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Seismic performance of hollow reinforced concrete columns under cyclic pure torsional loading

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ABSTRACT

This study aims for clarifying the torsional performance of hollow RC columns subjected to cyclic torsional loading. The experiments of the hollow RC columns with 400×400mm cross-section and 1600mm length were conducted under pure torsion. Two types of wall thickness (60mm and 100mm) and two types of pitch of hoop ties (30mm and 60mm) were prepared. These results are also compared to those of solid cross section columns. The pure torsional hysteresis curves, the torsional skeletons, and the failure mechanism are shown and the effects of thicknesses and pitch of hoop ties are clarified.

1. INTRODUCTION

The structural members subjected to large torsional loading, i.e. arch libs in arch bridges and L-shape pier, are increasing with the construction of long span bridges and the shortage of available area as shown in Photo 1. The strengths and rigidities of the members subjected to bending loadings, shear loadings and torsional loadings at the same time decline compared to those of the members under pure bending, pure shear and pure torsion loading condition. However, in general earthquake response analyses, the equivalent linear analyses are only conducted. In these analyses, the torsional rigidities are assumed to be nearly 0.1 times of the initial rigidities. The interaction curves between bending and torsion and the torsional nonlinearity aren't considered severely. Therefore, it isn't confirmed that these affect the response of bridges subjected to the motion of earthquake. It is because the torsional performance isn't clarified sufficiently.

For these reasons, the experiments were conducted under pure torsion or combined loading and the failure mechanism and load bearing mechanism were clarified in previous studies. Moreover, the pure torsional skeletons and the interaction curves between torsion and bending were proposed for torsional nonlinear dynamic analyses. Further, the torsional nonlinear dynamic analyses and the equivalent linear analyses were conducted for the RC arch bridge, and the equivalent linear analyses evaluated the torsional moment occurred at arch lib smaller compared to the torsional nonlinear dynamic analyses. However, these study based on the results of the members with solid section and weren't confirmed the applicability for the members with other section.

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Photo 1 RC arch bridge

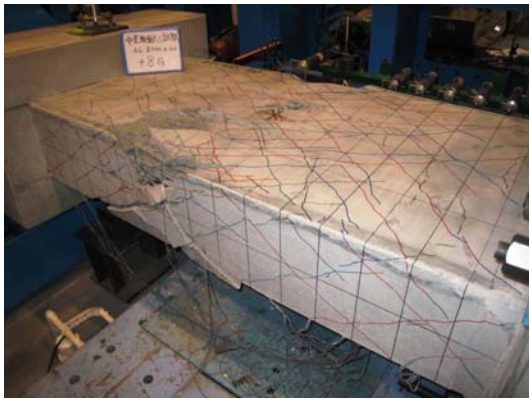


Photo 2 The 3-hollow specimen under pure torsion

From the above, the experiences of 1-hollow columns were conducted under pure torsional loading. The experiments of the hollow members had been conducted under pure torsion in our lab previously as shown in Photo. 2. 3-hollow girders considered as RC arch libs under pure torsional loading and combined loadings had been conducted and the pure torsional skeletons, the interaction curves between torsional and bending loading, the stiffening effect for torsional loading and the converting the amount of CFS (carbon fiber sheet) to that of hoop ties had been clarified. However, the experiences of hollow members are very few compared to that of solid members and seismic torsional performance of the hollow members isn’t clarified currently. Therefore, the experiments of 4 one-hollow RC columns were conducted under axial forces and pure torsion. In these tests, the hysteresis curves, the torsional skeletons, the distribution of cracks and the failure mechanism were clarified before the applicability of the proposal skeletons and interaction curves based on the previous experiments for members with other sections is confirmed. Two types of wall thickness (60mm and 100mm) and pitch of hoop ties (30mm and 60mm) were prepared.

