CYCLIC OUT-OF-PLANE FLEXURAL BEHAVIOR OF MASONRY WALLS REHABILITATED BY INSERTING STAINLESS PINS

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ABSTRACT :

We present the results of cyclic out-of-plane flexural tests of brick walls reinforced by inserting stainless pins. In seismic rehabilitation of historic URM buildings, preservation of their appearance poses the main difficulty. Inserting stainless pins diagonally in the plane perpendicular to the wall is a solution to overcome the difficulty. Since all stainless pins are inserted from mortar joints, no aesthetic alternation is caused by the method. In this paper, a series of cyclic flexural tests of brick walls are performed to study the effectiveness of the following two patterns of the reinforcement: (1) Stainless pins are inserted in parallel from one side of the wall. This reflects the pattern employed in practice. (2) Stainless pins are inserted from both sides of the wall so that they cross at the center plane of the wall. With this pattern, we aim to improve the seismic performance by making the reinforcement symmetric. From the tests, serious degradation of strength was observed in a couple of loading cycles when the former pattern of the reinforcement was applied. In contrast, almost no degradation was observed when the stainless pins were inserted in accordance with the latter pattern. From the results of the tests, we propose simple formulas for assessing the capacity of the reinforced brick walls. The effect of the latter pattern of the reinforcement was predicted well with the proposed formulas.

KEYWORDS: Seismic rehabilitation, historic brick building, URM, stainless steel

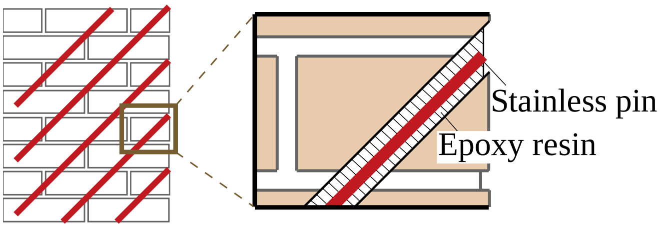
1. INTRODUCTION

There are many historic unreinforced masonry (URM) buildings in Japan as shown in Figure 1. In recent years, the number of cases for retrofitting such historic buildings is increasing for cultural and commercial uses. Seismic performance of this kind of buildings is, however, usually poor (Drysdale et al., 1993). With frequent occurrence of near-fault earthquakes of M7 in recent years and prediction of occurrence of extremely strong earthquakes of M8 with high probability, the demand is increasing for seismic rehabilitation of such historic URM buildings.

In rehabilitating historical brick buildings, it is usually required to preserve their cultural values, especially their appearance. Many kinds of techniques are available for seismic rehabilitation of URM buildings (ElGawady et al., 2004, Abrams et al., 2007). Nevertheless, there are still many problems to be resolved in seismic rehabilitation of historic URM buildings. Preservation of the appearance of existing buildings and durability of strengthening materials create main difficulties.

Inserting stainless pins into brick walls is put forth as a solution to overcome the difficulties mentioned above. Since each stainless pin is diagonally inserted from mortar joints in the plane perpendicular to the wall as shown in Figure 2, the change in the appearance of the walls is negligible. In fact, the method was applied to

Figure 1 Example of historic URM building in Japan



(a) Details

(b) Stainless Pins

Figure 2 Method of Inserting Stainless Pins

several historical buildings in Japan. However, since few research efforts have been devoted to study the effectiveness of the method, only a few data are available on the seismic behavior of the rehabilitated walls. Thus, the structural design of the seismic rehabilitation has been undertaken without the information quantitative enough.

In this paper, we conduct cyclic out-of-plane flexural tests of the brick walls to study the effectiveness of the following two patterns of the reinforcement: (1) Stainless pins are inserted in parallel from one side of the wall. This reflects the pattern employed in practice. (2) Stainless pins are inserted from both sides of the wall so that they cross at the center plane of the wall. With this pattern, we aim to improve the seismic performance by making the reinforcement symmetric. Further, we propose simple formulas for assessing the capacity of the reinforced walls. The validity of the formulas is examined by comparing the estimation obtained by the formulas with the experimental results.

