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EFFECTS OF AXIAL FORCE ON DEFORMATION CAPACITY OF STEEL ENCASED REINFORCED CONCRETE BEAM-COLUMNS

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SUMMARY

In this paper, an analytical work has been conducted to investigate the relations of axial force and deformation capacity of steel encased reinforced concrete beam-columns. The analytical model is defined a cantilever beam-column. Several parameters that influence inelastic performance of the beam-columns are investigated; including encased steel area ratios, sectional shapes of the encased steel, material strengths, and shear-span to depth ratios. Parametric study on moment - rotation angle relations of a beam-column under constant axial loading was carried out using idealized hysteretic stress-strain relations and discrete element approach. Analytical results showed that there was a maximum limit of axial force to ensure stable behavior of a steel encased reinforced concrete beam-column when it was subjected to both axial and repeated lateral loading under a constant rotation angle amplitude. The maximum axial force that the beam-column can resist under cyclic lateral loading was defined as stable limit axial force to ensure the required rotation angle amplitude. Analytical results indicate that the stable limit axial load ratio increases as steel strength increases or compressive strength of concrete decreases. The stable limit axial load ratio decreases as encased steel sectional area increases while I-section steel used and it is almost not influenced by steel sectional area while cross-section steel used. Shear-span to depth ratio is found the influential element that affects the stable limit axial load ratio most than other influential elements. Most beam-columns with shear-span to depth ratio 3 can not guarantee 1.0% radian rotation angle even though the limiting value of axial force specified by Standards for Structural Calculation of Steel Reinforced Concrete Structure of Architectural Institute of Japan (1987) is satisfied. Beam-columns with shear-span to depth ratio 5 can satisfy the AIJ Standard axial force limitation while rotation angle of 1.0% required.

INTRODUCTION

Encased steel reinforced concrete composite structures have been widely used in high-rise buildings in Japan. From the structural point of view, this kind of structure possesses structural characteristics of high compressive strength, large ductility and large energy dissipation capacity, and encased steel reinforced concrete composite columns are capable of resisting axial and lateral loading. However axial load ratio (axial load / squash load) of columns at lower stories of a high-rise building increases. High axial load ratio is apt to lead to fragile failure of the structure. Since effects of axial load on columns are great, the Standard for Structural Calculation of Steel Reinforced Concrete Structure (1987) of Architectural Institute of Japan [AIJ, 1987] (abbreviated as AIJ SRC Standard) has prescribed an upper limit of axial compressive load for a column member. However the limitation only guarantees a certain deformation capacity, which is described in terms of drift angle of a story (0.01 radian). A few experimental researches and numerical analyses have been done on elasto-plastic behavior and stable limit axial loads of columns subjected to constant axial load and repeated lateral load [Matsui *et al*. 1989, Li *et al*. 1996]. However, no systematic study on relations of axial force to deformation capacity is conducted by now.

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One objective of this paper is to investigate behavior and stable limit axial load of encased steel reinforced concrete beam-columns, which are subjected to axial and lateral loading condition corresponding to a given constant rotation angle amplitude. Another objective is to discuss the effects of material strength, encased steel area and shape, and shear-span to depth ratio on deformation capacity and stable limit axial load relations of the encased steel reinforced concrete beam-columns.

