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Research for Hollow Reinforced Concrete Bridge Piers in Korea

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Abstract**—**Hollow section for bridge columns has some advantages. However, current seismic design codes do not provide design regulations for hollow bridge piers. There have been many experimental studied for hollow reinforced concrete piers in the world. But, Study for hollow section for bridge piers in Korea has been begun with approximately 2000s. There has been conducted experimental study for hollow piers of flexural controlled sections by Yeungnam University, Sung kyunkwan University, Korea Expressway Corporation in 2009. This study concluded that flexural controlled sections for hollow piers showed the similar behavior to solid sections. And there have been conducted experimental study for hollow piers of compression controlled sections by Yeungnam University, Korea Institute of Construction Technology in 2012. This study concluded that compression controlled sections for hollow piers showed compression fracture of concrete in inside wall face. Samsung Construction & Trading Corporation has been conducted study with Yeungnam University for reduce the quantity of reinforcement details about hollow piers. Reduce the quantity of reinforcement details are triangular cross tie. This study concluded that triangular reinforcement details showed the similar behavior as compared with existing reinforcement details.

Keywords**—**Hollow pier, flexural controlled section, compression controlled section, reduce the quantity of reinforcement details.

I. Introduction

A hollow shaped cross section of reinforced concrete bridge pier provide several advantage from the structural design point of view, compared with a solid cross section. First, seismic design force produced by self-weight of structure and acceleration can be decreased by the reduced volume of pier. Second, hydration heat produced by Portland cement can be decreased by the reduced volume of pier, which results in mitigating cracking of concrete. Third, required amount of longitudinal reinforcement of the pier can be reduced, when the design code regulation for minimum longitudinal steel amount governs the design. In spite of these advantages, it is very difficult for design engineers not only to decide the amount of transverse steel for providing confinement effect, but also to decide reinforcement details such as the arrangement of longitudinal and transverse steel. This is because any current seismic design codes do not provide sufficient regulation for the hollow piers. So there have been many experimental studied for hollow reinforced concrete piers in the world. Study for hollow bridge piers in Korea has been begun with 2000s. For the hollow piers, several experimental studies were conducted.

Whittaker et al. (1987) [1] performed an experiment of circular hollow piers used for marine structures. They tested six specimens with the following dimensions: a column length of 3,100mm, outside cross-sectional diameters of 700mm and 600mm. And 0.75 defined by the inside diameter divided by the outside diameter. Their experiments showed that if the transverse reinforcement was arranged appropriately, the ductile behavior of the circular hollow columns was comparable to that of circular solid columns.

Zahn et al. (1990) [2] conducted a test a sectional analysis of a circular hollow pier with a single layer of longitudinal reinforcement. The test variables were hollow ratio and axial force ratio. They tested six specimens with the following dimensions: a pier length of 1,600mm; outside diameter of 400mm; inside diameters of 212mm, 250mm, and 290mm; and hollow ratios of 0.53, 0.63 and 0.73. They concluded that there was a difference in failure behaviour depending on the location of the neutral axis at failure, which meant whether the neutral axis was located inside the hollow or inside the wall section.

Chung et al. (1999) [3] performed an experiment of circular hollow columns. They tested seven specimens with the following dimensions: a column length of 1,882 mm, outside diameter of 600 mm, inside diameter of 332 mm, and hollow ratio of 0.55. Their experiment showed that if the transverse reinforcement was arranged appropriately, the ductile behavior of the circular hollow columns was comparable to that of circular solid columns.

Hoshikuma et al. (2000) [4] performed an experiment of circular hollow columns with single layer of bundled longitudinal reinforcement. They tested two specimens with the following dimensions: a column length of 6,528 mm, outside diameter of 1,524 mm, inside diameter of 1,245 mm, and hollow ratio of 0.82. They defined column failure as the state when the concrete strain reached 0.005 at the inside face of the wall section, and concluded that the neutral axis was located inside the hollow when the hollow ratio and longitudinal reinforcement ratio were large enough.

Yeh et al. (2001) [5] conducted a test for circular hollow columns of which main variables were the aspect ratio (column height/diameter of section), connection details of longitudinal steel, amount of transverse reinforcement, and arrangement of cross ties. They tested three specimens with the following dimensions: column lengths of 5,500 mm and 3,500 mm, outside diameter of 1,500 mm, and inside diameter of 900 mm, and hollow ratio of 0.6. The experiment showed that the failure

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behavior and ductility capacity varied according to the aspect ratio, presence of lap-splice of the longitudinal reinforcement, amount of transverse reinforcement, and shape of cross-ties.

