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INELASTIC BEHAVIOR OF MIXED FRAMES COMPOSED OF DIFFERENT STRUCTURAL TYPES OF MEMBERS

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ABSTRACT

Behavior of mixed frames composed of different structural types of members was investigated by performing an experimental work. Specimens were L-shaped frames which were designed by considering the stress distributions of building frames under earthquake loading. Experimental parameter was a classification of structural types of members, and total five specimens were tested, which were frames composed of a reinforced concrete column and a steel wide flange beam and a frame composed of a steel reinforced concrete column and a steel wide flange beam, etc. This paper presents the results of the experimental work. An elastic - plastic analysis of L-shaped frames was performed in order to explain the experimental behavior of the frames. The analytical behavior agreed well with the experimental behavior. From the analytical results of parametoric study, it is discussed what is the condition in order to design the mixed frames composed of reinforced concrete or steel reinforced concrete columns which show good earthquake resistant properties.

KEYWORDS

Experimental work; elastic-plastic analysis; seismic design; axial load ratio; hoop ratio; reinforced concrete column; steel reinforced concrete column; steel wide flange beam

INTRODUCTION

A pure structural system composed of beams and columns made of steel, reinforced concrete (RC) and steel reinforced concrete (SRC) has been popular in Japan. However, development of a combined system of RC or SRC columns and steel wide flange beams is recently investigated. The frames composed of RC or SRC columns and steel wide flange beams are characterized as a good combination of the capability of carrying high gravity load of RC or SRC columns with the spannability of steel beams. Then construction of such mixed frames has been increasing. This trendency is based on the structural characteristics and capability to reduce the construction cost and time.

Key point of frames composed of RC columns and steel wide flange beams is the moment transfer mechanism at the beam-to-column connections and a number of innovations have been reported with the results of the proof tests in Japan. The outlines of details of beam-to-column connections are setting the moment transfer devices which rely on the bearing stress generated in concrete by the plying action, composed of vertical plates projected from the flange of the beam or steel tube. And the transferring mechanism of such connections has been clarified, and also transferring the stress from members to members smoothly has been confirmed (Nishimura and Minami, 1989; Sakaguchi, 1992; etc.).

However only a few researches have been reported on the behavior of frames under cyclic horizontal load like the earthquake loading. Especially, it has not been clear whether columns can deflect keeping the full plastic moment at the column base, until the plastic hinges are formed at beam ends. In this paper the behaviors of mixed frames composed of different structural types of members under earthquake loading are discussed.

TEST RESEARCH

Test Program

In order to study the behavior of mixed frames under earthquake loading, five specimens was tested. The specimens were L-shaped frames which were designed by considering the stress distributions of building frames subjected to vertical and horizontal loads (see Fig. 1). Experimental parameter is a classification of structural types of members. Test program is shown in Table 1. Shape and dimensions of the specimens are shown in Fig. 2. Hoop ratio p_w of the columns equals to 0.33% for all specimens. Three specimens composed of SRC columns were tested in order to compare with the behavior of the frames composed of steel wide flange beam, SC beam and SRC beam, where SC beam is the beam that concrete is filled between the beam

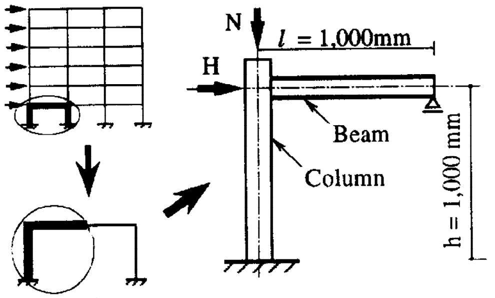
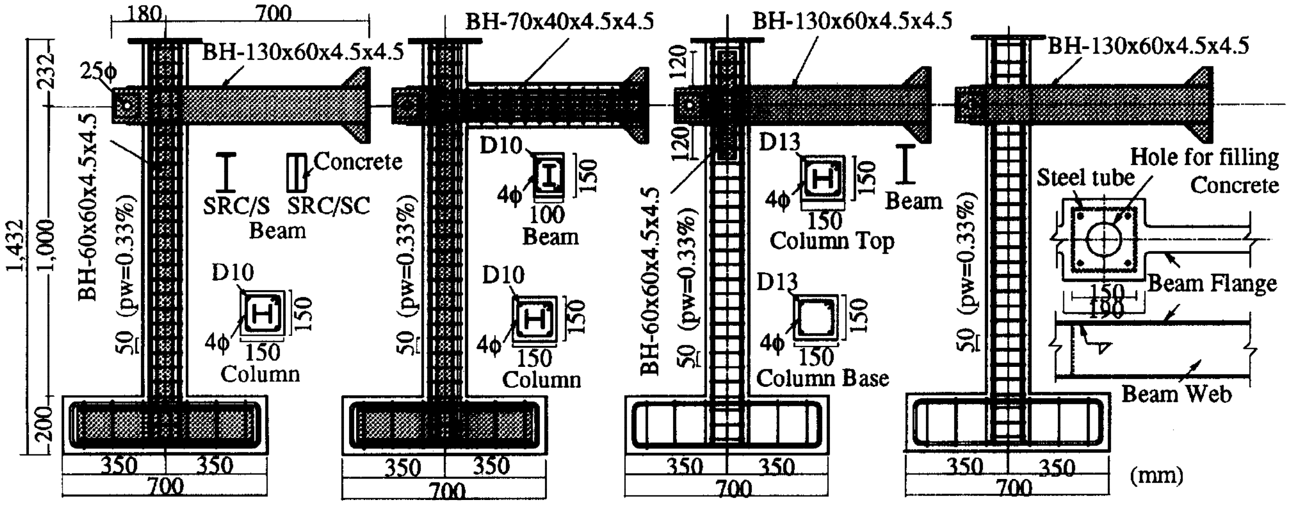