2. TEST MODELS AND TEST CASES

Photo 3 shows the photo of test specimen and Fig. 1 shows the position of the strain gauge in cross section of test specimen. The hollow RC columns had 400×400mm cross-section, 1600mm length, and footings at top and bottom. The target compressive strength of concrete was 40N/mm^2. The main rebars and the hoop ties were deformed bars. Main rebars were used D13 and hoop ties were used D6. The yielding stress of the main rebars and the hoop ties was 295N/mm^2.

Table 1 shows the test case and material test results. In this study, two types of wall thickness (60mm and 100mm) and pitch of hoop ties (30mm and 60mm) were prepared. In this study, these results were also compared to those of solid RC columns conducted previously as shown in table 1. In cyclic loading, the first loop loading was subjected up to the crack occurrence and the second loop loading was subjected up to the torsional yield. Here, torsional yield was defined as the declination of the initial rigidity and the previous study clarified that the torsional yield happened in the cracks development reaching to the center of cross-section. After the torsional yield, the cyclic loadings were subjected step by step using integer times of the angle of twist at the torsional yield. The axial force was set to be 10% of target compressive strength of concrete.

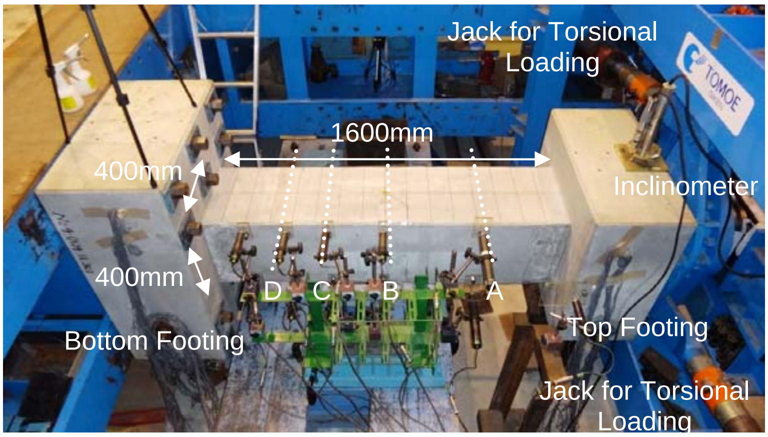


Photo 3 Test specimen and test setup

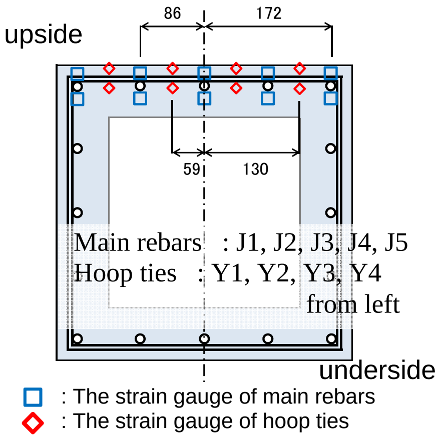


Fig. 1 The position of strain gauges

Table 1 The test cases and the material test results

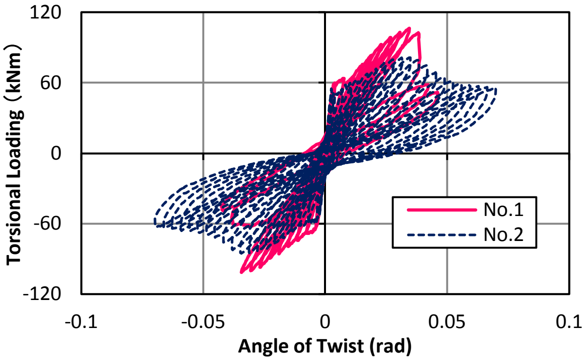
Parameters	No.1	No.2	No.3	No.4	No.5 (C/W)	No.6(C/W)
Cross Sections	Hollow				Solid	
Axial Force (%)	10					
Thicknesses (mm)	60		100			
Pitch of Hoop Ties (mm)	30	60	30	60	30	60
Raitio of Main Rebars (%)	2.48	2.48	1.69	1.69	1.27	1.27
Raitio of Hoop Ties (%)	1.88	0.94	1.28	0.64	0.96	0.48
Compressiv Strength (N/mm^2)	60.3	61.6	57.4	68.7	35.3	45.7
Tensile Strength (N/mm^2)	3.5	3.6	3.4	3.9	4.1	4.2
Elastic Modulus (N/mm^2)	27800	27100	25100	28800	23900	27300

