13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No.1342

EVALUATION METHOD OF THE DEFORMATION CAPACITY AND THE ENERGY DISSIPATION CAPACITY OF STEEL FRAMED REINFORCED CONCRETE MEMBERS CONSIDERING THE INFLUENCE OF VARYING AXIAL FORCE

Mareyasu DOI[1],Daisuke KATO[2],Norichika KATAYOSE[3]

SUMMARY

Reversed cyclic loading tests on steel framed reinforced concrete beam-columns encased cruciform section steel have been carried out, under varying axial force and constant axial force. The deformation capacity and the energy dissipation capacity of SRC beam-columns under varying axial force are discussed on the basis of these experimental results. The procedure is proposed to estimate the deformation capacity and the energy dissipation capacity of SRC beam-columns considering the influence of varying axial force. It is proved that this procedure corresponds to the results of experiments.

INTRODUCTION

A steel framed reinforced concrete（abbreviated as SRC hereafter）structure is composed of monolithic concrete encased steel members with longitudinal reinforcing bars and web reinforcing bars. SRC structures have been originally developed, and widely used for middle or high-rise buildings in Japan. Unfortunately, some old SRC buildings were severely damaged owing to 1995 Hyogoken-Nanbu earthquake [1].

It is necessary for the performance based seismic design of buildings to establish the rational evaluation method of the deformation capacity and the energy dissipation capacity of members. Especially, columns in lower stories of high-rise buildings are generally subjected to severe varying axial force under strong earthquake ground motion. There are a few experimental and analytical researches of SRC members encased cruciform section steel under varying axial force by Asakawa [2], Kon-no [3]. The scope of this paper is to establish the rational evaluation method of the deformation capacity and the energy dissipation capacity of SRC members, considering the influence of varying axial force.

In this research, reversed cyclic loading test on SRC beam-columns encased cruciform section steel have been carried out, under varying axial force or constant axial force. The specimens are models of the interior and exterior columns of middle or high-rise buildings during earthquake. Those specimens show

[1] Professor, Niigata University, Niigata, Japan, Email:mare@cc.niigata-u.ac.jp
[2] Professor, Niigata University, Niigata, Japan, Email:dkato@eng.niigata-u.ac.jp
[3] Researcher, Fujita Technical Institute, Atsugi, Japan, Email:katayose@nyc.odn.ne.jp

excellent deformation capacity. Though the equivalent viscous damping is a slight smaller in the case of varying axial force than constant axial force, all specimens show large energy dissipation capacity.

The deformation capacity and the energy dissipation capacity of SRC beam-columns under varying axial force are discussed on the basis of these experimental results. The procedure is proposed to estimate the deformation capacity and the energy dissipation capacity of SRC beam-columns considering the influence of varying axial force on the basis of these experimental results. It is proved that this procedure also corresponds to the experimental data based on the review of existing studies.

OUTLINE OF EXPERIMENT

The detail of the experiment shown in the following has been reported in the preceding papers by Doi [4], Katayose [5],[6], and Doi [7].

Specimen

Total 6 specimens were planned as shown in Table 1. The form and the dimension of the specimens are shown in Figure 1. The specimens are approximately one-fifth scale model of the actual existing column of the lower layer floor of a middle or high-rise SRC building. The encased steel used in the column part of all specimens was cruciform section (Grade SS400, 2H-125x60x5.5x8). The encased steel placed in the stub was H-shaped section (Grade SS400, H-175x60x7.5x11). The stub has enough strength and rigidity so that an influence might not arise in the result of the experiment by the difference in the form of the stub between specimen No.1, No.2, and No.5, and specimen No.3, No.4, and No.6. The longitudinal reinforcement and the lateral reinforcement in all specimens was Grade SD295. The nominal compressive strength of concrete was 21N/mm^2, and the maximum dimension of aggregate was 15mm.

