Inelastic Behavior of Hollow Reinforced Concrete Bridge Columns

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SUMMARY
The purpose of this study was to investigate the inelastic behavior of hollow reinforced concrete bridge columns, and to provide data for developing improved seismic design criteria. By using a sophisticated nonlinear finite element analysis program, the accuracy and objectivity of the assessment process can be enhanced. A computer program, RCAHEST (Reinforced Concrete Analysis in Higher Evaluation System Technology), for the analysis of reinforced concrete structures was used. Material nonlinearity is taken into account by comprising tensile, compressive and shear models of cracked concrete and a model of reinforcing steel. The smeared crack approach was incorporated. The proposed numerical method gives a realistic prediction of inelastic behavior throughout the loading cycles for several test specimens investigated. Additionally, the studies and discussions presented in this investigation provide an insight into the key behavioral aspects of hollow reinforced concrete bridge columns.

Keywords: Inelastic behavior; Hollow reinforced concrete bridge columns; Nonlinear finite element analysis program; Material nonlinearity; Smeared crack

1. INTRODUCTION

Current trends in bridge construction indicate increasing use of hollow section columns. Many successful bridge projects have utilized columns of hollow cross section provide adequate stiffness and strength but with substantial saving of dead load. This dead load reduction results in reduced material and foundation costs.

However, there are also some disadvantages in the use of hollow sections. Presently, there is no specific design criterion for their use although there have been successful projects incorporating bridge columns with hollow cross sections built around the world. Also, the inelastic behavior of hollow reinforced concrete bridge columns is still not fully understood although a few works have been conducted previously (Hoshikuma and Priestley, 2000; Mo *et al.*, 2003; Sheikh *et al.*, 2007; Cheon *et al.*, 2012).

The main goal of this study is to provide knowledge on the inelastic behavior of hollow reinforced concrete bridge columns. In this paper, hollow bridge columns are tested under a constant axial load and a quasistatic, cyclically reversed horizontal load. An analytical prediction method for the inelastic behavior of hollow reinforced concrete bridge columns is also used.

2. EXPERIMENTAL PROGRAM

An experimental program was designed to obtain performance data of hollow bridge columns having details typical of those currently in use in regions of moderate or low seismicity in the Korea. The bridge columns had circular hollow cross sections and were reinforced with well-distributed longitudinal reinforcement. The transverse reinforcement of the specimens was designed considering current recommendations and requirements for shear and confinement (KRBD, 2005).

The mechanical properties of the specimens are listed on Table 1 and the geometric details are shown in Fig. 1. The first character HC in the specimen designation stands for hollow column. The second character, O, represents with only outer lateral reinforcement. The other second character, IO, represents with both inner and outer lateral reinforcement. The third character, 100 or 90, means space of transverse reinforcement, respectively. The last character, L or H, represents insufficient or sufficient cross-tie, respectively.

Table 1. Specimen properties

Specimen	Cylinder concrete strength (MPa)	Longitudinal reinforcement (D16)		Transverse reinforcement (D13, D10)		Cross-tie (D10)		Axial force
		f_{yl} (MPa)	ρ_l (%)	f_{yt} (MPa)	Space (mm)	f_{yt} (MPa)	Space (mm)	$\frac{P}{f_{ck}A_g}$
HC-O-100					Outer D13 @100		5ea @200	
HC-IO-90-L	22.4	441.9	1.05	D13 376.6 D10 392.3	Outer, Inner D10 @90	392.3	5ea @270	0.1
HC-IO-90-H					Outer, Inner D10 @90		10ea @90	

