ELASTO-PLASTIC AND COLLAPSE BEHAVIOR OF BRACED FRAMES

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SUMMARY

To investigate the elasto-plastic and collapse behavior of braced frame having relatively large bracing, cyclic loading test was carried out. Constant and incremental horizontal sway amplitude tests were performed. Elasto-plastic deformation behavior was analized using three points model (Ref.1) as the cross section and I-K model (Ref.2) as the behavior of the mild steel. Agreement between the analytical elasto-plastic behavior and experimental one is fairly well. It is shown that the elasto-plastic and collapse behavior of the braced frame having relatively large bracing is affected by the stiffness and strength of the bracing and also by the loading history.

INTRODUCTION

A bracing is one of the important aseismic elements of the steel structure. Various kinds of the ordinary designed braced frames were experimented and it was found that the elasto-plastic behavior of the braced frame can be obtained by adding the behaviors of the frame and bracing (Ref.3). This paper presents the elasto-plastic and collapse behaviors of the braced frame with relatively large bracing. Alternately repeated cyclic loading tests under the constant and incremental horizontal sway amplitude conditions are performed. The influence of stiffness and strength of the bracing on elasto-plastic and collapse behavior of the braced frame is investigated. The width to thickness ratio of the bracing cross section is varied and the effect of this ratio on the collapse behavior is discussed.

Elasto-plastic analysis using three points model as the cross section and I-K model as the stress-strain relationship considering the Bauschinger's effect and the cyclic hardening effect of the material are performed and compared with the experimental results.

ANALYSIS

Specimen tested are shown in Fig.1. Elasto-plastic deformation analysis is carried out under the following assumptions. Wide flange sections subjected to strong axis and weak axis bending are simplified into three points model (Ref.1) having the same cross sectional area, moment of inertia and fully plastic moment as the original ones such as shown in Fig.2.

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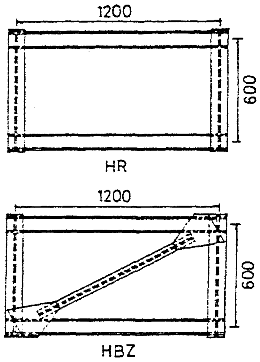


Fig.1 Specimen

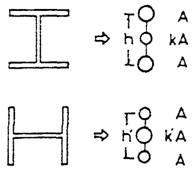


Fig.2 Three Points Model

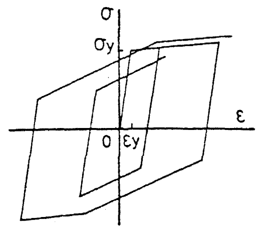


Fig.3 Stress-Strain Relationship

Table 1 Test Specimen

Specimen	Beam and Column	Bracing	S	D
HR	H-100x100 x6x8			
HBZ1	H-100x100 x6x8	H-100x50 x5x7	35.8	80
HBZ2	H-100x100 x6x8	H-100x50 x3.2x3.2	38.0	65

S: Slenderness Ratio
D: Distribution Coefficient of Lateral Force (%)

Table 2 Mechanical Properties

	Flange		Web	
	σy	σmax	σy	σmax
H-100x100x6x8	2.99	4.29	3.27	4.47
H-100x50x5x7	3.04	4.21	3.05	4.42
H-100x50x3.2x3.2	3.01	4.45	3.01	4.45

σy: Yield Stress (t/cm^2)
σmax: Tensile Strength (t/cm^2)

