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ELASTIC-PLASTIC BEHAVIOR OF REINFORCED CONCRETE COLUMN-STEEL BEAM JOINTS UNDER BI-DIRECTIONAL LOADING

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SUMMARY

To clarify elastic-plastic behaviors of exterior steel beam-reinforced concrete column joints under bi-directional loading, six one-thirds scale three-dimensional exterior subassemblages were tested.
The experimental variables are lateral loading directions to the principal axis x of the column cross section and applied axial load ratio to the compressive strength of the column. The loading directions are 0°, 22.5° and 45°. The axial load ratio is 0 and 0.2.
The specimens were designed so that the beam yielding and the shear failure of beam-column joints do not occur.
The cyclic load was applied at the top of the column with increasing displacement amplitudes while keeping a constant axial load in the columns.
As a conclusion, for each specimen, concrete crushing on the upper and bottom flanges of the embedded beams was remarkable. No significant strength degradation was observed after the specimens reached its maximum strength and the hysteretic response was stable, although the hysteretic responses showed the reversed S-shape with small energy dissipation. The initial stiffness and the maximum strength acting about x axis increased with the axial load ratio but decreased with the loading direction. The maximum load acting about x axis of the specimens loaded in 45° direction were seriously reduced in compare with that of the specimens loaded in 0° direction.

INTRODUCTION

To develop composite structural systems composed of reinforced concrete columns and steel beams, many kinds of details on steel beam-reinforced concrete column joints were proposed in Japan, and many experimental studies using steel beam-reinforced concrete column subassemblages have been conducted to make sure of seismic performance of the joint. However, these previous studies were mainly focused on planar beam-column joints. Accordingly, little information on the characteristics of beam-column joints under bi-directional loading is available.
From this point of view, the objective of this study is to clarify elastic-plastic behaviors of the three-dimensional exterior beam-column joints under bi-directional loading experimentally.

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EXPERIMENT

Six one-thirds scale three-dimensional exterior beam-column subassemblages were tested. The overall dimensions of the specimens, the cross sections and reinforcement details are shown in Fig.1. For all specimens, the distance between inflection points of column is 1,350 mm, and that of beam is 2,100 mm. The reinforced concrete column section is 300 mm square. The main longitudinal reinforcing bars of twelve deformed bars with a nominal diameter of 16 mm (D16 in Japan practice) were arranged symmetrically around the perimeter. The transverse reinforcing bars have a nominal diameter of 6 mm (D6 in Japan practice), and transverse reinforcement ratio p_w was 0.85%. The steel beam is built-up and has flange widths of 100 mm and depths of 250 mm. The flanges of the steel beams are continuous through the columns (through beam type). To increase the shear strength of the joints, the steel web panel with a thickness of 19 mm was used. The transverse reinforcing bars in the joints with a nominal diameter of 6 mm were arranged at a spacing 40 mm, and the transverse reinforcement ratio p_w was 0.53%. The specimens were designed so that the beam yielding and the shear failure of beam-column joints do not