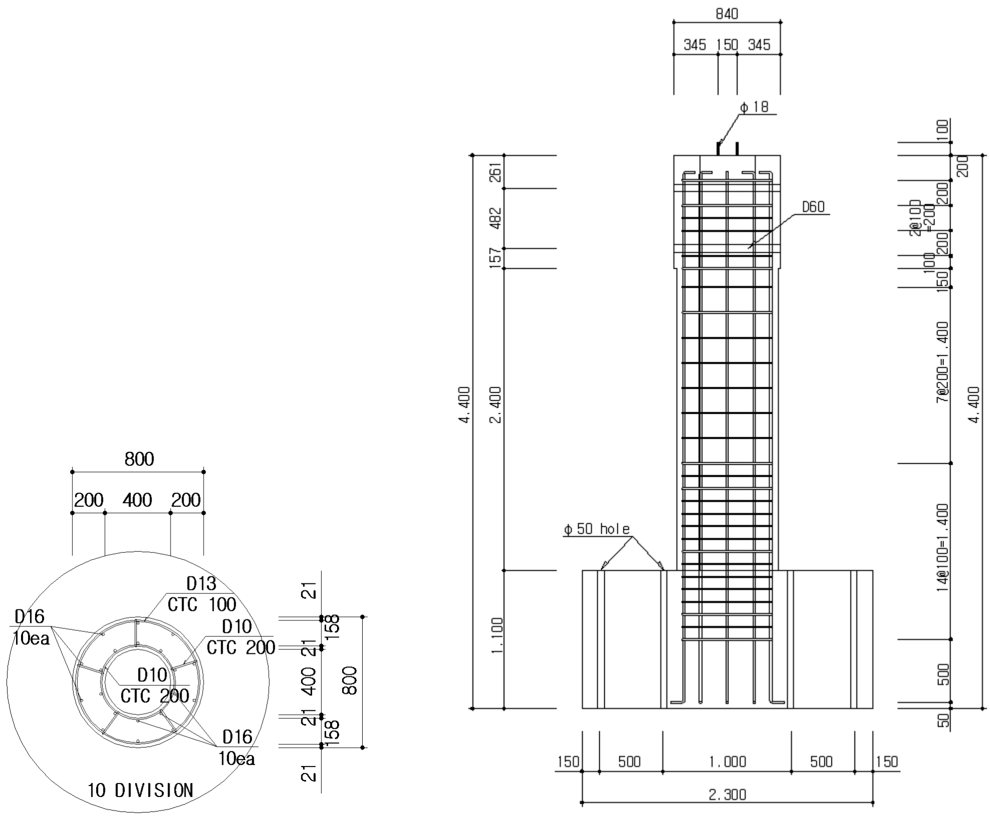


Figure 1. Sample of test specimens HC-O-100 (Unit: mm)

A schematic representation of the test set-up for specimens is shown in Fig. 2. The cyclic later point load was applied at the column top by a servo-controlled 2000 kN capacity hydraulic actuator with a ± 250 mm stroke reaching off the laboratory strong wall. All column specimens were tested under a $0.10 f_{ck} A_g$ constant compressive axial load to simulate the gravity load from bridge superstructures.