2. CYCLIC OUT-OF-PLANE BENDING TESTS

2.1. Test Specimens

We conduct experiments for 6 brick wall specimens. The differences among the specimens are the reinforcing pattern and the number and/or diameter of the stainless pins. Table 1 shows the classification of the reinforcing pattern and the loading conditions of the test specimens.

Figures 3 to 7 depict the schematic illustrations of the specimens. The specimens are comprised of 22 brick layers. Figure 3 shows the layout of the bricks at the odd and even number of layers. The height, width, and thickness of the specimens are 1,600mm, 1,420mm, and 430mm, respectively. The size of each brick is 210x100x60mm. The thickness of mortar joint is 10mm. The main material characteristics

Table 1 Classification of reinforcing pattern and loading conditions

specimen	Reinforcing pattern	diameter of pin	number of pins	loading condition
A	parallel	ϕ6mm	normal	cyclic
B	parallel	ϕ6mm	double	cyclic
C	parallel	ϕ8mm	normal	cyclic
D	cross	ϕ6mm	normal	cyclic
E	cross	ϕ6mm	double	cyclic
F	cross	ϕ8mm	normal	cyclic

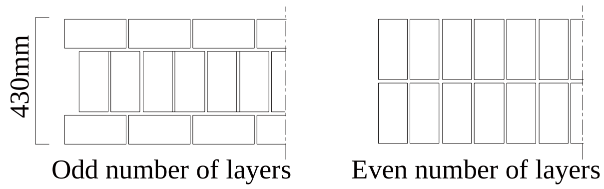


Figure 3 Layout of bricks

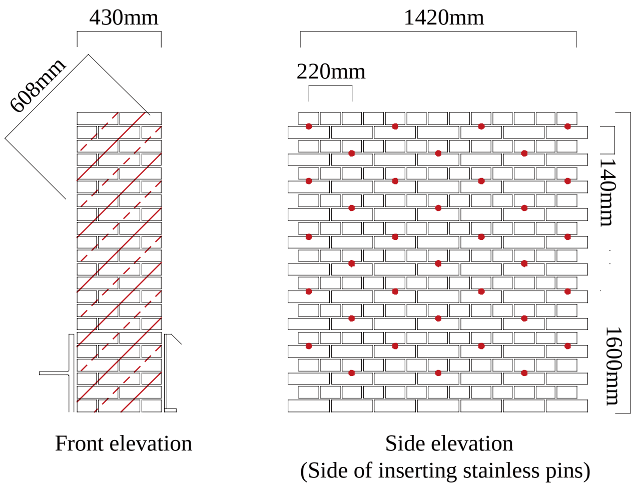


Figure 4 Specimen A and C (parallel, normal)

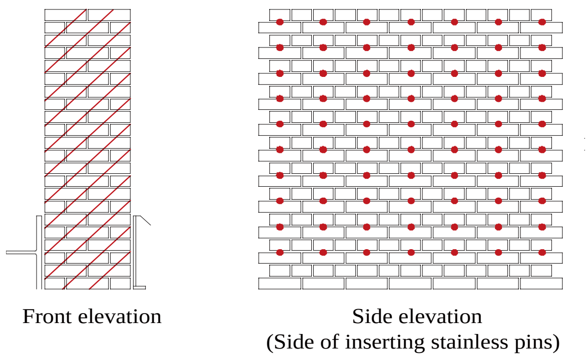


Figure 5 Specimen B (parallel, double)

