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CYCLIC BEHAVIOR OF STEEL FRAMES INFLUENCED BY LOCAL AND LATERAL BUCKLING

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SUMMARY

Steel portal frames subjected to constant vertical and alternating horizontal loads are tested in order to clarify the influence of local and lateral buckling in columns on the strength and behavior of steel rigid frames. Test strength is compared with theoretical strength by the plastic hinge method and the Merchant - Rankine formula, and it is recognized that the Merchant-Rankine formula shows a good agreement with the test strength. Furthermore, deformation capacity and energy absorption capacity are investigated.

INTRODUCTION

In order to establish method of plastic design and seismic design for steel building frames, it is needed to study the elastic-plastic behavior of frames up to the final collapse state. Actual steel building frames have various values of width-to-thickness ratio and slenderness ratio in the members. Then it is not doubtful that local and lateral buckling phenomena may appear in the members of a frame under external loading. Concerning this problem, we tested a series of steel portal frame specimens, having several width-to-thickness ratios in columns and slenderness ratios about out-of-plane of columns under the constant vertical and varying horizontal loads. Each effect of local or lateral buckling in column was reported at the 7th WCEE (Ref.1).

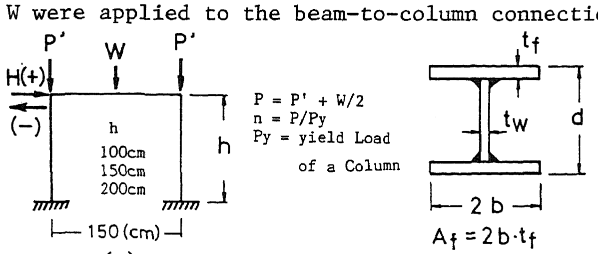
This paper presents the effects of local and lateral buckling in columns on the behavior and strength of mild steel portal frames under constant vertical and alternating horizontal loads and compares with the past test results (Ref.1 and 2). Ten specimens are tested for the purpose mentioned above.

TEST PROGRAM

The shape and loading conditions of frame specimens are shown in Fig.1. Specimens were welded by using columns and beams of mild steel wide flange sections. The size of columns and beams is shown in Table 1. Column cross sections are built up by welding and beam cross section is a hot rolled wide flange shape and is kept constant size. Specimens were proportioned to yield plastic hinges at columns. The panel plate of a beam-to-column connection is strengthened by welding doubler plates to protect yielding in shear prior to yielding of the members in bending.

The name of specimens, test parameters and material properties in each frame are shown in Table 2. Specimen name is indicated in the form of [A] - [B][C] , where [A] - [B] means the column cross section as shown in Table 1 and [C] column height (h = 100, 150 and 200cm, when [C] = 1, 2 and 3, respectively). Main test parameters are selected as follows; width-to-thickness ratios, b/tf and d/tw, concerned with flange and web local buckling, slenderness ratios about out-of-plane, h/iy, concerned with lateral buckling. A parameter h·d/Af also concerns with lateral buckling in columns and it is indicated in Table 2. Axial load ratio n(=P/Py) of a column is 0.3. The symbols are shown in Fig.1 and Table 2. Table 3 shows the nominal values of parameters in each frame. The values of the parameters obtained by nominal dimensions of members are as follows: b/tf=8.3, 11.1, 15.6, d/tw= 31.3, 42.2, h/iy=58.6-89.6, h·d/Af=250-844.

The amplitude of horizontal displacement is increased by 0.5% of the column height h in a stepwise manner every two cycles of loading completed. The properties of the materials in columns, yield stress σy, tensile strength σu, and yield stress ratio $\sigma y/\sigma u$, are shown in Table 2. The supporting conditions of a frame are as follows (Fig.2); the bottom of a column is fixed in bending, the top of a column and the center of a beam are restricted to the rotation about the y-axis, the top of a column is elastically restrained to the rotation about the x-axis. Test apparatus and loading systems are shown in Fig.3. The vertical loads P' and W were applied to the beam-to-column connection of a frame by the hydraulic jack.



