Interaction between Theory and Practice in Civil Engineering and Construction
Edited by Komurlu, R., Gurgun, A. P., Singh, A., and Yazdani, S.

ISBN: 978-0-9960437-2-4

TESTS AND ANALYSES OF RC SHEAR WALLS WITH VERTICALLY ALIGNED OPENINGS

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This study investigates fundamental behavior of reinforced concrete (RC) shear walls with vertically aligned openings through laboratory tests and numerical analyses. A series of structural tests was conducted using scaled models representing typical multi-story RC shear walls in Japan. Three 1/6 scale shear wall specimens were designed and manufactured with different opening configurations: W0 with no opening, W1 with single-aligned openings, and W2 with double-aligned openings. The specimens were subjected to static cyclic lateral loads. The W1 and W2 specimens with openings failed with concrete crushing at the wall bottom and shear failure of the beams above openings, while the W0 failed in shear. The maximum strengths were 318 kN, 145 kN, and 93 kN for the W0, W1, and W2 specimens, respectively; hence, the experimental strength reduction factors due to the openings were 0.46 and 0.29 for the W1 and W2. These results were simulated by FEM analyses mainly to investigate detailed behavior of the components of the W1 and W2 specimens. The analytical results, in particular the maximum strengths and failure patterns, agreed well with the experimental results. It was numerically verified that high compression was applied to the wall bottom with the tensile boundary column and the beams above openings, as observed during the tests, which should be considered in practical design for this type of wall.

Keywords: Cyclic loading test, FEM analysis, Reinforced concrete, Seismic performance, Strength reduction factor.

1 INTRODUCTION

Reinforced concrete shear walls are effective building components to provide high seismic resistance; therefore, the structural performance has been investigated by a number of researchers in the world. Openings are occasionally planned in the shear walls for lighting, ventilating, and doorway. Although the openings significantly affect the structural performance, limited investigations have been reported in the previous studies. This may be attributed to structural design concepts recommended by major design codes/standards, in which this type of wall is often modeled by each component.

On the other hand, in Japan, the structural performance of RC shear walls with openings has been directly evaluated considering several performance reduction factors. Recently, a new strength reduction factor has been implemented in AIJ (Architectural Institute of Japan) design standards, which was presented to evaluate strength reductions due to vertically aligned openings (AIJ 2010). However, this factor has not been verified experimentally, because of a lack of test data from reliable experimental simulations on fundamental behavior of this type of wall.

Therefore, the objective of this study is to obtain fundamental data on structural behavior/performance of RC shear walls with vertically aligned openings.

2 EXPERIMENTAL PROGRAM AND RESULTS

2.1 Specimens

Three 1/6 scale shear wall specimens were designed and manufactured with different opening configurations: W0 with no opening, W1 with single-aligned openings, and W2 with double-aligned openings. Shear walls with aligned openings along height behave in a similar manner to coupled shear walls. Therefore, separated partial stubs were applied to the specimens instead of a typical massive stub which fully covers the top of specimens. Figure 1 shows the structural details of the specimens. Tables 1 and 2 give the material properties of concrete and reinforcements used for the specimens.

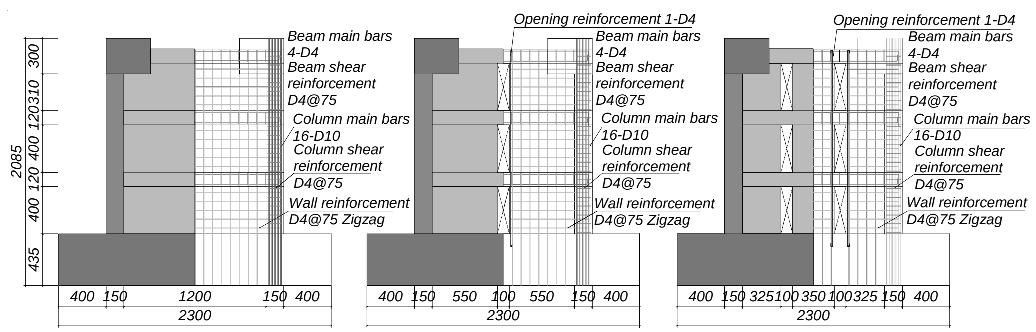


Figure 1. Structural drawing of specimens (W0, W1, and W2 from the left).

Table 1. Material properties of concrete.

Specimen	Compressive strength (N/mm^2)	Elastic modulus (kN/mm^2)	Strain at compressive strength (μ)
W0	25.8	25.6	1838
W1	26.5	26.3	1993
W2	26.6	25.7	1920

Table 2. Material properties of reinforcements.