Fig. 1 Test Model

Table 1 Test Program

Specimen	Column	Beam
SRC/S	SRC	Steel Wide Flange
SRC/SC	SRC	Concrete Filled Wide Flange
SRC/SRC	SRC	SRC
RC/S-1	RC	Steel Wide Flange
RC/S-2	RC	Steel Wide Flange



(a) SRC/S and SRC/SC (b) SRC/SRC (c) RC/S-1 (d) RC/S-2

Fig. 2 Specimens

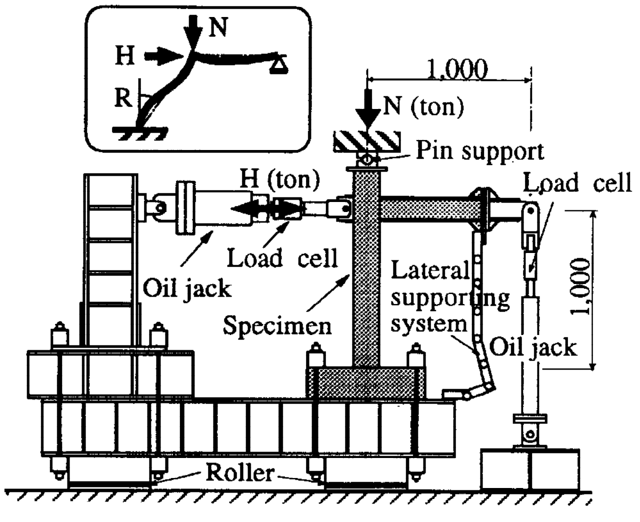


Fig. 3 Experimental Apparatus

Table 2 Mechanical Properties of Steel

	t, ϕ (mm)	σy (t/cm²)	σu (t/cm²)	Remarks
Steel Plate	t = 4.5	3.12	4.07	Wide Flange
Steel Bar	10	3.88	5.35	Main Bar (SRC)
	13	3.60	5.33	Main Bar (RC)
	4	2.90	3.88	Hoop (SRC,RC)

Table 3 Ultimate Strength of Members

Specimen	Column cMpc (t m)	Beam bMp (t m)	cMpc / bMp	Shear Strength of Connection pMp (t m)
SRC/S	1.87	1.54	1.21	2.05
SRC/SC	1.87	1.77	1.06	2.20
SRC/SRC	1.87	1.39	1.35	1.90
RC/S-1	1.81	1.54	1.18	2.05
RC/S-2	1.81	1.54	1.18	5.46

flanges. Two specimens composed of RC columns and steel wide flange beam were tested in order to compare with the behavior of the frames of SRC column and wide flange beam and to compare with the behavior of frames with different reinforcing way of beam-to-column connection. RC/S-1 was designed so that a part of the column was SRC member on the upper and lower of the beam-to-column connection panel (see Fig. 2 (c)). The connection panel of RC/S-2 was reinforced by a built up square steel tube welded to a diaphragm with a hole for filling concrete (see Fig. 2 (d)).