Method of experiment

Test setup was shown in Figure 2. The upper stub of a specimen was kept horizontally by the left side hydraulic jack 2 and the right side one. A fixed axial force was applied on the specimen No.2 and No.4 by hydraulic jack 1 and 2 (see Table 1). A varying axial force in proportion to the horizontal force was applied on the specimen No.1, No.3, No.5, and No.6 shown in Figure 3. As shown in Figure 1, the horizontal force on the direction of the principal axis of the section applied on the specimen No.1, No.2, and No.5, and in the direction inclined 45 degrees to the principal axis of the section, on the specimen No.3, No.4 and No.6. The maximum value of axial force ratio +0.5 on the side of compression is beyond the limiting value for axial force of SRC column in AIJ standard for structural calculation of SRC [8] (see Appendix 1). Reverse cyclic horizontal force was applied on all specimens corresponding to the following program; i.e. two loading cycles were applied corresponding to each rotation angle of 5,10,15, 20 and 40x10^{-3}radian.

Table 1 Summary of specimens.

Specimen	Range of axial force ratio	Direction of horizontal force (degree)	References
No.1	From +0.3 to -0.1	0	[4]
No.2	+0.3 (fixed)	0	[4]
No.3	From +0.3 to -0.1	45	[5],[6]
No.4	+0.3 (fixed)	45	[5],[6]
No.5	From +0.5 to -0.2	0	[7]
No.6	From +0.5 to -0.2	45	[7]

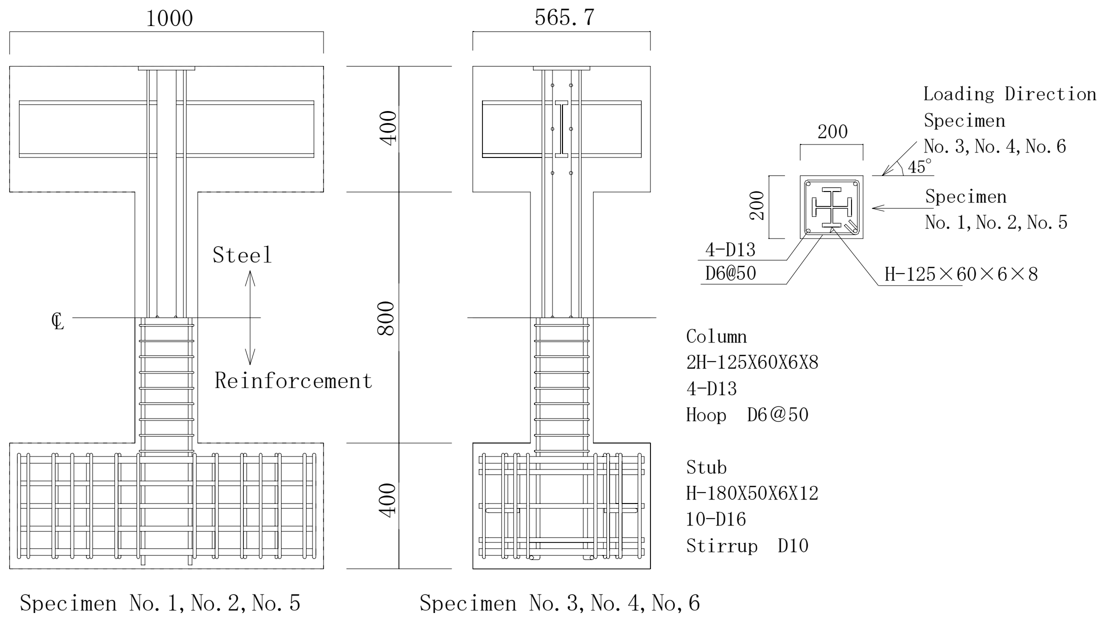


Figure 1. Details of specimens.

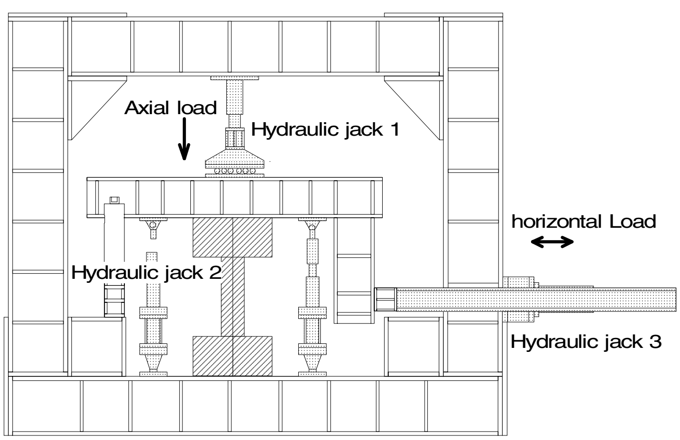


Figure 2. Test Setup.