II. Experiment

A. Study for Seismic Design Code of Hollow Bridge Piers

There have been three studies for hollow reinforced concrete piers. First, Yeungnam University, Sung kyunkwan University and Korea Expressway Corporation have been conducted study for flexural controlled sections of hollow bridge piers in 2009. Second, Yeungnam University and Korea Institute of Construction Technology have been conducted study for compression controlled sections of hollow reinforced concrete piers in 2012. Those studies have been conducted circular section for hollow bridge piers. Flexural and compression controlled sections were defined as the cross section with the neutral axis located inside the wall and hollow section respectively at failure, as shown in Fig. 1. Current seismic design codes do not provide sufficient regulation for the hollow piers. First and second studies were for seismic design code.

A group was defined as the P1 to P8. B group was defined as the RP1 to RP13. A group were used that concrete compression strength was 32.5MPa, yield strength of longitudinal steel was 499MPa and yield strength of transverse steel was 495MPa. RP1 to RP10 in B group were used that concrete compression strength was 39MPa and RP11 to RP13 was 27.5MPa. B group were used that yield strength of longitudinal steel was 481MPa and yield strength of transverse steel was 473MPa. The outside diameters of the sections in A group was 1,000mm. Inside diameter were 500mm, 750mm. So, hollow ratio has two types by 0.5, 0.75. The outside and inside diameters of sections in B group were 1,400mm and 980mm. Hollow ratio of B group was 0.7. Longitudinal steel volumetric ratio of total specimens was generally 1~2%. A and B groups were applied to applied to 3.5 of aspect ratio. Total specimens were applied to under the 0.1 of axial force ratio ($P_u/A_g f_{ck}$), but P5 in A group was applied to 0.15. The transverse volumetric ratio calculated by the actual cross sectional area and the area ignoring the hollow portion treated like a solid section. Table I shows variable of test specimens of A and B groups. The variable of ρ_l is longitudinal steels ratio. The variable of s_o is spacing of outside transvers steel, and the variable of s_i is spacing of inside transverse steel. The variables of ρ_{so} and ρ_{si} are outside transverse steel ratio and inside transverse steel ratio, respectively.

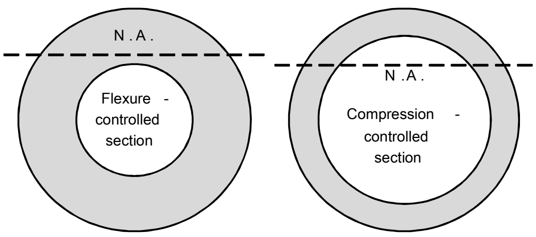


Fig. 1 Definition of flexural and compression controlled sections

TABLE I
VARIABLE OF TEST SPECIMENS (1)

No.	D_o mm	D_i mm	D_i/D_o	ρ_l	Transverse steel S_o: mm	S_i: mm	Volumetric ratio ρ_{so}	ρ_{si}
P1		-	-	0.0083				0.0138
P2				0.0117	40		0.0138	0.0302
P3		500	0.5	0.0136		-		
P4	1,000			0.0117	80		0.0069	0.0151
P5		750	0.75	0.0200	40		0.0138	0.0745
P6		500	0.5	0.0136	80	80	0.0069	*0.0151*
P7						-		
P8		750	0.75	0.0117	40		0.0138	0.0745
RP1					196		0.0019	0.0070
RP2						196		
RP3								
RP4				0.0100	98		0.0038	0.0140
RP5						98		
RP6								
RP7	1,400	980	0.7		49	-	0.0077	0.0280
RP8								
RP9				0.0200	196	196	0.0019	0.0070
RP10								
RP11					98	98	0.0038	0.0140
RP12				0.0100				
RP13								

This experiment was used that cyclic load under a constant axial load was applied by hydraulic actuators with capacities of 3,500kN and 4,000kN respectively, as shown in Fig. 2. The lateral load was applied under displacement control by increasing lateral drift ratio of ±0.25%, ±0.5%, ±0.75%, ±1.0%, ±1.5%, ±2.0%, ±2.5%, ±3.0%, ±3.5%, ±4.0%, ±5.0% and so on.