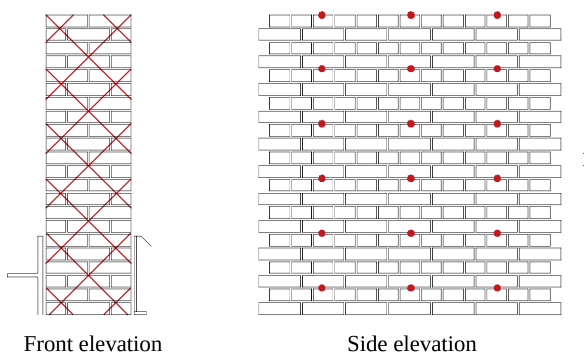


Figure 6 Specimen D and F (cross, normal)

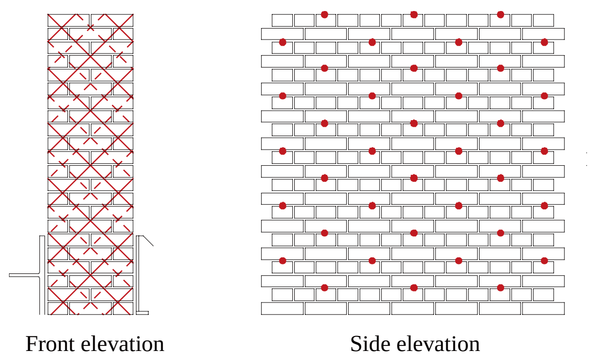
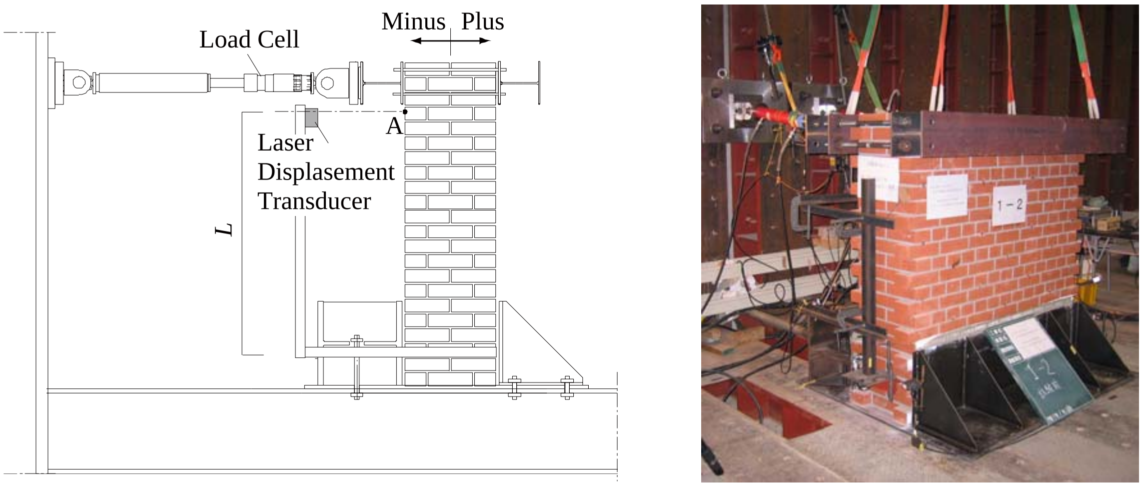


Figure 7 Specimen E (cross, double)



(a) From east (b) From northeast

Figure 8 Loading setup and measurement conditions

obtained from material tests are as follows. The flexural tensile bond strength of the mortar joint was $0.61 N/mm^2$. The tensile strengths of the stainless pins were 13.11kN for ϕ6mm, and 25.41kN for ϕ8mm.

The red circles in the front elevation of Figures 4 to 7 indicate the locations from where stainless pins are inserted. Figures 4 and 5 indicate the reinforcing pattern called *parallel*, and the reinforcing pattern shown in Figures 6 and 7 is called *cross*, in this paper. The solid line in the side elevation of Figure 4 indicates that 3 stainless pins are inserted on the line. And the dotted line in the same figure indicates that 4 pins are inserted on the line. This pattern of inserting stainless pins has been used in practice and is called *normal* in Table 1. The solid line in Figure 5 shows that 7 pins are inserted on the line. This pattern is called *double*. The solid line in Figures 6 and 7 shows that 3 pins are inserted on the line. And the dotted line in Figure 7 indicates that 4 pins are inserted on the line. These patterns are called *normal* and *double*, respectively.

