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STRUCTUAL SEISMIC PERFORMANCES OF SRC FRAMES HAVING STRONG AXIS BENDING COLUMN

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SUMMARY

In order to investigate the deformation characteristics and strength of steel encased reinforced concrete (SRC) frames having strong axis bending column subjected to cyclic lateral load under constant vertical load, four test specimens were tested on two parameters: the column length to section depth ratio and axial load ratio. The effect about the deformation characteristics of the experimental parameters was discussed.

INTRODUCTION

In Japan, SRC structures have been widely used not only for middle-rise buildings but also for high-rise buildings. Since the 1995 Hyogoken-nanbu earthquake, the importance of the structural performance design method recognized in Japan. And Building Standard Law was revised on 2000. It is important to grasp the hysteresis characteristic of the frames in consideration of not only the strength but also the deformation characteristics in the performance design.

SRC structure is composed of steel and reinforced concrete (RC) members. The elasto-plastic behavior is affected by the both behavior of steel and RC. It is difficult to estimate their hysteresis. In the research of the composite structure, there are many researches on the member, but few on the composite frame.

From the above, the objectives of this paper are to examine Architectural Institute of Japan (AIJ) design formula [1.], and to grasp the deformation characteristics.

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EXPERIMENT

Specimens

To examine the strength and the hysteresis characteristic of the SRC frame, the experiment was performed under the load condition shown in Fig.1.

Two experimental parameters are selected.

1) Clear-height of the column to the section depth ratio (L/D:6, 12 L: clear-height of the column, D: section depth)
2) Axial load ratio about the concrete section (n':0.3, 0.6 n' is calculated by using Eq.(1).)

$$n' = N / {}_cN \qquad {}_cN = b \cdot D \cdot {}_c\sigma_B \tag{1}$$

N: applied axial load, ${}_cN$: axial load about the concrete section,
b: section width, D: section depth, ${}_c\sigma_B$: compressive strength of the concrete

The loading program is shown in Fig.2. It increased the story drift angle of the frames R at intervals of 0.005 (rad.) to 0.02 (rad.), after that at intervals of 0.01 (rad.) to 0.04 (rad.) or it was loaded with the gradual increase repetition until column couldn't keep axial load any more. At the cycle of 0.01 (rad.) and 0.02 (rad.), the loading was repeated twice.

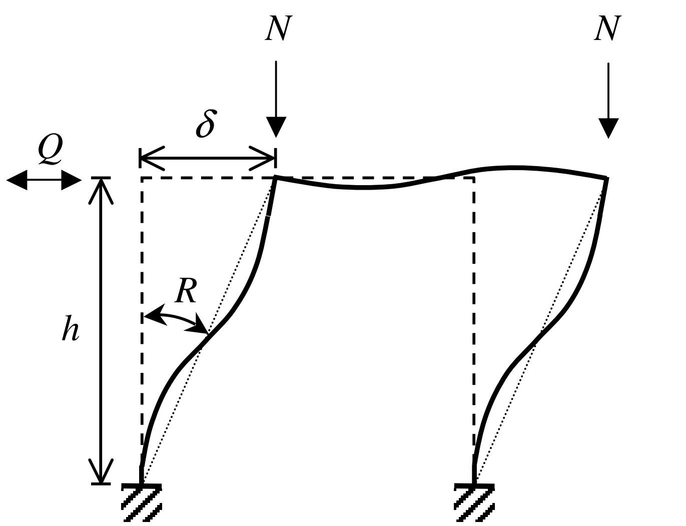


Fig.1 Loading Condition

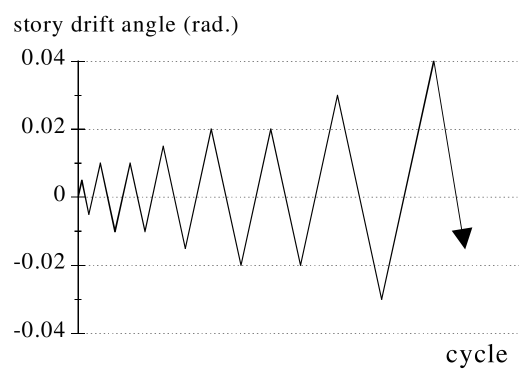


Fig.2 Loading Program

N: applied axial load, Q: cyclic horizontal load, δ: displacement,
h: length from centre of the upper beam to the upper end of the bottom beam,
$R(=\delta/h)$: story drift angle of the frames

Total four specimens were tested.

(Explanatory note of the specimen's name)

SRC-S12-03
→ Axial load ratio about the concrete section (0.3, 0.6)
→ Clear-height of the column to section depth ratio (12, 6)

The cross section configuration, shape, dimensions, and bar arrangement in the specimens are shown in Fig.3. Column section is 150×150 (mm). Beam section is 150×160 (mm). The encased steel is built-up section H-100×50×6×6 (mm). The size of the encased steel is shown in Table 1.

The distance between column's main re-bars (4-D6, SD295A) is 110 (mm), and hoops (4ϕ) are arranged for the space of 100 (mm). The distance between beam's main re-bars (8-D10, SD295A) is 120 (mm), and hoops (4ϕ) are arranged for the space of 50 (mm). Main reinforcements are welded to the end plate.

