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NONLINEAR ANALYSIS OF A BARBELL-SHAPED CROSS SECTION WALL USING FIBER SLICE

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Reinforced concrete shear walls are effective for resisting lateral loads imposed by wind or earthquakes. This study investigates the effectiveness of a wall fiber element in predicting the flexural nonlinear response of reinforced concrete shear walls. Model results are compared with experimental results for reinforced concrete shear walls with barbell-shaped cross sections without axial load. The analytical model is calibrated and the test measurements are processed to allow for a direct comparison of the predicted and measured flexural responses. Response results are compared at top displacements on the walls. Results obtained in the analytical model for barbell-shaped cross section wall compared favorably with experimentally responses for flexural capacity, stiffness, and deformability.

Keywords: Barbell-shaped cross section wall, Fiber slice, Nonlinear response, Plastic hinge.

1 BACKGROUND OF THE STUDY

Reinforced concrete shear wall is widely used as a structural element, as it has excellent resistance to lateral force due to seismic excitation or wind load, and it reduces lateral displacement by increasing horizontal stiffness of high-rise buildings. However, it is recently reported that structural damages to shear walls occur more than expected in recent earthquakes, even in the buildings that are engineered by relatively good seismic design. Accordingly, interest in the seismic safety of high-rise apartments with shear walls widely constructed in Korea, and social demands for an accurate evaluation of their seismic performance, are increasing.

Reinforced concrete shear wall structure is a structural system usually applied to high-rise apartments and hotels for which space is partitioned in a certain area, and it is designed so that the wall can resist the shear force following a horizontal load. In high-rise buildings, a high axial load is applied to shear walls. To evaluate the nonlinear behavior of reinforced concrete shear walls to the lateral load, a number of experimental and analytical studies have been performed worldwide, and recently, various nonlinear analysis models that can represent the nonlinear behavior of reinforced concrete shear walls have been suggested (Wallace 2012).

In this paper, we will use a fiber element model that can permit a more accurate analysis of the nonlinear behavior of shear walls, and study the applicability of the analytical model based on the existing experimental data.

In this study, reinforced concrete shear walls were modeled with fiber elements, where cross section and reinforcement details of shear walls can be arranged freely. Nonlinear analysis was performed by adding nonlinear shear spring elements that can represent shear deformation. This analysis result will be compared with the existing experiment results. To investigate the nonlinear behavior of reinforced concrete shear walls, reinforced concrete single shear walls with barbell-shaped cross section were selected.

2 ANALYSIS MODEL OF SHEAR WALLS

2.1 The Fiber Element Model

Figure 1 shows the common 3-dimensional structural behavior of reinforced concrete shear walls. To represent the 3-dimensional behavior of reinforced concrete shear walls, the cross section is divided into fiber slices as shown in Figure 2.

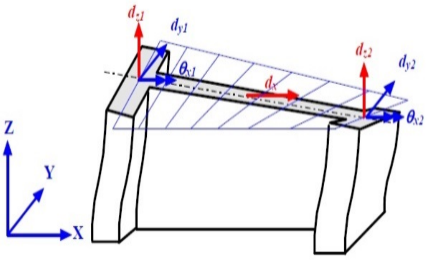


Figure 1. Structural behavior of shear walls.

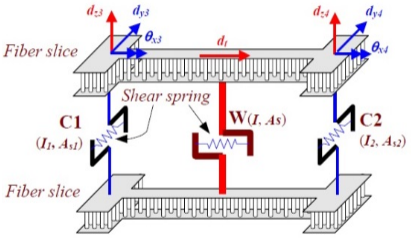


Figure 2. Fiber model for shear walls.