Bar number	Yield stress (N/mm^2)	Elastic modulus (kN/mm^2)	Tensile strength (N/mm^2)
D10 (SD345)	379	174	479
D4 (SD295A)	323	153	458
ϕ17	1176	201	1273

2.2 Experimental Methods

The specimens were subjected to static cyclic lateral loads by two horizontal jacks connected to the separated stubs, as shown in Figure 2. Tension rods were provided between the stubs to prevent tensile failure at the stub-beam/wall boundaries. Axial loads were not applied to the specimens, while they were designed with additional longitudinal rebars in the boundary columns so that realistic compressive forces would act on the cross-sections under lateral loads.

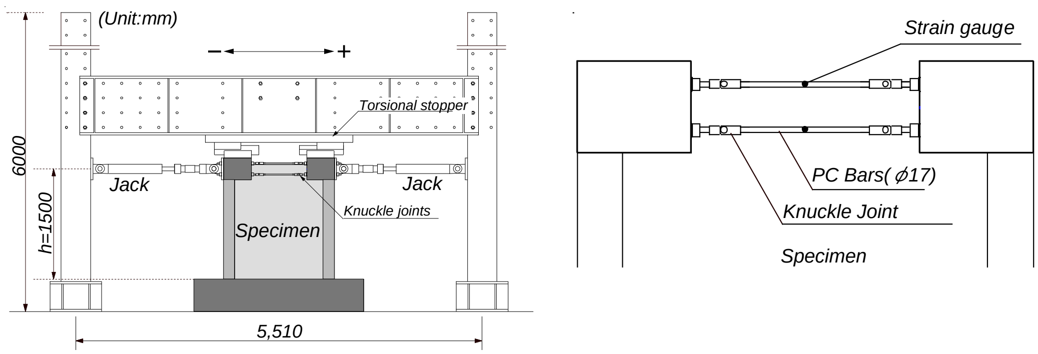


Figure 2. Experimental setup.

2.3 Experimental Results

The W1 and W2 specimens with openings failed with concrete crushing at the wall bottom and shear failure of the beams above openings, while W0 failed in shear, as shown in Figure 3. The failure mechanisms of W1 and W2 were similar to that of coupled shear walls. As a result, the seismic performance, in particular the maximum strengths of the specimens decreased due to the existence/higher number of openings: 318 kN, 145 kN, and 93 kN for the W0, W1, and W2, respectively, as shown in Figure 4; hence, the experimental strength reduction factors due to the openings were 0.46 and 0.29 for the W1 and W2.

ACI code describes that the seismic performance of shear walls with openings should be evaluated based on modeling of components assembling the walls (ACI Committee 318). FEM analyses were performed in the following to clarify key modeling of this type of wall for design analyses.

3 ANALYTICAL SIMULATIONS

3.1 Modeling of Specimens

Two-dimensional modeling was adopted for FEM analyses. Figure 5 illustrates the analytical modeling for W2. Concrete was replaced by 4-node quadratic isoparametric elements with a stress-strain relationship, as shown in Figure 6. Reinforcements were embedded in the concrete elements. A bilinear model was applied to the stress-strain relationship for the reinforcements. The material properties provided in Tables 1 and 2 were used for the stress-strain relationships.

As for the stress-strain relationship of concrete, Modified Ahmad model (Naganuma 1995) was adopted for the compressive stress-strain curve, as shown in Figure 6(a), while the Nakamura and Higai (1999) model was adopted in its stress-softening regions. Kupfer and Gerstle (1973) criterion was applied to evaluate failure under biaxial compression. Stiffness reduction due to cyclic stress was considered, as shown in Figure 6(b) (Naganuma and Ohkubo 2000). Furthermore, Al-Mahaidi (1979) model was adopted for evaluating shear transfer after cracking, as shown in Figure 6(c).

