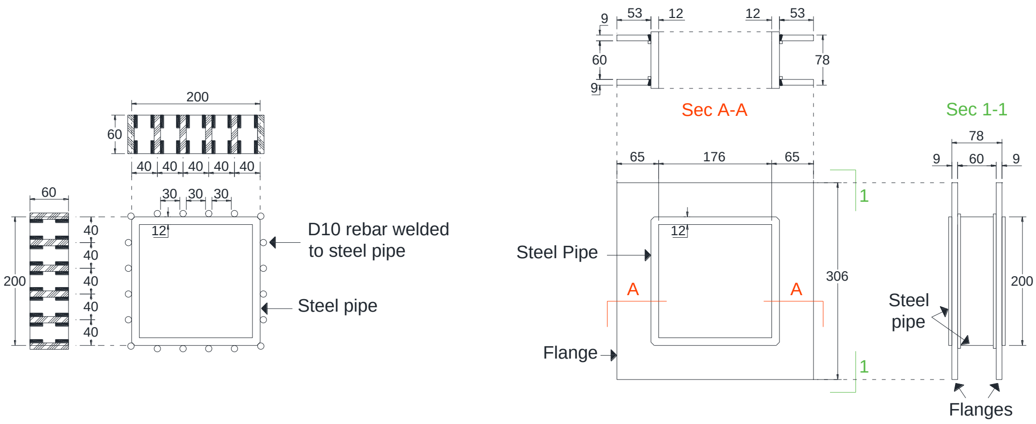


Figure 8: Details of strengthening techniques

Table 3: Properties of strengthening techniques

Specimen	Load (kN)		Stiffness (kN/mm)	
	Estimated	Measured	Estimated	Measured
S200P-R	220	4.1	450	267
S200P-B	10	5.3	5	138
S200P-R-B	220	20.7	450	437

3.2 Material properties

The compressive strength of the concrete varied slightly from 26.9 MPa to 28.5 MPa for each specimen, and the average was 27.8 MPa. The main wall reinforcement was D6 SD295 spaced at 40 mm and additional reinforcement was D10 SD295. Steel pipe was made from STKR400 steel. Material properties of elements are shown in Table 4.

Table 4: Material properties

Concrete	Compressive strength (MPa)	27.8			
	Tensile strength (MPa)	2.2			
Reinforcing bars	Tensile strength (MPa)	D6 (SD295)	440	D10 (SD295)	370
	Yield stress (MPa)		540		515
Structural steel	Tensile strength (MPa)	Pipe	350	Flange	380
	Yield stress (MPa)		410		465

3.3 Loading protocol

Figure 9 shows the loading rig. Four hydraulic jacks were connected to four loading plates of wall specimen to apply external force to specimen. By applying equal loads in opposite directions, pure shear loading was applied to wall panels. Cyclic loading was applied until peak shear angles reached ±0.0125%, ±0.025%, ±0.05%, ±0.1%, ±0.2%, ±0.4%, and ±0.6%. Specimens were loaded twice in each direction for a given shear angle.

3.4 Measurement plan

Total shear deformation angles of the specimens were measured using displacement transducers installed on front and back sides of specimens (Figure 10). The shear deformation component of the reinforcing steel pipe was also measured by installing a displacement transducer in the diagonal direction (Fig. 10).