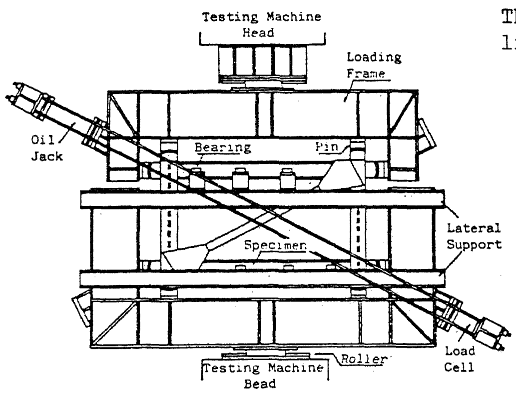


Fig.4 Loading System

Cyclic stress-strain relationship is initially bi-linear and subsequently tri-linear type such as shown in Fig.3 (Ref.2). Considering kinematic hardening and isotropic hardening rules, this model shows the Bauschinger's effect and cyclic hardening effect. From the buckling mode observed, the bracing is treated as the centrally compressed or tensioned simply supported bar whose effective length is a half length of the bracing. Each member is divided into eight line elements. Elasto-plastic behavior of the braced frame is obtained by the numerical integration procedure. Behaviors of the bracing and the surrounding frame are obtained separately. Load deformation relation of the braced frame is obtained by the summation of the resistances of the frame and the bracing at the same deflection. Some of the results are shown in Figs.5(c), 6(c) and 7(b). This analysis ignores the local buckling and fatigue crack effects.

Table 3 Test Series

Specimen	Axial Force of Column	δha(cm)	δhp(cm)
HR	1/3Ny	2.0	
	1/3Ny	4.0	
	1/3Ny	6.0	
HBZ1	1/3Ny	2.0	0.6
	1/3Ny	4.0	0.9
	1/3Ny	6.0	
HBZ2	1/3Ny	4.0	0.9
	1/3Ny	6.0	

δha: Constant Displacement Amplitude
δhp: Increment of Displacement Amplitude

EXPEIMENT

Fig.1 shows the specimen tested. Three kinds of specimens were tested such as shown in Table 1. HR indicates the unit rigid frame without bracing and HBZ the frame with single bracing. HBZ1 has relatively stocky bracing than HBZ2 specimen. To investigate the interaction behavior between the frame and bracing, relatively large bracings were used. All the members except for the bracing of HBZ2 specimen were made of rolled wide flange sections. The bracing of HBZ2 specimen was made of welded built-up wide flange section. The column was arranged to subject the weak axis bending such as shown in Fig.1. The bracing was rigidly jointed to the frame with gusset plate. Mild steel is used and the mechanical properties of the materials tested are shown in Table 2.

Fig.4 shows the loading system. The test specimen was set in the loading frame through pin-roller supports. Constant axial load of the column was applied by the testing machine. And the horizontal force was applied diagonally by the oil jack with load cell. To prevent the lateral buckling, upper and lower beams were supported by the roller bearings. Displacements were measured by the dial gages and strain distributions by wire strain gages.

Loading conditions of the test is shown in Table 3. The magnitude of the constant vertical load of the column is 1/3 of the yield axial force of the member (N_y). Alternately repeated cyclic horizontal loads were applied under the constant and incremental horizontal displacement amplitude conditions. Cyclic loadings were continued until the fracture at some parts of the specimen observed.

EXPERIMENTAL RESULTS

Load-Displacement Relationship

Fig.5 (a)-(d) show the horizontal load-deflection relationship of the frames without barcing. Under initial few loading cycles, the strength increases gradually with the increase in the number of the loading cycles due to the cyclic hardening effect of the material and also of the column under axial compressive load. As the cyclic loading proceeds, the local buckling deformation of the column flange increases. Fatigue cracks appears at the buckled flange tip of the column and the deterioration of the strength occurs. These fatigue cracks spreaded gradually to the web.

Figs.6-8 show the load-deflection relationship of the braced frames under the constant and incremental deflection amplitude tests. Decrease in the strength after the buckling of the compression bracing is large in the case of the specimen HBZ1. In the case of the constant deflection amplitude test, the strength on the compression side of the bracing deteriorates due to the Bauschinger's effect of the material and to the residual buckling deformation of the bracing, as the cyclic loading proceeds. The load-deformation relations in the tension side of the bracing show the slip type loop at the first few cycles. As the cyclic loading continued, the buckling deformation of the bracing did not disappear at the tension side loading, and the strength decreases gradually. Deterioration of the strength increases also due to the local buckling and fatigue crack at the column and bracing flanges.