2. PARAMERICAL ELEMENTS

Elements that will influence the value of stable limit axial force of a composite beam-column are taken into consideration in this analytical work. The influential elements include sectional dimensions of column, encased steel area ratios, sectional shapes of the encased steel, material strengths, and shear-span to depth ratios (*M/QD*). Sections of columns are 800x800 (mm^2) or 1000x1000 (mm^2) squares. Two kinds of encased steel shapes are selected which are illustrated in figure 1, one is an I-section to represent columns at the perimeter of a build (except the corner columns), and the other is a cross-section indicating the internal columns. Yield stresses of encased steel are 324MPa (steel Grade SS400, Japan Industrial Standard) and 440MPa (Grade 60-kilo steel, JIS). Reinforcing steel is using 12 deformed steel bars with diameter of 28 for the columns with cross section 800x800 (mm^2) and 35 for those of cross section 1000x1000 (mm^2) to make the longitudinal reinforcement ratio to 1.0%. Grade SS345 steel is used for the longitudinal reinforcement. Compressive strengths of 29.4 and 58.8MPa are used for concrete. Shear-span to depth ratios of beam-column are 3 and 5. Dimension, encased steel properties, standard compressive strength for concrete (F_c), and yield stresses for structural steel ($_s\sigma_y$) and reinforcing steel ($_m\sigma_y$) of all of the beam-columns analyzed are listed in Table 1.

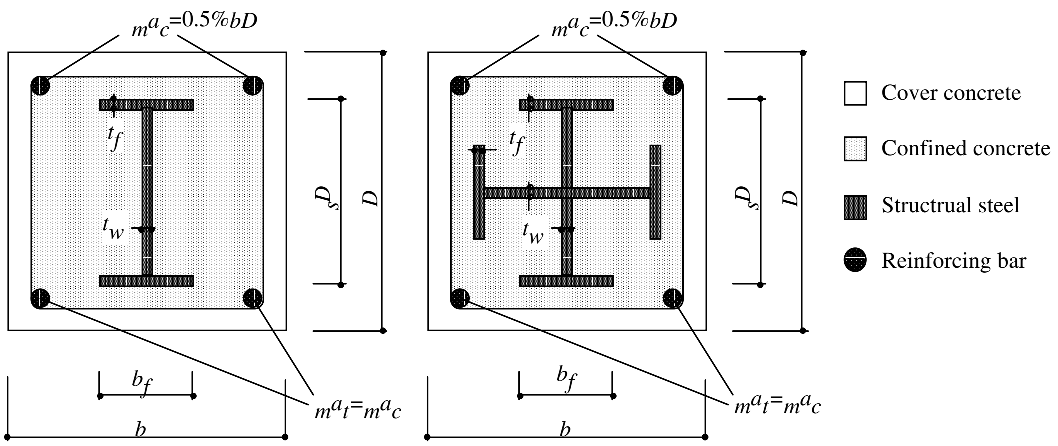

Figure 1 Cross Section of Steel – Concrete Composite Beam-columns

3. METHOD OF SIMULATION

3.1 Analytical Model

A cantilever was selected as analytical model for a encased steel reinforced concrete beam-column. The beam-column is divided into two parts: bending part and rigid part as shown in figure 2. Curvatures (ϕ) of the sections in the bending part are assumed to be uniformly distributed. The curvature, ϕ , can be expressed as follows:

$$\phi = \frac{\delta}{L_p(L - L_p/2)} \tag{1}$$

In which, δ = lateral displacement at the top of the cantilever member, L = length of the cantilever column, and Lp = length of the bending part. On an assumption that the lateral displacement at the member top (δ) is made to coincide with the displacement at the top of an entire elastic cantilever $\{\delta_e = M/(3EI) = \phi L^2/3\}$, the length of the bending part will be led to 0.422 times of the column length, L.