All specimens were designed so as to form the first plastic hinge at the column base and the second one at the beam end under horizontal load and not to be broken at the beam-to-column connection. The average compressive strength of concrete Fc was 227 kg/cm^2. The flexural strength of the members and the shear strength of the beam-to-column connection are shown in Table 3. Loading apparatus is shown in Fig. 3. The cyclic horizontal load H was applied at the column top under constant vertical load N = 0.3 No on the column, where No is the compressive strength of the column section. The axial load 0.3 No corresponds to the axial load of columns at first story of middle - high rise buildings.

Results of Test

The experimental relations of horizontal load H and the rotation angle of the column R are shown in Fig. 4. In this figure, the dotted lines indicate the relationships of theoretical load and deflection which is composed of three regions; the first condition is column and beam in elastic, the second is column in plastic and beam in elastic, the third is column and beam in plastic. The full plastic moment of the cross section in the plastic hinge was calculated by using the yield strength of steel and the reduced concrete strength Fc' [AIJ, 1987].

$$F_c' = (0.85 - 2.5 \cdot {}_sp_c) \cdot F_c \qquad (1)$$

Where ${}_sp_c$ = compression steel ratio, Fc = compressive strength of concrete

All specimens attained the strength that the beam and the column keep each full plastic moment. For all specimens, crushing of the concrete began at the column base at R = 1.5/100 rad., and at last the frames collapsed at the column base. Four specimens except RC/S-1 attained the maximum strength at R = 2/100 rad., and RC/S-1 reached at R = 1.5/100 rad.. The strength of the frames composed of SRC column deteriorated slowly after displacement exceeded the value corresponding to maximum strength by crushing of concrete, buckling of main bar (at R = 3.5/100 rad.) and steel flange (at R = 4/100 rad.). There was not a large difference between H-R relations of three specimens SRC/S, SRC/SC and SRC/SRC. The specimens composed of RC column could not hold axial load and collapsed brittly at the column base (at R = 2/100 rad. for RC/S-1 and R = 2.5/100 rad. for RC/S-2). There is a difference between the deformation capacity of the two specimens composed of RC column, however these frames collapsed at the column base in the same way, so it did not depend on the difference of the reinforcing way at the connection.

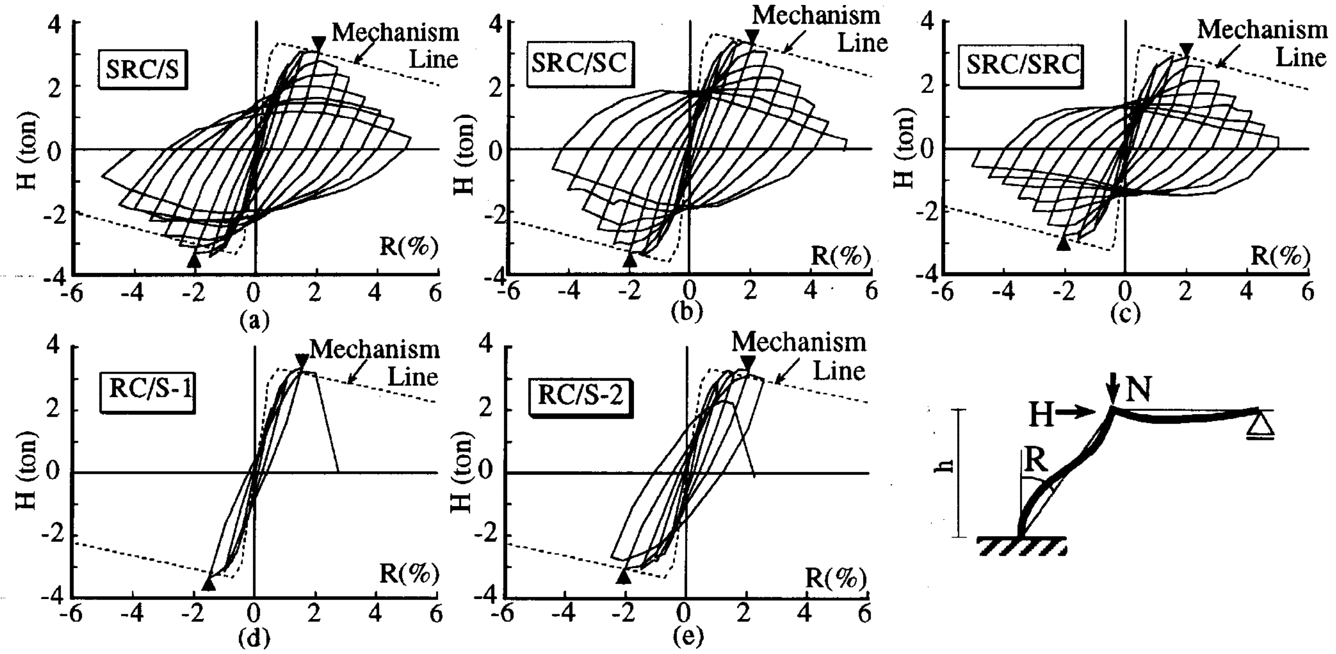


Fig. 4 Experimental relations of horizontal load and rotation angle of column

Comparison between Analytical Results and Test Results

The analytical results of relationships of moment at the column base cMbase and rotation angle of column R are shown in Fig. 8, comparing with the test results. In the test results buckling of the main bar occurred at R