These fiber elements can model steel slices and concrete slices by assigning a stress-strain relation to each slice. Fiber slice can express the axial force and the bending moment behavior in the walls. W, C1, and C2 represent the shear behavior of walls and the columns attached to the walls. W is the spring that represents the in-plane shear stiffness of the shear wall, and C1 and C2 are springs that represent the Y direction shear stiffness of the attached columns. It is assumed that the cross section of the shear walls maintains its plane when an in-plane wall deformation occurs. Following this assumption, the strain of the fiber element in the cross section is proportional to the distance from the neutral axis. The stress of each slice is calculated using the stress-strain relation from the strain of each fiber slice, and the bending moment is calculated by summing the moments to the center of the cross section.

2.2 Shear Spring Element

If a fiber element is used in the nonlinear analysis model of reinforced-concrete shear walls, the material nonlinearity of concrete and reinforcement is reflected, and only the flexure behavior of the shear wall can be evaluated efficiently. However, the shear deformation cannot be assigned only by the fiber element. To compensate for this shortcoming, a nonlinear shear spring element that can represent the shear deformation should be added in the analytical model. Figure 3 shows the force-displacement relation of the nonlinear shear spring element.

To achieve an accurate prediction of nonlinear behavior of reinforced concrete shear walls, accurate evaluations of the initial stiffness, cracking strength, shear yielding strength, and yielding displacement of the nonlinear shear spring are important. Various parameters that define the nonlinear shear spring should be established depending on the failure mode of the shear wall. Defining each parameter of the nonlinear shear spring considering the failure mode of the shear wall can predict the nonlinear behavior of reinforced concrete shear walls with accuracy.

2.3 Stress-strain of the Material

As seen above, the fiber element model can idealize the steel element and the concrete element by assigning a stress-strain relationship. Figure 5 shows the stress-strain relationship of the steel slice and the concrete slice, respectively.

3 ANALYTICAL SHEAR WALL MODEL

In this paper, a barbell-shaped cross section single wall without an axial load as shown in Figure 4 was selected, and the experimental result and the analytical result were compared (Sittipunt et al. 2001).

As shown in Figure 4, the height, length, and thickness of the barbell-shaped cross section single wall are 1900mm, 1500mm, and 100mm, respectively. Shapes of the specimens are all the same. The strength of reinforcing bar and concrete strength of each specimen are set differently by specimen. Horizontal load is applied at 2150mm height from the bottom of the wall. Table 2 shows experimental parameters of specimens.

The nonlinear response analysis of reinforced concrete shear wall was carried out using CANNY-2010 software (Li 2010). In a nonlinear static response analysis, the lateral force increased until the base section of shear wall reached ultimate states.

4 DISCUSSION OF ANALYSIS RESULT

In this study, a nonlinear analysis of reinforced concrete shear wall was accomplished by using a fiber element model described in Section 2.1 to verify the validity of the analytical model. The validity was confirmed by comparing the result of the experimental research with the result obtained from the nonlinear response analysis.

In the analytical model to examine the nonlinear behavior of a barbell-shaped section single wall subjected to no axial load, the cross section of the shear wall is divided into concrete slice and steel slice as shown in Figure 2, and for the nonlinear shear spring, the shear strength-shear deformation relation was set as shown in Figure 3. Various equations have been suggested to estimate the shear strength and the shear stiffness. The nonlinear shear spring parameters were estimated by JBDPA code equations (AIJ 2004). The calculated parameters of the nonlinear shear spring used in this analysis are shown in Table 1.

The analysis was implemented up to the yielding point, and the results before and after the yielding was compared based on the yielding point. Here, the yielding point was set based on the time when the longitudinal reinforcement yields on the tension side of the wall. The flexure cracking strength was defined as the time when the concrete cracks.

In a shear-wall structure, the plastic hinges are concentrated on the lowest floor when an ultimate load is applied. Therefore, high curvature ductility is required to sufficiently absorb the seismic energy. Depending on how the length of a plastic hinge is set, the value of the plastic deformation angle and wall displacement differs. The plastic deformation angle and the plastic hinge length can be used to determine the curvature of the wall, and the curvature effects on the lateral displacement. Usually the length of a plastic hinge is $(1/2)l_w$ of the effective depth of the wall (Paulay 1991).