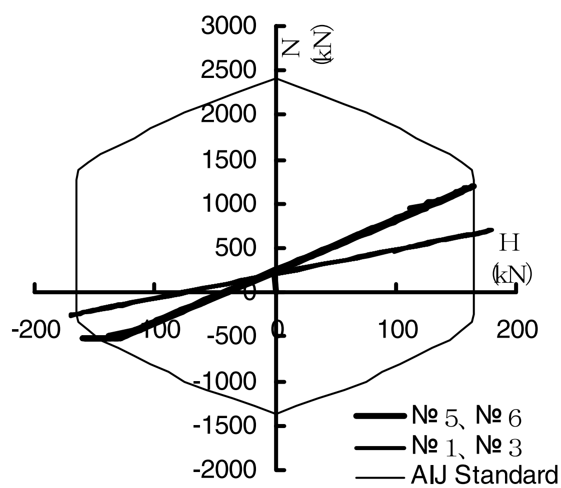


Figure 3 Axial force histories.

RESULT OF EXPERIMENT

Maximum strength and limit deformation

The horizontal force and the rotation angle at the maximum strength and at the limit deformation are shown in Table 2. The limit deformation is defined here as the rotation angle when the strength of the specimen declines to the 80% of the maximum strength. P-Δ effect isn't being taken into consideration in Table 2. The ultimate strength in the principal direction of the section calculated by AIJ standard for calculation of SRC was also shown in Table 2 [8]. In the calculation of the strength, it was presumed that the critical section was located at the end of the column. The strength didn't decline below 80% of the maximum strength for the varying axial load specimens on the side of negative loading, and for the constant axial force specimens.

Table 2. Maximum strength and limit state.

	Maximum Strength		Limit state		Ultimate strength by AIJ standard (kN)
	Horizontal force (kN)	Rotation angle ($x10^{-2}$ rad)	Horizontal force (kN)	Rotation angle ($x10^{-2}$ rad)	
No.1	173	2.50	138	8.82	158
	-179	-3.75	-	-	-153
No.2	185	2.00	-	-	158
	-186	-2.00	-	-	-158
No.3	181	3.24	145	7.98	158
	-174	-4.00	-	-	-153
No.3	179	2.26	-	-	158
	-175	-2.01	-	-	-158
No.5	165	2.00	129	6.51	166
	160	-4.00	-	-	-145
No.6	179	2.00	133	6.05	166
	175	-4.01	-	-	-145

Load-deformation relation

Horizontal force - rotation angle relationships of the six specimens are shown in Figure 4. The area of hysteresis curve on the side of negative loading is a little large in comparison with the side of positive loading. This tendency was remarkable in specimen No.5 and No.6 of which axial force changed widely. It is assumed that this is caused by the influence of opening and closing of the crack in the end of the column part of specimen by the dominant axial force on the side of negative loading. On the side of negative loading, the strength didn't decline, and the value of the maximum strength exceeded that of the calculation. But, as for specimen No.5 and No.6 (axial force ratio from +0.5 to -0.2), the maximum strength was low in comparison with specimen No.1 and No.3 (axial force ratio from +0.3 to -0.1). The strength decline of specimen No.5 and No.6 after the maximum strength was larger than that of specimen No.1 and No.3, and the deformation capacity declined. The strength decline wasn't shown in any specimens by taking the P-Δ effect into consideration, and the great deformation capacity was shown in the ultimate state (see Figure 4).

The equivalent viscous damping h_{eq} for the second repetition loop (abbreviated as the stationary loop hereafter) in each displacement amplitude of the varying axial force specimen is shown in Figure 5.

The value of h_{eq} increases in accordance with the growing of the rotation angle, and was large on the side of negative loading in comparison with the side of positive loading for the range of the rotation angle from $1x10^{-2}$ to $2x10^{-2}$ radian. On the side of negative loading, the crack of concrete at the end part of column opens, and the steel portion is in the state of tension. On the side of positive loading, the concrete portion cannot support compressive force until the crack of concrete closes. The energy dissipation capacity represented by h_{eq} was a little large on the side of negative loading for specimen No.5 or No.6 in comparison with specimen No.1 or No.3, and was equivalent on the side of positive loading for the above all specimen.