In the case of the incremental deflection amplitude test, maximum stength deteriorates at the first few cycles due to the Bauschingers effect of the material, on the compression side of the bracing. In the case of the incremental deflection amplitude tests, the buckling deformation of the bracing almost disappeared at the tension side loading. And the strength does not change so much after the few loading cycles.

Experimental results coincide fairly well with the analytical ones in the first few cycles. As the cyclic loading proceeds, deterioration of the strength occurs to the experimental result due to the local buckling deformation and fatigue crack.

Vertical Deformation

Figs.11-12 show the relationship between the vertical deformation of the column and the number of the loading times. The former shows the results of the constant deflection amplitude tests and the latter the incremental ones. The solid line shows the result of HBZ1 specimen having stocky bracing, the dot-and-dash line the HBZ2 specimen and the broken line the HR specimen without bracing.

Axial deformation increases with the increase in the deformation amplitude. In the case of the braced frames, the increment in the axial deformation is large at the tension side loading of the bracing due to the large axial force induced to the column and the beam. Axial deformation of the column increases as the stiffness and strength of the bracing increases because of the interaction between the bracing and the surrounding frame. As the axial deformation increases, local buckling deformation of the flange and web of the column increases and the deterioration of the resistance occurs.

Deterioration of the Strength

Figs.9-10 show the relationship between the maximum strength and the number of the loading times (x 1/2 Cycle). The frame without the bracing show the cyclic hardening behavior until the fatigue crack appears at the column flange, in spite of the local buckling deformation of the column flange. ● shows the strength at the tension side of the bracing and o shows the strength at the compression side.

In the case of the constant deformation amplitude tests, the maximum strength decreases as the increase of the number of the loading cycles, because of the difference of the mechanism of deformation of the bracing at the tension and compression side loading. Under the small displacement amplitude tests, the difference of the strength between the tension and compression side loading of the bracing is large. As the deformation amplitude increases, the maximum strength decreases with the increase in the number of the loading cycles, regardless of the tension and the compression side loading of the bracing. This is due to the fact that the axial deformation and the fracture of the column are large in the case of the large deformation amplitude tests. The strength of HBZ2 specimen having the bracing composed of relatively thin plate element converges to that of the frame without bracing, as the cyclic loading proceeds.

In the case of the incremental deformation amplitude tests, the maximum strength decreases in the first few cycles at the compression side loading of the bracing due to the Bauschinger's effect and increases gradually in the tension side loading due to the plastic elongation of the bracing. Strength decreases after the local buckling deformation increases and the fatigue crack appears at the column and bracing flanges.

Collapse Mode of the Specimen

Cyclic loadings were continued until the fracture occured at some part of the specimen. Table 4 shows the number of the loading times when the local buckling or the fatigue crack appeared. The local buckling of the column flange appeared first except for the specimen HBZ2 having the bracing with relatively thin plate element. In the case of HBZ2 specimen, the local buckling of the bracing flange occured first. The local buckling of the column web occured early in the case of the braced frames. Fatigue crack at the flange of the bracing of HBZ2 specimen occured at an early stage. First crack of the bracing observed at the tension flange in the case of HBZ2 specimen, while in the case of HBZ1 specimen having stocky bracing, crack observed at the compression flange at the buckling deformation. In the case of the bracing having relatively thin flange, the local buckling occurs at both sides of the flange. Tension flange at the buckling deformation subjects the bending compressive stress at the initial stage of the tension side loading and then buckling occurs at the flange.

Local buckling deformation and fatigue crack at the column flange increases as the stiffness and strength of the bracing increases due to the interaction behavior of the bracing and the frame. The local buckling of the beam occured only to HBZ1 specimen, because of the large axial force induced to the beam and column when the tensile force is applied to the bracing.