Figure 6 shows the lateral load-lateral displacement relation of the shear wall W1. The overall behavior of the shear wall based on the stiffness and the displacement was similar in the experiment result and the analysis result. It was confirmed that the initial stiffness and the yield strength of the shear wall were almost the same in the experimental and the analytical results. However, the yielding displacement of the shear wall was higher in the experiment than the analysis. It is theorized that the stiffness degradation following the cyclic loading causes this higher yielding displacement in the experiment.

Figure 7 shows the lateral load-lateral displacement relation of W2. Overall lateral load-lateral displacement relation until reaching the yield point was similar in the experimental and analytical results. However, the analytical result showed some difference in the post-cracking stiffness and the yield displacement of the wall. This shear wall was controlled primarily by the web-crushing failure in the experiment. The analytical result showed some difference in behavior pattern to the behavior of the wall in the experiment. The overall behavior of the shear wall based on lateral load-lateral displacement relation was similar in the experimental and analytical results. In this analysis of shear wall, after the nonlinear shear spring element was the first to reach the yield state, the shear wall became the ultimate state. Assuming that the shear spring is elastic, the yield strength of shear wall increased. Thus, the yield strength of the shear wall was almost the same in the experimental and analytical results. However, the yielding displacement of the shear wall was still higher in the experiment than the analysis. This issue will be discussed in detail in the future studies.

Table 1. Shear force-deformation parameters in nonlinear shear spring
(These values correspond to parameters shown in Figure 3).

Specimens	Initial elastic stiffness K_0(kN/cm)	Cracked stiffness ratio A(%)	Post-yielding stiffness ratio B(%)	Cracking strength F_c(kN)	Yielding strength F_y(kN)
W1	2.355×10^8	16	0.1	395.7	581.1
W2	694580	16	0.1	389.9	575.3

Table 2. Experimental parameters of barbell-shaped section wall specimens.

Parameters		W1	W2
Concrete compression strength f_{ck} (MPa)		36.6	35.8
Horizontal web reinforcement	Yield stress (MPa)	450(D10)	
	Spacing (mm)	150	100
	Reinforcement ratio (%)	0.52	0.79

Longitudinal web reinforcement	Yield stress (MPa)	450(D10)	
	Spacing (mm)	200	150
	Reinforcement ratio(%)	0.39	0.52
Longitudinal reinforcement in boundary elements	Yield stress (MPa)	473(D16), 425(D12)	
	Spacing (mm^2)	1430(6-D16+2-D12)	
	Reinforcement ratio (%)	2.29	
Transverse reinforcement in boundary elements	Yield stress (MPa)	444(□6)	
	Spacing (mm)	100	
Calculated results(kN) (ACI 318-99)	Flexural capacity	496	515
	Shear capacity	482	621
Observed response(kN)	Maximum load	491	608
	Load at web crushing	351	350
	Mode of failure	Web Crushing	

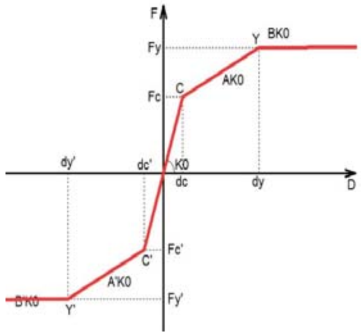


Figure 3. Shear force-deformation relation of shear spring.