Table 1 Section Details and Material Properties

No. 0	*b* (1)	*D* (2)	steel (3)	*sD* (4)	*bf* (5)	*tw* (6)	*tf* (7)	*sp* (%) (8)	Bars (9)	Material properties (10)
1	800	800	I	492	198	8	12	1.33	12D28	
2	800	800	C	492	198	8	12	2.65	12D28	
3	800	800	B	492	198	16	25	2.65	12D28	
4	800	800	I	500	199	9	16	1.65	12D28	
5	800	800	C	500	199	9	16	3.29	12D28	
6	800	800	B	500	199	19	32	3.28	12D28	Compressive strength
7	800	800	I	512	201	11	22	2.19	12D28	of concrete:
8	800	800	C	512	201	11	22	4.35	12D28	Fc=29.4MPa
9	800	800	B	512	201	28	40	4.40	12D28	58.8MPa
10	800	800	I	518	203	13	25	2.54	12D28	
11	800	800	C	518	203	13	25	5.05	12D28	
12	800	800	I	524	204	14	28	2.81	12D28	
13	800	800	C	524	204	14	28	5.59	12D28	Yield stress of
14	800	800	I	482	300	11	15	2.18	12D28	structural steel:
15	800	800	C	482	300	11	15	4.35	12D28	sσy=323MPa (Grade SS400)
16	800	800	I	494	302	13	21	2.90	12D28	440MPa (Grade 60-kilo
17	800	800	C	494	302	13	21	5.77	12D28	steel)
18	1000	1000	I	412	202	10	19	1.14	12D35	
19	1000	1000	C	412	202	10	19	2.27	12D35	
20	1000	1000	B	412	202	28	31	2.23	12D35	
21	1000	1000	I	598	199	10	16	1.20	12D35	Yield stress of
22	1000	1000	C	598	199	10	16	2.40	12D35	reinforcement:
23	1000	1000	B	598	199	22	30	2.38	12D35	mσy=343MPa (Grade SD345)
24	1000	1000	I	622	203	14	28	1.93	12D35	
25	1000	1000	C	622	203	14	28	3.84	12D35	
26	1000	1000	B	622	300	32	35	3.87	12D35	
27	1000	1000	I	706	201	14	25	1.92	12D35	
28	1000	1000	C	706	201	14	25	3.83	12D35	
29	1000	1000	B	706	201	36	38	3.80	12D35	
30	1000	1000	I	668	303	28	37	3.91	12D35	
31	1000	1000	C	668	203	14	28	3.97	12D35	

(1) *b* : width of column section (mm)
(2) *D* : depth of column member (mm)
(3) steel : shape of encased steel
I: I-section steel
C: Cross-section steel
B: Built-up I-section steel
(4) *sD* : depth of encased steel (mm)
(5) *bf* : width of steel flange (mm)
(6) *tw* : web thickness of encased steel (mm)
(7) *tf* : thickness of steel flange (mm)
(8) *sp* : encased steel area ratio
(9) Bars : longitudinal reinforcement, number of steel bars and its diameter (mm)

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3.2 Stress – Strain Relations

Stress-strain relations used in the analysis are shown in figure 3. A Popovics [1973] stress-strain relationship was basically used for concrete and confinement effect of lateral reinforcement was considered according to the regulations given by Mander [1988]. Confined concrete and cover concrete in a steel – concrete composite section are illustrated in figure 1. A typical elastic-perfectly plastic-strain-hardening model was used for normal strength steel (Grade SD345 reinforcing steel and SS400 structural steel). For high-strength structural steel (Grade 60-kilo steel), AIJ' s [1994] proposed model was used in its stress-strain relation. A Kato [1973] cyclic stress-strain curve was adopted in unload and reload branches for both normal strength steel and high-strength steel.

3.3 Method of Analysis

A strain-compatibility solution was used to generate moment-curvature curve of a beam-column subjected to axial load and cyclic lateral load within a given displacement amplitude. Considering the relationship between the curvature (ϕ) at the bending part and the lateral displacement (δ) at the top of the column (equation 1), flexural moment or hysteresis load - displacement relations could be obtained.