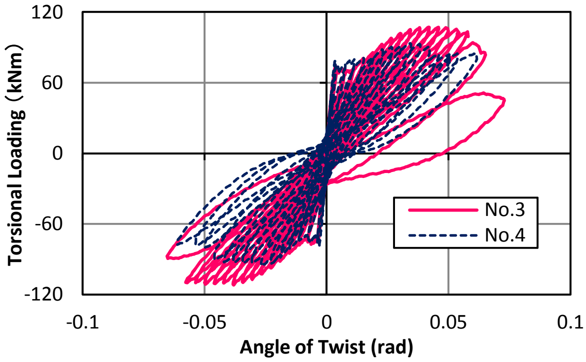
(C/W) The test has been compiled with.

3. TEST RESULTS

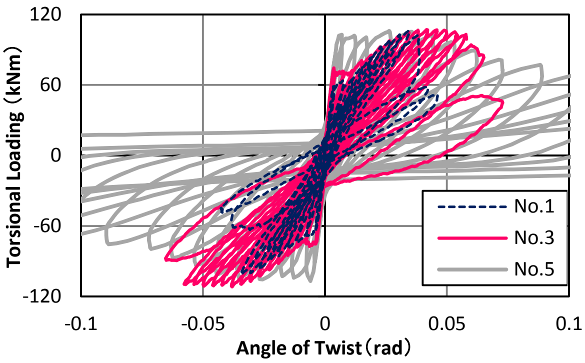
3.1 Torsional Hysteresis Curves and Torsional Skeletons

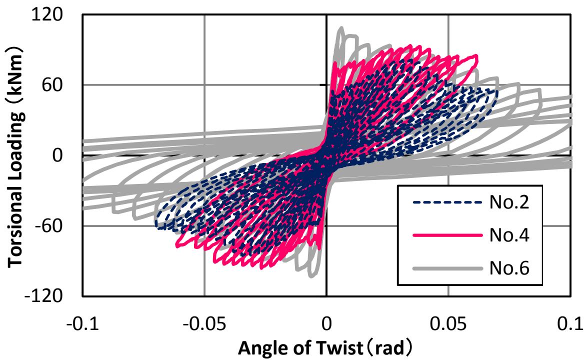
In the torsional hysteresis curves, torsional loading was calculated based on loadings measured by load cells on two jacks for torsion as shown in Photo 3. The angle of twist was measured by the inclinometer on the top footing. Fig. 2 shows the comparisons of the torsional hysteresis curves. Fig. 3 shows the comparisons of the torsional skeletons in the test cases with same pitches of hoop ties. Here, the torsional skeletons show the line connecting the crack point, the torsional yielding point and the maximum strength point. In all specimens with hollow sections, the existences of the torsional yielding point were confirmed as well as the specimens with solid sections.