Figure 2. Photograph of experimental setup

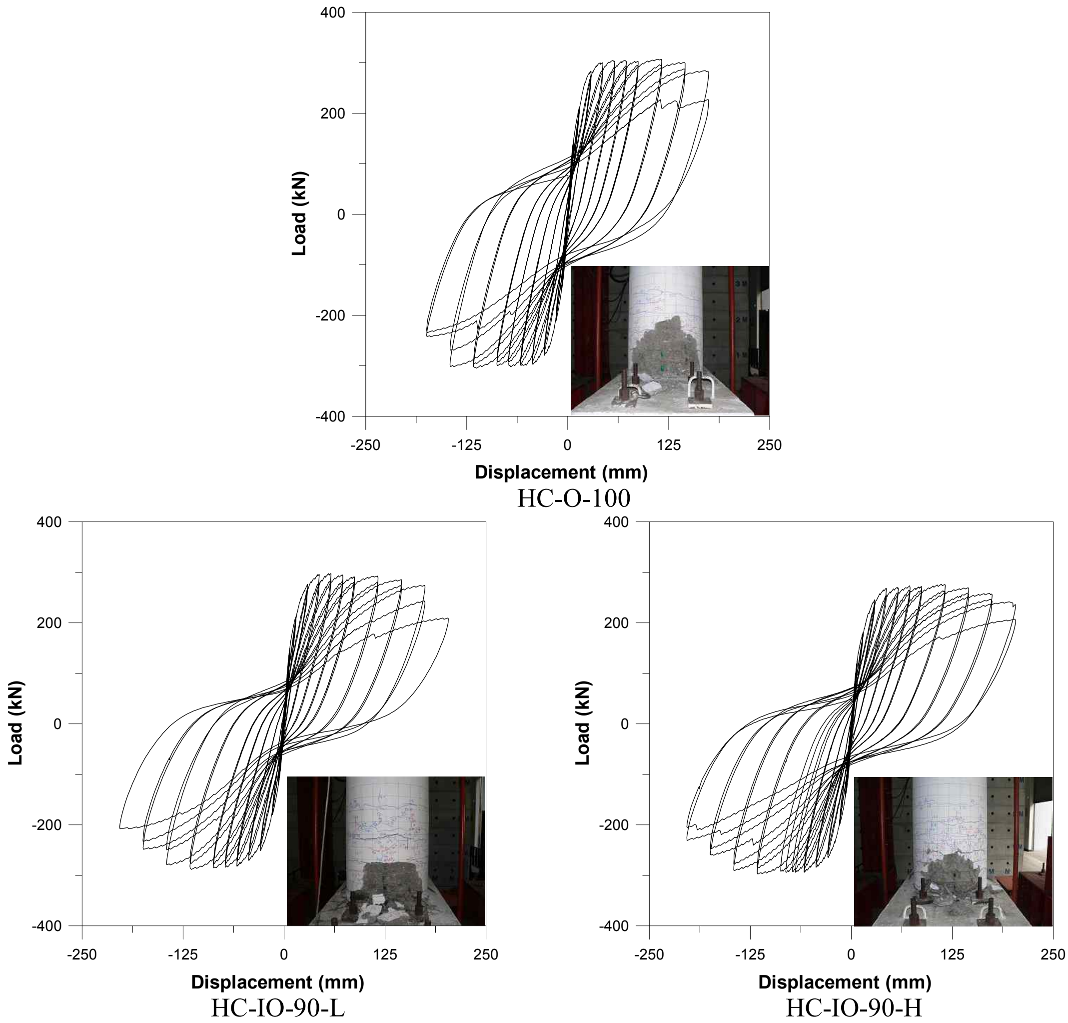


Figure 3. Load-displacement relationship for specimens

Similar procedures were used for each test. Axial load was applied at the beginning of a test and was maintained constant during the test. The displacement history was based on nominal drift ratio. Specimens were subjected to two cycles each at lateral displacement amplitudes of 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0 and 7.0 percent until failure. The displacement cycles were repeated to measure the strength degradation.

The lateral load-displacement responses for specimens are shown in Fig. 3. Figure 3 also shows the damage pattern of the specimens at failure. It has been observed that the neutral axis of specimens is located in the wall at failure. The physical phenomena which occurred during the test, namely: cracking, yielding, spalling of cover concrete and buckling of rebars, are indicated.

All three hollow column specimens exhibited ductile behavior under cyclic loading. The ductility factors ranged from 7.6 to 7.8. From the diagrams a good seismic performance of the hollow column specimen in terms of ductility and energy dissipation is expected.

It can be seen from Fig. 3 that specimen HC-O-100 provided the performance similar to specimen HC-IO-90-L and HC-IO-90-H. The effect of configuration of transverse reinforcement and quantity of cross tie used in this study on the load-displacement relationship of specimen is small and negligible.

3. ANALYTICAL STUDY

For an accurate assessment of the inelastic behavior characteristic of hollow bridge columns, three-dimensional finite element analysis and reliable constitutive modeling are required. However, difficulties in developing a reliable three-dimensional material model and the extensive number of calculations required pose several problems in the actual problem application (Maekawa *et al.*, 2001).

Therefore, a two-dimensional finite element model for hollow bridge columns is developed in this study. The model was created and analyzed using general-purpose finite element software, RCAHEST (Kim *et al.*, 2003; Kim *et al.*, 2005; Kim *et al.*, 2007; Kim *et al.*, 2009). RCAHEST is a nonlinear finite element analysis program used for analyzing reinforced concrete structures. The proposed structural element library RCAHEST is built around the finite element analysis program shell named FEAP, developed by Taylor (2000). From the results of the experimental and numerical tests, the numerical model is calibrated. A full description of the nonlinear material model for reinforced concrete is given by Kim *et al.* (2003; 2005; 2007; 2009).

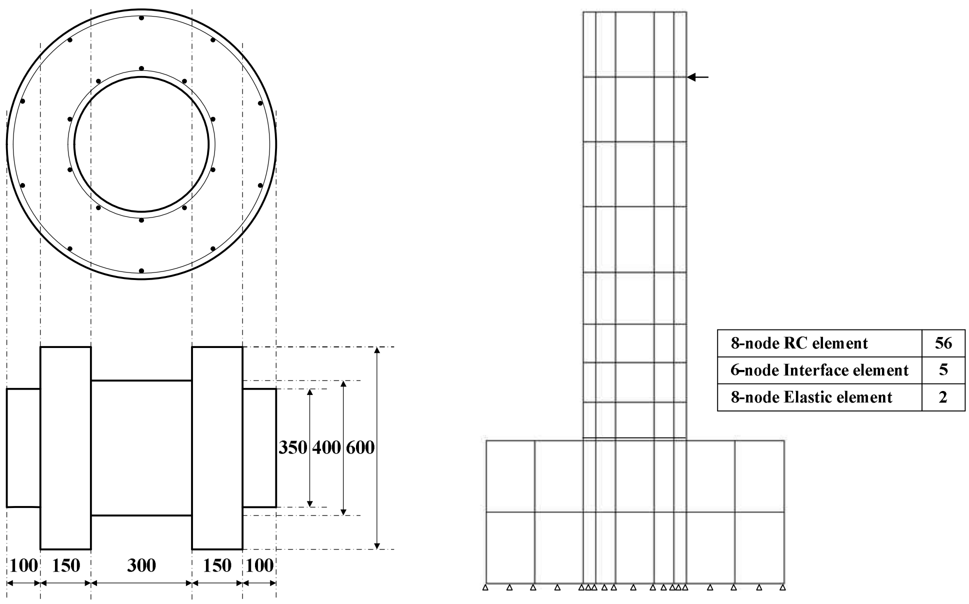
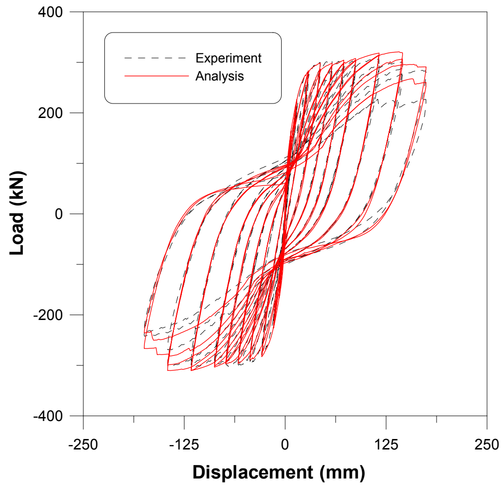