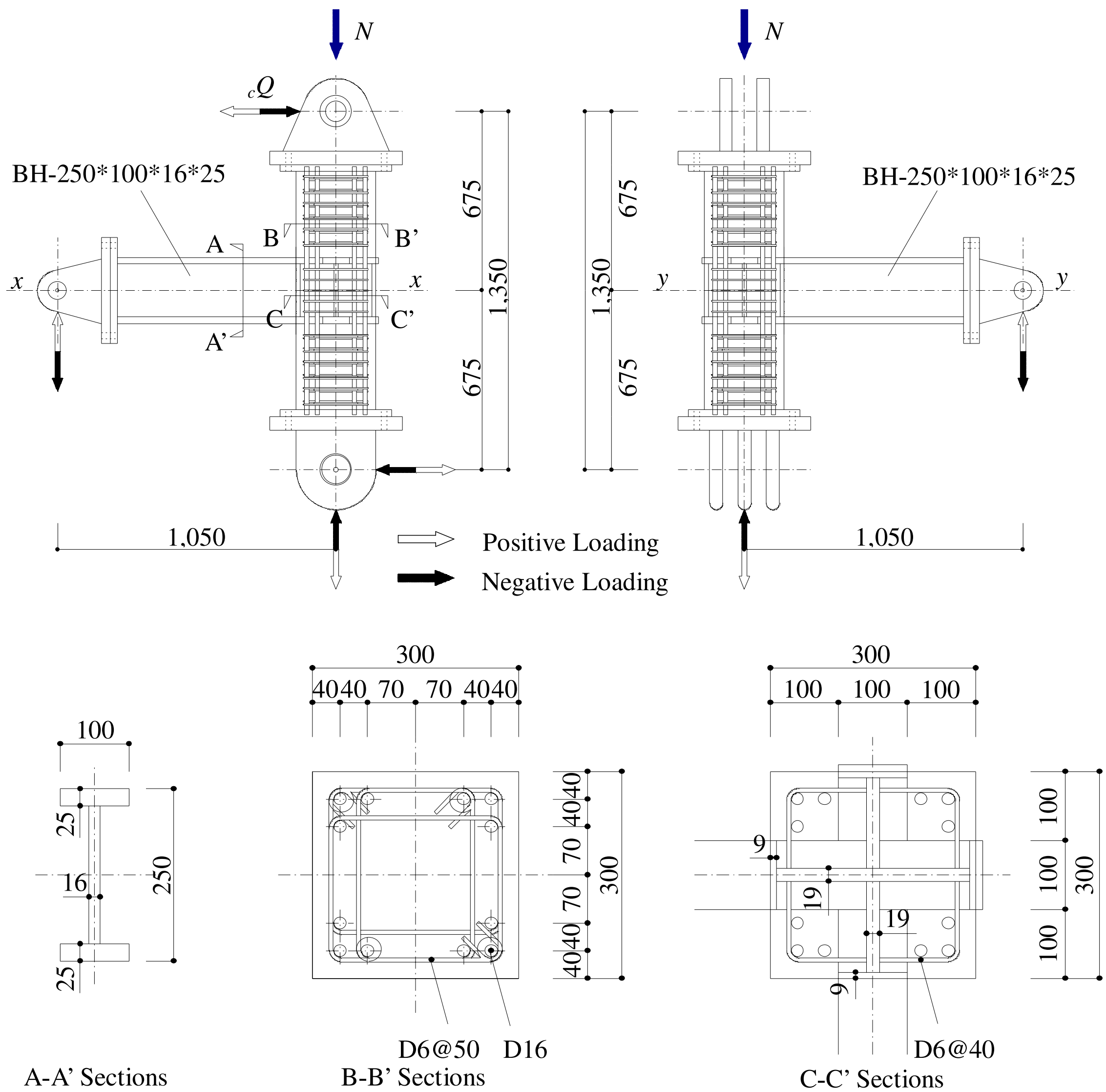


Fig.1 Overall dimensions of specimen, cross sections and reinforcement details

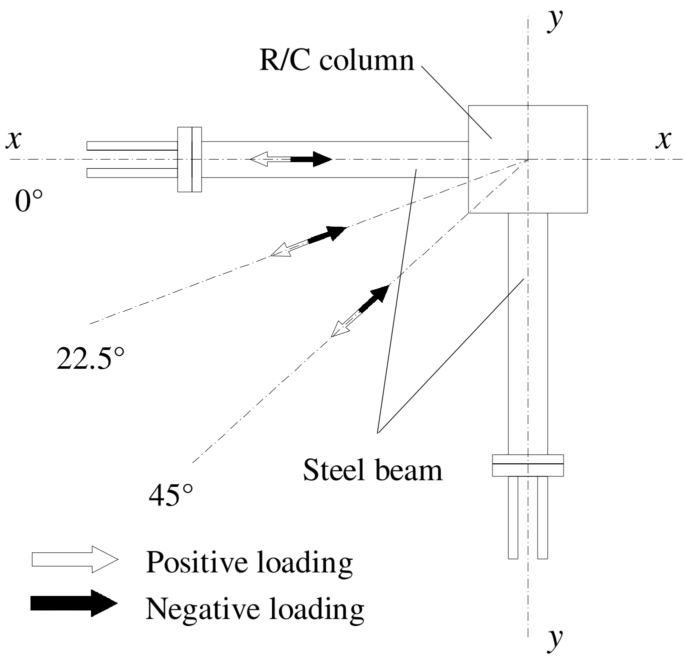


Fig.2 Loading condition

Table.1 Properties of test specimens

		BDL0	BDL0+2	BDL225	BDL225+2	BDL45	BDL45+2
RC Column	Cross Section	300×300 mm					
	Longitudinal Reinforcement	SD345 12-D16 p_g = 2.65 %					
	Transverse Reinforcement	SD295 4-D6@50 p_w = 0.85 %					
	Concrete Strength	F_c = 27 N/mm^2					
	Applied Axial Load	0	556 kN	0	556 kN	0	556 kN
S Beam	Cross Section	SM490 BH-250×100×16×25					
Joint	Web panel	SS400 PL19					
	Transverse Reinforcement	SD295 2-D6@40 p_w = 0.53 %					
	Face Bearing Plate	SM490 PL9					
Loading direction θ		0°		22.5°		45°	

occur. The ratio M_c / M_b of the flexural strength M_c of the column with axial loads to that M_b of the steel beam is 1.38. Therefore, it is expected that bearing failure on the upper controls failure mode of the specimens and bottom flanges of the embedded steel beam. The experimental variables are lateral loading directions to the principal axis x of the reinforced concrete column cross section and the axial load applied to the column.

The loading directions θ are 0, 22.5° and 45° as shown in Fig.2. In BDL series, an axial column load is not applied. In addition, applied axial column load in BDL+ series is 556 kN, which corresponds to 20 % of ultimate compressive strength of the reinforced concrete column. The magnitude of axial load is