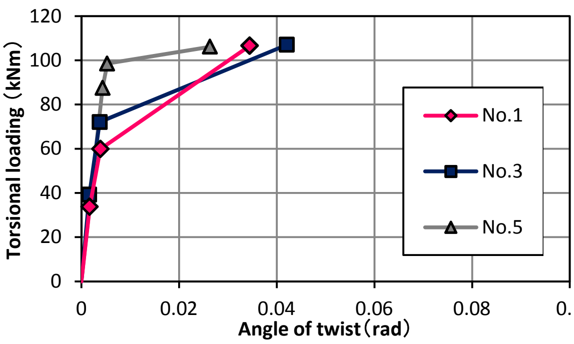
(a) Thickness 60mm (b) Thickness 100mm

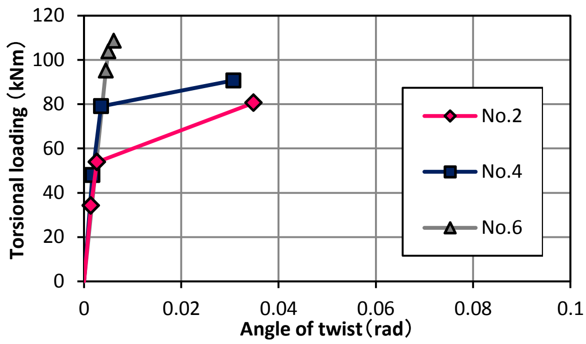




(c) 30mm pitch of hoop ties (d) 60mm pitch of hoop ties

Fig. 2 Torsional hysteresis curves





(a) 30mm pitch of hoop ties (b) 60mm pitch of hoop ties

Fig. 3 Torsional skeletons

In Fig. 2(a) and (b), compared to the torsional hysteresis curves of the hollow RC columns with same thickness, the initial rigidities were almost same and the rigidities after the torsional yield were higher in the cases of 30mm pitch of hoop ties than those of 60mm pitch of hoop ties. However, the rigidities after maximum strength of 30mm pitch of hoop ties were lower compared to that of 60mm pitch of hoop ties. This tendency of hollow RC columns was different from that of solid RC columns.

Compared to the torsional hysteresis curves of the hollow RC columns with same pitch of hoop ties, the initial rigidities were almost same. Also, in Fig. 2(c) and (d), the thicker the thicknesses were, the lower the rigidities after the torsional yielding were, and the larger the rigidities after the maximum strength were.