The following assumptions and approach were used to generate the moment-curvature curve for columns:

1) Assumptions:

- a linear strain distribution was assumed,
- there was no slip between the structural steel or reinforcing bars and the surrounding concrete,
- the effects of residual stresses in structural steel were not included,
- the concrete confinement provided by lateral reinforcement was considered,
- buckling of the structural steel and reinforcing steel did not occur

2) Approach:

- the section was discreted into a large number of strips,
- in each strip, stresses in the core, cover, and steel portion were calculated as functions of the strains using the corresponding stress-strain relation curve,
- for a given value of the displacement at the free end of the cantilever and a given applied axial load, the depth of the neutral axis (or the strain of the center of cross section) was iterated to satisfy the equilibrium condition expressed as the formula: $N_{computed} = N_{applied}$,
- the value of the moment corresponding to that curvature and the strain of the center of cross section was then calculated,
- by changing the displacement at the top of the cantilever and repeating the aforementioned procedures, the moment-curvature curve was generated.

3.4 Verification of Analysis

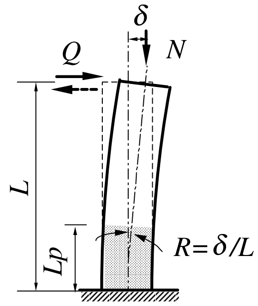


Figure 2 Analytical Model

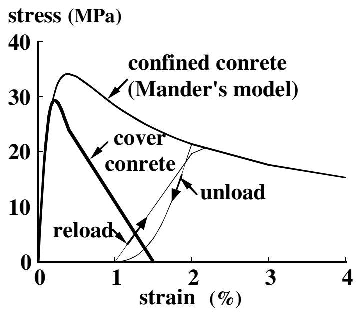
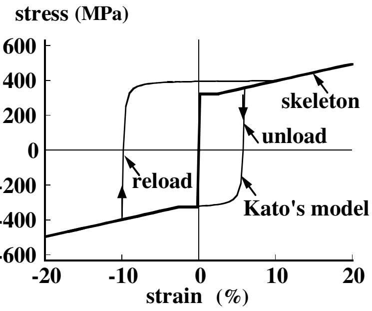
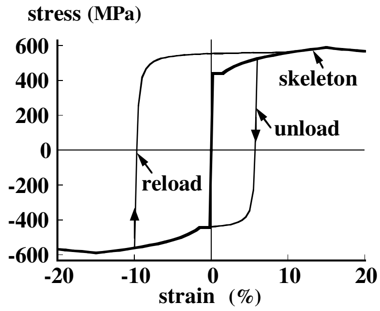


Figure 3 (a) Concrete



(b) Grade SS400 Steel



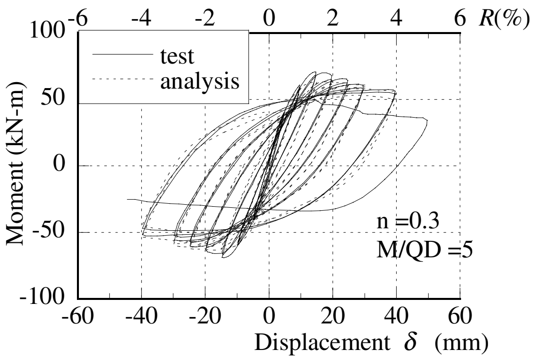
(c) Grade 60-kiro steel

Figure 3 Stress – Strain Relations

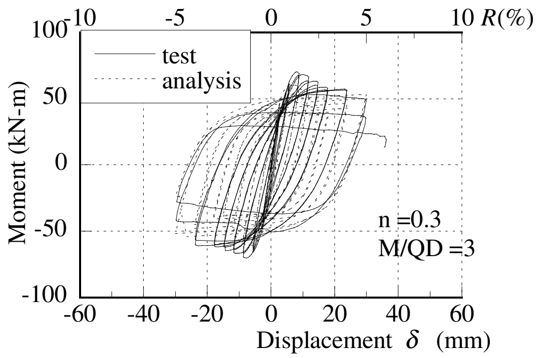
Application of the proposed analytical method was verified by comparing with experiments conducted at Kyushu University [Ikeda *et al*, 1999]. Figure 4 illustrates the comparision results on specimens with shear-span to depth ratio of 3 and 5 which were subjected to constant axial load and repeated lateral loading. Comparisions indicate that the assumption of the length of bending portion in analytical model described in section 3.1 was suitable for specimens of shear-span to depth ratio of 5, since the analytical results in load (moment at critical section) – deformation (lateral displacment at top of column (δ), rotation angle $R=\delta/L$)

