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Numerical Evaluation of Reinforced Concrete Shear Walls under Bi-Axial Loading for Nuclear Auxiliary Buildings

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1. Introduction

Reinforced concrete (RC) shear walls are widely used as primary lateral load–resisting members in seismic-resistant structures, particularly in nuclear power plant auxiliary buildings, where structural integrity under seismic loading is critical. These buildings typically consist of grid-type wall systems, resulting in complex structural responses during earthquakes.

Most previous studies have evaluated the seismic performance of RC shear walls under uni-axial lateral loading, and current design provisions are largely based on this assumption. However, actual earthquake motions act simultaneously in multiple horizontal directions, generating bi-axial loading demands that may lead to structural responses different from those predicted by uni-axial loading conditions.

Experimental studies on bi-axial loading are limited due to the complexity of testing procedures, making nonlinear finite element analysis an effective alternative for investigating such behavior. Previous numerical studies have shown that bi-axial loading may reduce lateral strength and stiffness, yet the influence of wall geometry, particularly aspect ratio, has not been sufficiently clarified.

Since RC shear walls in nuclear auxiliary buildings often have low aspect ratios, their response may be more sensitive to bi-axial loading effects. Therefore, this study investigates the seismic response of RC shear walls under bi-axial loading using nonlinear finite element analysis. A validated three-dimensional model is employed to perform a parametric study focusing on aspect ratio effects, and the results are compared with uni-axial loading cases to identify performance trends under bi-axial loading conditions.

2. Finite element analysis model

In this study, nonlinear finite element analysis was conducted using the DIANA program to simulate the behavior of reinforced concrete (RC) shear wall specimens. The numerical model was developed to reproduce the experimental boundary conditions, material properties, and loading configuration as closely as possible. Figure 1 shows the test set-up.

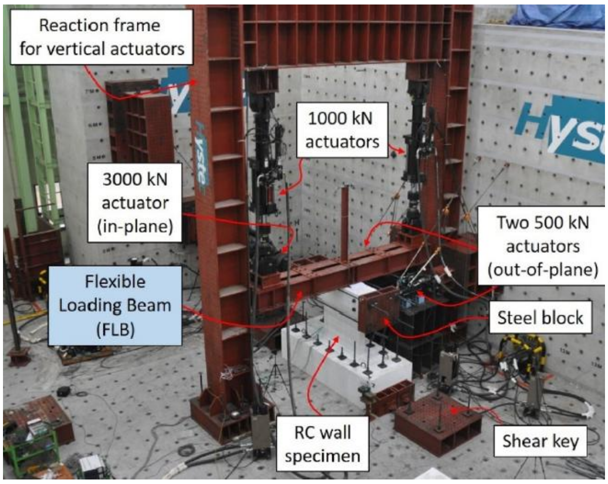

Fig. 1. Test set up (Chae and Park)

Concrete behavior was modeled using a smeared crack approach. The JSCE tension stiffening model was adopted to represent tensile behavior after cracking, while the Maekawa cracked concrete model was used to capture nonlinear compressive response and stiffness degradation. Reinforcing bars were modeled as embedded elements with an elastic–plastic constitutive relationship.

Boundary conditions were defined to replicate the experimental setup by restraining translational and rotational degrees of freedom at the wall base, effectively simulating a fixed-base condition.

The test and analysis model are used for referenced model of the next chapter 3. The dimensions of tested wall were 1,500 mm (length) x 1,200 mm (height) x 180 mm (thickness). The compressive strength of concrete was 43 MPa and the yield strength of reinforcing bar was 460 MPa.

The numerical model was validated using experimental results obtained under unidirectional loading conditions. The experimental data used for model validation were obtained from Chae and Park (2022), confirming that the proposed model can reliably simulate the in-plane shear behavior of RC shear walls. Figure 2 compares the lateral force–displacement relationships for specimens SW2 and SW3, showing good agreement in stiffness, strength, and hysteretic response.

Although the numerical analyses were performed under cyclic displacement-controlled loading, the results are presented in terms of envelope curves for clarity. It should be noted that the loading history and cycle amplitudes in the numerical analysis are not strictly identical to those used in the experiments, particularly in the post-peak region. In both the experiments and analyses, the post-peak response is characterized by rapid strength degradation and potential instability. In the numerical analysis, such softening behavior may lead to convergence difficulties, limiting the reliability of detailed hysteretic comparisons. Therefore, the present study focuses on the comparison of peak strength and global response characteristics rather than cycle-by-cycle post-peak behavior.