The list of four specimens is shown in Table 2. Axial load ratio (n) is calculated by using Eq.(2)

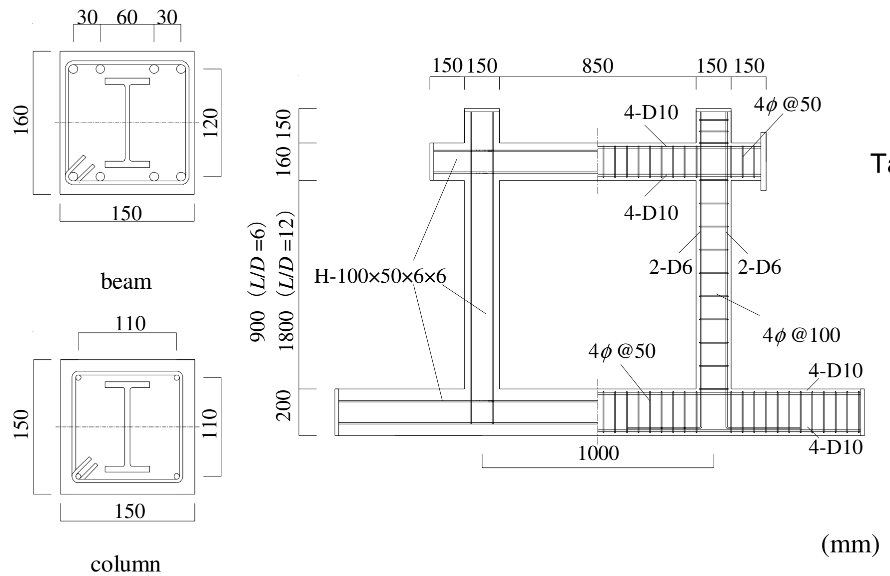


Fig.3 Details of Specimens

Table 1. Size of the H-section

H (mm)	B (mm)	t_w (mm)	t_f (mm)
101.3	49.6	5.62	5.67

H: depth, B: width,
t_w, t_f: thickness of web, flange

Table 2. Dimension and Properties of the Specimens

		b (mm)	D (mm)	$_mp$ (%)	$_sp$ (%)	$_c\sigma_B$ (MPa)	material age (day)	N (kN)	n'	n
SRC-S12-03	column	152.6	150.7	0.48	4.64	20.7	70	143	0.3	0.16
	beam	151.7	162.6	1.99	4.33					
SRC-S12-06	column	151.5	150.2	0.49	4.69	23.6	80	322	0.6	0.34
	beam	152.8	162.7	1.98	4.30					
SRC-S06-03	column	152.0	150.5	0.48	4.67	23.7	101	163	0.3	0.17
	beam	153.8	164.2	1.94	4.23					
SRC-S06-06	column	150.9	151.2	0.48	4.68	24.4	108	344	0.6	0.35
	beam	151.8	161.6	2.00	4.35					

b: section width, D: section depth, $_mp$: reinforcement ratio, $_sp$: steel ratio, $_c\sigma_B$: compressive strength of concrete,
$_s\sigma_Y$, $_m\sigma_Y$: yield point of the steel, reinforcement N: applied vertical load, n': axial load ratio about the concrete section,
n: axial load ratio about the SRC section

$$n = N / {}_{SRC}N \qquad {}_{SRC}N = b \cdot D \cdot {}_c\sigma_B + {}_sA \cdot {}_s\sigma_Y + {}_mA \cdot {}_m\sigma_Y \tag{2}$$

$_{SRC}N$: section compressive strength, $_s\sigma_Y$, $_m\sigma_Y$: yield stress of the steel, reinforcement, $_sA$, $_mA$: area of the steel, reinforcement

The test coupons were picked from the flange and web of the steel, the main reinforcement (D6, D10) and the shear-reinforcing bar (4ϕ). The tensile test result is shown in Table 3. Mixing proportion of the concrete is shown in Table 4. Measured slump is 18.4 (cm).

Table 3. Material Properties of the Steel

	ϕ (mm)	E (GPa)	σ_Y (MPa)	σ_U (MPa)	σ_Y/σ_U	ε_Y (%)	elongation (%)
flange		188.1	363.8	495.7	0.73	0.193	36.5
web		189.2	301.3	438.7	0.69	0.159	42.9
D10	8.85	189.1	472.3	619.7	0.76	0.250	23.1
D6	5.93	214.4	473.0	581.8	0.81	0.221	18.4
4ϕ	3.95	202.5	588.9	596.1	0.99	0.291	13.4

ϕ: diameter, E: Young's modulus, σ_Y: yield point, σ_U: tensile strength,
σ_Y/σ_U: yield ratio, ε_Y: yield strain ($\varepsilon_Y=\sigma_Y/E$)

Table 4. Mixing Proportion of the Concrete

unit weight (kg/m^3)						W/C	s/a	F_c	G_{max}	slump
cement	water	fine aggregate		coarse aggregate	AE agency					
		sea	crushed			(%)	(%)	(MPa)	(mm)	(cm)
400	200	364	364	900	0.800	50.0	45.1	27	15	18

W/C: water cement ratio, s/a: sand-coarse aggregate ratio, F_c: design strength of concrete,
G_{max}: maximum diameter of coarse aggregate

Loading Apparatus

Loading apparatus is shown in Fig.4. The specimens were placed so that the columns are vertical to the test floor. A clearance between the basis beam and the test floor was filled up with the mortar. Vertical load was applied through the loading beam, and cyclic horizontal load was applied.