Fig.13 shows the plastic deformation of the column and bracing. In the case of the column, the horizontal deformation is linearly proportional to the plastic rotation angle θ, while in the case of the bracing the horizontal deformation is proportional to the second power of the plastic rotation angle θ. Consequently, damage of the bracing is large in the case of small deflection amplitude test and damage of the surrounding frame is large in the case of large deflection amplitude tests. In the case of incremental deflection amplitude test,, the bracing is damaged seriously due to the initial small deflection amplitude loadings. Fig.14 shows the state of some

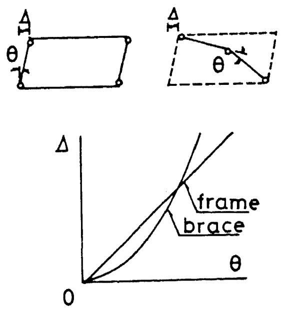
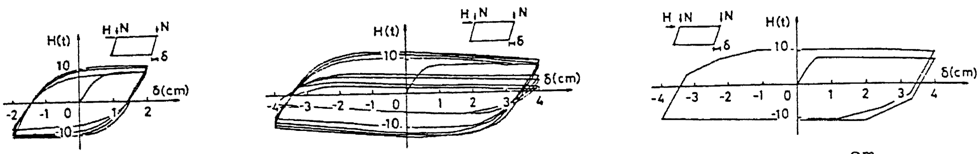


Fig. 13 Plastic Deformation

Table 4 History of Damage (1/2 cycle)

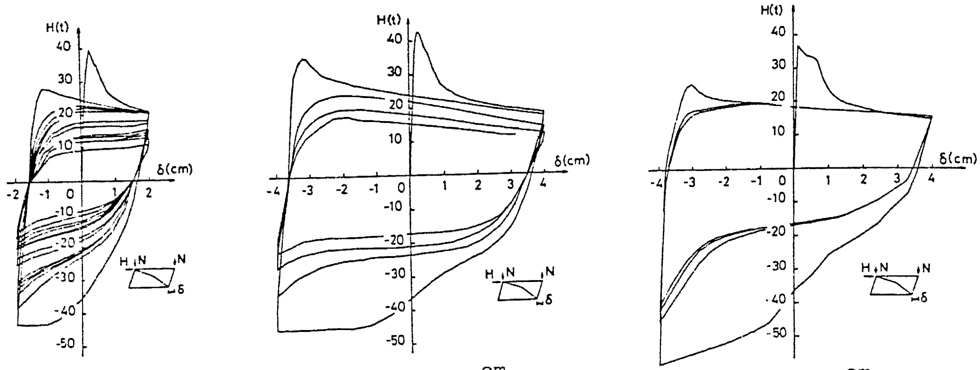
Specimen	Loading History	COLUMN			BEAM		BRACING	
		FLB	WLB	FCR	FLB	WLB	FLB	FCR
HR	2.0	4			18		/	/
	4.0	1	11	3				
	6.0	1	11	2				
HBZ1	2.0	2		6	26	26	3	12
	4.0	1	1	3	2		3	2
	6.0	1	1	2	2	4	3	2
	p.0.6	5	7	8	10			8
	p.0.9	3	5	6	8			6
HBZ2	4.0	1	1	5			1	3
	6.0	1	1	2			1	2
	p.0.9	3	3				1	5

FLB: Flange Local Buckling
WLB: Web Local Buckling
FCR: Flange Crack



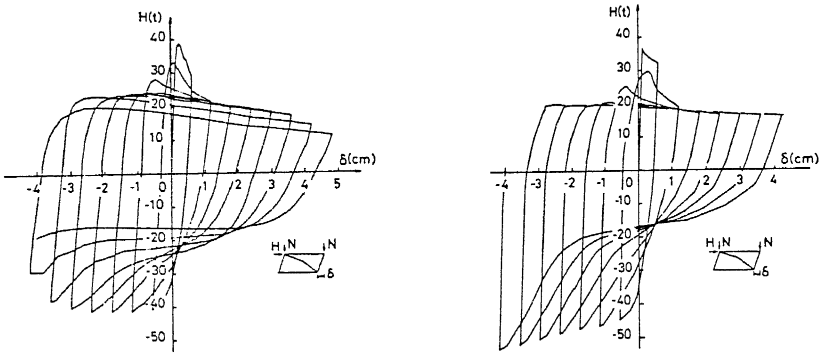
(a) δha=2.0cm (b) δha=4.0cm (c) δha=4.0cm (Cal.)