Fig. 2 Quasi – Static test set up

B. Study for Developed Technology of Hollow Bridge Piers

Samsung Construction & Trading Corporation and Yeungnam University have been study for reduce the quantity of reinforcement details about hollow piers. This study was for technology development of hollow bridge piers. Reduce the quantity of reinforcement details are triangular cross tie. Those details are shown in Figs. 3 (a), (b), (d) and (f) appeared existing reinforcement detail for hollow piers. Figs. 3 (c) and (f) appeared developed red- reduce the quantity of reinforcement details. Normally, existing reinforcement means that 135° bend or full hook should be specified for at least one end of the cross tie. There hollow bridge piers sections have increased construction complexity and hence increased labor coasts. However, reduce the quantity of reinforcement detail has economic feasibility, rationality, and facilitates shorter construction periods. This study was used that concrete compression strength was 22MPa, yield strength of longitudinal steel was 376MPa and yield strength of transverse steel was 343, 353MPa. This study was conducted experiment for circular and rectangular section of hollow bridge piers. Specimens of circular and rectangular section applied each 3.5, 4.5 of aspect ratio. The outside and inside diameter of circular section was each 1,400mm, 980mm. The outside length on side of rectangular section specimen was 1,000mm and inside length on side was 500 mm. hollow ratios of circular and rectangular section specimens were each 0.7, 0.5. Total specimens were applied to 0.1 of axial force ratio. Table II shows variable of test specimens. For each specimen, the pier footing was connected to the laboratory strong floor with post tensioning bar. The cyclic load under a constant axial load was applied by hydraulic actuators with capacities of 3,500kN and 4,000kN respectively too. 'L' was arranged 90°, 135° hook cross tie in specimen. 'T' was arranged triangular cross tie. 'NT' was arranged triangular cross tie, and there was no inside transverse steel.

TABLE II
VARIABLE OF TEST SPECIMENS (2)

No.	D_i/D_o	ρ_l	Transverse steel			
			S_o: mm	S_i: mm	Volumetric ratio ρ_{so}	Volumetric ratio ρ_{si}
C-L	0.7	0.013	80	80	0.0047	0.0047
C-T		0.013	80	80	0.0047	0.0047
C-NT		0.013	80	400	0.0047	0.0009
R-L	0.5	0.0153	80	80	0.0083	0.0083
R-NT		0.0138	80	400	0.01	0.002

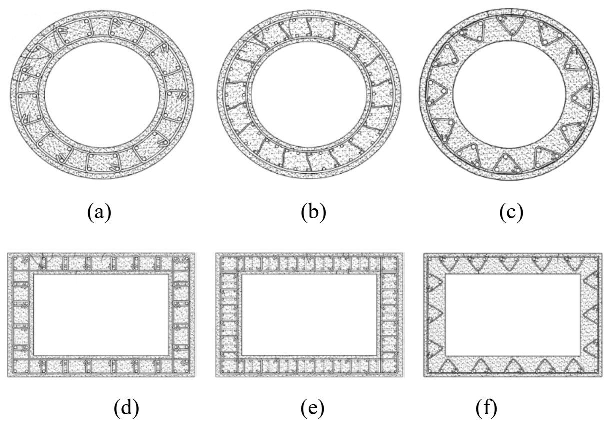


Fig. 3 Reinforcement details for hollow piers [6], [7]: (a), (b), (d), (e) classification of cross tie detail; (c), (f) development of cross tie detail

III. EXPERIMENTAL RESULT

A. Study for Seismic Design Code of Hollow Bridge Piers

In A group, the solid section pier (P1) and hollow section piers with hollow ratio of 0.5 (P2, P3, P4, P6 and P7) were damaged in the following: occurrence of initial flexural crack, yielding of the outermost longitudinal steel, crushing and spalling of the cover concrete, and fracture of the longitudinal steel. The hollow piers with hollow ratio of 0.75 (P5 and P8) showed the similar behavior to the hollow piers with hollow ratio 0.5. However, final failure was due to compression failure of the core concrete rather than the fracture of the longitudinal steel.

In B group, specimens RP1 to RP4 and RP9 with inside transverse steel spacing of 196mm were damaged in the following: occurrence of initial flexural crack, occurrence of flexural-shear crack, yielding of the outermost longitudinal steel, crushing and spalling of the cover concrete, buckling of the longitudinal steel, and compression failure of the core concrete. The similar behavior was appeared in RP5, RP6, RP10, RP11, RP12 and RP13 with transverse steel spacing of 98mm distributed near both faces of the wall and specimens RP7 and RP8 with transverse steel spacing of 49mm distributed only near outside wall face, but the main failure mode was fracture of the longitudinal steel rather than compression failure of the core concrete. Fig. 4 shows the hysteretic response of lateral load-displacement of the specimens by A group. Fig. 5 shows the hysteretic loops of the specimens by B group.