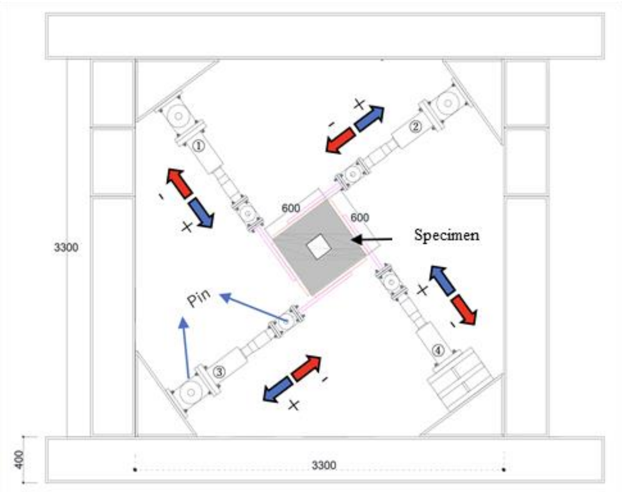


Figure 9: Loading rig

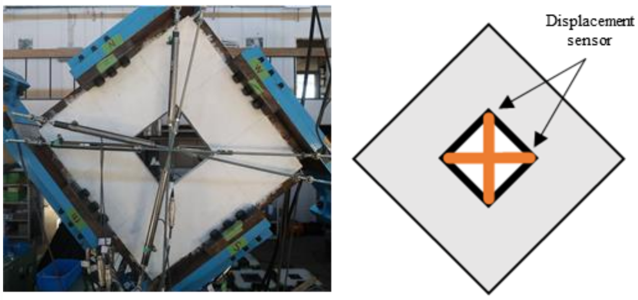


Figure 10: Displacement sensor layout for specimen and steel pipe

4 EXPERIMENTAL RESULTS

4.1 Load-deformation relationship

Table 5 shows a summary of the peak shear forces resisted by specimens at each target shear strain. Figure 11 shows the load-deformation relationships of three specimens reinforced with steel pipes. For specimen S200P-R, the main reinforcing bars yielded at 0.2% and the specimen reached a shear strength of 124 kN at an angle of 0.6%. For specimen S200P-B, the rebar yielded at a shear angle of 0.13%, and a shear strength of 125 kN was reached at 0.4%. For specimen S200P-R-B, the reinforcing bars yielded at a shear angle of 0.17%, and a shear strength of 141kN was reached at 0.4%.

Table 5: Summary of peak shear forces

Specimen	Peak shear force at indicated shear strain (kN)						
	0.0125%	0.025%	0.05%	0.1%	0.2%	0.4%	0.6%
SS2	38	49	62	84	127	160	157
S200	17	25	32	49	80	115	120
S200A	18	25	35	52	79	123	134
S200P-B	35	47	61	80	113	125	118
S200P-R	26	37	44	60	90	122	124
S200P-R-B	30	42	54	70	100	141	139

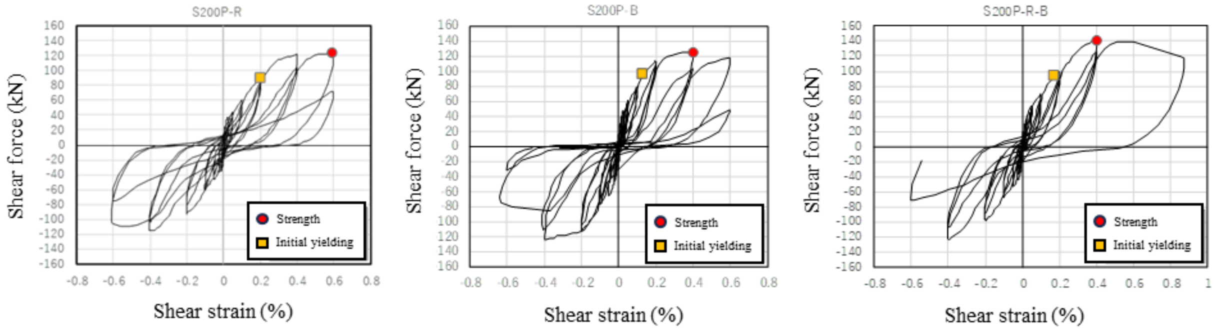
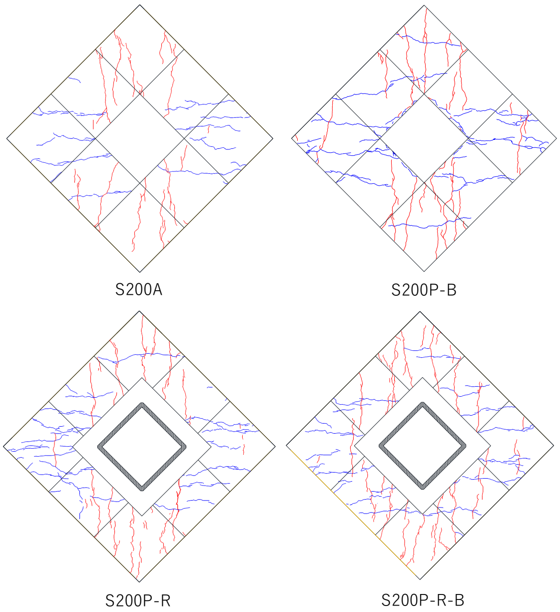