Fig.5 Load-Deformation Relationship (HR)



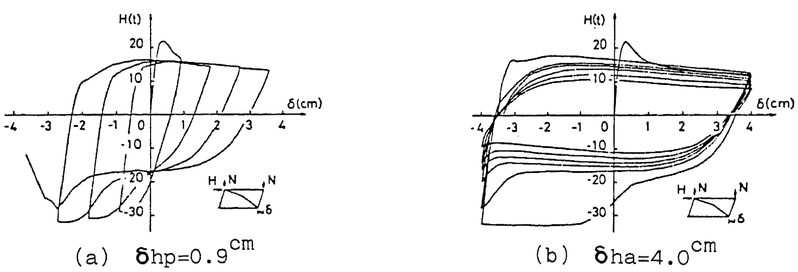
(a) δha=2.0cm (b) δha=4.0cm (c) δha=4.0cm (Cal.)

Fig.6 Load-Deformation Relationship (HBZ1)



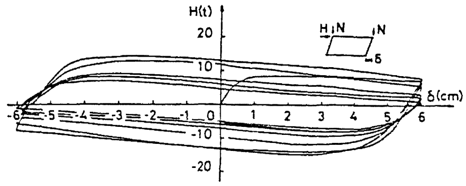
(a) δhp=0.6cm (b) δhp=0.6cm (Cal.)

Fig.7 Load-Deformation Relationship (HBZ1)

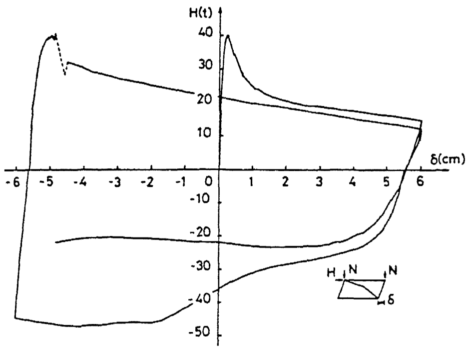


(a) δhp=0.9cm (b) δha=4.0cm

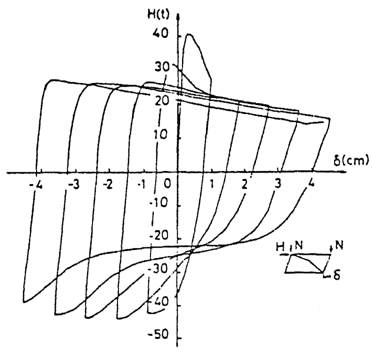
Fig.8 Load-Deformation Relationship (HBZ2)