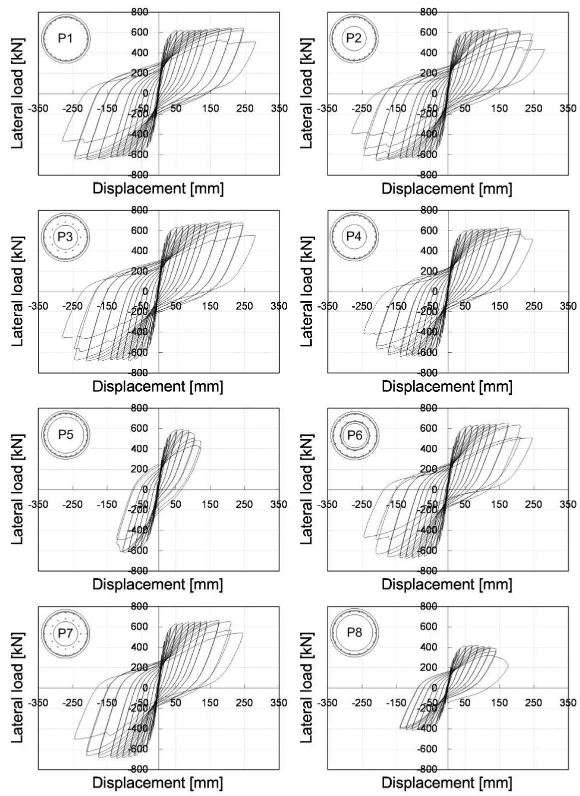


Fig. 4 Hysteretic response of lateral load-displacement by A group

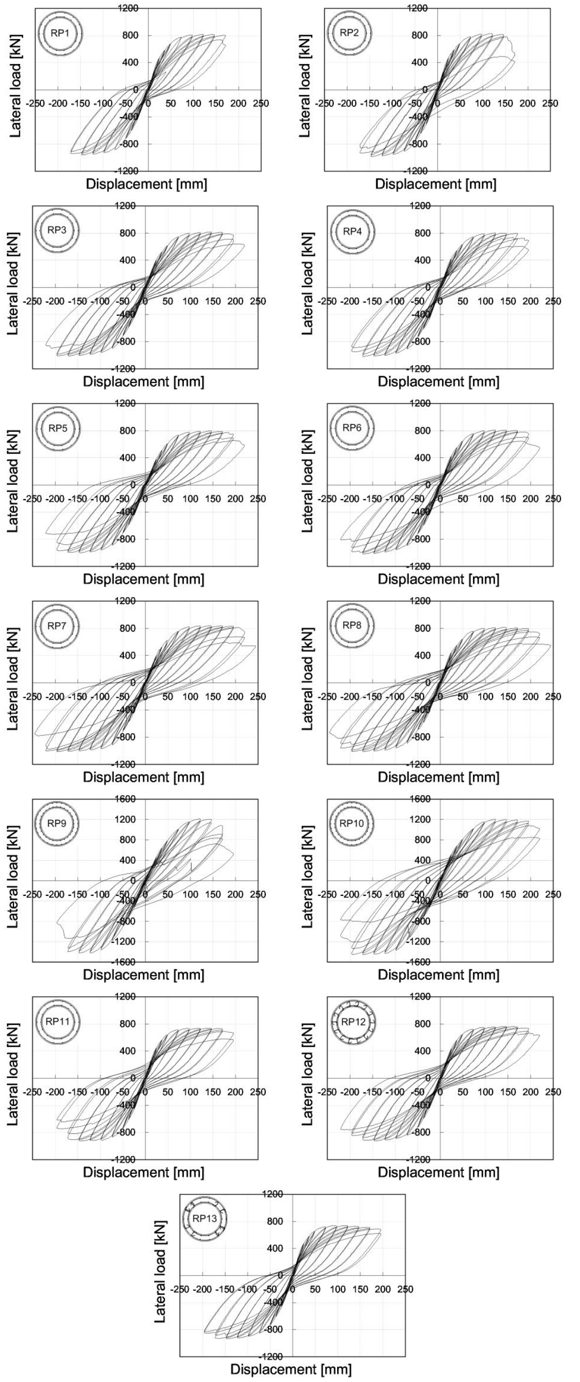


Fig. 5 Hysteretic response of lateral load-displacement by B group

B. Study for Developed Technology of Hollow Bridge Piers

The lateral load-displacement responses of the specimens are shown in Fig. 6. The similarities in the shapes of the hysteresis curves are primarily due to the geometry of the test set up. Generally specimens were damaged in the following: initial flexural crack, yielding of the outermost longitudinal steel, spalling of the cover concrete, buckling and fracture longitudinal steel Fig. 6 shows hysteresis curve of lateral load-displacement of the specimens in this study.