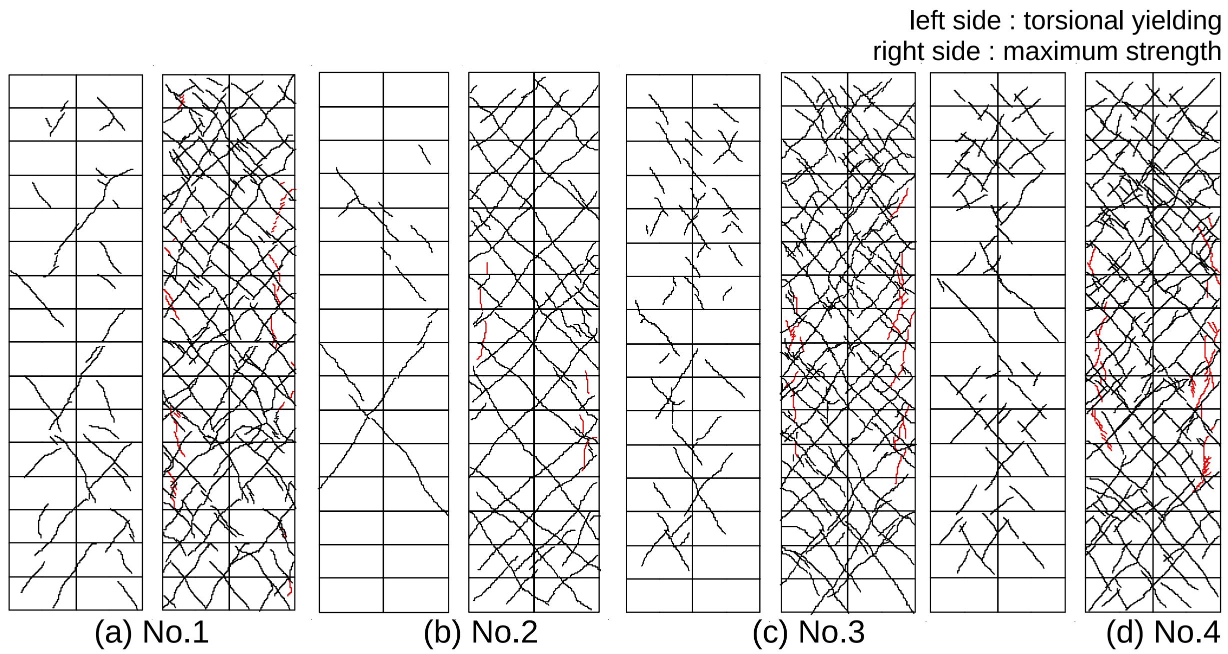


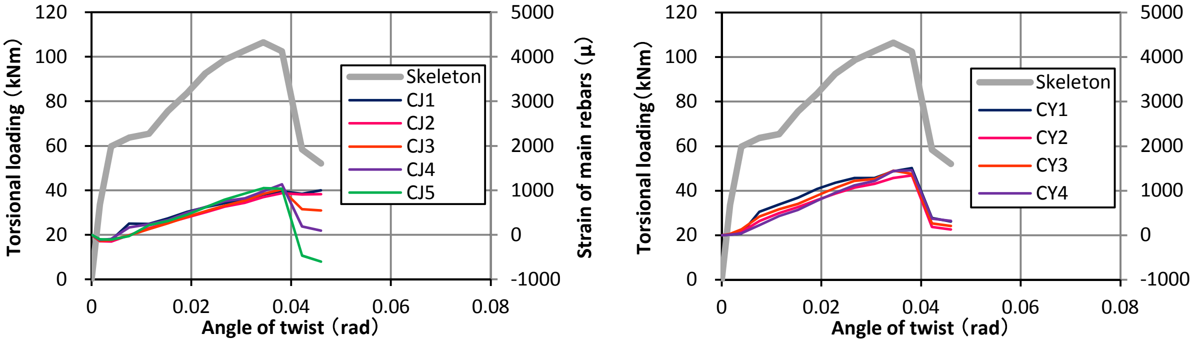
Fig. 4 Distribution of cracks

Compared the torsional skeletons of hollow and solid columns with same pitch of hoop ties, the thicker the thicknesses were, the larger the crack strength and the torsional yield strength as shown in Fig. 3. In the cases of test specimens with solid sections, the torsional yield strength were nearly 1.15 times of the crack strength, but the torsional yielding strength of all specimens with hollow sections were larger than 1.50 times of the crack strength. In particular, the torsional yielding strength of No.3 specimens was 1.84 times of the crack strength. The maximum strengths in the all cases of 30mm pitch of hoop ties were almost same. In the cases of 60mm pitch of hoop ties, the maximum strength of the test specimen with solid section was largest. On the other hand, in Fig. 3, the pitch of hoop ties didn't affect the crack strength and the torsional yield strength, but the maximum strengths of the test specimens of 30mm pitch of hoop ties were larger than those of 60mm pitch of hoop ties.

3.2 Distribution of Cracks

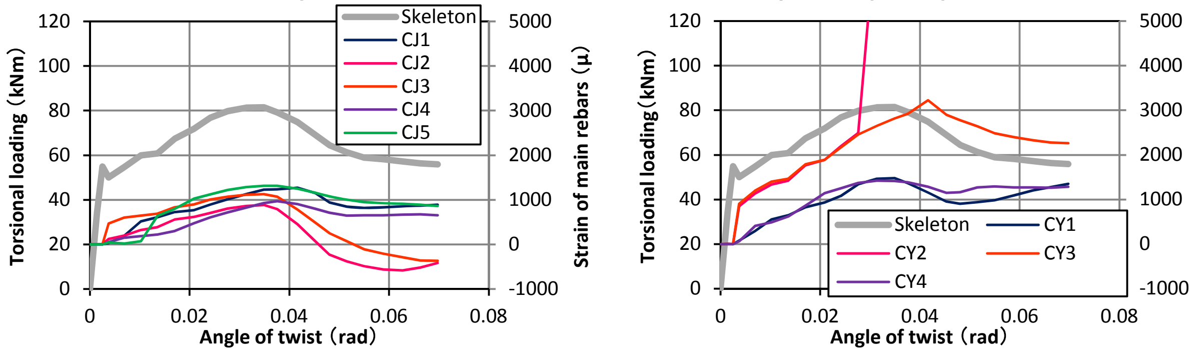
Fig. 4 shows the distribution of cracks in the loop of torsional yielding and the maximum strength. In all test cases, the diagonal cracks occurred from the center of columns surface at first. Because of effect of axial forces, the crack angles to the axis of the members were smaller than 45 degree. In the distribution at torsional yielding, the cracks of the test cases of 100mm thickness were more dominant in the center of column surface than that of 60mm thickness as shown in Fig. 4. Also, the number of the cracks increased and the cracks were distributed when the hoop ties were increased.