The evaluation of the deformation capacity and the energy dissipation capacity

Table 3 shows the outline of the database regarding the structural performances of SRC members under varying axial force.

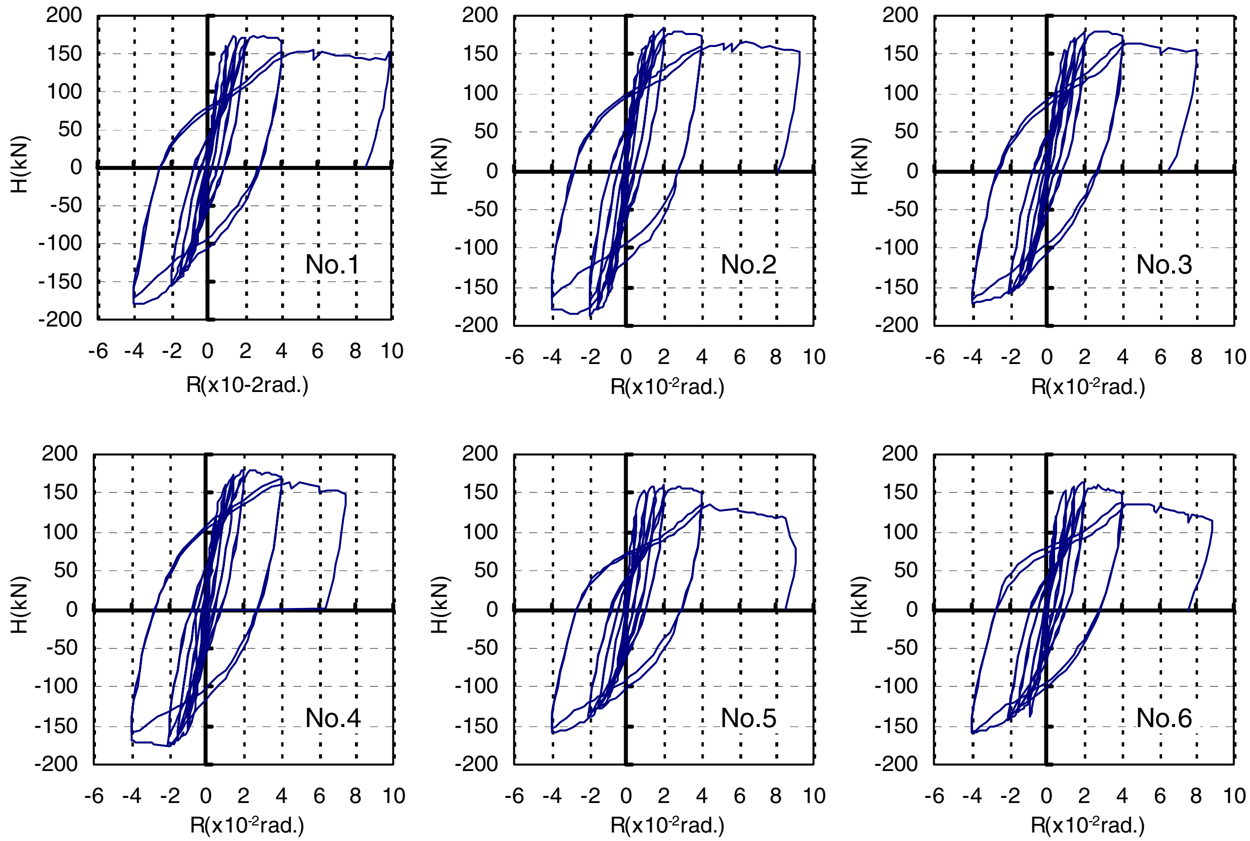
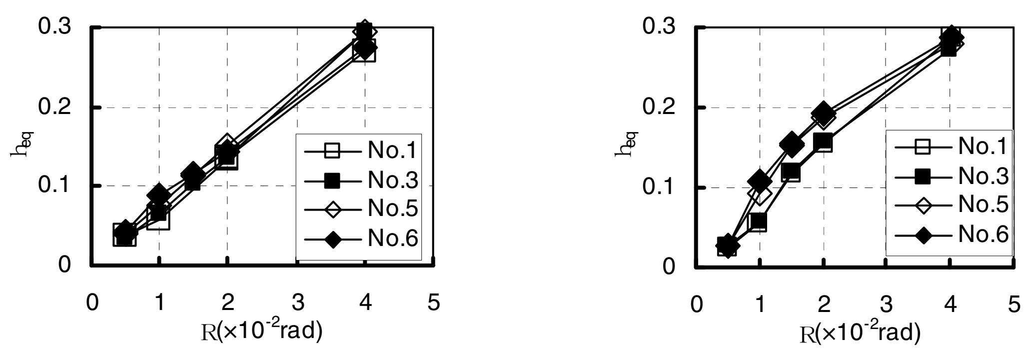