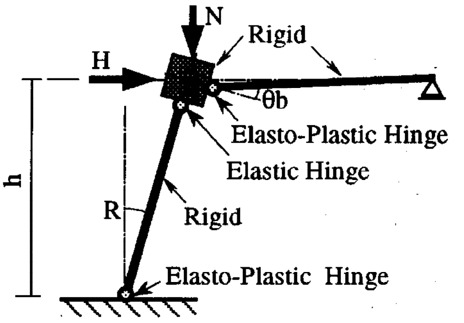
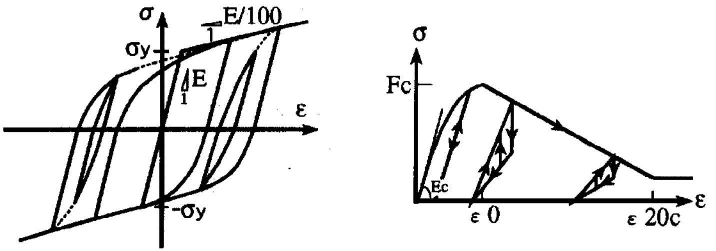


Fig. 6 Analytical model



(a) Steel

(b) Concrete

Fig. 7 σ – ε relations

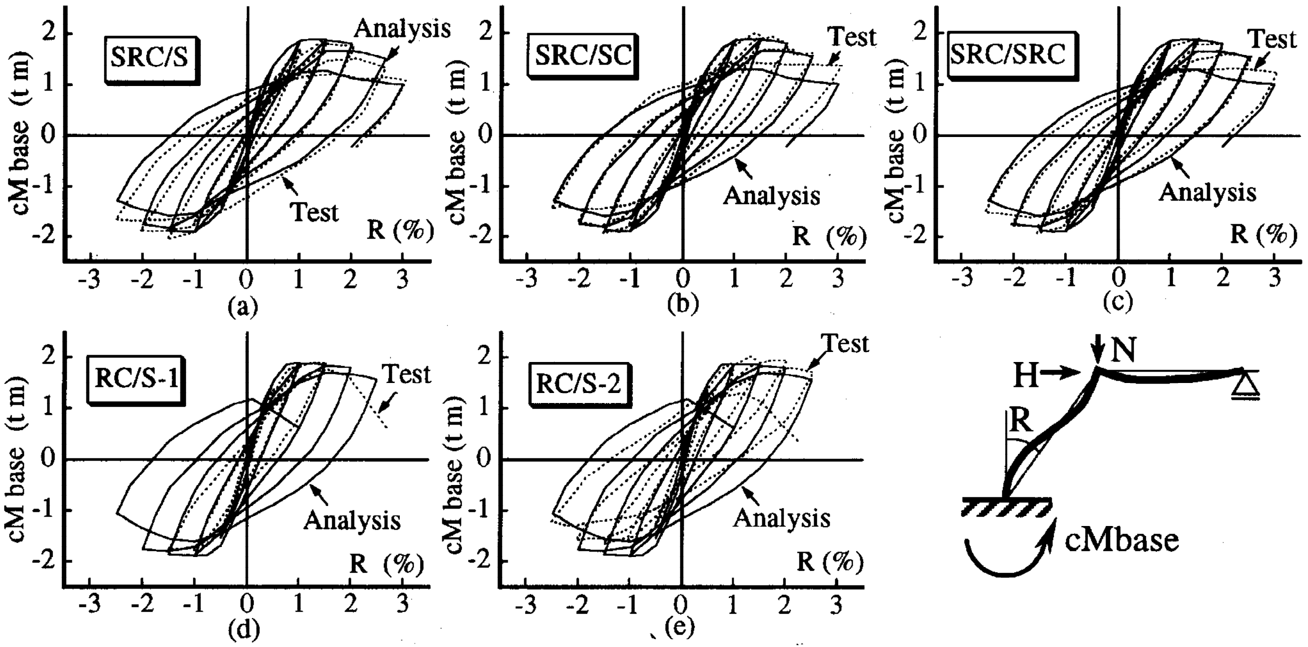


Fig. 8 Comparison of analytical results and test results for behavior of column bases