Figure 11: Load-deformation relationships of specimens with steel pipes

4.2 Damage of specimens

Figure 12 shows the damage conditions of the four specimens with strengthening techniques at shear strains of 0.2%. S200P-R and S200P-R-B showed more cracks at cycles up to 0.2% than S200A and S200P-B. S200P-B, which had good adhesion, showed many cracks along the interface between steel pipe and concrete, and spalling began to occur at 0.4% (Fig. 13). The specimens with flanges showed different cracking than the specimens without flanges. The cracks in S200A and S200P-B occurred mainly in the center diagonal regions, but the cracks of specimens with flanges were more uniform and cracks spread out from the main diagonal, suggesting the flanges provided stiffness to opening region and increased the force transfer around the opening, not just in the diagonal direction.

A comparison of the maximum crack widths for specimens with strengthening techniques at each cycle is shown in Figure 14. The maximum crack widths were smaller than 1 mm up to a shear angle of 0.2%, after which the crack widths increased rapidly as the main wall reinforcement yielded. For S200P-B, the crack width at the corner of the opening increased to 5 mm. In contrast, S200A had the smallest crack width, indicating that the additional internal reinforcement was effective in preventing crack expansion until shear strength was reached.



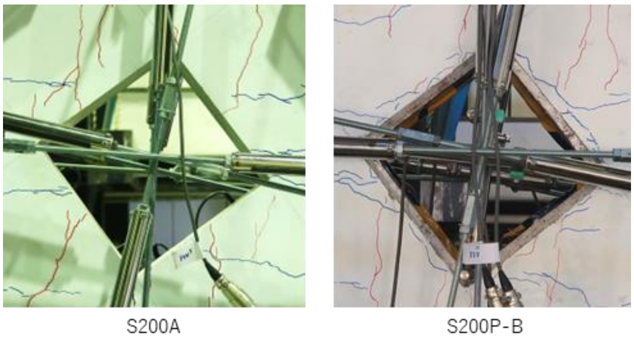


Figure 12: Crack maps at shear strains of 0.2%

Figure 13: Cracks around opening and steel pipe

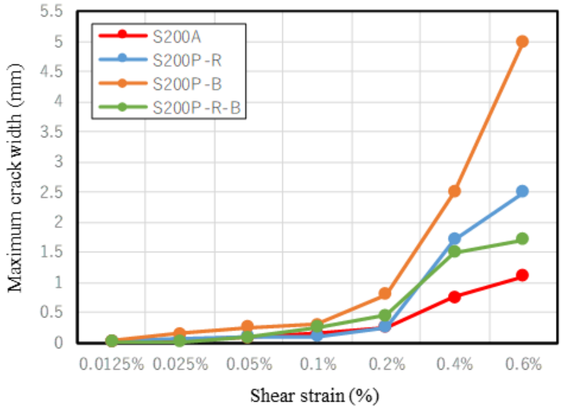


Figure 14: Variation of maximum crack width with shear strain

4.3 Comparison of envelopes

The envelopes of all six specimens are shown in Figure 15. Until shear strength was reached, the shear load resisted by specimens with strengthening techniques is between that of the solid wall and wall with opening. Up to a shear deformation angle of 0.2%, which roughly corresponds to the short-term allowable stress, the shear resistance was the largest for solid wall, followed by S200P-B, S200P-R-B, and S200P-R, and finally S200A suggesting that pipe reinforcement placed in openings is more effective than additional internal reinforcement bars placed around openings. The three specimens reinforced with steel pipes all had larger shear strengths than wall with opening demonstrating the effectiveness of the steel pipe.