Figure 4 Relationship of horizontal force and rotation angle.



(a) Positive Loading

(b) Negative Loading

Figure 5 Equivalent viscous damping.

Table 3 Database

Steel type	References	Number of Specimens	N_{cmax}/N_u	N_{tmax}/N_u	m_s	p_w
Cruciform	Asakawa [2]	2	0.78	-0.33	0.53	1.19
	Kon-no [3]	3	0.50	-0.12,-0.25	0.16,0.34	0.43
	Author [4]-[7]	4	0.29,0.44	-0.11,-0.19	0.58	0.64
H-shape	Tanaka [9]	3	0.68	-0..22	0.16	0.95
	Kumata [10]	3	0.48	-0.16	0.29	0.71
	Shohara [11]	3	0.23,0.39	-0.16,-0.22	0.18,0.20	0.36,0.72

N_{cmax} is the maximum compressive axial force. N_{tmax} is the maximum tensile axial force. m_s is the flexural strength ratio of steel portion. p_w is the hoop ratio

Deformation capacity

The limit deformation R_{80} is taken as the index of the deformation capacity. R_{80} of a member in case of the constant axial force is being given in literature [12] as follows.

Figures 6 through 8 shows the relationships between R_{80} and axial force ratio (N_{cmax}/N_u) on the side of positive loading where the axial force becomes compression, between R_{80} and flexural strength ratio of steel portion (m_s) and between R_{80}, and the web reinforcement ratio (p_w) respectively. Data on the figures are composed of 4 specimens of varying axial force in this research (see Table 1) and 5 specimens [2],[3] for which cruciform section steel was used, and 8 specimens [9],[10],[11] for which H-shape steel was used (see Table 3). Some of these specimens encased H-shape steel contain a bare type of column base [11], because of a few data on varying axial force. For the specimen of which the strength didn't decline below 80% of the maximum strength, the maximum value of rotation angle in the experiment is regarded as the limit deformation.

The lower estimation of the limit rotation R_{80} for the full web type of SRC members subjected to the constant axial force is being given by Shohara and Doi [12],[13] is given as follows.

$$R_{80} = 4 - 10\eta \quad \left(\times 10^{-2}\,radian\right) \quad > 0.5 \quad \text{for flexural failure} \tag{1}$$

$$R_{80} = 10m_s - 1.5 \quad \left(\times 10^{-2}\,radian\right) \quad > 0.5 \quad \text{for shear failure} \tag{2}$$

where, η is axial force ratio and m_s is the ratio of the flexural strength of steel portion to that of SRC.

The lower estimation of R_{80} by Equation (1) and Equation (2) was shown in Figure 6 and Figure 7 respectively. The failure mode for the varying axial force specimen cannot be defined in the similar way for the constant axial force specimen. Therefore, all data were plotted no only in Figure 6 but also in Figure 7. R_{80} mostly decreases with increasing of the value of N_{cmax}/N_u, and increases with increasing of the value of m_s. Equation (1) and Equation (2) are mostly adapted to the lower estimation of R_{80} in the case of the varying axial force, as well. The correlation between p_w and R_{80} isn't so clear as the correlation for N_{cmax}/N_u and m_s.