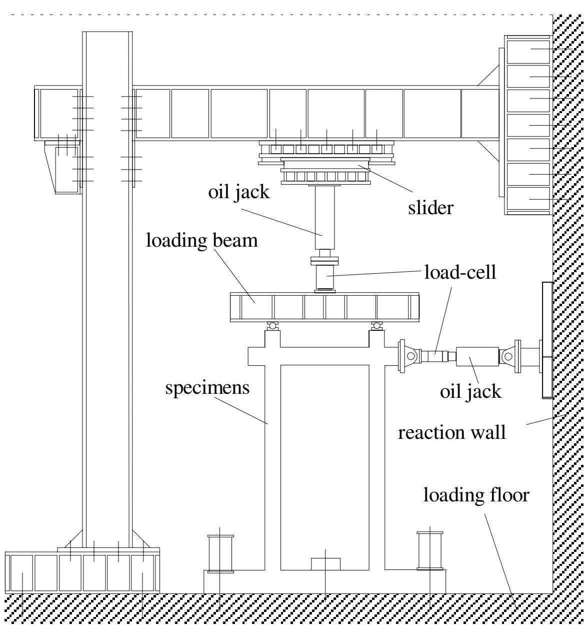


Fig.4 Loading Apparatus

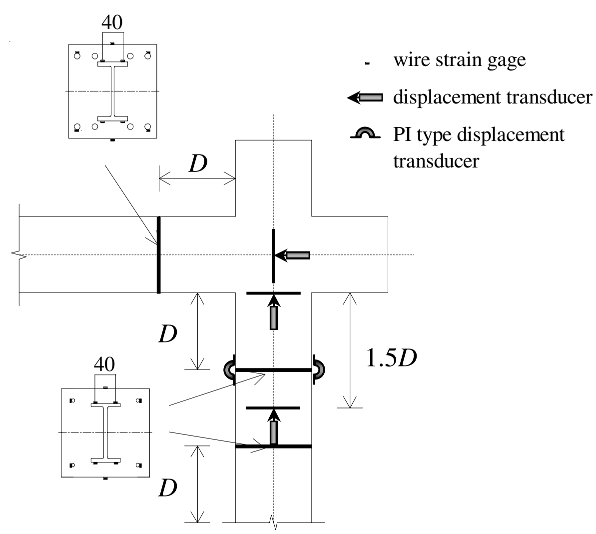


Fig.5 Position of Measurement

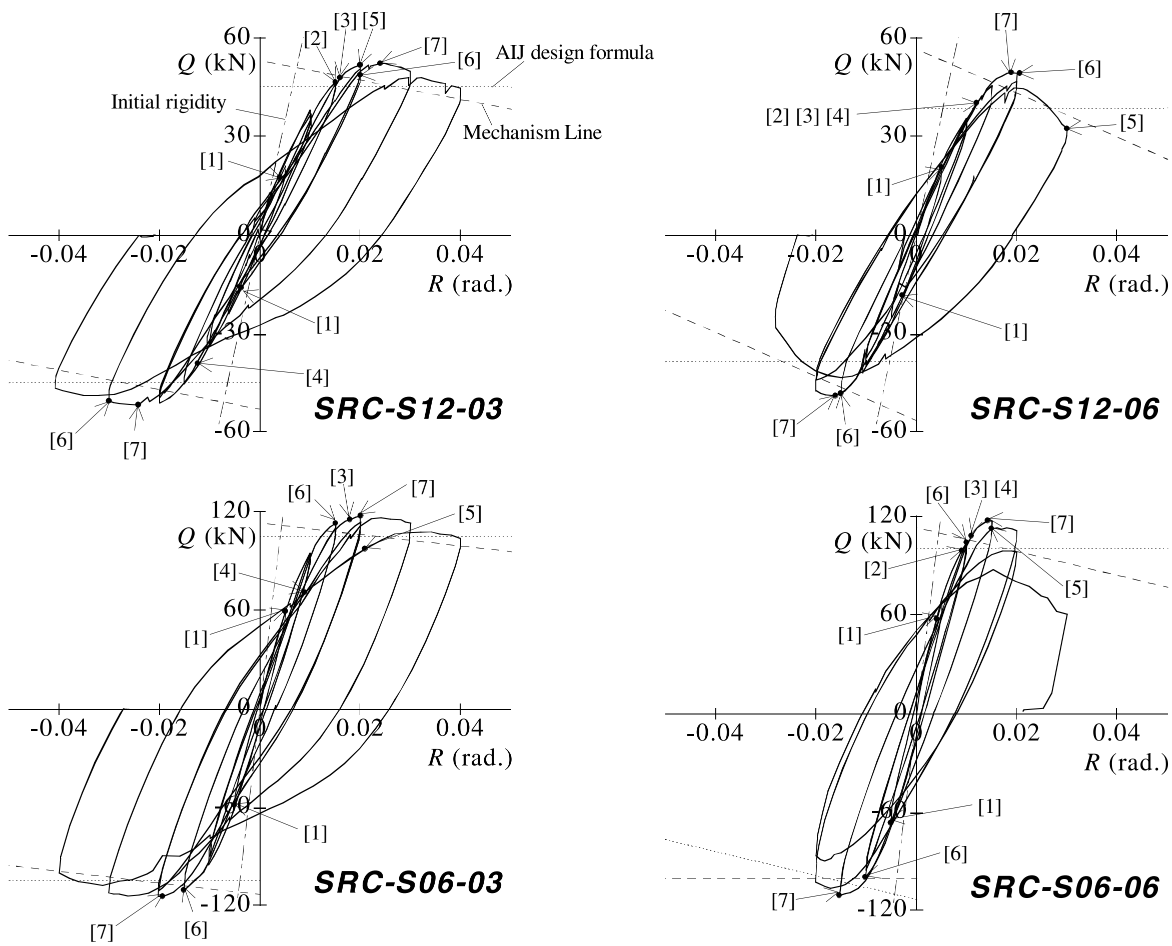
Method of Measurement

The position of displacement transducers and strain gages are shown in Fig.5. Load is measured by the load cell between the oil jack and the specimen. Strain gage is pasted to each position (see Fig.5). Horizontal displacement is measured in the center of the beam. In order to measure the vertical displacement, the displacement transducer is placed in the top of the column and the position of 1.5D from the top of the column. And the PI type displacement transducer was placed in the top and the bottom of test wall side column.

EXPERIMENTAL RESULT

The Relations of Horizontal Load and Story Drift Angle of the Frames

The relations of horizontal load and story drift angle of the frames are shown in Fig.6. The chain line means initial rigidity calculated by the slope-deflexion method. In calculation, the flexural rigidity of the section is obtained by using Eq.(3). The dashed line means the mechanism line calculated by Eq.(4), as an assumption that maintained the fully plastic moment M_p. The stress distribution of the section is shown in Fig.7. The distance between the plastic hinges is the clear-height of the column. The dotted line means the ultimate flexural strength of AIJ design formula.