curve was in great agreement with the tests in respect of initail stiffness (ratio of analytical value of initail stiffness K_{ana} to test value K_{exp} equal to 1.0 for both specimens tested under axial load ratio, n, 0.3 and 0.5). Reasons that analysis gave lower estimation on flexural strengths (M_{ana} / M_{exp}=0.92 for specimen under n=0.3, 0.83 for specimen under n=0.5) is confined effect due to structural steel on concrete not taken into consideration in analysis. On the other hand, in the case of specimens with shear-span to depth ratio of 3, high estimation on initail stiffness by analysis occurred while Lp=0.422L used. A modification on Lp was conducted and found initial stiffness can be estimated exactly using Lp=0.5L.

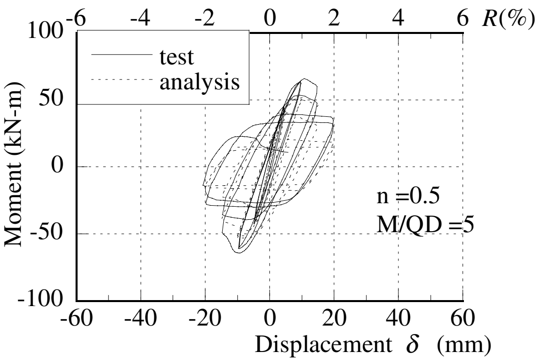
4. RESULTS



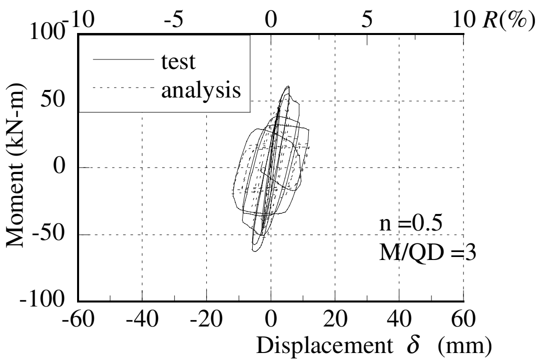
(i) Specimen under axial load ratio 0.3
Lp=0.422L
K_{ana}/K_{exp}=1.0, M_{ana}/M_{exp}=0.92



(i) Specimen under axial load ratio 0.3
Lp=0.50L
K_{ana}/K_{exp}=1.0, M_{ana}/M_{exp}=0.87



(ii) Specimen under axial load ratio 0.5
Lp=0.422L
K_{ana}/K_{exp}=1.0, M_{ana}/M_{exp}=0.83



(ii) Specimen under axial load ratio 0.5
Lp=0.50L
K_{ana}/K_{exp}=1.0, M_{ana}/M_{exp}=0.84

(a) Shear-span to depth ratio of 5 **(b) Shear-span to depth ratio of 3**

Figure 4 Verification of Analytical Method

(Specimen section: b=200mm, D=200mm; Encased I-section steel: sD=125mm, bf=60mm, tw=6mm, tf=8mm; Reinforcement 4D13; compressive strength of concrete 27.1~29.7MPa, yield stress of flange, web and reinforcing steel: ${}_f\sigma_y$=327MPa, ${}_w\sigma_y$ =349MPa, ${}_m\sigma_y$ =377MPa, respectively; shear - span to depth ratio, M/QD=5 or 3)