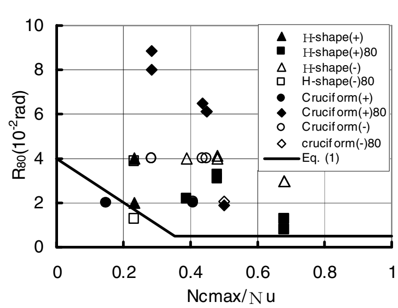


Figure 6. Relation between $R_{80.}$ and N_{cmax}/N_u

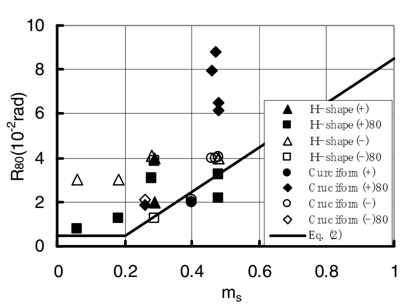


Figure 7. Relation between R_{80} and N_{cmax}/N_u and m_x

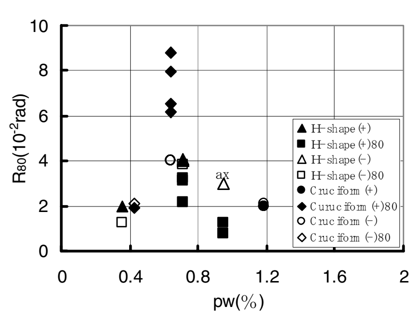
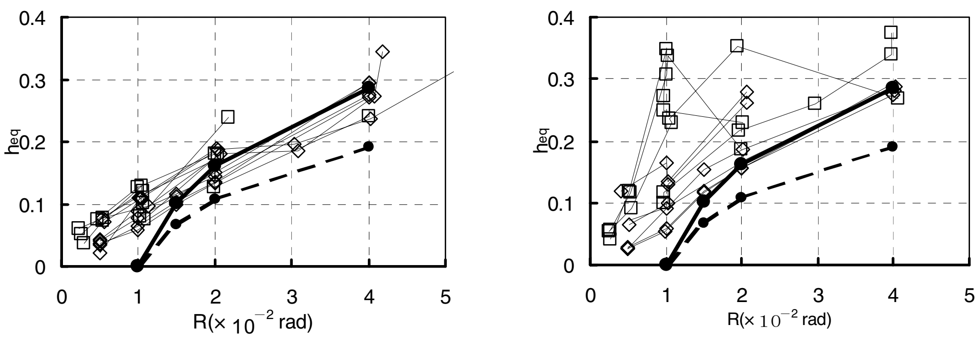


Figure 8. Relation between R_{80} and p_w

Energy dissipation capacity

The equivalent viscous damping h_{eq} was taken as an index of the energy dissipation capacity. According to the result of the experiment by Doi [4] and Katayose [5,6], the difference of h_{eq} was hardly admitted between in varying axial force specimen No.1 and No.3 and in constant axial force specimen No.2 and No.4. Therefore, the relationship between h_{eq} against the stationary loop and the rotation angle R are shown only for the varying axial force specimen in Figure 9. The data of the following specimens are shown in Figure 9, i.e. 4 specimens in this research and 2 specimens by Asakawa [2] in which cruciform section steel was used, and 8 specimens by Kumata [10] and Shohara [11] for which the H-shape steel was used.



(a) Positive Loading (b) Negative Loading

Figure 9 Equivalent viscous damping

The lower estimation of h_{eq} of SRC members in the case of constant axial force is being given by Shohara [12], as follows.

$$h_{eq} = 1.5\left(1 - q/\sqrt{R}\right)/\pi \qquad \text{for flexural failure} \qquad (3)$$

$$h_{eq} = \left(1 - q/\sqrt{R}\right)/\pi \qquad \text{for shear failure} \qquad (4)$$

where R is rotation angle of the member $\left(\times 10^{-2} \, radian\right)$

$$q = 1 - 0.2\left(R - 1\right)/\left(R_{80} - 1\right) \qquad (5)$$

The estimated value of h_{eq} by Equation (3) and by Equation (4) in the case that axial force ratio is 0 was shown together in Figure 9. The value of h_{eq} mostly increases with increasing of rotation angle. Equation (3) or Equation (4) can be mostly adapted to the lower estimation of h_{eq}. not only on the side of positive loading but also on the side of the side of negative loading.