2.2. Loading Conditions

Loading conditions are shown in Figure 8(a) and (b). The brick wall specimen is placed on the strong reaction steel beams and fixed by the wide-flange shape and equal-leg angle steel members. Two horizontal hydraulic jacks are connected to the top of the wall specimen. At the top, two wide-flange shape members are attached to the specimen using PC steel bars. Grout or hard rubber was inserted between the brick specimen and the steel beams. Cyclic loading was applied to each specimen. The cyclic loading was conducted by increasing the amplitude of the rotation angle $R = u / L$. Here, u is the horizontal displacement of point A, and L is the distance between point A and the base of the measurement frame as shown in Fig. 8(a). The amplitude of R was increased as follows: 0.0025, 0.005, 0.01, 0.0015, 0.02, 0.03, 0.05 (radian).

3. TEST RESULTS

Figures 9 to 11 illustrate the test results. Figure 9 shows the representative failure modes of the mortar joints of specimens. Figure 9(a) shows the stepping pattern fracture observed in side E of specimen C. And Figure 9(b) shows the flat pattern fracture observed in side W of specimen D. Figures 10(a) to (d) show the fracture patterns of mortar joints in specimens B to E. The restoring force characteristics of all the specimens are shown in Figure 11. Observations from the test results can be summarized as follows.

(1) Specimens with the parallel-type reinforcement (Specimens A, B, C);

- As shown in Sides W and E in Figures 9(a), 10(a), and (b), the parallel-type reinforcement causes the stepping pattern fracture of mortar joints.

- Specimens A to C recorded the maximum strength of 29.1kN, 31.0kN and 39.7kN, respectively.
- As indicated in Figures 11(a) to (c), the skeletons for two opposite loading directions are significantly different.
- Significant degradation of restoring force can be seen in a couple of loading cycles. At large rotation angle, restoring force is significantly small, especially at the negative loading directions of specimens B and C.

(2) Specimens with the cross-type reinforcement (Specimens D, E, F);

- As indicated by Sides W and E in Figures 9(b), 10(c), and (d), the cross-type reinforcement prevented the occurrence of the stepping pattern fracture of mortar joints. The mortar fracture was flat.
- Specimens D to F recorded the maximum strength of 37.0kN, 33.2kN and 29.1kN, respectively.
- As indicated in Figures 11(d) to (f), the skeletons in two opposite loading directions are symmetric.
- Even at large rotation angle, degradation of restoring force is small.

4. DISCUSSIONS

4.1. Evaluation of Reinforced Strength

We propose simple formulas for assessing the capacity of walls reinforced by inserting stainless pins in accordance with the “cross” pattern. The rocking resistance F_R due to gravity can be expressed as

$$F_R = \frac{WD}{2H}. \tag{4.1}$$

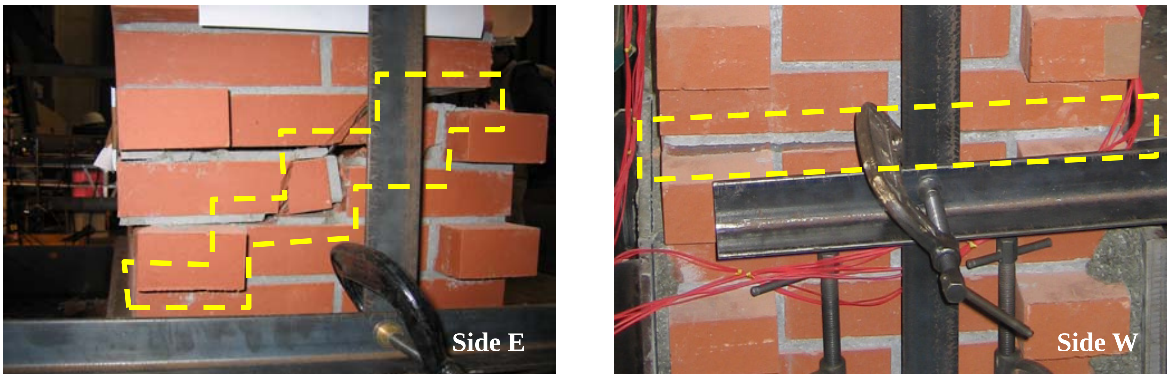
And the restoring force F_P provided by the stainless pins can be written as