corresponding to compressive stress level for exterior column of the lowest story in a moment resisting frame structure of about ten stories. The properties of test specimens and the mechanical properties of materials are listed in Table 1 and Table 2, respectively.

The test set-up and loading system is shown in Fig.3. The cyclic load is applied at the top of the column with increasing displacement amplitudes while keeping a constant axial load in the columns. The loading scheme of specimens loaded in 45° direction is shown in Fig.4. The loading is controlled by drift angle R

Table.2 Mechanical Properties of materials

Materials \ Stress			σ_y (N/mm^2)	σ_u (N/mm^2)	E_s (N/mm^2)
Steel	PL9	(SM490)	349	534	2.10×10^5
	PL16		376	538	2.07×10^5
	PL25		350	526	2.08×10^5
	PL19	(SS400)	265	418	2.07×10^5
Reinfoecing Bars	D16	(SD345)	409	591	1.80×10^5
	D6	(SD295)	310	492	1.67×10^5
Concrete		note	σ_B (N/mm^2)	F_t (N/mm^2)	E_c (N/mm^2)
		1)	29.3	2.87	2.39×10^4
		2)	30.9	1.82	2.44×10^4

*) 1: Values used for Specimen BDL Series

2: Values used for Specimen BDL+ Series

σ_y : Yield Stress

σ_u : Maximum Strength

σ_B : Compressive Strength

F_t : Splitting Strength

E_s, E_c : Yang's Modules Steel and Concrete, respectively

Fig.3 Test set-up

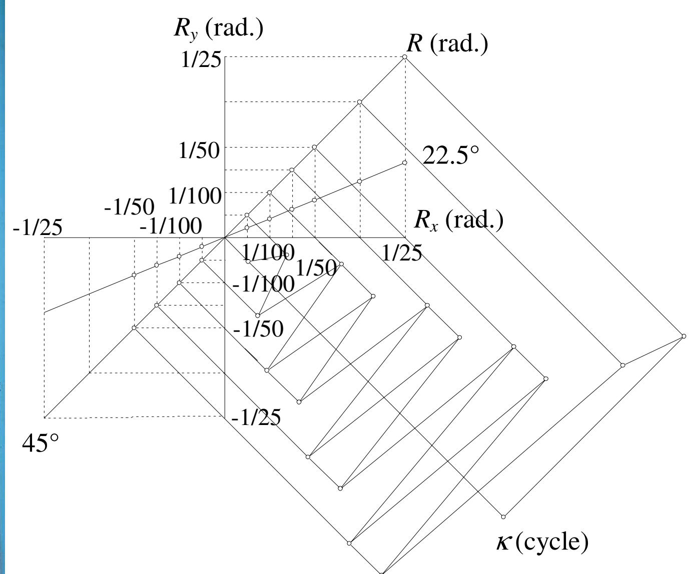


Fig.4 Loading scheme

at the top of column. As shown in Fig.4, The drift angle R is defined so that the drift angle R_x about x axis agrees with that of the specimens loaded in 0° direction.

