CYCLIC LOADING TEST OF REINFORCED CONCRETE COLUMN WITH HOLLOW SECTION AND HIGH LONGITUDIAL STEEL RATIO UNDER HIGH AXIAL LOADING

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<u>Abstract</u>

Reinforced concrete bridge columns with hollow section subjected to inelastic cyclic loading have been reported to suffer from the damage at not only outside but also inside of columns, where is invisible at the bridge inspection. Therefore it is important in the seismic design to determine the acceptable limit-state for the RC hollow columns in terms of inspectability and repairability. However there are few researches on the seismic performance of the RC columns with hollow section, particularly with high longitudinal steel ratio and high axial loading.

In this study, the failure mode and damage progress at inside and outside of the section of the reinforced concrete column with hollow section were clarified based on the cyclic loading tests for scaled-model columns. And the effect of axial loading on the seismic performance of the RC hollow columns was also investigated.

Introduction

In the seismic design of bridges, reinforced concrete columns are generally designed to be failed in flexure at the bottom of the column so that a plastic hinge forms around the column bottom in order to absorb the earthquake energy and to ensure the stable ductility behavior during a strong earthquake. A structural member in which plastic hinge develops shall be selected considering its inspectability and repairability after a strong earthquake, and design limit state of main structure member is determined from the inspectability and repairability.

Several research projects [1,2, 3, 4, 5, 6, 7] have been conducted to investigate nonlinear behavior of RC column with hollow section under cyclic loading, and design limit state and evaluation method of nonlinear ductility capacity have been determined based on the results from these experiments. Figure 1 shows the structural condition of those research tests.

In recent years, however, the wall thickness of hollow section tends to be smaller.

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Figure 1 Structural conditions of reinforced concrete columns with hollow section tested in previous researches

This is because the height of bridge columns constructed in mountain area in Japan tends to be very tall due to the natural boundary conditions, and thus it is generally required to reduce its inertia force to mitigate the seismic performance demand for foundations. The structural condition of column with thin wall is generally severe because thinner wall results in higher axial stress and higher longitudinal reinforcement ratio. The seismic performance of RC columns with such structural condition has not yet been investigated through cyclic loading tests. Additionally, as Hoshikuma and Priestly reported that RC columns with hollow section consisting of thin walls exhibited severe damage at inside faces rather than outside faces [4], it is necessary to develop a method to determine the design limit state of such columns considering the damage of the inside face of hollow section.

In this study, the cyclic loading tests for scaled-model columns with hollow section are conducted to identify failure mode and damage progress focusing on the damage of inside faces of hollow section under the structural condition of high axial stress and high longitudinal reinforcement ratio.

Specimen and instrumentation

a) Specimen properties

Two column specimens were constructed and tested under cyclic loading. To clarify the effect of axial loading on failure mode, two specimens with the same structural property were constructed. Table 1 shows the specimen properties. The columns have the dimensions of 975 mm width and 730 mm depth with 150 mm thick walls. The specimen subjected to higher axial stress is called here in Specimen-1 (S1), and that subjected to lower axial stress is called here in Specimen-2 (S2).



(b) Figure of test setup

Figure 2 Test set-up

Figure 2 shows the specimen tested in this study. This is a 1/7 scale model of a RC column with hollow section constructed in Japanese mountain area. The model is designed with high longitudinal steel ratio and subjected to high axial loading due to the thin wall in hollow section. As shown in Figure 2, the specimen was laid horizontally and the footing was mounted to the reaction wall through the base concrete. A lateral load was provided by a large stroke actuator at 4200 mm height from the base, resulting in an effective aspect ratio of 4.3, and a vertical load was applied at the top of the column by an axial loading apparatus.

Figure 3 shows the reinforcement details of the specimen and Table 1 shows the specimen details. The specimen is reinforced longitudinally with 102 of 16 mm diameter deformed bar (D16), providing a longitudinal steel ratio, ρ_1 , of 6.41%. Hoop reinforcement of 10 mm diameter deformed bar (D10) is used to confine the concrete core, spaced at 40 mm pitch and cross-tie is provided at 80 mm pitch, resulting in a volumetric reinforcement ratio, ρ_s , of 2.9%. Figure 4 shows arrangement of cross tie in flange wall. In practice of reinforcement arrangement for a hollow section, 90 degree hook is generally used at the inner face side and 135 degree hook is used at the outer face side of the wall. In this study, cross ties were arranged in the same way.