(a) (b) Column Section

Fig.1 Specimen and Loading Conditions

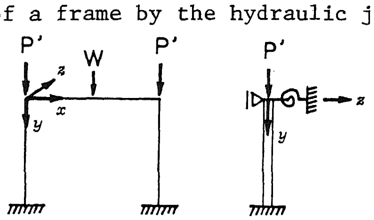


Fig.2 Supporting Conditions

Table 1 Cross Sections of Members

(a) L - Series

Member	Group	d	2b	tw	tf	b/tf	d/tw	Remarks
Column	L-1	100	100	3.2	6	8.3	31.3	Built up
	L-2	100	100	3.2	4.5	11.1	31.3	
	L-3	100	100	3.2	3.2	15.6	31.3	
	L-4	135	100	3.2	6	8.3	42.2	
	L-5	135	100	3.2	3.2	15.6	42.2	
Beam		100	100	6	8	6.3	16.7	Rolled

(b) T-Series (Ref.1)

Member	Group	d	2b	tw	tf	b/tf	d/tw	Remarks
Column	T-1	100	50	3.2	6	4.2	31.2	Built up
	T-2	100	50	3.2	3.2	7.8	31.2	
Beam		100	100	6	8	6.3	16.7	Rolled

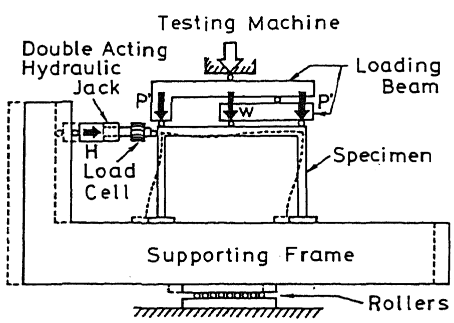


Fig.3 Experimental Arrangement

Table 2 Test Program

	Loading Condition			Parameters					Materials			
Frame Name	P (t)	W (t)	n= P/Py	b/tf	d/tw	h/ix	h/iy	h·d/Af		σy t/cm^2	σu t/cm^2	$\sigma y/\sigma u$
L-12	16.3	6.0	0.3	8.3	30.9	34.5	58.1	246	f	3.56	4.80	0.74
									w	3.43	4.34	0.79
L-22	11.3	4.1	0.3	11.4	30.9	34.7	60.7	338	f	3.05	3.76	0.81
									w	3.25	4.33	0.78
L-32	8.7	3.3	0.3	16.1	31.1	35.3	64.1	475	f	3.17	4.31	0.74
									w	2.60	3.33	0.78
L-42	13.5	5.2	0.3	8.0	41.8	25.7	60.8	326	f	2.73	3.97	0.69
									w	2.61	4.19	0.62
L-52	8.4	3.4	0.3	15.9	41.4	26.7	68.7	646	f	2.59	4.20	0.62
									w	2.64	4.23	0.62
L-13	13.7	5.5	0.28	8.1	32.3	45.8	76.7	318	f	3.20	4.57	0.70
									w	2.57	4.21	0.61
L-23	10.4	5.4	0.3	11.5	31.1	46.2	81.9	462	f	3.00	4.32	0.69
									w	2.57	4.21	0.61
L-33	7.3	4.4	0.3	16.2	31.9	46.8	86.7	656	f	2.61	4.17	0.63
									w	2.57	4.21	0.61
L-43	13.7	6.1	0.3	7.9	42.6	34.3	80.5	427	f	2.73	3.97	0.69
									w	2.61	4.19	0.62
L-53	8.4	4.2	0.3	16.1	41.0	36.1	92.2	874	f	2.59	4.20	0.62
									w	2.64	4.23	0.62

Table 3 Nominal Parameters

	h = 100 cm			h = 150 cm			h = 200 cm		
Group	hd/Af	h/iy	h/ix	hd/Af	h/iy	h/ix	hd/Af	h/iy	h/ix
L-1	167	39.1	22.9	250	58.6	34.3	334	78.2	45.8
L-2	222	40.1	23.0	333	60.1	34.5	444	80.2	46.0
L-3	313	42.6	23.4	469	63.9	35.1	626	85.2	46.8
L-4	225	40.2	17.0	338	60.3	25.5	450	80.4	34.0
L-5	422	44.8	17.7	633	67.2	26.6	844	89.6	35.4
T-1	333	84.7	24.2						
T-2	625	98.0	25.1						

ix, iy : radii of gyration of a column for in-plane and out-of-plane in flexure
f : flange plate, w : web plate
σy : yield stress, σu : tensile strength,
$\sigma y/\sigma u$: yield stress ratio