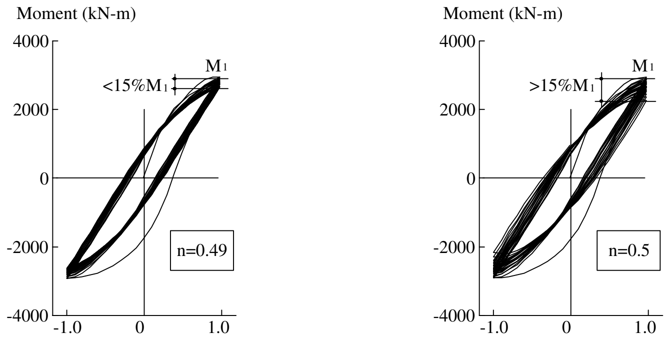
4.1 Behavior of Steel Reinforced Concrete

The fact that axial loads applied to internal columns of a high-rise frame almost did not vary due to seismic loading has been verified by dynamic analyses, and the axial load can be considered constant [Yukino, 1998]. Researches showed that there exists a stable limit axial load for a column subjected to combination of axial loading and flexural loading [Matsui *et al.* 1989, Li *et al.* 1996]. The stable limit axial load can be defined as the maximum value of vertical load, under which flexural strength of column does not decrease under combined constant axial loading and repeated lateral loading within constant lateral displacement amplitude. In this paper, degradation of flexural resistance is not larger than 15% of the maximum flexural strength in first cyclic loading. If the axial load applied to the column is higher than this limit axial load, flexural strength of column decreases quickly corresponding to the horizontal cyclic loading.

Two examples of the simulation results of encased steel reinforced concrete columns under axial load levels of n=0.49 and n=0.50 are shown in figure 5. Notation n represents the ratio of axial load N to axial load-carrying capacity N_u which is calculated according to the AIJ SRC Standard.

$$N_u = {}_c r_u \cdot b \cdot D \cdot F_c + {}_s A \cdot {}_s\sigma_y + {}_m A \cdot {}_m\sigma_y \tag{2}$$

Where, ${}_c r_u$= 0.85-2.5$b_f \cdot t_f/(b \cdot D)$, ${}_m A = {}_m a_c + {}_m a_t$, ${}_m a_c$ and ${}_m a_t$ are areas of compression and tension reinforcement shown in figure 1.



(a) Stable **(b) Unstable**

Figure 5 Behavior of column under constant axial load

(column No.1, M/QD=5, Fc=29.8Mpa, SS400 steel)

Comparing these two curves in figure 5, it can be seen that hysteresis loops of the cantilever under axial load level n=0.49 are stable and the degradation of resistance is within 15% of the maximum flexural strength of first cyclic loading even though lateral loading was repeated 20 times. On the contrary, the column under n=0.50 shows unstable behavior, its load resisting capacity dropped abruptly due to lateral repeated loading. The axial load ratio n=0.49 can be determined to be the stable axial load ratio (n_{cl}) of the column, which guarantees the deformation amplitude of 1.0% in terms of rotation angle R (=δ/L).

4.2 Stable limit axial load ratio

4.2.1 Effects of material strength

Figure 6 and 7 show relations of stable limit axial load ratio to rotation angle of columns No. 1 to 17 listed in table 1 with shear-span to depth ratio 5 used. Results of columns using two kinds of compressive strengths of concrete and the same steel (Grade SS400) were shown in figure 6. Solid and empty circles represent analytical results and solid and dashed lines are recursion curves. Results scattering at the same rotation angle was caused by difference of encased steel. A slight decrease occurs in the stable limit axial load ratio while higher compressive strength of concrete used. Differences on stable limit axial load ratio between columns using Fc=58.8MPa and columns using Fc=29.4MPa appear to enlarge as rotation angle increases. Figure 7 shows the effects of encased steel strength on the stable limit axial ratio for these columns. The stable limit axial load ratios increase while high strength steel is used.

4.2.2 Effects of encased steel

Two graphs concerning the effects of encased steel area and steel shape on the stable limit axial load ratio are presented in figure 8. A comparison of the columns with the same steel area ratio but using different steel shape indicates that the stable limit axial load ratio of columns using cross-section steel is larger than that of columns using I-section steel (built-up I-section steel included). It can be observed that there is no significant difference in the stable axial load ratio due to encased steel sectional area for columns using cross-section steel. However, the stable limit axial load ratio of columns using I-section steel appears to decrease as steel area increases.