[1] Flexural cracks was observed first
[2] Occurrence of reinforcement's yielding (bottom of the column)
[3] Occurrence of reinforcement's yielding (top of the column)
[4] Occurrence of steel's yielding (bottom of column)
[5] Occurrence of steel's yielding (the top of the column)
[6] Occurrence that concrete is broken by applied pressure
[7] Maximum strength

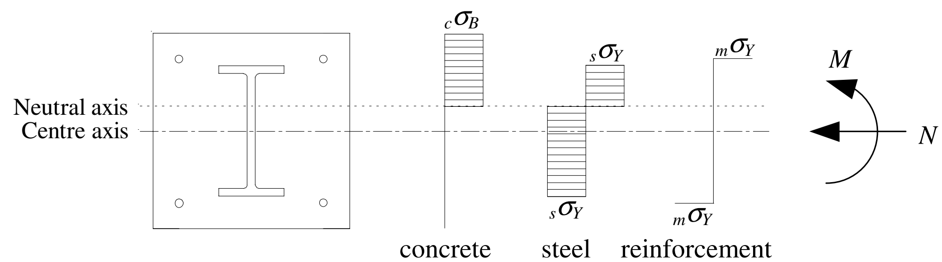
Fig.6 Q-R Relations

$$_{SRC}EI = {}_{s}EI + {}_{m}EI + {}_{c}EI \tag{3}$$

$_{SRC}EI$, $_{s}EI$, $_{m}EI$, $_{c}EI$: flexural rigidity of SRC section, steel, reinforcement, concrete

$$4M_P = QL + 2N\delta \tag{4}$$

M_p: fully plastic moment, N: applied vertical load Q: cyclic lateral load, δ: displacement, L: clear-height of the column



$_c\sigma_B$: compressive strength of concrete $_s\sigma_Y$: yield point of the steel $_m\sigma_Y$: yield point of the reinforcement

Fig.7 Stress Distribution for the Plastic Moment

The comparison between experimental behavior in early stage and the calculated initial rigidity are shown in Fig.8. In the early stages, the calculated initial rigidity overestimated experimental behavior of SRC-S12-03 and SRC-S06-03. After the maximum strength, experimental behavior is stable and followed in the slope of the mechanism line.

The calculated initial rigidity fit experimental behavior of SRC-S12-06 and SRC-S06-06 in near the 0.001 (rad.). But the initial rigidity overestimated after that. After the maximum strength, negative slope of experimental curve are larger than that of the mechanism line. Axial load couldn't be maintained any more at the final stage, and loading was finished.

Twice loading was applied in the cycle of 0.01 (rad.) and 0.02 (rad.) respectively. Though no decrease of the strength can be observed in the second cycle of 0.01 (rad.), it decreases greatly in the second cycle of 0.02 (rad.) in all specimens.

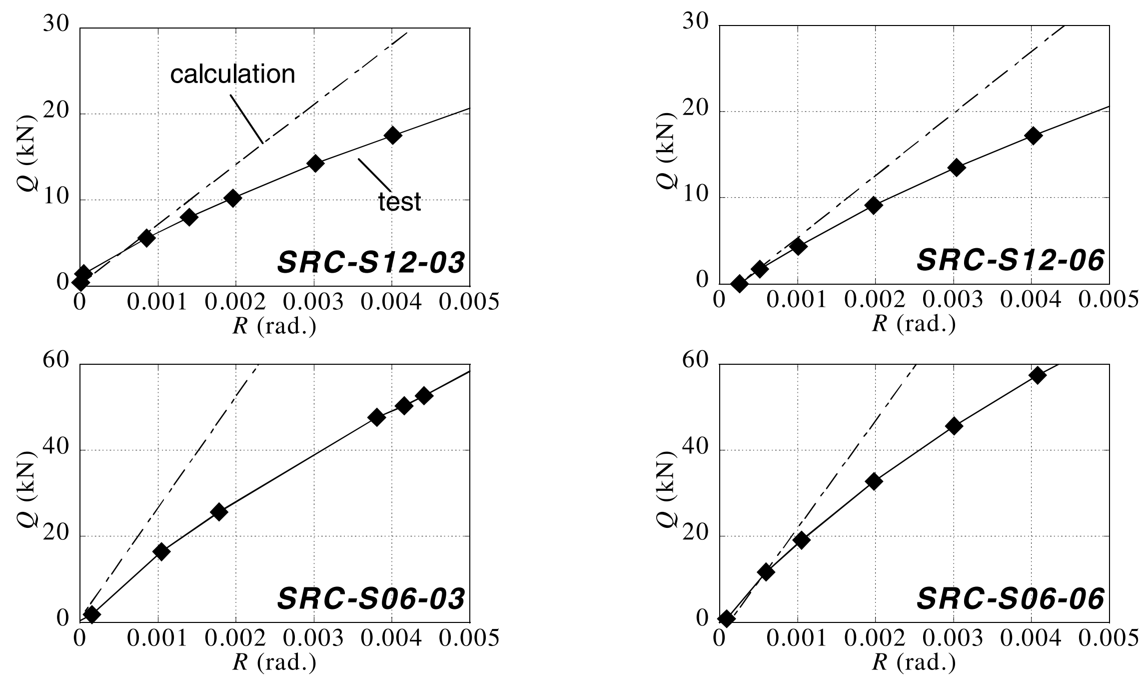


Fig.8 Comparison of Initial Rigidity

Flexural Strength

The method of simple superposition is adopted for calculating the flexural strength of the SRC column in AIJ design formula. A modified method is used for slender column, which taken in the consideration of the P-δ moment. Table5 shows the comparison of the strength. The experimental maximum strength ${}_{ex}M_{max}$ is calculated by Eq.(5).