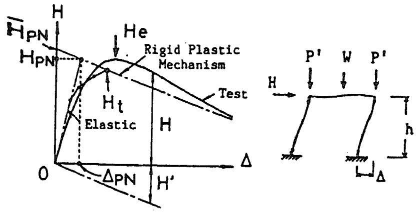
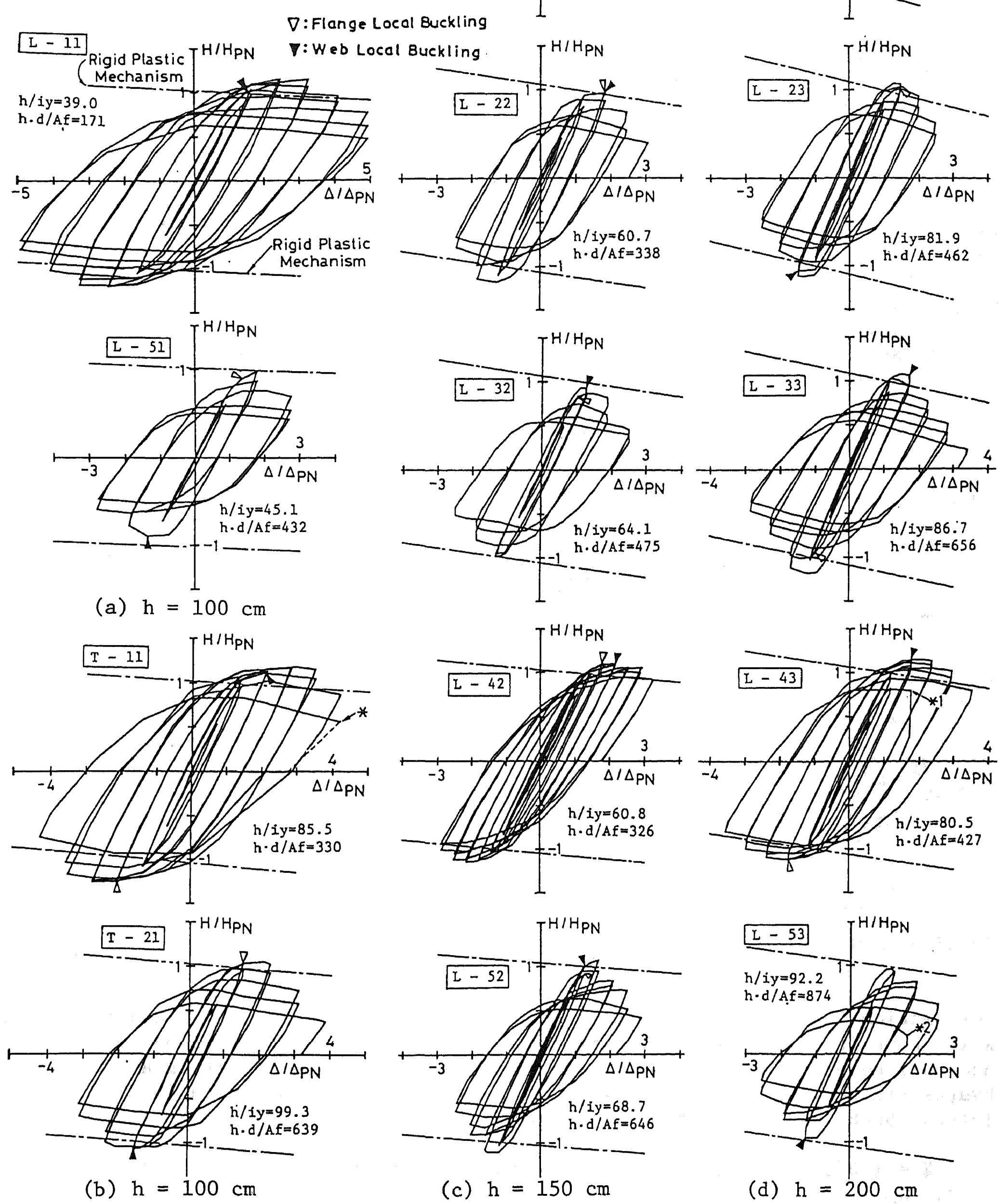