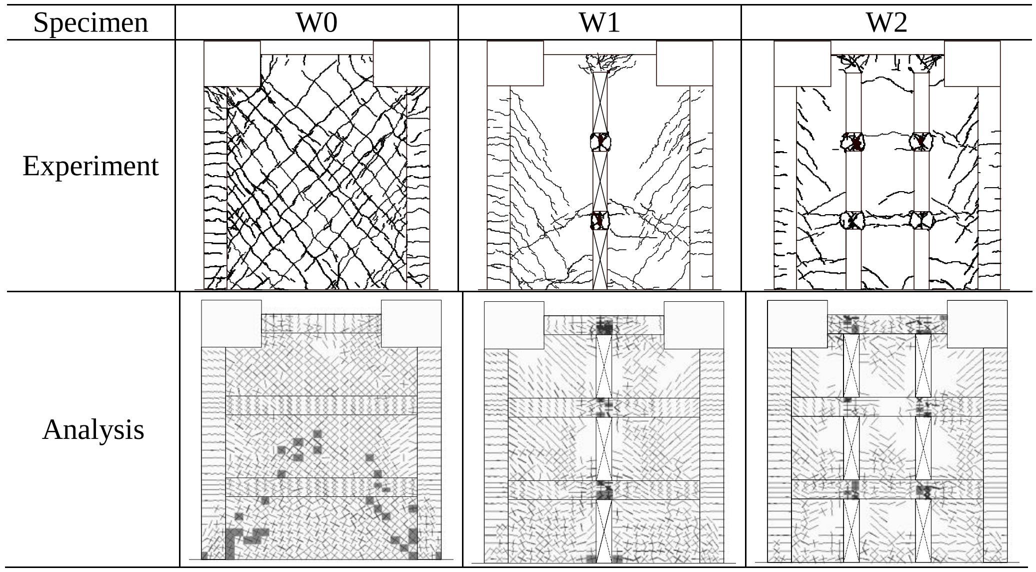


Figure 3. Experimental and analytical damage at 0.5% rad.

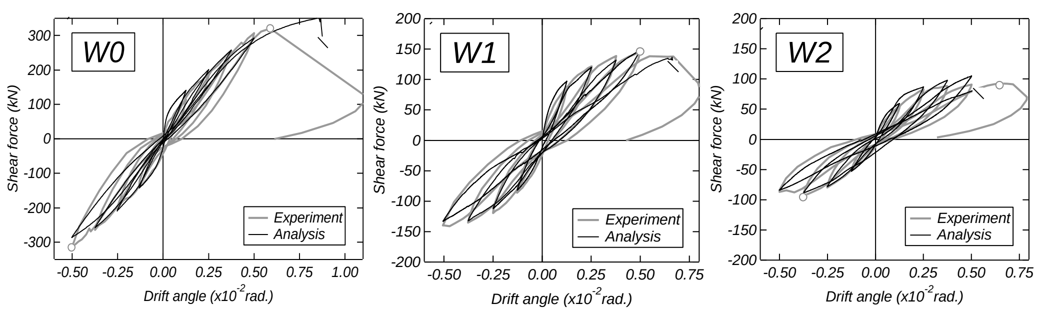


Figure 4. Experimental and analytical shear force-drift angle relationships.

3.2 Analytical Results

Figures 4 compares the shear force vs. drift angle relationships for all specimens with the experimental results, which show good agreements up to a drift angle of 0.5% rad. Figure 3 also compares the analytical damage at 0.5% rad. with the experiments, where gray color indicates elements with concrete beyond strain at the compressive strength. Focusing on the W1 and W2, the damage was significant at the boundary beams above openings for both specimens and the wall bottom with the boundary column on the tensile side for the W1, which means that these are key elements for macro modeling to evaluate inelastic behavior of this type of wall. Figure 7 additionally shows the minimum principle stress contours for all specimens at 0.5% rad. It was found for the specimens with openings that high compression was applied to the wall bottom with the tensile column and the boundary beams. Such higher stresses were consistent with the damage patterns provided in Figure 3.

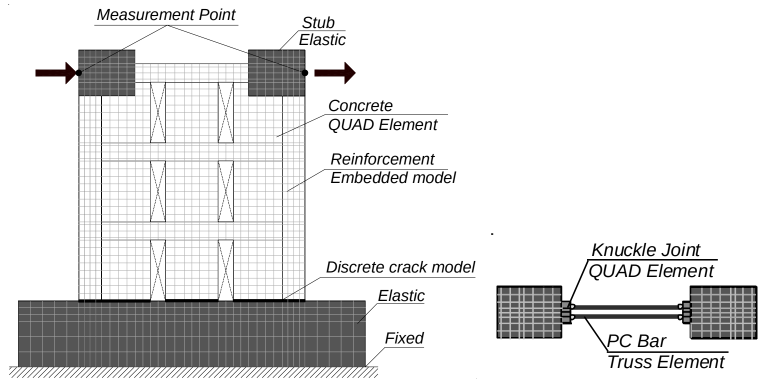
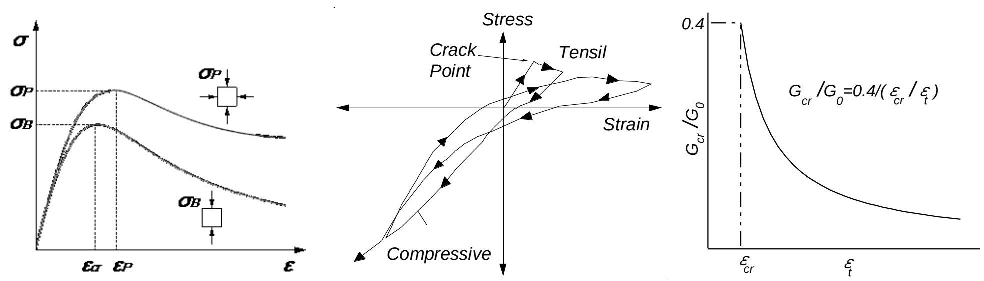


Figure 5. Modeling of W2 for FEM analysis.