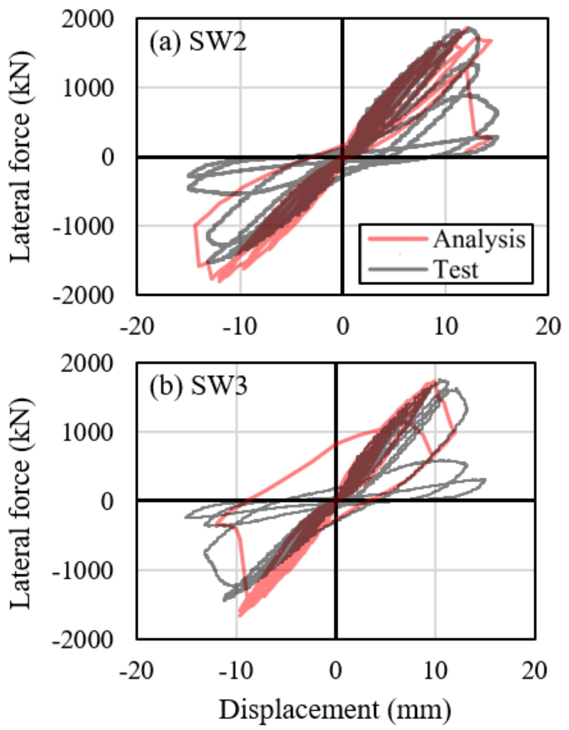

Fig. 2. Comparison of test (Chae and Park) and Finite element analysis results.

3. Analysis results

Figure 3 shows the lateral force–displacement responses obtained from numerical analyses in which the horizontal reinforcement ratio of the reference wall model was varied. The bold black lines represent results under uni-axial loading, while the slotted gray lines indicate responses under bi-axial loading. Although the results are presented separately for clarity, the analyses were conducted for walls with different horizontal reinforcing bar ratio

For the reference model with an aspect ratio of 0.8, the peak strengths under bi-axial loading were 1731.57 kN in the push direction and –1663.18 kN in the pull direction, compared with 1861.54 kN and –1800.47 kN obtained under uni-axial loading. This corresponds to strength ratios (Bi/Uni) of 0.93 and 0.92 for push and pull loading directions, respectively, indicating a reduction in lateral strength under bi-axial loading conditions.

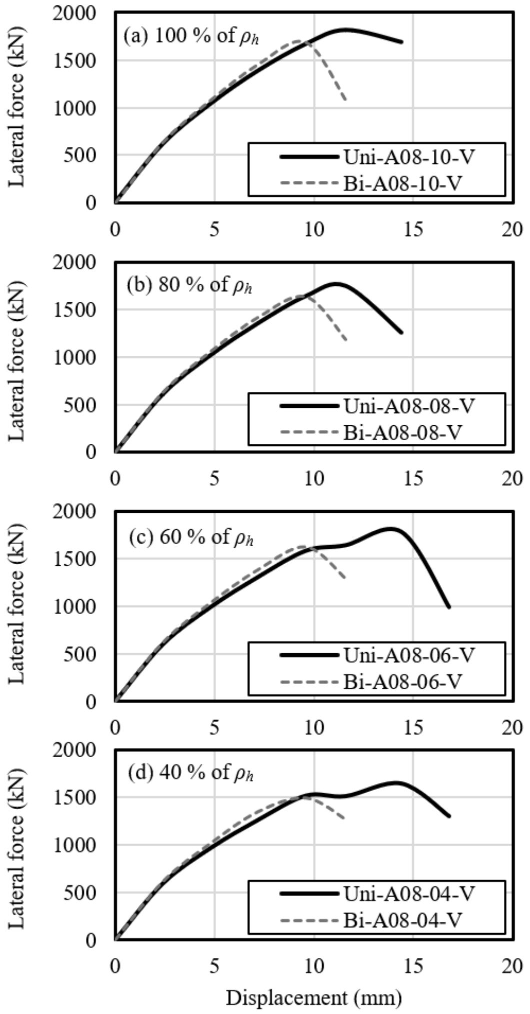

Fig. 3. Analysis results according to horizontal reinforcing bar ratios

Across all analysis models, a slight increase in stiffness was observed under bi-axial loading due to the presence of out-of-plane loading, resulting in an earlier occurrence of peak strength compared with the uni-axial loading condition. In addition, the deformation capacity of the walls was reduced under bi-axial loading, indicating lower ductility compared with the uni-axial loading state.

Additionally, variations in the horizontal reinforcement ratio did not result in significant differences in peak strength, and the strength reduction trend between uni-axial and bi-axial loading conditions showed behavior similar to that observed in the experiments.

3. Conclusions

This study investigated the seismic behavior of reinforced concrete shear walls subjected to bi-axial loading using nonlinear finite element analysis. The validated numerical model successfully reproduced the experimental responses and was used to examine the effects of aspect ratio and horizontal reinforcement ratio.

Variations in horizontal reinforcement ratio produced relatively minor differences in strength. These findings highlight the importance of considering bi-axial loading effects, particularly for low-aspect-ratio shear walls, in seismic evaluation and design.

ACKNOWLEDGMENTS

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