Fig.4 Definition of Symbols



(a) h = 100 cm

(b) h = 100 cm (c) h = 150 cm (d) h = 200 cm

Fig.5 Experimental Results under Alternating Horizontal Load

The points and the method of measurement of out-of-plane deformation of columns are shown in Fig.6.

TEST RESULTS

Figure 5 shows non-dimensional loading history in the relation between horizontal load H and horizontal displacement Δ. Figure 5(a) and (b) are the test results reported at the 7th WCEE and column height of these frames is 100cm. In this figure, the marks ∇ and ▼ indicate the points at the first occurrence of flange local buckling and web local buckling in column, respectively. Dash-dot line indicates the plastic collapse mechanism of a frame. The mark * shown in Fig.5(b) means a point that the frame could not sustain vertical load. In Fig.5 (d), the mark *1 is the point that the loading system could not follow the out-of-plane deformation of a column, and the mark *2 indicates the point that the plastic hinge formed near the center of a column about weak axis due to the increase of out-of-plane deformation and the frame collapsed.

The following observations are made from the test results: (1) Deterioration of the horizontal force starts at the occurrence of web local buckling induced after flange local buckling in a column. (2) It shows a tendency that the load carrying capacity of a frame with large width-to-thickness ratio in columns cannot attain the mechanism line independent of the values of h/iy and h·d/Af. (3) The out-of-plane deformations were observed in the columns of the frames with h = 150 and 200cm in the early horizontal stages as shown in Fig.7. However, we could not recognize the bifurcation point of lateral buckling in the frames.

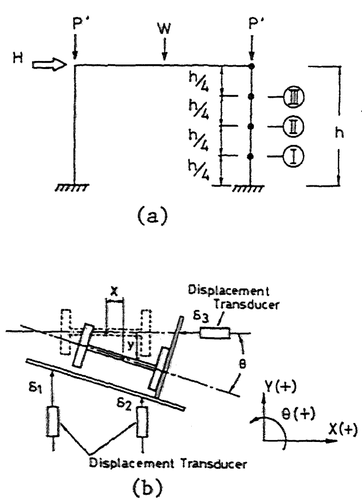


Fig.6 Measurement of Out-of-Plane Deformation

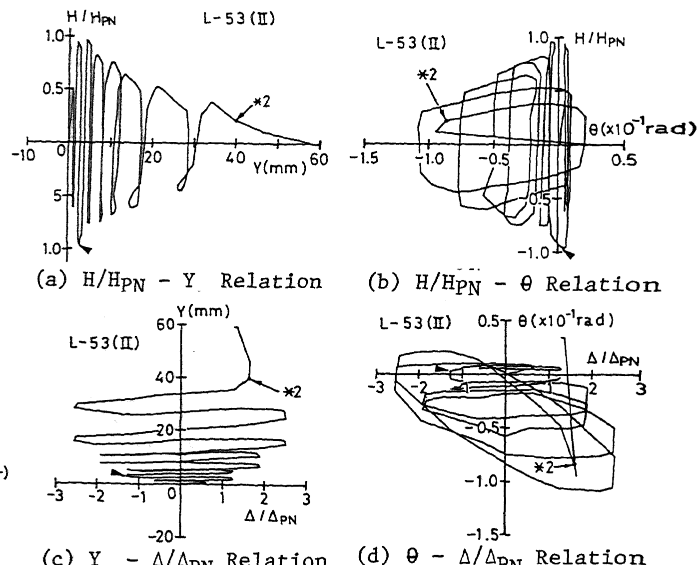


Fig.7 An Example of Out-of-Plane Deformation at the point II (L - 53)