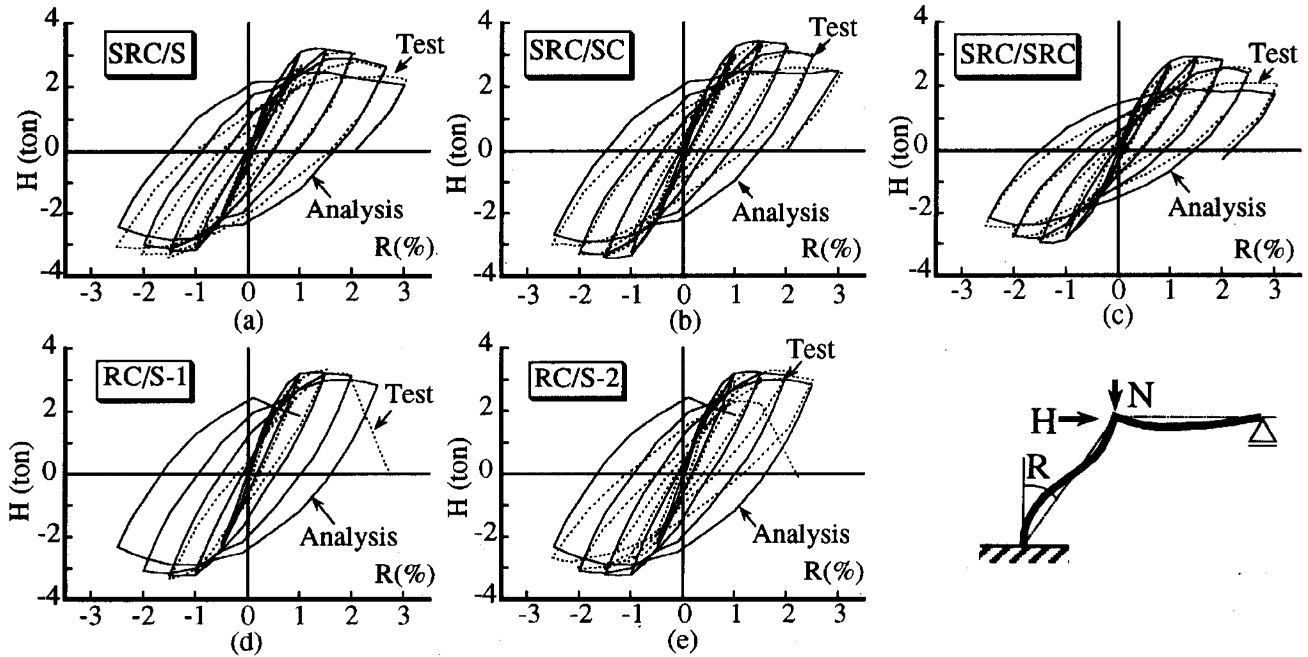


Fig. 9 Comparison of analytical results and test results for behavior of frames

= 3.5/100 rad. for all frames with SRC columns, so the analytical relations were calculated up to the rotation angle of the column R = 3/100 rad.. In this figure, solid lines indicate the analytical results and dotted lines show the experimental results. Deterioration of moment capacity in the analysis is due to the deterioration of concrete strength after the concrete strain exceeded the value corresponding to the maximum strength. The RC columns can not hold the axial compressive load N = 0.3 No, and the moment deteriorates suddenly. On the other hand the SRC columns show the strength deteriorates slowly by crushing of concrete. The analytical results agree well the test results for all specimens. The calculated results of horizontal load H and rotation angle of column R are shown in Fig. 9. The analytical results show a little larger energy dissipation capacity than the test results, however it seems that the analytical results agree well the test results for all specimens.

Parametoric Study

From both the test results and the analytical results, it has become clear that the behavior of the frame depends on the behavior of the column. The behavior of columns depends on mainly the axial compressive load and the hoop ratio. So the effect of these factors on the behavior of columns was studied in this research. Analytical parameters are shown in Table 4. Analytical model, size of cross sections and mechanical properties of steel and concrete are the same of the test condition.