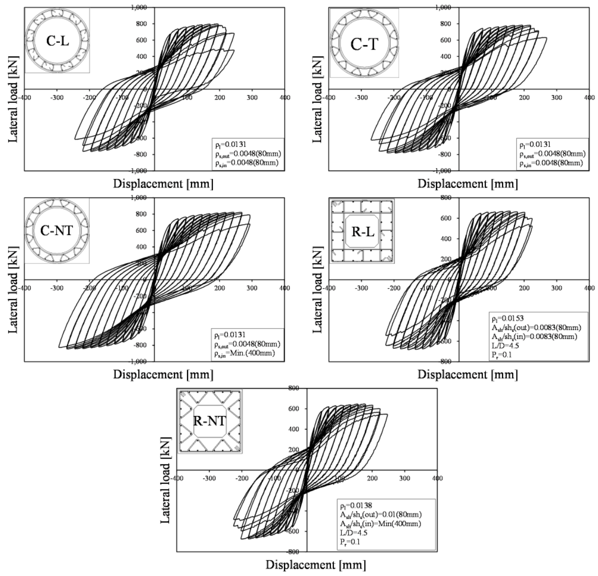


Fig. 6 Hysteresis curve of specimens (Reduce the quantity of reinforcement details)

When the longitudinal steel was occurred buckling, existing reinforcement detail was occurred opening the hook of 90°. But, reduce the quantity of reinforcement detail was not occurred opening the hook. Fig. 7 shows failure of specimens.

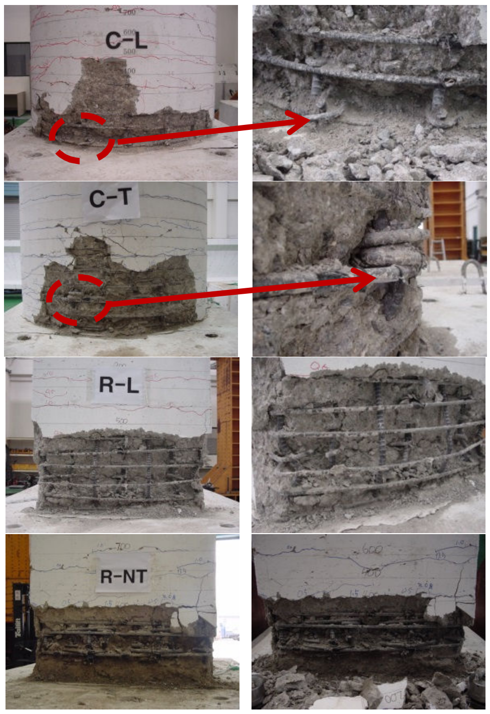


Fig. 7 Failure of specimens

IV. Comparative Analysis of Experimental Result

Ductility of the reinforced concrete pier can be quantitatively evaluated by displacement ductility factor μ_Δ as (1):

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y} \quad (1)$$

where, Δ_y is the yield displacement and Δ_u is the ultimate displacement. Fig. 8 shows yield and ultimate displacements were determined from the envelope of the load-displacement curve. The yield displacement was defined as the displacement corresponding to the intersection of the maximum lateral load and secant stiffness at 75% of maximum lateral load. When fracture did occur the longitudinal and transverse steel, ultimate displacement was defined as the displacement corresponding to the drift ratio at the previous cycle just before the fracture of the steel. When fracture did not occur in the steel, ultimate displacement was defined as the displacement corresponding to undergoing a 15% reduction in lateral load. Table III showed displacement ductility factor of specimens.

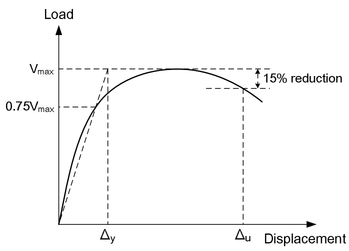


Fig. 8 Definitions of yield and ultimate displacement

TABLE III
DISPLACEMENT DUCTILITY FACTOR (1)