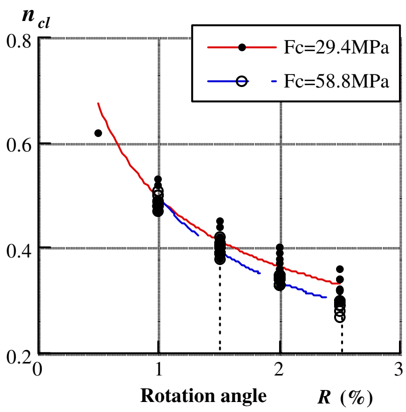


Figure 6 Effects of concrete strength
(column No.1~17, M/QD=5, SS400 steel)

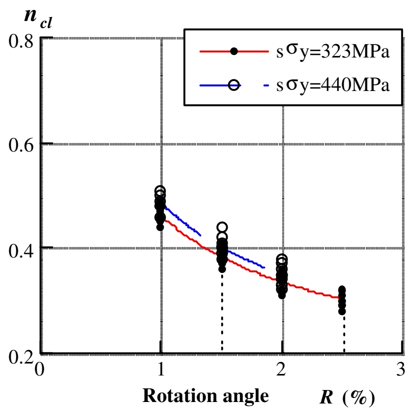
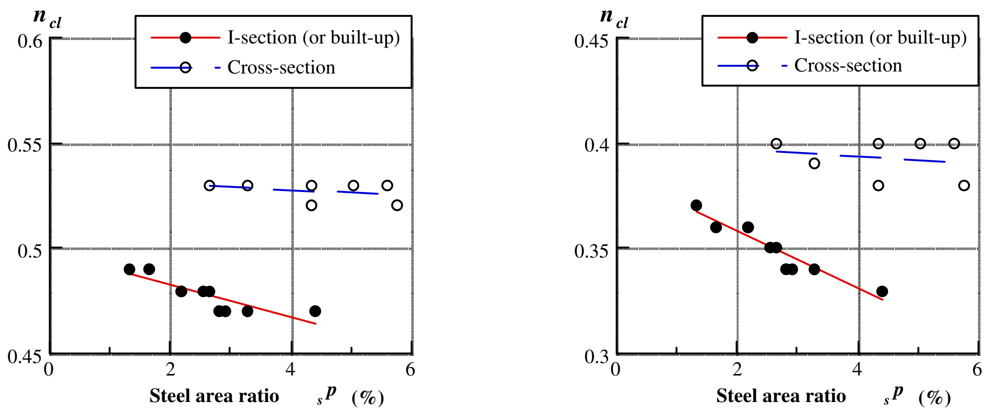
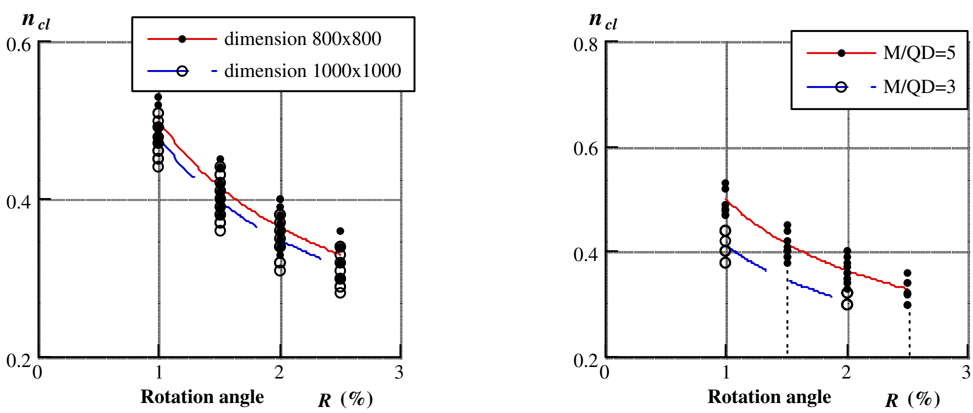