Table 4 Analytical Parameters

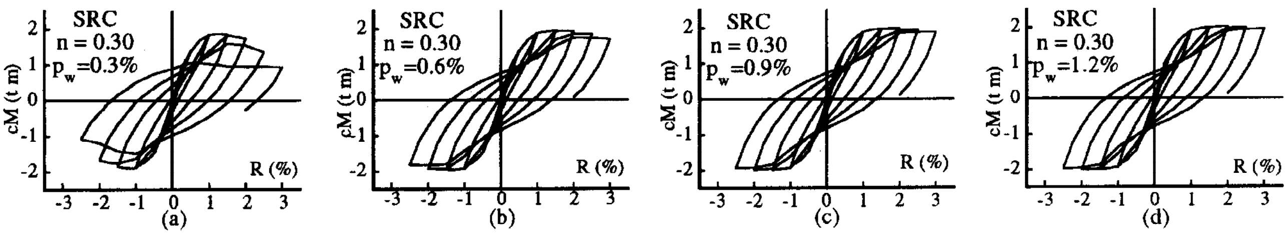
Type of column	Axial load ratio **n**	**n'**	Axial load N (ton)	Hoop ratio p_w	Remarks
RC column	0.20	0.27	13.9	from 0.2% to 1.2%	bDFc = 51.1ton sA sσy = 18.3 ton
	0.30	0.40	20.8		
	0.40	0.54	27.8		
	0.50	0.68	34.7		
SRC column	0.20	0.34	17.2	from 0.1% to 1.2%	bDFc = 51.1ton sA sσy = 35 ton (H-shaped steel; 24.0 ton)
	0.30	0.51	25.8		
	0.40	0.67	34.4		
	0.50	0.84	43.1		

n = N / (bDFc + sA sσy), **n'** = N / (bDFc)

where sσy: Yield stress of steel
b,D: Width and depth of column section
Fc: Compressive strength of concrete
sA: Area of steel section

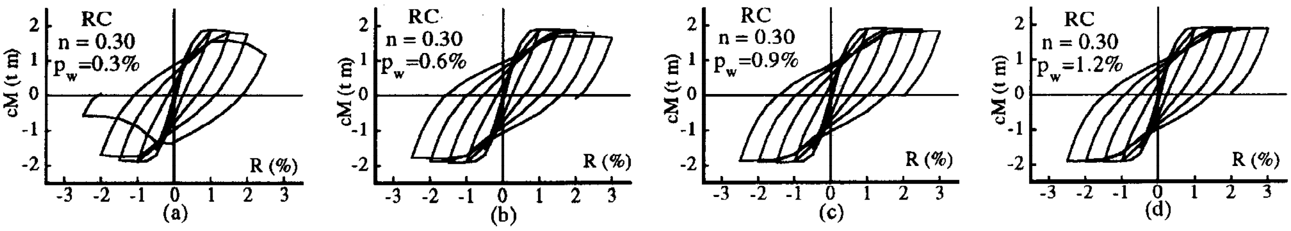
The calculated results for SRC columns with **n** = 0.3 are shown in Fig. 10. From this figure, it is clear that the resisting moment deteriorates at rotation angle R = 2.5/100 rad. on the condition **n** = 0.3 and p_w = 0.3%, however the behavior become good for columns with hoop ratio pw = 0.6%. The calculated results for RC columns with **n** = 0.3 are shown in Fig. 11. From this figure, it is clear that the column corresponding to the specimen composed of RC column (**n** = 0.3, p_w = 0.33%) is unstable about R = 2.5/100 rad. (see Fig. 11 (a)), however the behavior of RC column with pw = 0.6% shows stable.

Relations of the axial load ratio **n** and required hoop ratio pw satisfying criterion shown in Table 5 were studied. The results are shown in Fig. 12, and the behaviors of column are shown from Figs. 13 to 16.



(a) (b) (c) (d)

Fig. 10 Behavior of SRC columns

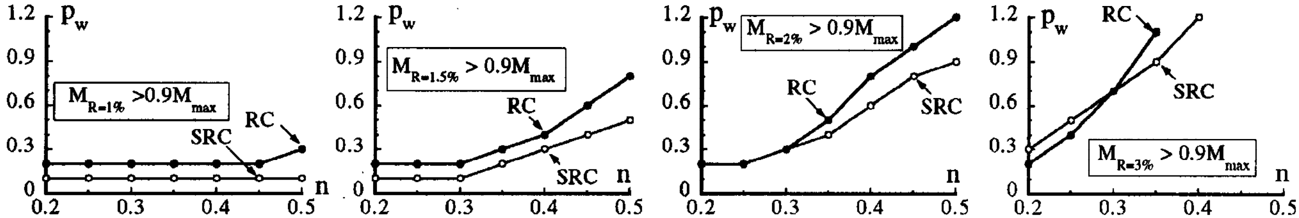


(a) (b) (c) (d)