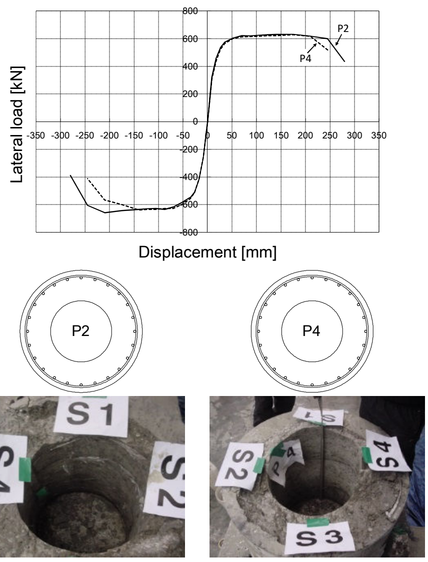
No.	Δ_y: mm	Δ_u: mm	μ_Δ
P1	30.5	245.0	8.0
P2	28.5	245.0	8.6
P3	30.5	245.0	8.0
P4	29.0	210.0	7.2
P5	33.0	123.5	3.7
P6	31.5	210.0	6.7
P7	31.5	210.0	6.7
P8	30.5	140.0	4.6
RP1	59.1	171.5	2.9
RP2	59.1	147.0	2.5
RP3	66.2	196.0	3.0
RP4	66.2	196.0	3.0
RP5	66.2	196.0	3.0
RP6	66.2	196.0	3.0
RP7	68.8	220.5	3.2
RP8	68.8	220.5	3.2
RP9	82.0	171.5	2.1
RP10	82.0	196.5	2.4
RP11	53.7	196.0	3.6
RP12	53.7	196.0	3.6
RP13	53.7	196.0	3.6

A. Study for Seismic Design Code of Hollow Bridge Piers

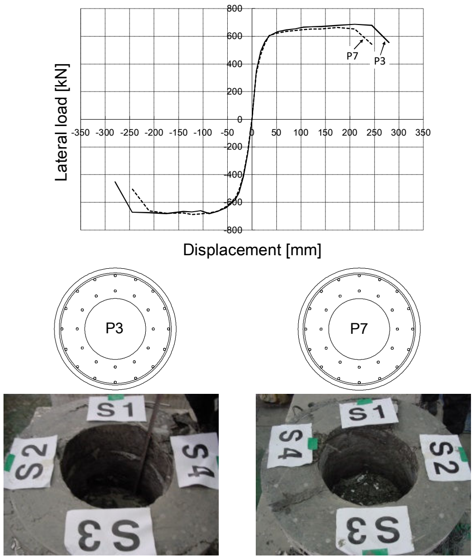
First analysis compared influence of outside transverse steel. Specimens P2 and P4 with hollow ratio 0.5 had one layer of longitudinal steel and transverse steel near the outside wall face. In P3 and P7 with hollow ratio of 0.5, the longitudinal steel was distributed near both faces of wall section, but the transverse steel was distributed only near the outside wall face. In RP2 and RP4 with hollow ratio of 0.7, the longitudinal and transverse steel were distributed near both faces of wall section. The different amount of outside transverse steel ratio was the only different test variable of each pair of the specimen with the same steel configuration. Specimens P2, P3 and RP4 had twice amount of outside transverse reinforcement ratio compared with specimens P4, P7 and RP2, respectively, which resulted in half spaces with the same diameter of transverse steel.

Total specimens showed almost identical behavior in the initial elastic state. But, ultimate displacements of specimens P2, P3 and RP4 with larger outside transverse ratio, were slightly greater than those P4, P7 and RP2, respectively. The displacement ductility factors of P2, P3 and RP4 were each 8.6, 8.0 and 3.0 respectively, which were greater than 7.2, 6.7 and 2.5 of P4, P7 and RP2, respectively. Therefore, test result showed that the displacement ductility factor increased as the amount of outside transverse steel increased.

All specimens cut plastic hinge region after experiment. Damages were not observed in the inside face of wall section with the hollow ratio of 0.5, which was classified as the flexural controlled section. In the compression controlled section of which hollow ratio was 0.7, damages were observed in the inside wall face as well as crushing and spalling of the outside face of wall. The height of inside damaged region of RP4 was 60mm, which was smaller than 250mm of the specimen RP2. Therefore, test result showed that large amount of outside transverse steel resulted in decreasing damaged area of the inside wall face. Fig. 9 compares the test results of P2, P4, P3, P7, RP2 and RP4.



(a)