Fig.9 shows the comparison of between the calculated ultimate flexural strength and the measured maximum strength. In Fig.9, the thick line means the ultimate flexural strength for the slender column. The thin line means that for the short column. The dotted line means the fully plastic moment, and the circles means the experimental maximum strength. The assumption in calculation is same as mentioned above. For the reduction factor of concrete strength ${}_{c}r_{U}$, Eq.(6) was used when the ultimate strength was calculated, Eq.(7) was used when the fully plastic moment was calculated.

The ratio of the measured maximum strength and the ultimate flexural strength calculated by AIJ design formula was 1.12-1.28. And, in case of L/D=6 specimens, experimental strength reached to the fully plastic moment. When the test result of slender column was compared with the AIJ design formulas for short column, the experimental maximum strength was estimated well.

$$4\,{}_{ex}M_{\max} = {}_{ex}Q_{\max} \cdot L \tag{5}$$

${}_{ex}M_{\max}$: experimental maximum strength, ${}_{ex}Q_{\max}$: measured maximum horizontal load

Table 5. Comparison of the Strength

	${}_{ex}M_{\max}$ (kNm)		M_p	${}_{cal}M_U$ (kNm)		${}_{ex}M_{\max}/{}_{cal}M_U$	
	plus	minus	(kNm)	slender	long	slender	long
SRC-S12-03	23.5	-23.3	23.9	22.7	**20.3**	1.04	**1.16**
SRC-S12-06	22.2	-22.1	25.5	22.3	**17.4**	1.00	**1.28**
SRC-S06-03	26.4	-25.8	25.1	**23.6**	22.9	**1.12**	1.15
SRC-S06-06	26.5	-25.0	25.9	**22.6**	21.3	**1.17**	1.24

${}_{ex}M_{\max}$: experimental maximum strength, M_p: fully plastic strength

${}_{cal}M_{\max}$: the ultimate flexural strength calculated by AIJ design formula

${}_{ex}M_{max}/{}_{cal}M_U$: the ratio of the experimental maximum strength and the ultimate strength

$$ {}_{c}r_U = 0.85 - 2.5\,{}_{s}p_c \tag{6}$$

$$ {}_{c}r_U = 1.0 \tag{7}$$

${}_{c}r_U$: reduction factor of concrete strength ${}_{s}p_c$: compression steel ratio

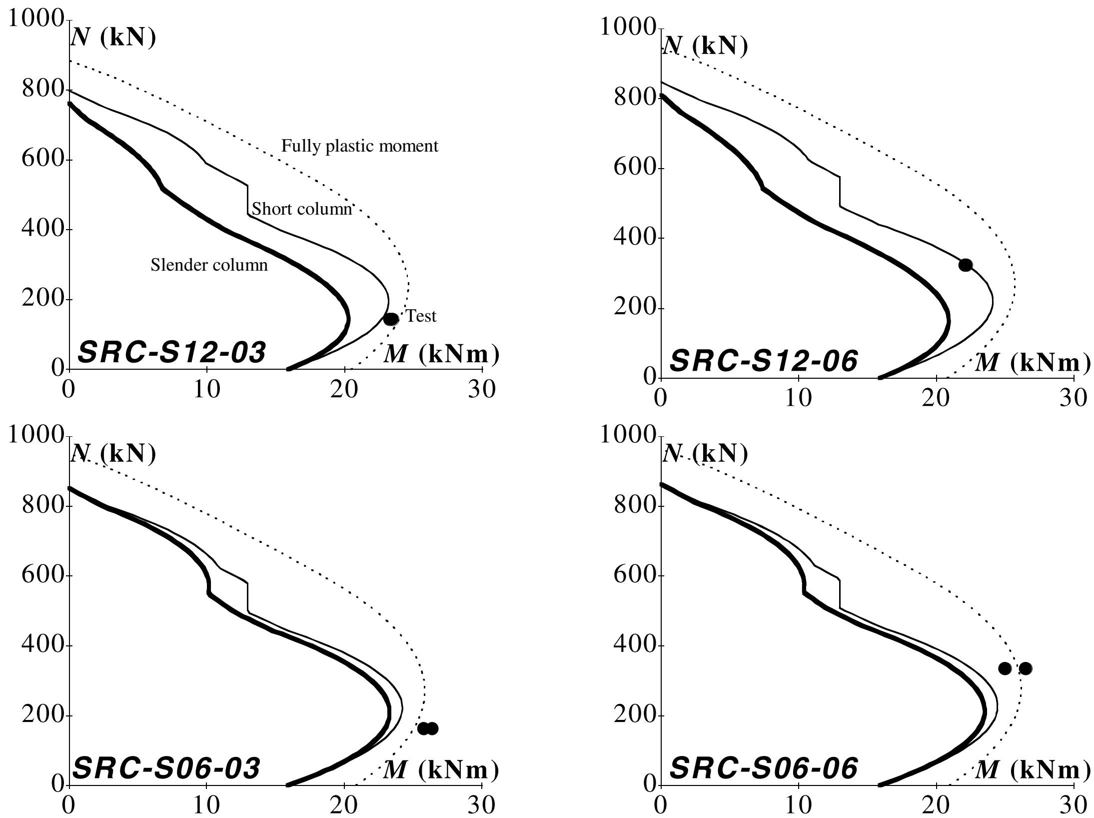


Fig.9 M-N Relations

Failure Mechanism

The crack pattern of each specimen in the final stage is shown in Fig.10. A flexural crack was observed at the cycle of 0.005rad in all specimens. In SRC-S12-06 and SRC-S06-06, the cover concrete fell off around the column. The failure mechanism of all specimens was the flexural failure.