The cracks in maximum strength developed to the corners of section and the number of cracks and the width was extended compared to the distribution of the cracks in torsional yielding. Also, the axial cracks described by red lines in Fig. 4 occurred just before maximum strength and they were confirmed along the main rebars arranged at the corner of the section.



(a) Strain of main rebars (b) Strain of hoop ties

Fig. 5 Strain of main rebars and hoop ties (No.1)



(a) Strain of main rebars (b) Strain of hoop ties

Fig. 6 Strain of main rebars and hoop ties (No.2)

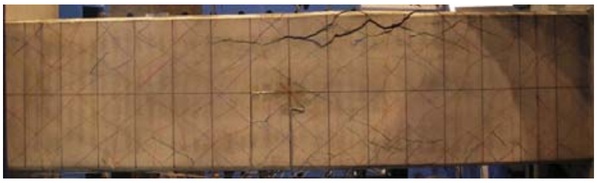
3.3 Strain of Main Rebars and Hoop Ties

When these tests were conducted, in every section (from A to D) shown in Photo 3, the strain gauges were pasted to 10 points on the main rebars and 8 points on the hoop ties. The yielding strain of main rebars (Diameter: 13mm) was 2095μ and that of hoop ties was 1950μ.

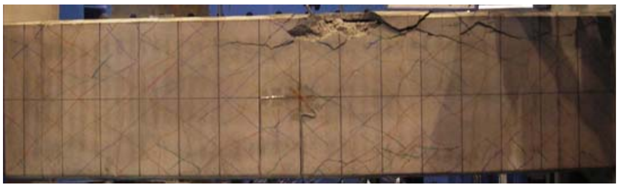
Fig. 5 and Fig. 6 show the strain of main rebars and hoop ties of the maximum angle of twist in the every loading loop. In Fig. 5 and 6, the torsional skeletons were also described. Fig. 5 shows the strain in No.1 specimen and Fig.6 shows the strain in No.2 specimen. The strains at the C section in Photo 3 were used because the axial cracks developed and the cover concrete peeled at the C section as shown in Fig. 4. The strain of main rebars decreased because of axial forces and didn't change before torsional yielding. After the torsional yielding, the strain increased equally in all main rebars. The strain distributed in the section after the maximum strength. In particular, the compressive strain occurred intentionally on the main rebar arranged at the corner of section (CJ5). The steel yielding weren’t confirmed in any main rebars.

The strains of hoop ties were almost 0 before the torsional yielding, but they increased equally in any hoop ties after the torsional yielding as well as main rebars. However, the strains decreased after the maximum strength. In Fig. 6 (b), the strains of CY2 and CY3 were different from those of CY1 and CY4 because the hoop ties arranged No.2 specimen were few and the strain of hoop ties directly under every crack was easy to increase. In the specimens prepared 60mm pitch of hoop ties, the yielding of hoop ties were confirmed at the C section in No.2 and the D section in No.4. On the other hand, in the specimens prepared 30mm pitch of hoop ties, the yielding of hoop ties wasn’t confirmed.