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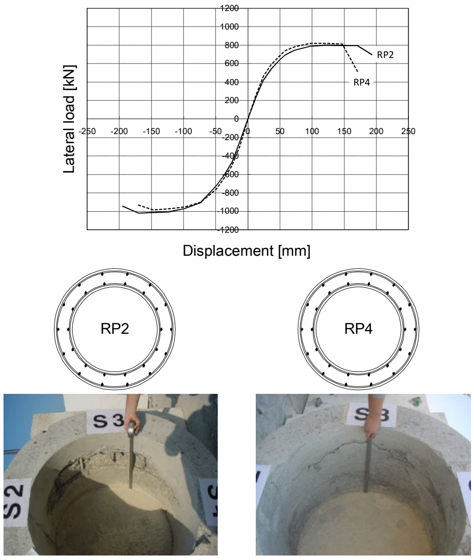
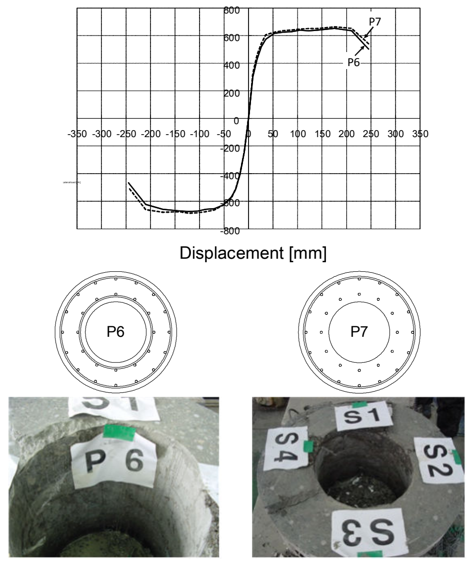


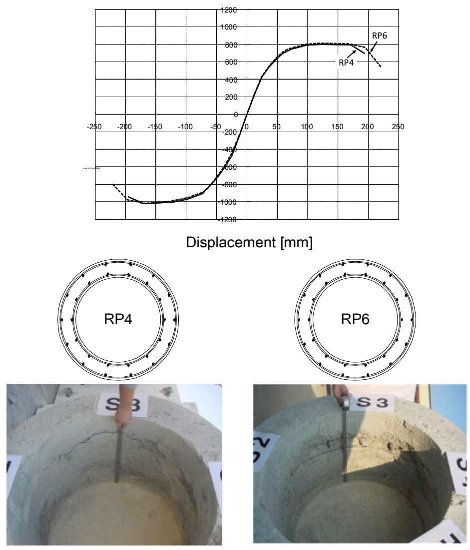
(c)

Fig. 9 Envelop of load-displacement curves and failure of inside wall: (a) Specimen P2, P4; (b) Specimen P3, P7; (c) Specimen RP2, PR4

Second, analysis compared influence of inside transverse steel. Specimens P6 and P7 with hollow ratio of 0.5 had the identical configuration and steel amount except inside transverse steel. There was no inside transverse steel in P7. Specimens P6 and P7 showed identical load-displacement relationship and equal displacement ductility factor of 6.7. It implied that the pier behavior was not influenced by the inside transverse steel in the flexural controlled section. Specimens RP4 and RP6 with hollow ratio 0.7 also had the identical configuration and steel amount except inside transverse steel. The spacing of inside transverse steel was 196mm and 98mm for RP4 and RP6. RP4 and RP6 showed similar load-displacement relationships and the equal displacement ductility factor of 3.0. There was a little difference in damaged region of inside wall. The height of inside damaged region was 100mm for both RP4 and RP6, respectively. It means that the difference in amount of inside transverse steel did not provide significant confinement of concrete. The spacing of outside transverse steel was 49mm and 98mm for RP8 and RP6. RP8 did not have inside transverse steel. And RP6 had inside transverse steel of which spacing was 98mm. The height of inside damaged region of RP8 and RP6 was 600mm and 100mm. Therefore the test result showed that existence of the inside transverse steel could reduce damaged region of inside wall face in case of the compression controlled sections. Fig. 10 compares the test result of P6, P7, RP4, RP6 and RP8.



(a)



(b)

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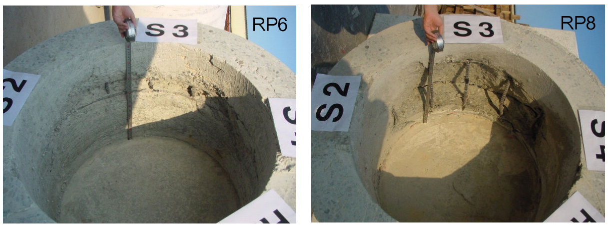


(c)

Fig. 10 Envelop of load-displacement curves and failure of inside wall: (a) Specimen P6, P7; (b) Specimen RP4, RP6; (c) Specimen RP6, RP8

B. Study for Developed Technology of Hollow Bridge Piers

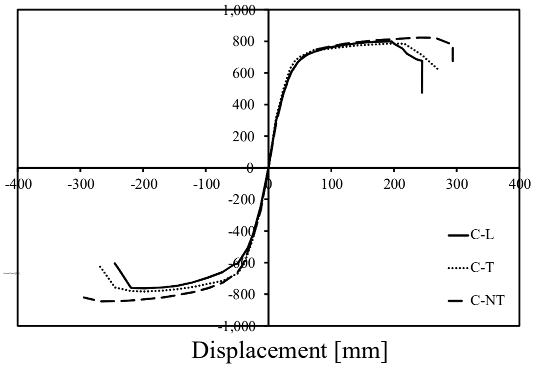
Displacement ductility factor equation and decision method of yield and ultimate displacement appeared in front of page. Table IV showed displacement ductility factor of specimens in this study.