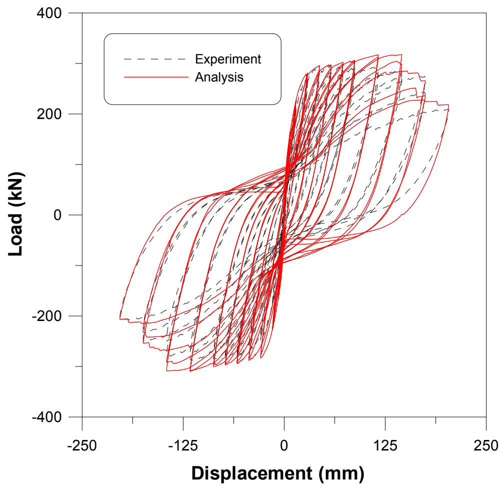
Figure 4. Finite element model for specimen

Figure 4 shows the method for transforming a hollow section into rectangular strips to using the plane stress elements of RCAHEST. For rectangular sections, equivalent strips are calculated. After the internal forces are calculated, the equilibrium is checked. In this transformation of a hollow circular section to a rectangular section, a section with minimum error was selected through iterative calculations concerning the moment of inertia for the sectional and area of concrete and reinforcements, to ensure that the behavior was similar to the actual behavior of the bridge columns with circular sections.

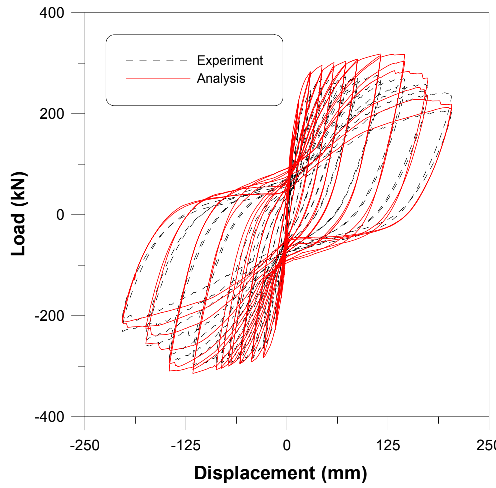
Figure 4 also shows the finite element discretization and the boundary conditions for 2 dimensional plane stress nonlinear analyses of the hollow reinforced concrete bridge columns. The interface element between the footing and the column enhances the effects of the bond-slip of steel bars and the local compression. In particular, in the plastic hinge zone of the body of the bridge columns, the section deemed dangerous, was divided into elements of a smaller size for a clearer depiction of plastic behavioral characteristics after reinforcement failure. All test specimens were modeled with a total of 63 elements and 224 nodes.



HC-O-100



HC-IO-90-L



HC-IO-90-H

Figure 5. Comparison of results from the experimental results

The lateral load-displacement responses for specimens are shown in Fig. 5. The analytical results show reasonable correspondence with the experimental results. The predicted ultimate strength was slightly larger than the actual strength of the hollow bridge columns, however, in general, the analytical model presented herein correlated reasonably well with the experimentally observed behavior of the bridge columns for each test.

4. CONCLUSIONS

This paper has attempted to establish a framework for prediction of the inelastic behavior of hollow reinforced concrete bridge columns. An experimental and analytical study was conducted to quantify performance measures and examine one aspect of detailing for hollow reinforced concrete bridge columns. A comparison with test data confirms that good predictions were obtained in regards to load capacities, failure modes, and load-deformation responses of hollow reinforced concrete bridge columns. More efforts should be directed to include certain procedures in the current design codes to direct the engineers toward an acceptable method for evaluating the existing hollow reinforced concrete bridge columns.

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