$$F_P = \frac{T}{\sqrt{2}} \cdot \frac{D}{2} \cdot \frac{n}{H} = 0.35 \frac{TDn}{H}, \tag{4.2}$$

where W is the weight of the test specimens above the fracture line, D is the thickness of the wall specimens, H is the distance between point A (Figure 8(a)) and the base of the measurement frame, T is the tensile strengths of the stainless pins, and n is the number of effective stainless pins. The total strength F_T can be expressed as

$$F_T = F_R + F_P. \tag{4.3}$$

In Table 2, we show the predictions of F_R, F_P, and F_T. Here, the following values are taken: W = 15.68kN, D = 0.43m, H = 1.02m, T = 13.11(kN) for ϕ6mm pins, and 25.41(kN) for ϕ8mm pins. In addition, we indicate F_T by the dotted red line in Figure 9 to make comparisons with the test results.



(a) Stepping pattern fracture in Specimen C (b) Flat pattern fracture in Specimen D

Figure 9 Representative failure modes of mortar joints

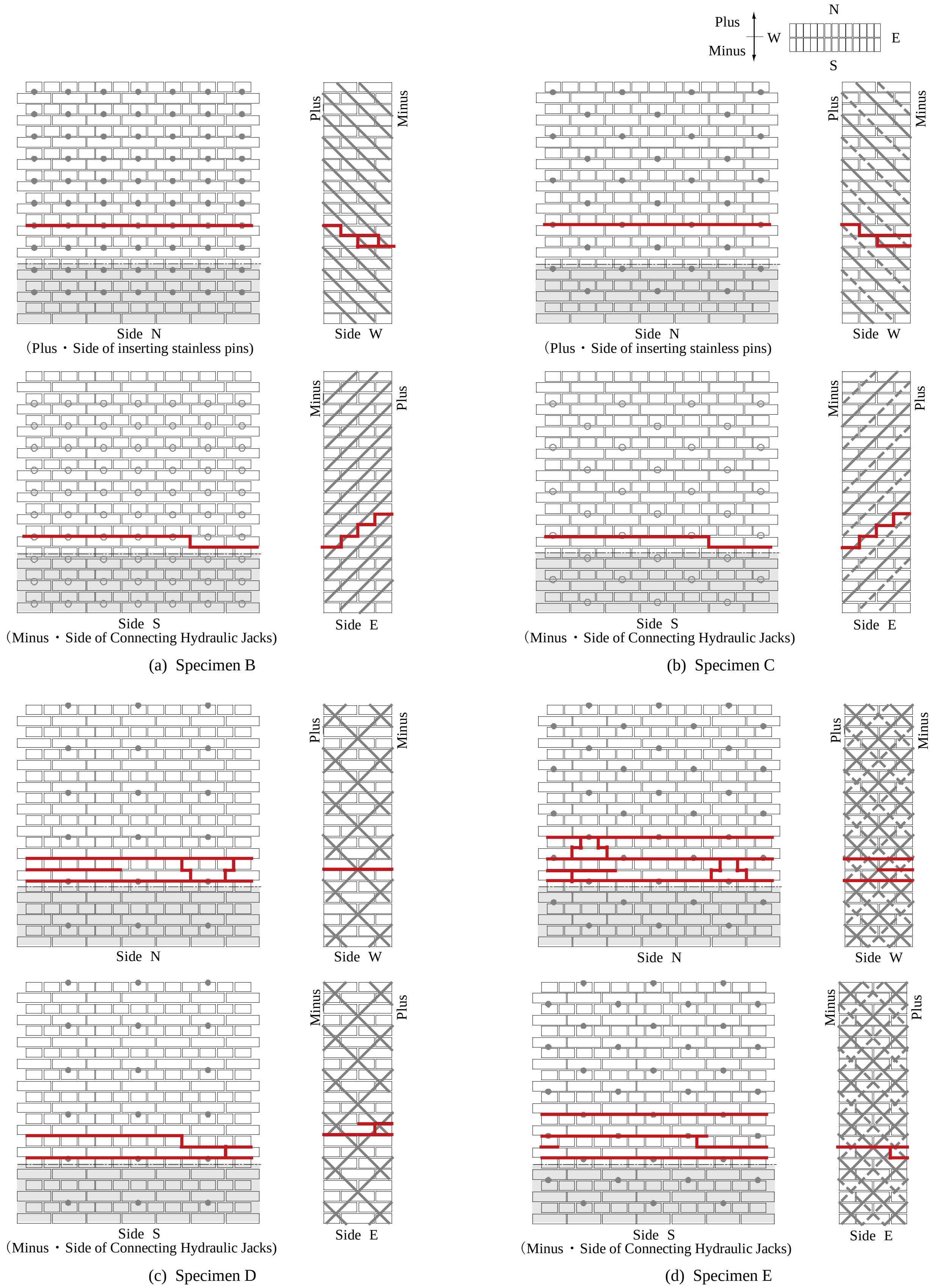
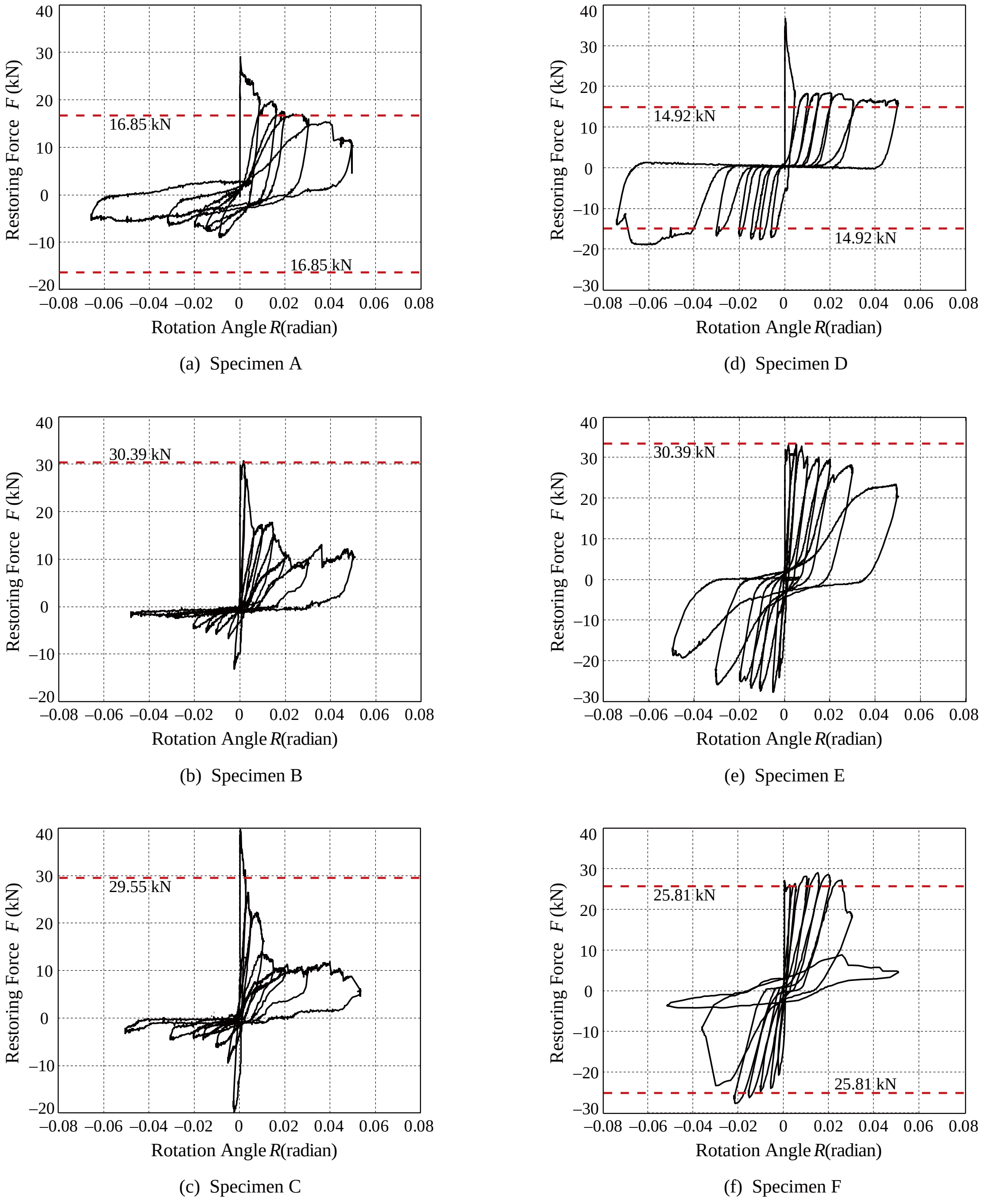