TEST RESULTS

Typical Cracks and Damage Progression

For specimens loaded in 0 and 45° directions, a detailed review of the sequence and progression of cracking or damage are shown in Fig.5. For each specimen, the failure is characterized by severe concrete crushing between the concrete column and steel beam. And vertical cracks which initiate from the corners of the steel beams were remarkably observed. These cracks are caused by bearing stresses above and

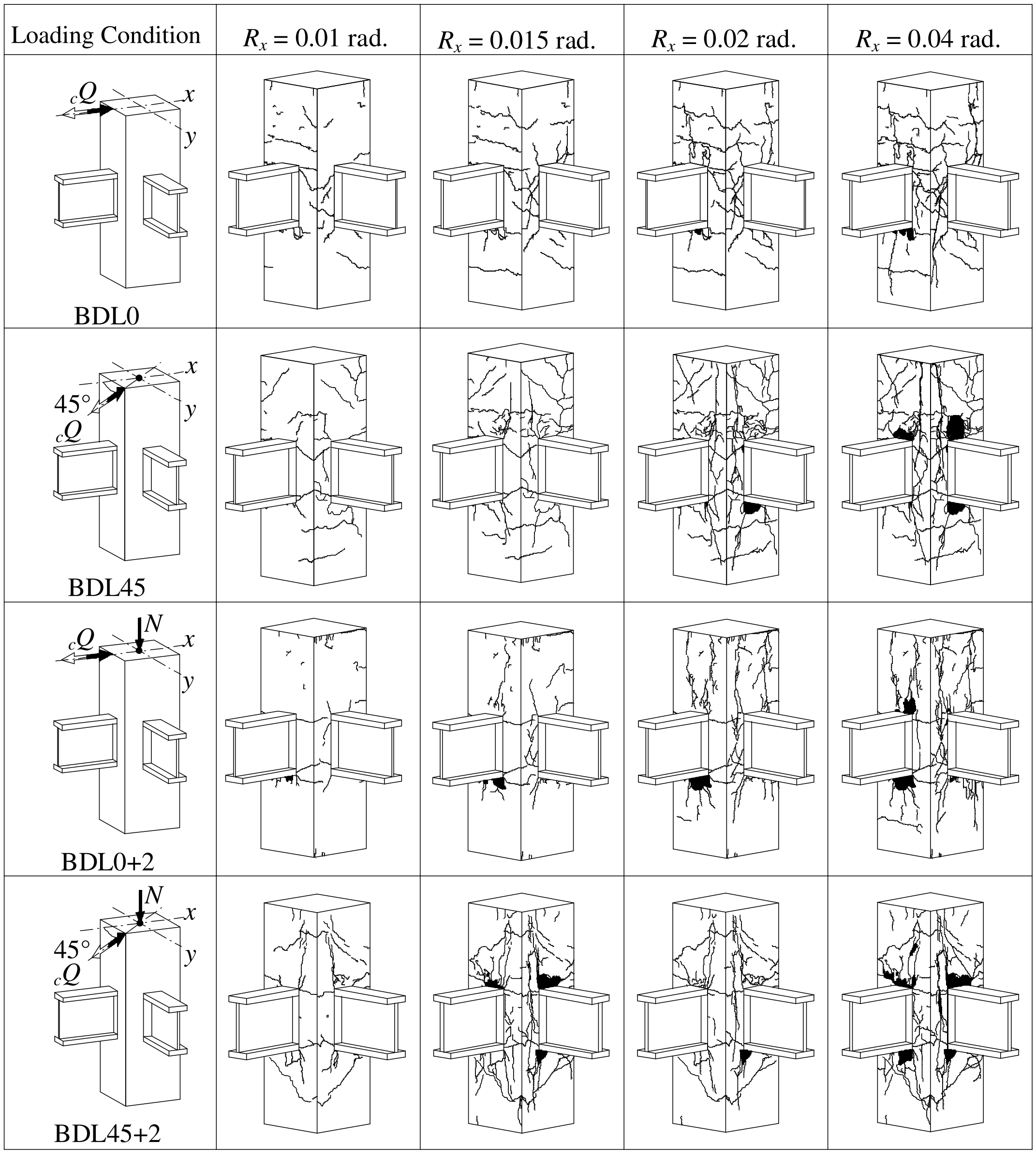
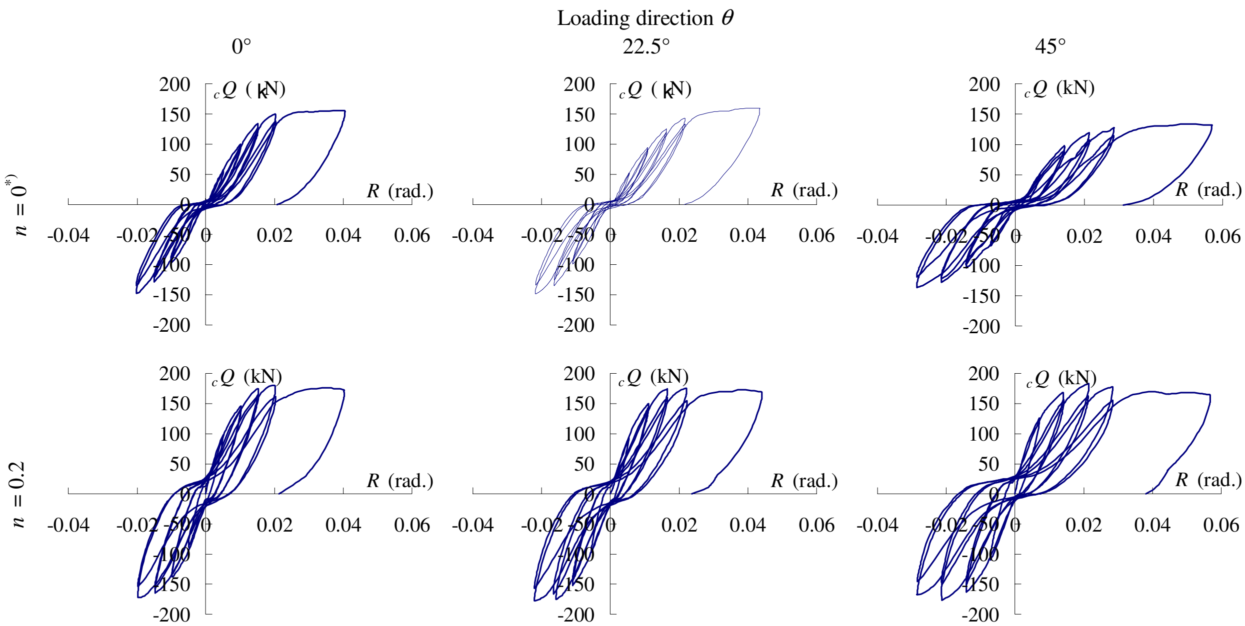