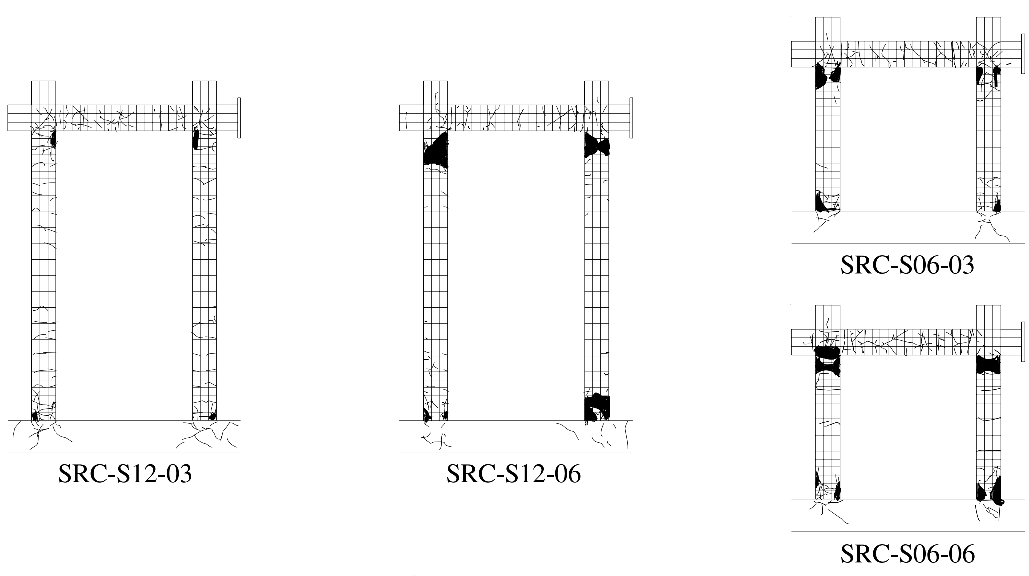


Fig.10 Crack Pattern (Final stage)

ANALYTICAL CONSIDERATION

Introduction

The calculated initial rigidity overestimated the experimental behavior, or fit only in the initial stage. The influence of the decrease of the effective geometrical moment of inertia and the nonlinearity of the material can be considered as the cause. Therefore it is excessive that the flexural rigidity of the column section is calculated by Eq.(3)

For grasp the actual flexural rigidity of the section, it is discussed about the relations between the bending moment M and the curvature ϕ, by using the section dividing method.

Assumptions

The following assumptions are used.

(1) Plane section before bending remains plane after bending.
(2) Shear deformation is ignored.
(3) Buckling of the steel and reinforcement doesn't occur.
(4) Tensile stress of the concrete is ignored.
(5) The stress-strain relations of the steel are defined as follows.
  H-section: Bi-linear model
  Reinforcement: Perfectly elastic plastic model
(6) The stress-strain relations of the concrete are defined as follows.
  Cover concrete: Popovics model [2.]
  Concrete restrained by hoop: Sakino-Sun model [3.]

The models of the stress-strain relation are shown in Fig.11.

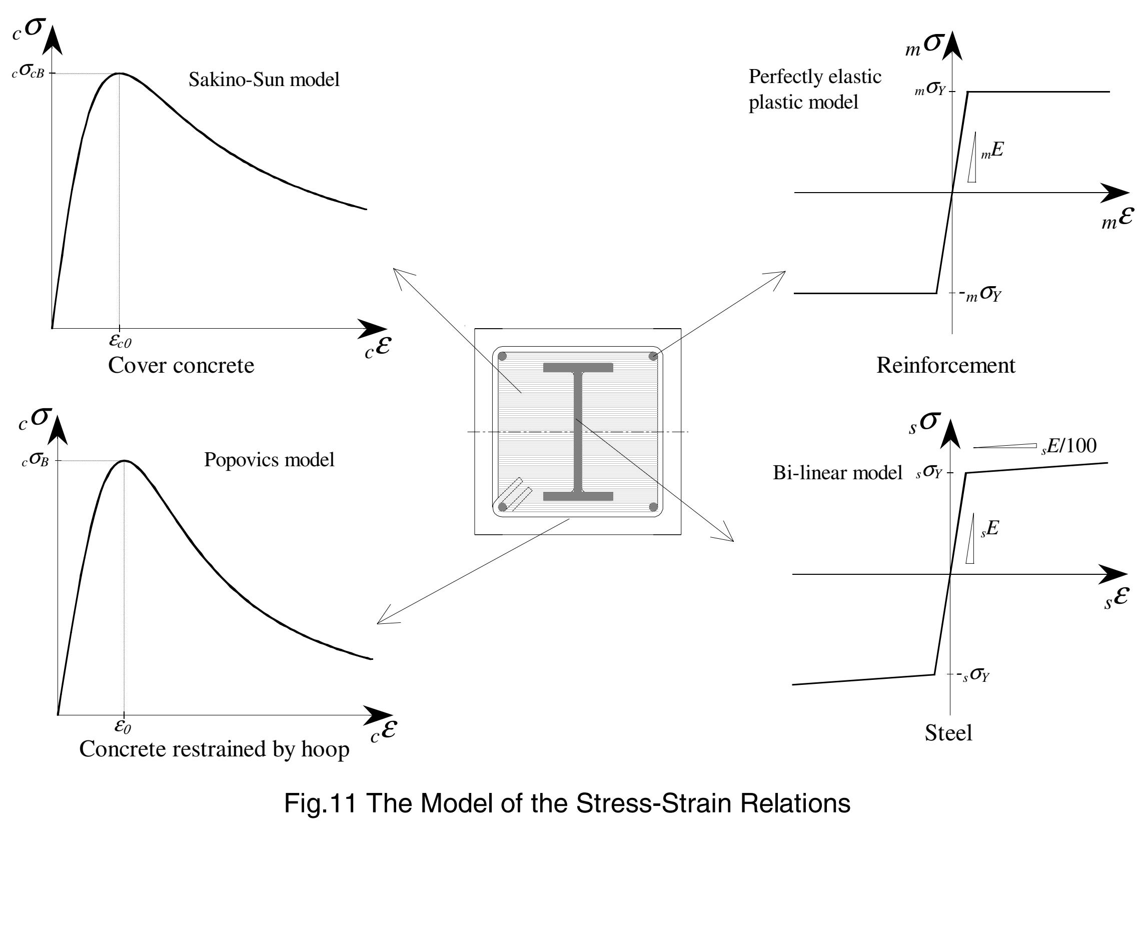


Fig.11 The Model of the Stress-Strain Relations

Method of Analysis

The section of the column was divided into a large number of strips (see Fig.12). Concrete part was divided into 50 strips. Steel flange and web part was divided into 3 strips and 20 strips respectively. Reinforcement is assumed to be the point with area. The strain ε_i of each element adopt in the point of the gravity of each element.