CONCLUSION

The lower layer floor column of the high-rise building in earthquake was presumed, and the static loading test of the SRC member in which the cruciform section steel was used, which the principal axis of the section, a main axial force and the reverse cyclic horizontal force in the 45 degrees direction are received under the varying axial force which was in proportion to the horizontal force from was used for was settled.

For the specimens subjected to large range of varying axial force, the strength decline after the maximum strength on the side of positive loading was large in comparison with the specimens subjected to small range of varying axial force, and the decline of the deformation capacity was recognized. But, the strength decline was hardly seen in consideration of the P-Δ effect. The energy dissipation capacity defined by the equivalent viscous damping was equivalent on the side of positive loading, and a slight large on the side of negative loading.

It can be proved, within the range of this research, that the lower estimation of the limit rotation angle as the index of deformation capacity and of the equivalent viscous damping as the index of energy dissipation capacity in case of the constant axial force can be applied for the case of varying axial.

Appendix 1

The limiting value of axial force N1 of SRC beam-column is given as follows [8].

$$N_1 \leq bDF_c/3 + 2{}_sA \cdot {}_sf_c/3 \quad \text{(A-1)}$$

where b is section width, D is section depth, F_c is design standard strength of concrete, ${}_sA$ is area of steel section, and ${}_sf_c$ is allowable compressive strength of steel.

Appendix 2

Equivalent viscous damping is defined Equation (A-2) in this paper.

$$h_{eq} = \Delta W/(2\pi W) \quad \text{(A-2)}$$

where ΔW is the strain energy calculated on the each stationary loop. W is the equivalent elastic strain energy calculated on the maximum deformation point of the each stationary loop .

REFERENCES

1. Editorial Committee for the report on the Hanshin-Awaji Earthquake Disaster, "Report of the Hanshin-Awaji Earthquake Disaster - Building Series Volume 2", Architectural Institute of Japan, 1998.
2. Asakawa T., et al, "Lateral loading test on pre-cast wall structure reducing to columns at the ground story (Part 5) ", *Summaries of Technical Papers of Annual Meeting*, AIJ, 1994;C1: 479-480.
3. Kon-no S., et al, "Experimental study on high-rise buildings with lower floor composed of SRC structure (Part 1 through 3)", *Summaries of Technical Papers of Annual Meeting*, AIJ, 1998; C1: 1029-1034.
4. Doi M., et al, "Static Loading Test on SRC Beam-Column under Varying Axial Force", *Journal of Constructional Steel*, 2000; 8: 517-524.
5. Katayose T., Doi M., "Experimental Study on Deformation Capacity of SRC Beam-Column under Varying Axial Force", *Proceedings of the Japan Concrete Institute*, 2001; 23(1): 661-666.
6. Katayose T., Doi M., "Static Loading Test on SRC Beam-Column under Varying Axial Force and Biaxial Horizontal Force, *Journal of Constructional Steel*, 2001; 9:199-206.
7. Doi M., et al, "Deformation Capacity and Energy Absorption Capacity of SRC Beam-Column under Varying Axial Force", *Proceedings of the Japan Concrete Institute*, 2002; 24(2): 1345-1350.
8. Architectural Institute of Japan, "AIJ standards for structural calculation of steel reinforced concrete structures (1987)".
9. Tanaka K., et al, "Experimental study on mechanical properties of steel reinforced concrete short columns using high strength concrete", *Proceedings of the Japan Concrete Institute*, 1991; 13(2): 451-456.
10. Kumata Y., et al, "Study on a seismic behavior for RC columns encased H-shaped steel with wide flange (Part 1 through 2)", *Summaries of Technical Papers of Annual Meeting*, AIJ, 1995; C1: 685-688.
11. Shohara R., et al, "Seismic behavior of bare type of SRC column bases under large tension (Part 1 trough 2)", *Summaries of Technical Papers of Annual Meeting*, AIJ, 1998; C1:1319-1322.
12. Shohara R. and Doi M., "Ductility and Ds-Value of Steel Encased Reinforced Concrete Buildings", *Journal of Structural and Construction Engineering (Transactions of AIJ)*, 2001; 540: 149-154.
13. Doi M., "Deformation Capacity and Energy Absorption Capacity of Steel Framed Reinforced Concrete Members Encased Cruciform Section Steel", *Journal of Constructional Steel*, 2001; 9: 193-198.