Fig.5 Sequence and progression of cracking

below the steel beam. In the case of specimens without the axial column load, at the cycle of R=0.015 rad., concrete crushing and vertical cracks were observed. In subsequent loading, the vertical cracks were progressed to bond splitting cracks along the longitudinal reinforcing bars. In the case of specimens with axial column load, concrete crushing between concrete column and steel beam occurred at early loading cycle (R=0.005 rad.) in compare with the specimens without axial column load. However, in spite of these differences, there were many similarities in the progression of cracking. Generally, the more severe cracking was observed with axial column load and loading direction.

Hysteretic Response

The relationships between the applied lateral load and drift angle at the top of the column are shown in Fig.6. The vertical axis represents the applied lateral load $_cQ$. P-Δ effect derived from the applied axial load is considered in the applied lateral load $_cQ$. Horizontal axis gives the drift angle R. For each specimen, although slight pinching was observed during initial loading cycles, the overall behavior was



n: axial load ratio to the compressive strength of the column

Fig.6 Hysteretic Responses

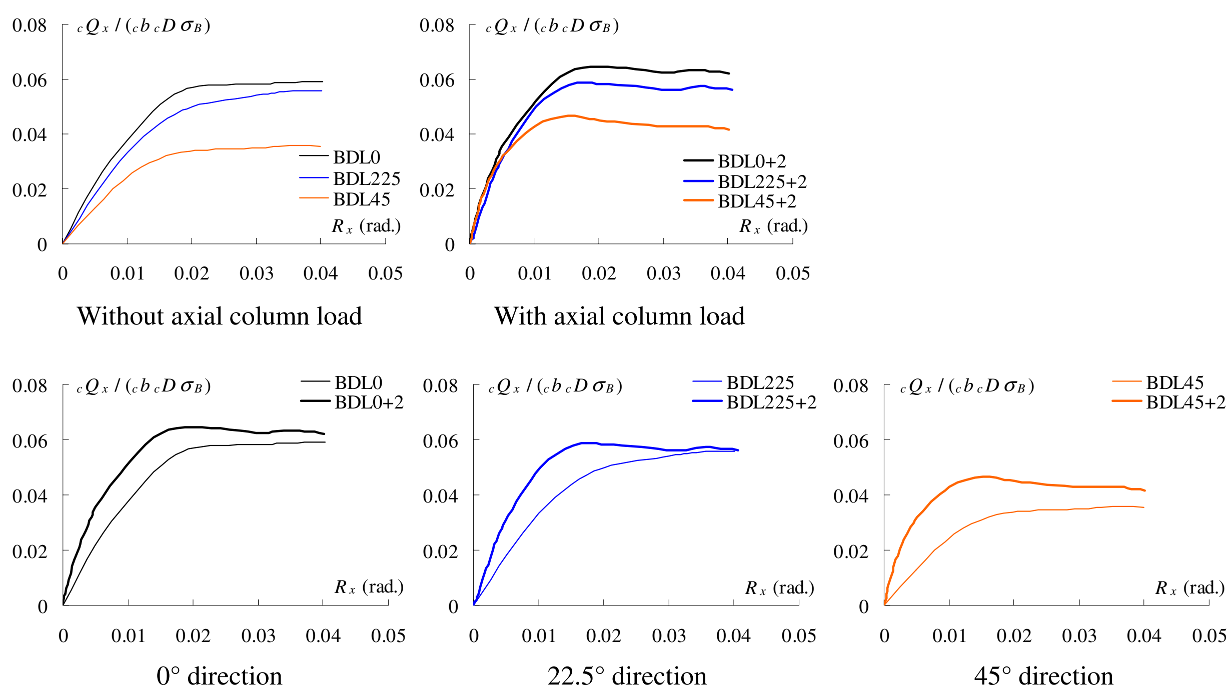


Fig.7 Skeleton curves for hysteretic response

almost elastic. In subsequent loading, pinching behavior was remarkably observed.

In BDL series, as the loading amplitude increased to *R*=0.015 rad., concrete crushing between the concrete column and steel beam was observed at a column shear of about 120 - 130 kN, which was about 75 - 90 % of the maximum strength. At loading cycle of *R*=0.02 rad., initial tensile yielding of longitudinal reinforcing bars was recorded from strain gauges attached at the level of the upper and below flange of the beam. However, the strength degradation was not seen up to the maximum applied distortion of

R=0.04%.

In BDL+ series, at loading cycle of R=0.005 rad., concrete crushing was observed at a column shear of about 90 kN, which was about 50 % of the maximum strength. However, pinching behavior with the loading cycle was smaller than that of the specimens without axial column load. This is the reason that the applied axial compression load in the column contributes to closing cracks in the column and joint, and the gaps between steel flanges and column concrete. Therefore, the degree of fatness increases. Specimen BDL45+2 reached its maximum strength at R=0.015 rad. and initial tensile yielding of longitudinal reinforcing bars was observed. On the other hand, Specimen BDL0+2 and 225+2 reached its maximum strength at R=0.02 rad., but tensile yielding of longitudinal reinforcing bars was not observed at the final loading amplitude. In addition, for each specimen, no significant strength degradation was observed after specimens reached its maximum strength and the hysteretic response was stable. Note that for loading direction, specimens loaded in 45° direction were seriously reduced stiffness at the loading cycle of R=0.015 rad. compared with the other specimens. One of the reasons for this degradation might be related to the fact that the bond performances in the corners of the column were deteriorated by vertical cracks occurred from the corners of both steel beams. Further, for all specimens, no significant shear yielding occurred in the steel web panel since thick steel panel was used.

Fig.7 shows the skeleton curves for hysteretic responses. The vertical axis represents ${}_cQ_x$ / (${}_cb_cD\sigma_B$), where ${}_cQ_x$ is column shear force acting about x axis, ${}_cb$ and ${}_cD$ are width and depth of column cross section, respectively. Horizontal axis gives the drift angle R_x. In BDL series, it is shown that initial stiffness decreases with the loading direction. However, in BDL+ series, the differences of initial stiffness were not observed regardless of the loading direction. In addition, initial stiffness increases with the axial load ratio regardless of the loading direction.