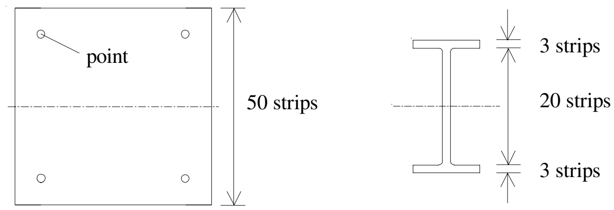


Fig.12 Divided the Section

Curvature ϕ was given to the section, and the strain of the central axis of the cross section ε_0 was assumed. The stress σ_i of element i is calculated from the stress-strain relations shown in Fig.11 and using assumption (1). Axial load N is calculated by using Eq.(8). The central strain of the section ε_0 was iterated so that axial load N is equal to applied axial load in experiment. The bending moment M is calculated by using Eq.(9). By increasing the curvature ϕ in turn and repeated this process, the M-ϕ relations of the section were calculated.

$$N = \sum ({}_s\sigma_i \cdot d_sA + {}_c\sigma_i \cdot d_cA) + 4\,{}_m\sigma \cdot {}_mA \tag{8}$$

$$M = \sum ({}_s\sigma_i \cdot d_sA \cdot y_i + {}_c\sigma_i \cdot d_cA \cdot y_i) + 2\,{}_m\sigma \cdot {}_mA \cdot {}_md \tag{9}$$

${}_s\sigma_i$, ${}_c\sigma_i$, ${}_m\sigma_i$: stress of element i (steel, concrete, reinforcement), d_sA, d_cA: area of element i (steel, concrete), ${}_mA$: area of reinforcement

y_i: distance between the center of gravity of cross section and element i, ${}_md$: distance between main re-bars

Result

The comparison of experimental behavior and the analytical result is shown in Fig.13. The experimental curvature ϕ was calculated by the strain obtained from WSG pasted on the steel flange of the part the bottom of column. The line connected with the points means experimental behavior. The thick line means

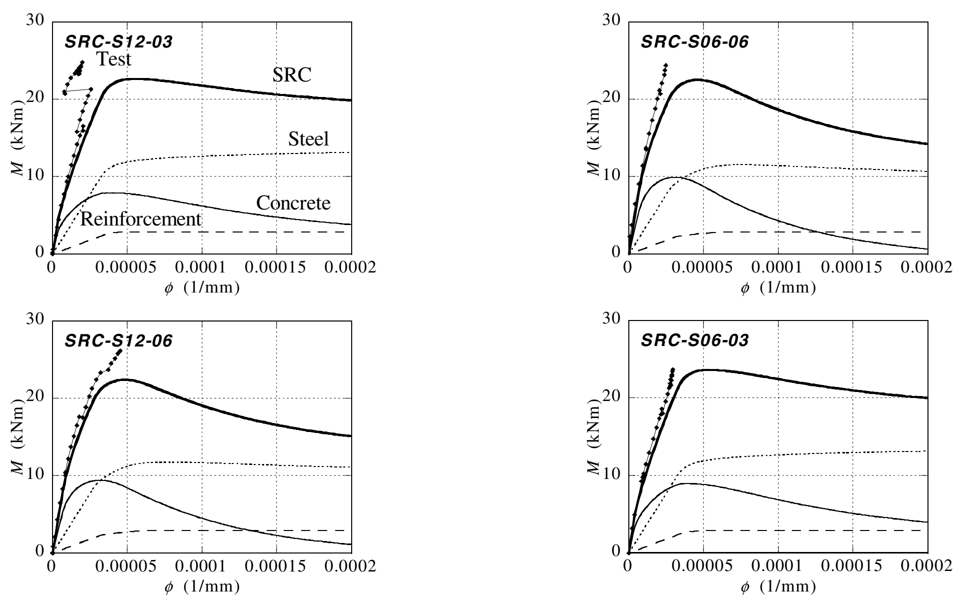


Fig.13 Results of Analysis

analytical result. The dotted, thin, dashed line means the part of the steel, concrete, reinforcement, respectively.

Comparison is effective in the elastic range and in the plastic range without reversal strain. Analytical result fit experimental behavior in the elastic range. The decrease of the section strength is the cause of that of the concrete part.

It is discussed that horizontal rigidity of the frame in consideration of the decrease of the flexural rigidity of the section. The flexural rigidity of this column ${}_{SRC}EI'$ is used as the rigidity of a secant between the origin and 0.6 times of the maximum value ${}_{an}M_{max}$ as shown in Fig.14. The results are shown in Fig.15. The chain line means horizontal rigidity of the frame based on above mentioned the flexural rigidity. Horizontal rigidity is estimated well in all specimens. The dashed line is mechanism line. In SRC-S12-03 and SRC-S06-03, the decrease of the section strength after the maximum strength is less than that of SRC-S12-06 and SRC-S06-06. The following two things are correspond with the M-f behavior above mentioned. The experimental behavior followed in the mechanism line after maximum strength in SRC-S12-03 and SRC-S06-03, and negative slope of experiment curve are larger than that of the mechanism line in SRC-S12-06 and SRC-S06-06.