Fig. 11 Behavior of RC columns

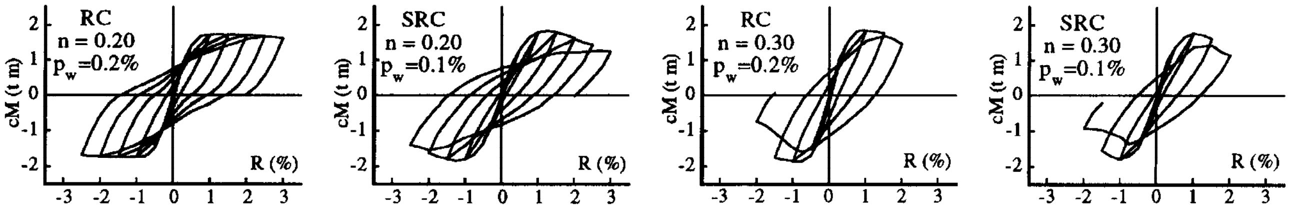
Table 5 Criterion

Rank	Criterion
I	Resisting moment keeps 0.9 times of maximum strength at R = 1/100 rad.
II	Resisting moment keeps 0.9 times of maximum strength at R = 1.5/100 rad.
III	Resisting moment keeps 0.9 times of maximum strength at R = 2/100 rad.
IV	Resisting moment keeps 0.9 times of maximum strength at R = 3/100 rad.

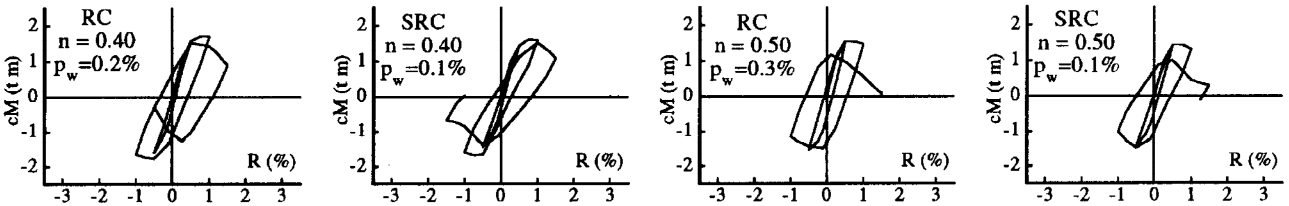


(a) Criterion I (b) Criterion II (c) Criterion III (d) Criterion IV

Fig. 12 Relations of axial load ratio and hoop ratio satisfying criterions

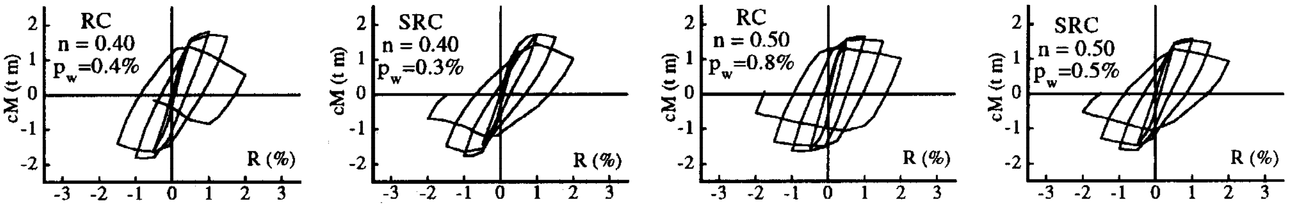


(a) RC, n = 0.20 (b) SRC, n = 0.20 (c) RC, n= 0.30 (d) SRC, n=0.30



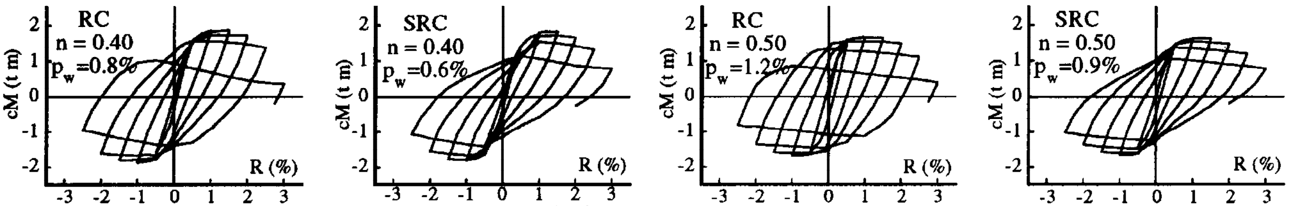
(e) RC, n = 0.40 (f) SRC, n = 0.40 (g) RC, n = 0.50 (h) SRC, n = 0.50