TABLE IV
DISPLACEMENT DUCTILITY FACTOR (2)

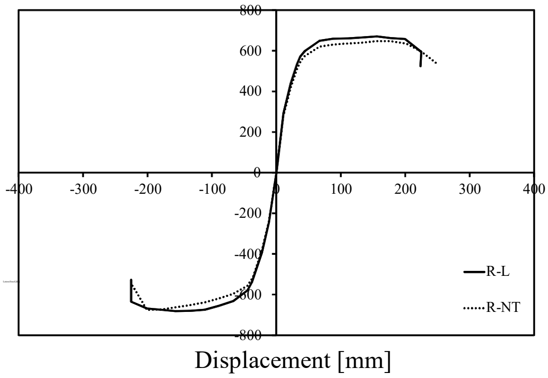
No.	Δ_y: mm	Δ_u: mm	μ_Δ
C-L	47.0	221.0	4.7
C-T	42.0	246.0	5.9
C-NT	50.0	294.0	5.9
R-L	37.0	224.0	6.1
R-NT	38.0	224.0	5.9

Specimens C-L, C-T and C-NT were circular section. Specimens C-L and C-T with hollow ratio 0.7 were differently arranged type of cross tie. However, amount of transverse steel equaled. Shape of cross tie in C-L was 90°, 135° hook shape and C-T was triangular shape. Transverse steel of these specimens were distributed near both faces of the wall section by 80mm. Specimen C-NT with hollow ratio 0.7 was arranged cross tie of triangular shape. Amount of outside transverse steel was arranged equal to specimens C-L and C-T of 80mm. But, amount of inside transverse steel was differently arranged. The spacing of inside transverse steel of C-NT was 400mm. Three specimens showed similar load-displacement behavior. Damaged region of inside face wall did not occur in C-T and C-NT. Spalling of inside face wall of specimen C-L was occurred. Ultimate displacement was a little different too. Displacement ductility factor of Specimen C-T and C-NT were 5.9, respectively, which were greater than 4.7 of C-L. Because, longitudinal steel was occurred buckling, existing reinforcement detail of 90°, 135° hook shape was due to occur opening the hook of 90°.

Specimen R-L and R-NT were rectangular section. Specimens R-L and R-NT with hollow ratio 0.5 equaled to amount of outside transverse steel of 80mm. But, shape of crosstie and amount of inside transverse steel were different. These specimens showed similar load-displacement behavior and damaged region of inside face wall did not occur too. Because, these specimens were flexure controlled section. Displacement ductility factor similarly appeared by 6.1 and 5.9. Fig. 11 compares the test result of C-L, C-T, C-NT, R-L and R-NT.



(a)



(b)

Fig. 11 Envelop of load-displacement curves: (a) Circular section; (b) Rectangular section

V. CONCLUSION

Three studies was conducted quasi-static test of hollow reinforced concrete bridge piers. Specimens were total 18EA. Based on this test result, conclusion of these studies was following:

1) The experimental results showed that failure behavior of circular hollow RC bridge pier was referable to the location of the neutral axis at failure. When the neutral axis was located inside the wall section, i.e. between the inside face and outside face of the wall, the inside face of the wall did not show any damages and the columns showed very ductile behavior. The section with this type of failure mode may be called "flexure-controlled section". However, if the neutral axis was located inside the hollow, i.e. the depth of the neutral axis was greater than the wall thickness, relatively brittle failure was observed due to the concrete crushing and spalling of the inside face of the circular wall. The section with this type of failure mode may be called "compression-controlled section".
2) The circular hollow piers with the flexural controlled section showed similar failure behavior to that of the solid circular pier. And failure of inside face wall did not occur.
3) The circular hollow piers with the compression controlled section, the damaged region of the inside wall face became

decreased as the amount of transverse steel near the inside face increased. But, inside transverse steel did not influence on displacement ductility factor.

4) The circular hollow piers with the compression controlled section, if outside transverse steel increased, displacement ductility factor was increased too.
5) Shape of triangular cross tie for developed technology of hollow bridge pier in hollow RC piers appeared similar failure behavior as compared with existing reinforcement detail of 90°, 135° hook shape in hollow RC piers.
6) Next study for rectangular hollow RC bridge pier will conduct.

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