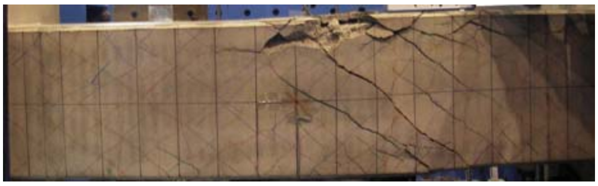
(a) the occurrence of the axial cracks



(b) the development of the axial cracks



(c) the peeling of cover concrete



(d) the converting to skew bending

Photo 4 The failure mechanism in No.1 specimen

4. CONSIDERATION OF TORSIONAL FAILURE MECHANISM

It is considered that the concretes mainly bore the torsional loadings because the strains of main rebars and hoop ties didn’t change before the torsional yielding as well as the specimens with solid section. For this reason, the thicker the thickness was, the larger the effective area of the concrete. The crack strengths and the torsional yielding strengths also improved. In addition, it is the same reason that the pitch of hoop ties didn’t affect the crack strength and the torsional strength.

After the torsional yielding, it is considered that the concrete and the rebars bore the torsional loading because the strains of main rebars and hoop ties began to increase. Also, the columns bore the torsional loadings by forming the space truss because the strains of the main rebars and hoop ties equally increased in all bars.

Before the maximum strength, the axial cracks along the main rebars arranged at the corner occurred and developed as shown in Fig. 5 and Fig. 6. The axial cracks were confirmed in all test specimens. The axial cracks were similar to the cracks due to bond splitting, which were confirmed under shear loading generally. The cracks due to bond splitting were known the strength decreased rapidly because of disappearance of bond of concrete and bars. The occurrence of the cracks only along the main rebars arranged the corner of the section was considered that the cracks occurred at the edge of the main rebars and connected to the other cracks along the sequence of main rebars. Connecting the axial cracks to the diagonal cracks depend on the torsional loadings encouraged to occur the peeling of cover concrete as shown in Photo 4. The peeling of cover concrete reduced the effective area of concrete for torsional loading and the concrete located at the section peeled cover concrete decreased strain locally. As results of these, compressive failure of concrete occurred and the columns showed the brittle failure. It is considered that the No.1 and No.3 specimens showed brittle failure because the effective area of concrete decreased despite the specimens had hollow sections. In particular, the effect was largest in No.1 specimen (60mm thickness) compared to the other specimens. On the other hand, in No.2 and No.4 specimens, the steel yielding of hoop ties were confirmed before compressive failure of concrete. For this reason, the torsional deformation concentrated in hoop ties and their columns showed toughness failure compared to No.1 and No.3 specimens.

In Fig. 5(a) and Fig. 6(a), the strains of main rebars in the C section confirmed the peeling of cover concrete showed the linear distribution considered the center of column surface as the origin after the maximum strength. For this reason, it is considered that the load bearing mechanism transitioned from the form of space truss to that of skew bending.

From the above, if the hollow section were selected as the section of members, maximum strength can be improved by increasing the thickness. Moreover, the crack strength and the torsional yielding strength of columns with hollow section were lower than that with solid section and the maximum strengths were almost same. However, in the case of low thickness, the effect of the development of the axial cracks and the peeling of cover concrete due to axial cracks is pronounced. The peeling of cover concrete may make the column brittle failure due to compressive failure of concrete. In terms of toughness, it is desirable to make the wall of hollow section thick sufficiently.

5. CONCLUSIONS

The following remarks can be made as conclusion of this study.

1) The torsional yielding could be confirmed in the columns with hollow section as well
as that with solid section.
2) The thickness of wall of hollow column affected the crack strength, the torsional yielding strength and the toughness after the maximum strength.
3) The load bearing mechanism changed form of space truss to form of skew bending
due to the peeling of cover concrete.
4) The columns with hollow section tend to show the brittle failure despite same amount
of main rebars and hoop ties compared to that with solid section. The effect on the
failure mode of the peeling of cover concrete in hollow column was larger

because the original effective concrete in hollow column was smaller than the one in solid column.

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