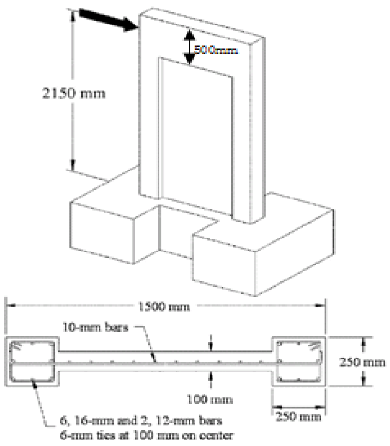
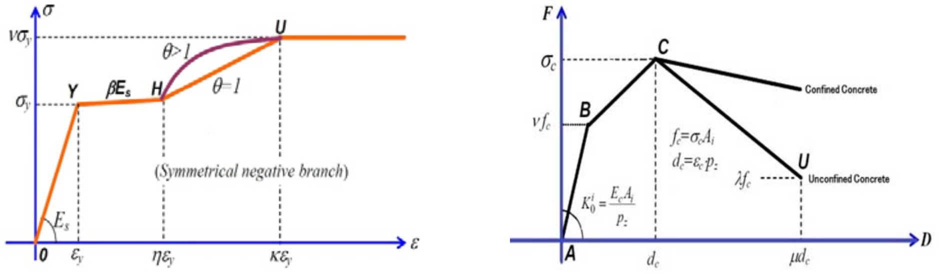


Figure 4. Geometry and reinforcement details of barbell-shaped section wall specimens.

5 CONCLUSION

In this study, a nonlinear analysis of reinforced concrete shear wall was accomplished using a fiber element model. Results obtained in the analytical model for barbell-shaped cross section wall compared favorably with experimentally responses for flexural capacity, stiffness, and deformability. Thus, the yield strength of the shear wall was almost the same in the experimental and the analytical results. However, the yielding displacement of the shear wall was still higher in the experiment than the analysis. This issue will be discussed in detail in future studies.



(a) Steel stress-strain relations (b) Idealized concrete stress-strain relations

Figure 5. Stress-strain relation of fiber slice.

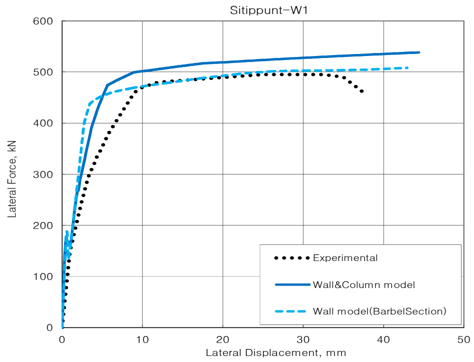


Figure 6. Lateral load-displacement relation (W1).

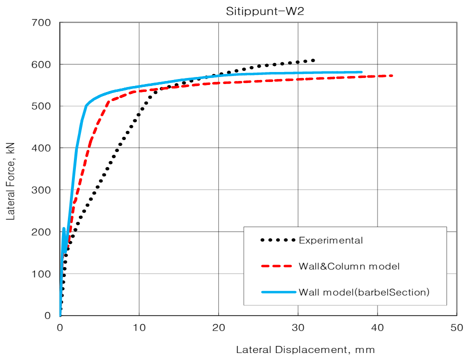


Figure 7. Lateral load-displacement relation (W2).

Acknowledgments

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References

AIJ, *Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings* (Draft), Maruzen, Tokyo, 2004.

Li, Kang-Ning, *Three-Dimensional Nonlinear Dynamic Structural Analysis Computer Program Package-Users Manual,* CANNY Consultants PTE LTD, Singapore, 2010.

Paulay, T., and Priestley, M. J. N., *Seismic Design of Reinforced Concrete and Masonry Buildings*, John Wiley & Sons, 1991.

Sittipunt, C., Wood, S. L., Lukkunaprasit, P., Pattararattanakul, P., Cyclic Behavior of Reinforced Concrete Structural Walls with Diagonal Web Reinforcement, *ACI Structural Journal*, Vol. 98. No. 4, pp. 554-562, 2001. 07-08.

Wallace, J.W., Behavior, Design, and Modeling of Structural Walls and Coupling Beams-Lessons from Recent Laboratory Tests and Earthquakes, *International Journal of Concrete Structures and Mechanics*, Vol.6, No.1, 3-18, March 2012.