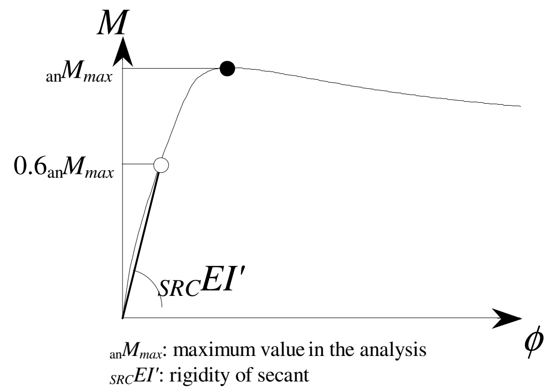


Fig.14 Rigidity of Secant

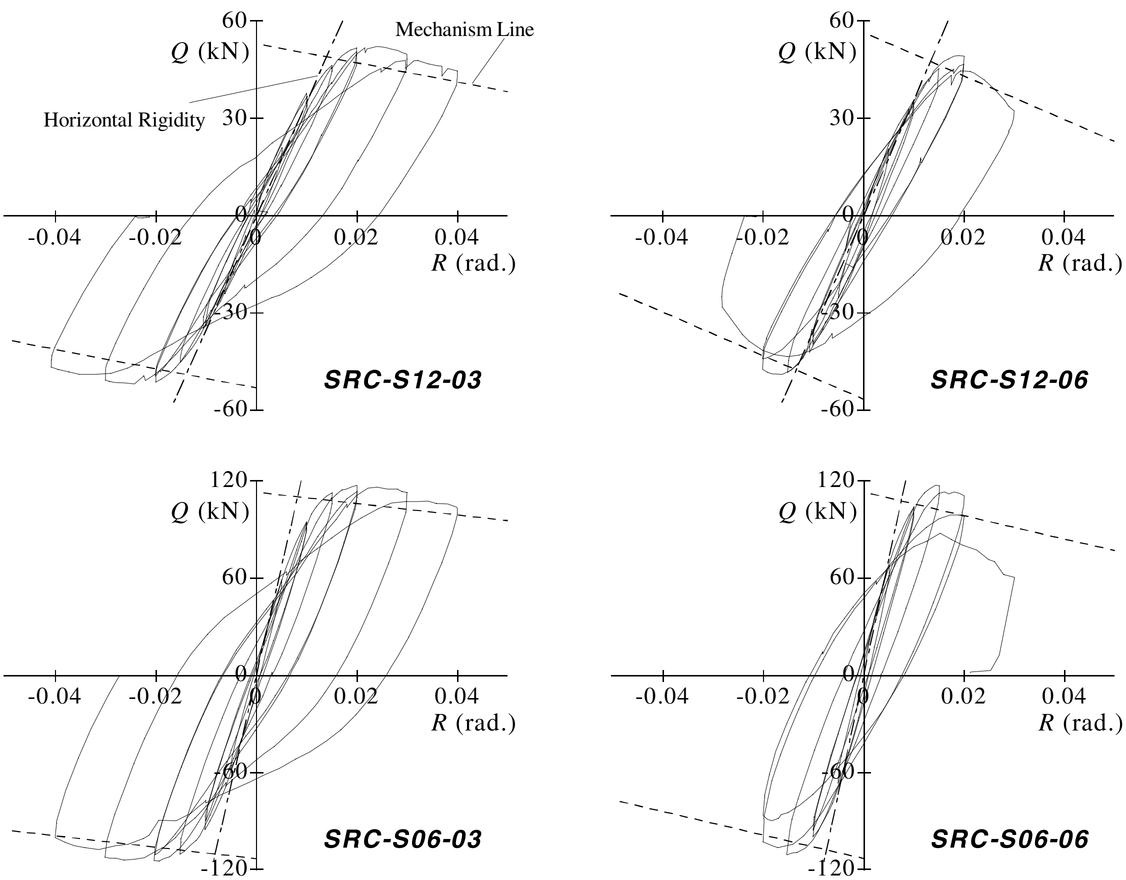


Fig.15 Comparison between Experimental Behavior and Analytical Result

CONCLUSIONS

An experimental work of the SRC frames having strong axis bending column subjected to cyclic lateral load under constant axial load was performed. And the influence of the strength and the deformation characteristics on two experimental parameters was investigated.

1) Though the experimental behavior of SRC-S12-06 and SRC-S06-06 fit the initial rigidity by the calculation in near 0.001 (rad.), the calculated initial rigidity overestimated experimental behavior in all specimens. After the maximum strength, the experimental behavior of SRC-S12-03 and SRC-S06-03 was stable and followed in the mechanism line. But negative slope of experiment curve are larger than that of the mechanism line in SRC-S12-06 and SRC-S06-06.
2) Twice loading was applied in the cycle of 0.01 (rad.) and 0.02 (rad.) respectively. Though no decrease of the strength is observed in the second cycle of 0.01 (rad.), it decreases greatly in the second cycle of 0.02 (rad.) in all specimens.
3) Experimental maximum strength was exceeded the ultimate strength calculated by AIJ design formula in all specimens by 12%-28%. In specimens of short column, the strength reached the fully plastic strength. The experimental maximum strength was estimated well when the test result of slender column compare with the AIJ design formulas for short column.
4) The failure mechanism of all specimens was the flexural failure.
5) Horizontal rigidity in consideration of the decrease of the flexural rigidity is estimated well in all specimens by using the rigidity of secant line between origin and 0.6 times of the analytical maximum value (${}_{an}M_{max}$).
6) The following two things can be predicted by analysis: the experimental behavior followed in the mechanism line after maximum strength in SRC-S12-03 and SRC-S06-03, and negative slope of experiment curve are larger than that of the mechanism line in SRC-S12-06 and SRC-S06-06.

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