(a) Stress-strain relationship (b) Hysteresis (c) Shear Transfer

Figure 6. Constitutive laws for concrete.

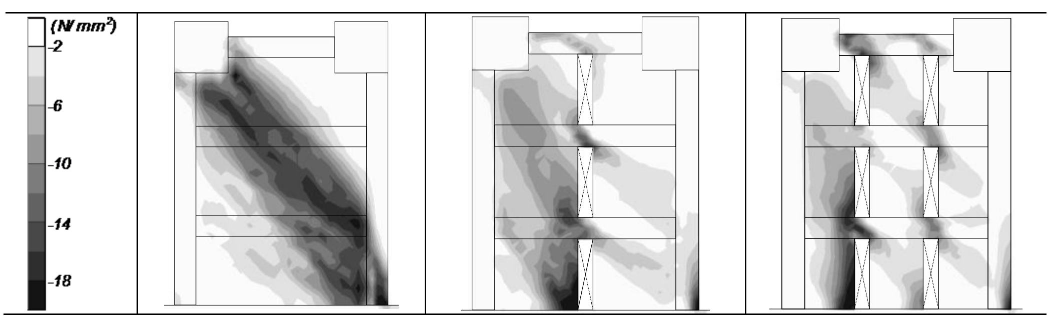


Figure 7. Minimum principle stress contours at 0.5% rad.

Figure 8 presents the transitions of the total axial and shear forces applied to the boundary beams. Higher axial compression was applied to the beams with increases of the wall drift angle; therefore, the beams were subjected to high shear forces which resulted in the shear failure of the beams, as shown in Figure 3. It means that the high axial compression applied to the boundary beam above openings must be considered in the design analyses for this type of wall to prevent its premature brittle failure.

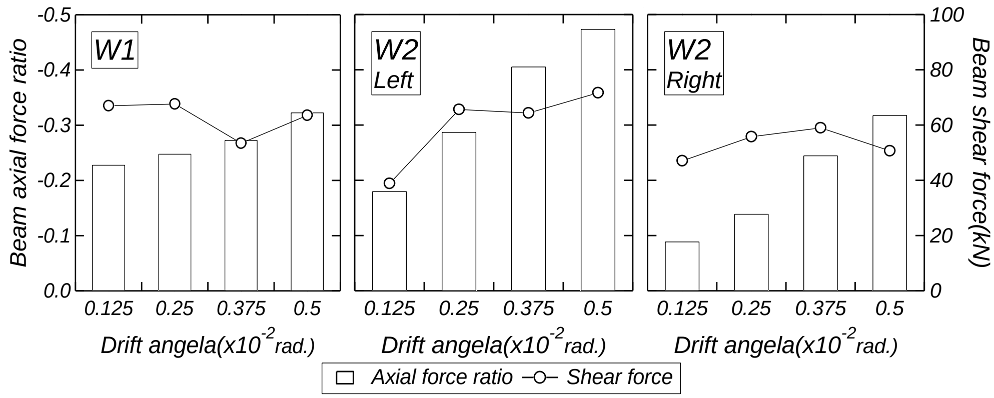


Figure 8. Transitions of total axial and shear forces applied to the boundary beams.

4 CONCLUDING REMARKS

This paper reported a series of laboratory tests conducted with three scaled shear wall specimens with/without vertically aligned openings. Consequently, the failure mechanisms of the specimens with openings (W1 and W2) were similar to that of coupled shear walls. The maximum strengths of the specimens decreased due to the existence/higher number of openings.

The observed behavior of the specimens was simulated by FEM analyses, to investigate key modeling of the walls with openings for design analyses. In conclusion, the damage patterns and shear force-drift angle relationships obtained from the analyses agreed well with the experimental results. The analytical results on the specimens with openings (W1 and W2) indicated that high compression was applied to the wall bottom with the boundary column on the tensile side and the boundary beams above openings. In particular, the high axial compression on the beams must be considered in the design analyses to prevent the premature brittle failure.

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