Maximum Strength

${}_cQ_x$ - ${}_cQ_y$ interaction curves for each axial load level is shown in Fig.8. The vertical and horizontal axis

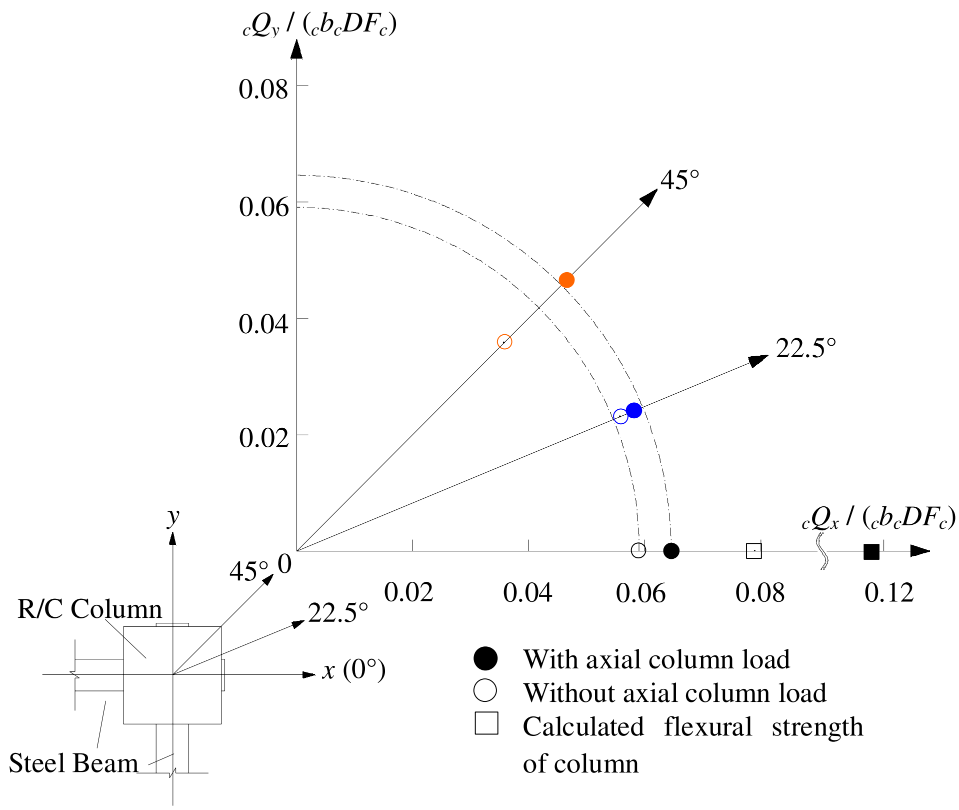


Fig.8 Maximum strength

represents ${}_cQ_y$ / (${}_cb_cD\sigma_B$) and ${}_cQ_x$ / (${}_cb_cD\sigma_B$), respectively. The radius of circular interaction curves correspond to the maximum strength of specimens loaded in 0° direction. The experimental values of specimens loaded in 0° direction are much smaller than the ultimate flexural strength of the column for each axial load level. In addition, considering to crack observations and hysteretic responses mentioned above, it is expected that failure mode of all specimens is controlled by bearing failure. The maximum strength increases with the axial load ratio regardless of the loading direction and corresponds to the circular interaction except Specimen BDL45. The maximum load acting about x axis of the specimens loaded in 22.5° direction is nearly equal to that of the specimens loaded in 0° direction. However, the maximum load of the specimens loaded in 45° direction is seriously reduced.

CONCLUSIONS

From observation of test results, the following conclusions on the elastic-plastic behavior of three-dimensional exterior beam-column subassemblages were obtained;
1) For each specimen, the failure is characterized by concrete crushing between the concrete column and steel beam regardless of the axial column load and the loading direction.
2) No significant strength degradation was observed after the specimens reached its maximum strength and the hysteretic response was stable, although the hysteresis loop showed pinching behavior.
3) The initial stiffness and the maximum load acting about x axis increased with the axial load ratio but decreased with the loading direction.
4) The maximum load acting about x axial of the specimens loaded in 45° direction is seriously reduced.

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