A constant axial load of 1880 kN for Specimen-1 and 430 kN for Specimen-2 was applied, providing 4.4 N/mm² and 1.0 N/mm² of the axial stress at the bottom of the column, respectively. The axial stress 4.4 N/mm² is the axial stress of the column of 30 m -40 m height. The axial stress 1.0 N/mm² is used for comparison.

Figure 1 compares structural condition of specimens between this tests and previous researches. The figure shows the specimens in this test have relatively large axial stress and



Figure 3 Reinforcement details of the specimen

		S1	S2	
Height (mm)		4200		
Dimension section (mm)		975 × 730		
Aspect ratio		4.3		
Long. bar	type	SD	345	
	diameter (mm)	16		
	long. steel ratio (%)	6.	41	
Hoop and cross ties	type	SD345		
	diameter (mm)	10		
	spacing (mm)	40 (80 ; cross-ties)		
	volumetric reinforcement rato (%)	2.9		
Axial stress	(N/mm ²))	4.4 1.0		

Table 1 Specimen details

especially large longitudinal reinforcement ratio.

Tables 2 and 3 show material properties used in the specimens. The cylinder strength of concrete was 56.8 N/mm² in Specimen-1 and 48.7 N/mm² in Specimen-2. The D16 and D10 reinforcing bar had yield strengths of 393.4 N/mm² and 390 N/mm², respectively.

b) Instrumentation

Lateral force was measured by the actuator. The lateral displacement was measured at the loading point of column by a laser displacement sensor.

Linear-variable-displacement-transducers (LVDTs) were used for curvature measurement at the plastic end region. Strain gauges were employed for the measurement of reinforcement bar strain.

A small video camera was set in the hollow part to observe damage of inside faces during cyclic loading as shown in Figure 5. The video camera can capture severe damage such as spalling of cover concrete, but slight damage such as flexural cracks might be missed due to the limitation of the resolution of the video camera.

	Compressive strength (N/mm2)	Elastic modulus (kN/mm2)	
S 1	56.8	32.9	
S2	48.7	30.1	

Table 2Concrete properties

	Elastic	Yield	Tensile
	modulus	strength	strength
	(N/mm^2)	(N/mm2)	(N/mm2)
D10	179.4	389.0	543.0
D16	190.4	393.4	453.2



Figure 4 Arrangement of cross-tie in wall of hollow section



Small video camera



A small video camera was inserted from the hole on the top of the column.

Figure 5 Small video camera set inside

c) Loading procedure

The columns were loaded quasi-statically and subjected to cycles of force reversals under the force control until yielding of the longitudinal reinforcing bar placed at the outer edge of the wall. A reference displacement 1 $_0$ was determined as a displacement when the longitudinal reinforcing bar at the edge of the wall yielded at the bottom section of Specimen-1, and the same $_0$ is used for easy comparison between Specimen-1 and Specimen-2. The lateral displacement was increased stepwisely (± 1 $_0$, ± 2 $_0$, ± 3 $_0$,) under the displacement control after yielding. The number of cyclic loading in each step up to 1 $_0$ was single, and that after 1 $_0$ was three.

Experimental results

Figure 6 shows the lateral force vs. lateral displacement hysteresis and Figure 7 shows the envelop curves. Lateral displacement in Figures 6 and 7 is modified by removing the displacement caused by strain penetration of longitudinal bar into the footing.

In this research, ultimate state was defined as the stage when an extensive deterioration of lateral force was observed in the lateral force vs. lateral displacement hysteresis. Point A, Point B, Point C and Point D in Figure 6 indicate the first yield displacement, the displacement when spalling of outside cover concrete was occurred, the displacement when spalling of inside cover concrete was occurred, and the displacement when buckling of the longitudinal reinforcing bar was occurred, respectively.