<u>Deformation Capacity</u> The relation between deformation capacity R and parameter X is shown in Fig.9, where deformation capacity $R(=\Delta m/\Delta_{PN} - 1)$ is based on the accumulated plastic displacement at the maximum horizontal force in accumulated hysteretic curve as shown in Fig.8. X is an index concerned with local and lateral buckilng and defined as follows;

$$X = (b/tf)\cdot\sqrt{\sigma yf/E}\cdot\{(d/tw)\cdot\sqrt{\sigma yw/E}\cdot(h/iy)\}^{1/2} \qquad (1)$$

where σyf, σyw and E are the yield stresses of flange and web plates and Young's modulus, respectively. The test results are compared with the past test results of the frames under monotonic horizontal load. We can recognize a good correlation between deformation capacity R and parameter X, and the influence by the difference between monotonic and cyclic loading is small on the deformation capacity. In the figure, a dash-dot line indicates a regression curve obtained by using least square method and the line is expressed as the following equation.

$$R = 17.1\,X^{-2} + 3.3\,X^{-1} \qquad (2)$$

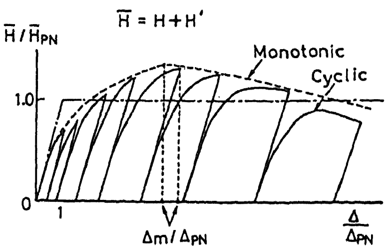


Fig.8 Definition of Deformation Capacity

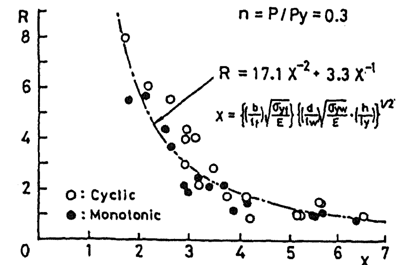


Fig.9 Deformation capacity R versus Parameter X

Horizontal Strength of Frames The experimental strength of the frames He is compared with the theoretical one Ht obtained by using the plastic hinge method, ignoring the effects of buckling phenomena in members and strain-hardening of materials (Fig.10). The relation between He/Ht and b/tf is shown in Fig.10(a). We can recognize the correlation between strength and flange local buckling in columns. He/Ht - h/iy relation is shown in Fig.10(b). There is no correlation between these two parameters. Fig.10(c) shows the relation between He/Ht and h·d/Af instead of h/iy. We can recognize that the experimental strength becomes smaller than the theoretical one in case of the frame with large b/tf and h·d/Af.

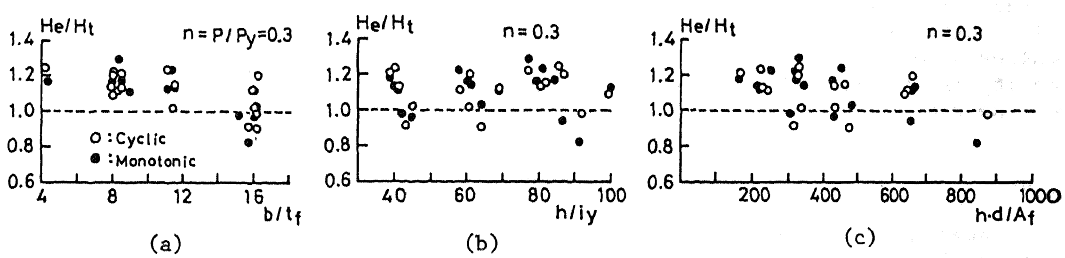


Fig.10 Comparison of Test and Theoretical Results

Test results are compared with the Merchant-Rankine formula for the strength of steel frames (Fig.11). It is assumed that the formula is to be expressed for the loading conditions of the test frames.

$$H_f/\overline{H_{PN}} + P/Pe = 1.0 \qquad (3)$$

where H_f, $\overline{H_{PN}}$, Pe, P are the failure load, the rigid plastic collapse load, the elastic critical load and the applied vertical load of a frame, respectively. It is well known that the formula is not considered the influence of local and lateral buckling in a frame. However, it seems to show a fairly good agreement with the test results affected by local and lateral deformations. It may be said that the formula is effective for steel frames even if in the case that plastic hinges form at columns and the behavior is affected by instability phenomena besides the P·Δ effect.