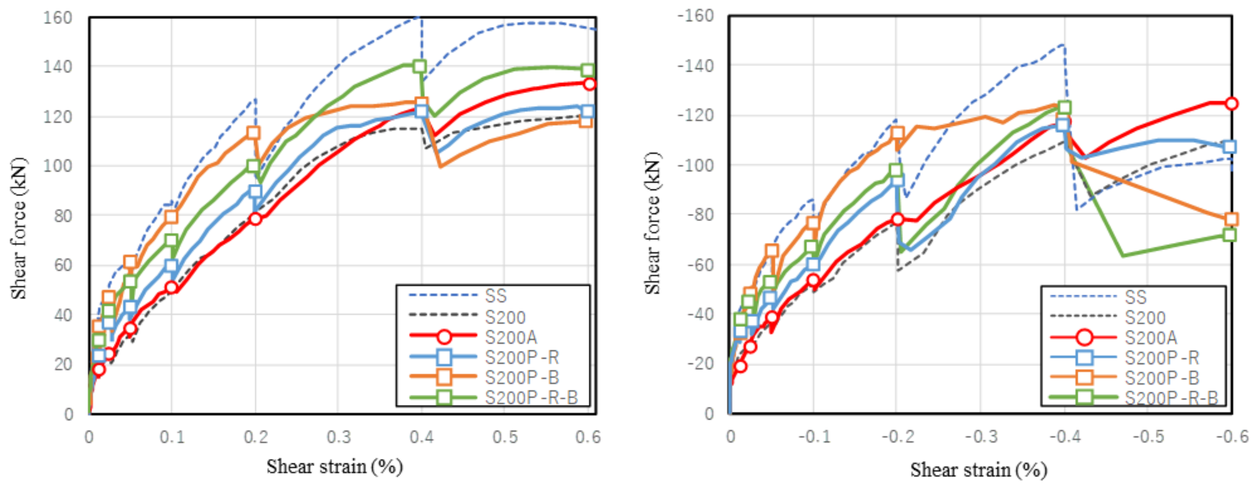


Figure 15: Measured force-displacement envelopes

4.4 Bearing capacity of reinforcement methods

Figure 16 shows the ratio of shear resisted by specimens reinforced with steel pipes to that of specimen reinforced with additional rebars for each shear angle. Specimens with steel pipes resisted more shear than S200A for strains up to 0.4%. The greatest increase in relative shear resistance was observed at 0.025% and it gradually became smaller with increases in shear strain.

Table 3 shows that the shear strength of specimen with steel pipe only is about 5 kN larger than that of the specimen with opening. This increase in strength is about 50% of the strength of the steel pipe element, suggesting that the steel did not yield. The specimen with flanges without adhesion reached approximately the same strength as specimen with steel pipe only. This result indicates that the flange lacking good adhesion is ineffective in increasing the strength of the wall, even though the bending moment that the steel pipe with flange can resist is much larger than steel pipe only. The specimen with flanges and good adhesion reached the highest shear strength of walls with openings, indicating that the combined effects of flange and good adhesion is sufficient to increase shear strength. Although the increase in shear strength of specimen with flange and good adhesion is only 10% of the calculated yield strength of steel pipe and flange element, it was nearly four times larger than the load resisted by the other pipe reinforcement techniques.