Figure 7 Effects of steel strength
(column No.1~17, M/QD=5, *Fc*=29.8MPa)



(a) Rotation angle *R*=1.0% **(b) Rotation angle *R*=2.0%**

Figure 8 Effects of encased steel
(column No.1~17, M/QD=5, *Fc*=29.8MPa , SS400 steel)



(a) Sectional dimensions
(M/QD=5)

(b) Shear-span to depth ratio
(column No.1~17)

Figure 9 Effects of column dimensions
(*Fc*=29.8MPa , SS400 steel)

4.2.3 Effects of column dimensions

Figure 9 (a) shows the effects of column sectional dimensions on the stable limit axial load ratio and it was observed that stable limit axial load ratio decrease as section of column increases. Comparisons between the analytical results of shear-span to depth ratio 3 and 5 indicated that the stable limit axial load ratio decreases 20 percent while the columns are of shear-span to depth ratio equal to 3. According to AIJ SRC Standard, compression force acting on a column under earthquake loading shall be not larger than the value specified by equation (3).

$$N_l \leq \frac{1}{3} \cdot b \cdot D \cdot F_c + \frac{2}{3} \cdot {}_sA \cdot {}_s\sigma_y \quad (3)$$

Ordinate in figure 10 is ratio of the calculated stable limit axial load (n_{cl}) to AIJ SRC Standard axial force limitation ($n_l = N_l/N_u$). Beam-columns with *M/QD*=5 can satisfy the AIJ SRC Standard limitation while rotation angle of 1.0% required. On the contrary, most *M/QD*=3 beam-columns can not guarantee 1.0% radian rotation angle at the axial force limitation of AIJ SRC Standard.

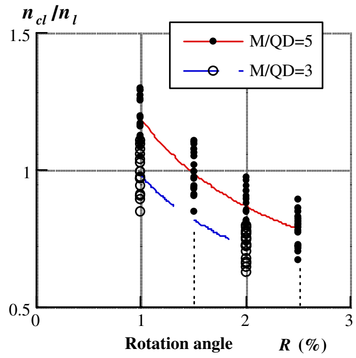


Figure 10 $n_{cl} / n_l - R$ **relations**
(column No.1~17, *Fc*=29.8MPa, SS400 steel)

5. CONCLUSIONS

1. Parametric study on moment - rotation angle relations of a beam-column under constant axial load and cyclic lateral loading was carried out using idealized hysteretic stress-strain relations and discrete element approach. Analysis method proposed by authors was verified to estimate test results in good agreement.
2. Analytical results showed that there was a maximum limit of axial force to ensure stable behavior of a encased steel reinforced concrete beam-column when it was subjected to both axial and repeated lateral loading under a constant rotation angle amplitude. The maximum axial force that the beam-column can resist under cyclic lateral loading was defined as stable limit axial force to ensure the required rotation angle amplitude.
3. Several parameters that influence inelastic performance of the beam-columns are investigated; including dimensions of column section, encased steel area ratios, sectional shapes of the encased steel, material strengths, and shear-span to depth ratios. Analytical results indicate that the stable limit axial load ratio increases as steel strength increases or compressive strength of concrete decreases. The stable limit axial load ratio decreases as encased steel sectional area increases while I-section steel used and it is almost not influenced by steel area while cross-section steel used. Shear-span to depth ratio is found the most influential element that affects the stable limit axial load ratio compared with all other influential elements.
4. Most *M/QD*=3 beam-columns can not guarantee 1.0% radian rotation angle even though the AIJ Standard axial force limitation is satisfied.

6. REFERENCES

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