Fig. 13 Behavior of columns satisfying the criterion I



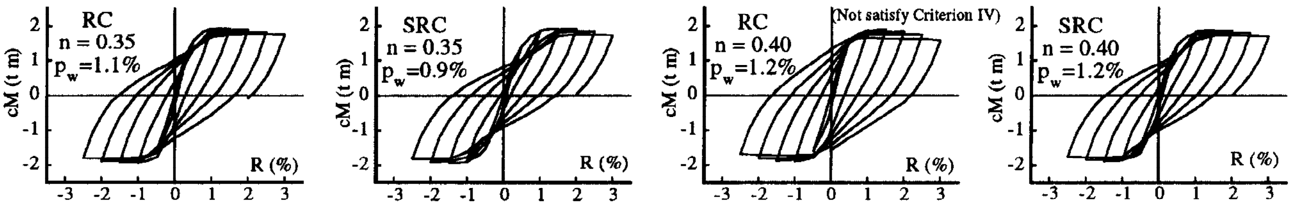
(a) RC, n = 0.40 (b) SRC, n = 0.40 (c) RC, n = 0.50 (d) SRC, n = 0.50

Fig. 14 Behavior of columns satisfying the criterion II



(a) RC, n = 0.40 (b) SRC, n = 0.40 (c) RC, n = 0.50 (d) SRC, n = 0.50

Fig. 15 Behavior of columns satisfying the criterion III



(a) RC, n = 0.35 (b) SRC, n = 0.35 (c) RC, n = 0.40 (d) SRC, n = 0.40

Fig. 16 Behavior of columns satisfying the criterion IV

In case of the columns satisfying the criterion I, the required hoop ratio is almost the minimum value for RC columns and SRC columns prescribed in AIJ standard [AIJ, 1991, AIJ, 1987] . RC columns show the same behaviors of SRC columns for all axial load ratios. The columns satisfying the criterion I with **n** = 0.2 show stable, however the column with high axial load ratio show poor earthquake resistant properties. The strength of columns with **n** = 0.4 and 0.5 deteriorate rapidly at rotation angle R = 1/100 rad.. The behavior of columns satisfying the criterion II with higher axial load ratio are shown in Fig. 14. The required hoop of the columns satisfying the criterion II with n = 0.2, 0.25, 0.3 are same in the criterion I, however more hoop is required in the criterion II with large axial load ratio, and the behavior of columns satisfying the criterion II is better than the behavior of columns satisfying the criterion I. The behavior of columns with large axial load ratio satisfying the criterion III are shown in Fig. 15. The columns satisfying the criterion III shows much better earthquake resistant properties than the columns satisfying the criterion I and II. The criterion IV is the most strict condition, however the strength of the columns satisfying this criterion does not deteriorate up to the rotation angle R = 2/100 rad. For all criterions, hoop ratio of SRC columns is required less than one of RC columns except the criterion IV and lower axial load.

CONCLUSIONS

It has become clear from the test results that;

1) The frames composed of SRC column with hoop ratio $p_w = 0.33\%$ and steel wide flange beam showed stable hysteresis loops, though the strength deteriorated after the rotation angle of the column was 2/100 rad. by crushing of concrete and buckling of main bars and steel flanges at the column base.
2) The frames composed of SRC column and concrete filled wide flange beam, and SRC column and SRC beam showed almost the same behavior of the frame composed of SRC column and steel wide flange beam.
3) The frames composed of RC column with pw = 0.33% and wide flange beam could not hold axial load and collapsed and showed poor energy dissipation capacity comparing with the frames of SRC column and steel wide flange beam.
4) For all specimens, the behavior of frames depended on the behavior of column, and the flexural strength of the column section deteriorated at the base when the story moment of the frame reached the maximum.

It has become clear from the analytical results that;

5) The analytical behaviors agreed well the experimental behaviors for all specimens.
6) Frames which the strength does not deteriorate until the rotation angle attains 3/100 rad., can be designed for RC columns and SRC columns by using sufficient hoop.
7) Relations of axial load ratio and required hoop ratio for columns satisfying some criterion indicated in Table 5, are shown in Fig. 12. The behavior of columns satisfying the criterions are shown from Figs. 13 to 16.

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