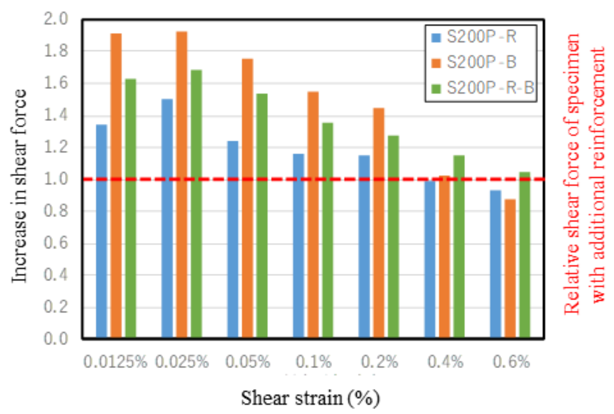


Figure 16: Increase in shear resistance of specimens with strengthening techniques

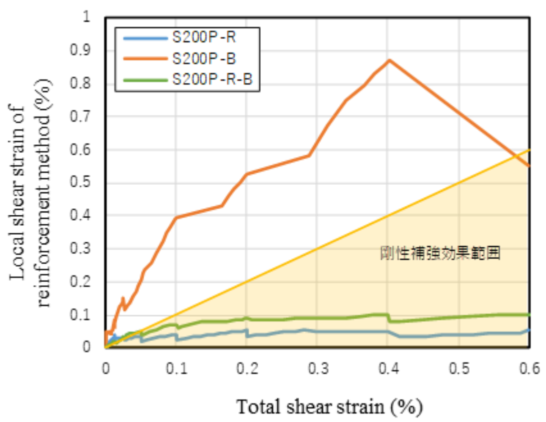


Figure 17: Variation of shear deformation of steel pipe with total shear strain of specimen

4.5 Stiffness of reinforcement methods

Figure 17 shows the relationship between shear deformation angle of steel pipe versus overall shear deformation angle. For S200P-B, the deformation angle of the steel pipe is large relative to the overall deformation angle, but for S200P-R and S200P-R-B, it is small, suggesting the addition of the flange increases stiffness around the opening region. Experimental stiffness of strengthening techniques was estimated as the difference in shear force between specimens with and without reinforcement at a shear angle of 0.0125% divided by the shear displacement. A comparison of the experimental and calculated values of stiffness is shown in Table 3. The results show that the experimental stiffness of the pipe with flanges is about twice as stiff as that of the steel pipe only. The experimental stiffness of the reinforcement with flanges and good adhesion is the largest, approximately three times as large as the pipe only, and within 5% of the calculated value. Considering that an effective reinforcement method is one that provides sufficient stiffness around the opening so that its local deformation is less than or equal to the total deformation of the specimen, the trend shown in Figure 17 indicates that shortening the length of the flanges may still result in an effective reinforcement technique.

5 CONCLUSIONS

To propose a rational post-installation strengthening technique and observe the performance of a range of reinforcing methods, experiments were conducted on six specimens and a comparison was made in terms of shear stiffness, shear strength, and damage. The findings of this study are summarized below.

(1) Walls with steel pipes resisted larger shear forces than the wall with standard additional internal reinforcement up to shear strains of 0.2% indicating the effectiveness of the steel pipe reinforcement method.

(2) In terms of increasing overall stiffness of wall, the pipe with good adhesion was the most effective and increased shear stiffness by approximately 70% on average relative to wall with standard reinforcement up to shear strains of 0.2%,

(3) In terms of increasing shear strength of wall, the pipe and flange with good adhesion was most effective and increased ultimate strength by 5% compared with standard reinforcing method.

(4) In terms of cost and installation, the pipe with good adhesion is considered the most effective, and if shear strength is not a critical issue, this reinforcement represents the best performing and most cost-effective strengthening technique.

(5) Good adhesion was effective in increasing initial stiffness.

(6) Flanges were effective in reducing the deformation of the opening region.

(7) Flanges with good adhesion were effective in increasing shear strength.

(8) Wall with steel pipe had fewer, wider cracks while walls with pipes and flanges had more cracks with smaller widths.

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