Figure 10 Fracture patterns of mortar joints



(a) Specimen A
(d) Specimen D
(b) Specimen B
(e) Specimen E
(c) Specimen C
(f) Specimen F

Figure 11 Restoring force characteristics

Table 2 Prediction of strengths

specimen	number of effective pins: n	strength by rocking resistance: F_R (kN)	strength by the stainless pins: F_P (kN)	total strength: F_T (kN)
A	7	3.31	13.54	16.85
B	14	3.31	27.08	30.39
C	7	3.31	26.24	29.55
D	6	3.31	11.61	14.92
E	14	3.31	27.08	30.39
F	6	3.31	22.50	25.81

4.2. Relation between Fracture Pattern and Restoring Force Characteristics

Major findings from the behaviors in the tests and the comparisons of the predictions with the test results are summarized as follows;

(1) Specimens with the parallel-type reinforcement;

- Significant differences of the restoring force characteristics exist between the two opposite loading directions. The reason for this could be due to asymmetry of the reinforcement where stainless pins are subjected to tension in one direction and dowel action in the other direction.
- Increasing the number and/or diameter of stainless pins in this condition can lead to the stepping pattern fracture of mortar joints, which leads to significant decrease of the strength capacity of the wall, because the increase makes the difference greater between the reinforced and unreinforced parts of mortar joints.

(2) Specimens with the cross-type reinforcement;

- Occurrence of the stepping pattern fracture of mortal joints was avoided. All other problems associated with the parallel-type reinforcement were resolved.
- The predictions and the test results agree well in the case of the cross-type reinforcement, although there are differences between predictions and test results in the case of the parallel-type reinforcement.

5. CONCLUSIONS

We have conducted cyclic out-of-plane flexural tests of the brick walls reinforced by inserting stainless pins. The main findings from the tests include:

a) When stainless pins are inserted in parallel from one side of the wall, which reflects the reinforcement applied in practice, significant differences of the restoring force characteristics exist between the two opposite loading directions. Moreover, increasing the number and/or strength of stainless pins can decrease the capacity of the rein forced wall.
b) When stainless pins are inserted so that it crosses at the center plane of the wall, all the problems mentioned above were resolved.
c) We have proposed a simple formula for predicting the strength of the reinforced walls. The estimation of the strength agreed well with the test results of the cross-type of reinforcement.

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