Energy Absorption Capacity The relations between the accumulated energy $\Sigma Wi/(H_{PN}\cdot\Delta_{PN})$ and plastic displacement $\Sigma\Delta i/\Delta_{PN}$ are shown in Fig.13. Definition of symbols is given in Fig.12. The values in parentheses in the figure denote the

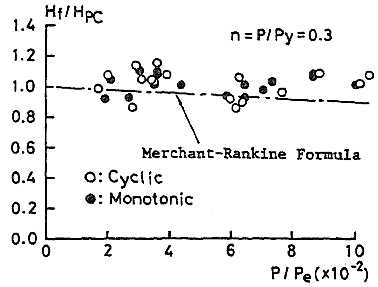
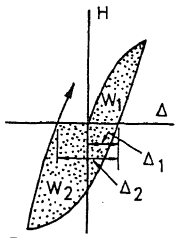


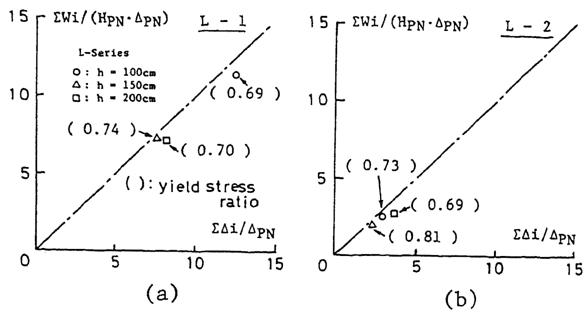
Fig.11 Comparison of Test and Merchant-Rankine Formula



$\Sigma W_i = W_1 + W_2 + \cdots$

$\Sigma \Delta_i = \Delta_1 + \Delta_2 + \cdots$

Fig.12 Definition of ΣWi and ΣΔi



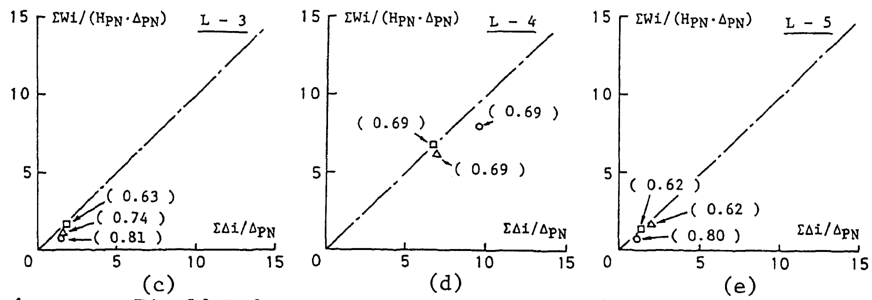


Fig.13 Relations between Accumulated Energy and Plastic Displacement

yield stress ratios. When evaluating Wi and Δi in each cycle of loading, these hysteretic loops are taken up to the maximum horizontal load that the specimen has experienced, and this figure shows the influence of slenderness ratios concerned with lateral buckling in the same conditions of b/tf, d/tw. We can recognize that energy absorption capacity becomes smaller with the increase in the values of width-to-thickness ratio and slenderness ratio. Energy absorption capacity is affected by the material properties of each frame, especially yield stress ratio, too.

CONCLUSIONS

Steel portal frame specimens were tested under the constant vertical and alternating horizontal load. The merchant-Rankine formula shows a good agreement with the experimental strength within engineering accuracy. Energy absorption capacity of the frames becomes smaller as the value of width-to-thickness ratio and slenderness ratio about out-of-plane of a frame becomes large. However, the influence of h/iy and h·d/Af disappears with the increase in the values of width-to-thickness ratio. Energy absorption capacity is affected by the material properties, especially yield stress ratio. The horizontal strength of the frames is influenced by the strain-hardening of the materials rather than the lateral-torsional deformation in the range of the test conditions, since the out-of-plane deformation is small at the maximum horizontal load.

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