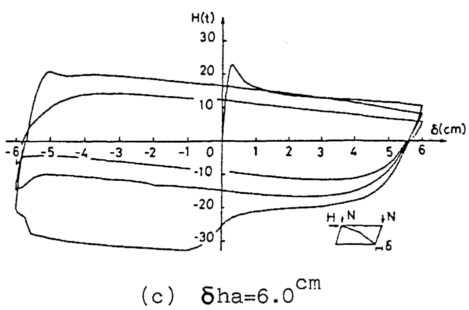
(d) $\delta ha=6.0^{cm}$



(d) $\delta ha=6.0^{cm}$



(c) $\delta hp=0.9^{cm}$



(c) $\delta ha=6.0^{cm}$

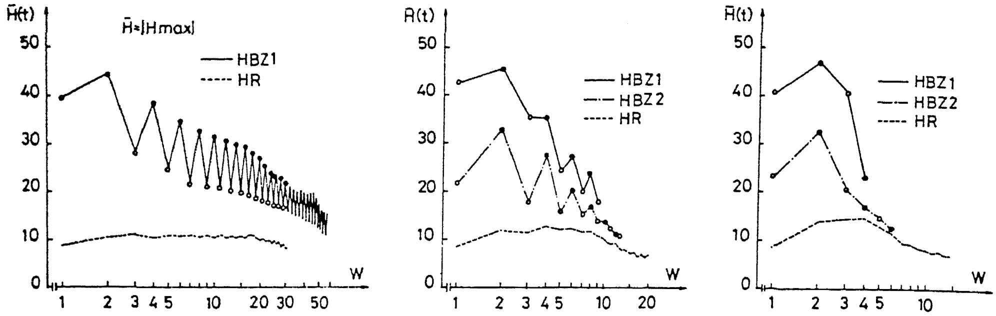
specimen after the experiment.

CONCLUSION

To investigate the elasto-plastic deforamtion and collapse behavior of braced frame having relatively large bracing, constant and incremental deformation maplitude cyclic horizontal loading test is performed using the unit rigid frame with single type bracing such as shown in Fig.1.

Elasto-plastic behavior obtained is compared with the analytical results using the three points model as the cross section and I-K model as the stress-strain relationship of the material. Coincidence between the analytical and experimental results is fairly well so long as the local buckling deformation is small and fatigue crack is not observed.

Deterioration of the strength is due to local buckling and fatigue crack at the flange. It is found that the local buckling and fatigue crack at the column flange increases as the stiffness and strength of the bracing increases due to the interaction behavior of the brace and the surrounding frame. In the case of the bracing having the section with relatively large width-to-thickness ratio flange, the local buckling and fatigue crack appears on the early stage. Different types of damage are observed according to the loading history of the braced frame. In the case of the small deflection amplitude test, the damage of the bracing is serious whereas the damage of the surrounding frame is serious in the case of large deflection amplitude test. In the case of the incremental deflection amplitude test, the damage of the bracing is serious due to the initial small deflection amplitude loading.



(a) δha=2.0[cm] (b) δha=4.0[cm] (c) δha=6.0[cm]

Fig.9 Maximum Strength (Const. Def.)

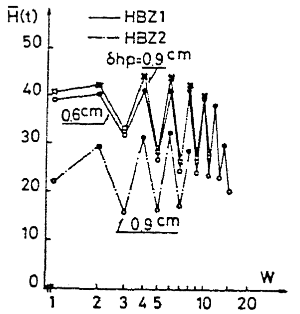
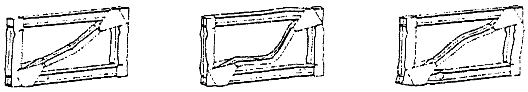


Fig.10 Maximum Strength (Incr. Def.)



(a) δha=2.0[cm] (b) δha=4.0[cm] (c) δha=6.0[cm]

Fig.14 Specimen After Test (HBZ1)

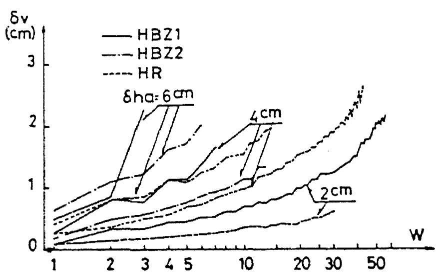


Fig.11 Vertical Displacement (Const. Def.)

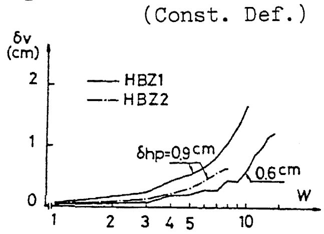


Fig.12 Vertical Displacement (Incr. Def.)

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