Taking the average of lateral force and lateral displacement in the push and pull direction, the maximum strength in Specimen-1 and in Specimen-2 reached 1124 kN and 1084 kN, respectively. The yield displacement of Specimen-1 and Specimen-2 were almost same but the ultimate displacement of Specimen-1 and Specimen-2 was 113 mm and 172 mm, respectively.

Figure 8 and 9 show the damage progress of Specimen-1 and Specimen-2, respectively.



- A: Yielding of long. Bar,
- B: Spalling of outside cover concrete,
- C: Spalling of inside cover concrete
- D: Fracture of long.bar

Figure 6 Lateral force vs lateral displacement



		displacement (mm)		force (kN)			
		yield	max	ultimate	yield	max	ultimate
S1	positive	28.8	72.2	96.2	893	1092.2	1054.9
	negative	28.6	129.8	129.8	854	1154.7	1154.7
	average	28.7	101	113	873.5	1123.5	1104.8
S2	positive	27.5	191.5	191.5	805	1066.1	1065.2
	negative	29.4	152.5	152.5	783.5	1097	1097
	average	28.4	149.9	172	794.3	1081.6	1081.1

Figure 7 Envelop curves of specimens

Horizontal cracks in the flange walls and diagonal cracks in the web walls were observed before 1 $_0$ in both the specimens.

As shown in Figure 8, spalling of cover concrete at the outside faces was observed but spalling of cover concrete at inside faces was not observed at 3 $_0$ in Specimen-1. At 4 $_0$, buckling of longitudinal bar arranged at the inside and outside faces of the wall was observed. At the same loading step, the 90 degree hook of the cross ties at the inner face was unhooked from the core concrete. However, the 135 degree hook at outside faces hooked well to the core concrete until the end of the test. Consequently, the damage degree at the inside faces was more severe than that at the outside faces.



(b) Damage observed at face M (upper : outside, lower : inside)

Figure 8 Damage observed in Specimen-1

As shown in Figure 9, spalling of cover concrete at the outside faces was observed but spalling of cover concrete at the inside faces was not observed at 4 $_0$ in Specimen-2. Spalling of cover concrete at the inside faces was observed at 5 $_0$. Buckling of longitudinal reinforcing bar arranged at the inside and outside faces of the wall was observed and the hook ends of the cross ties coming out from the core concrete occurred only at the inside faces at 6 $_0$ in Specimen-2. Likewise in Specimen-1, the hook ends at outside faces had not come out from the core concrete until the end of the test.

From these results, it is found that spalling of cover concrete at outside flange walls occurred in smaller displacement than that at inside flange walls and longitudinal



(b) Damage observed at face M (upper : outside, lower : inside)

Figure 9 Damage observed in Specimen-2

reinforcing bars buckled at both the sides almost simultaneously in both Specimen-1 and Specimen-2. And it is found that the 90 degree hook at inside face is easier to be unhooked than the 135 degree hook at outside face.

The failure mode of Specimen-1 was compressive failure in flange walls but that of Specimen-2 was concrete failure in web walls, which means the axial stress has significant effect on the failure mode of the RC column with hollow section. The failure mode of the RC column with hollow section under high axial stress is not desirable because the column would lose the axial loading capacity. This should be considered when the design limit state of RC columns with hollow section.

Conclusion

In this study, cyclic loading tests were conducted to investigate failure characteristics of RC hollow columns with high longitudinal bar ratio under high axial loading. Followings are the conclusions derived from the study.

1) It is found that spalling of cover concrete at outside flange walls occurred in smaller displacement than that at inside flange walls, and longitudinal reinforcing bars buckled at both the sides almost simultaneously.

2) The axial stress has significant effect on the failure mode of a RC column with hollow section. The failure mode under high axial stress is not desirable as a RC bridge column because the column would lose the axial loading capacity. This should be considered when the design limit state of RC columns with hollow section is designed.

3) Unhooking of the 90 degree hook in cross ties was observed at inside faces and the damage degree at inside faces was more severe than that at outside faces. This is because the 90 degree hook at inside faces is easier to open and thus to be unhooked than the 135 degree hook at outside faces. It is necessary to make special consideration on reinforcement details of the cross ties arranged in the walls of hollow section in order to prevent severe damage at the inside faces.

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