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STABILITY EVALUATION OF STEEL BRACED FRAMES UNDER INELASTIC CYCLIC LOADING

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This paper deals with the inelastic cyclic analysis and stability (strength and ductility) evaluation of steel braced frames. The inelastic cyclic performance of steel braced frames is examined through finite element analysis using the commercial computer program ANSYS. First some of the most important parameters considered in the practical design and ductility evaluation of steel braces are presented. Then the details of finite element modeling and numerical analysis are described. Later the accuracy of the analytical model employed in the analysis is substantiated by comparing the analytical results with the available test data in the literature. Finally, the effects of some important structural and material parameters on cyclic elastoplastic behavior of steel braced frames are discussed and evaluated. It is concluded that the numerical method and finite-element modeling employed in the numerical analysis can predict with a reasonable degree of accuracy the experimentally observed cyclic behavior of steel-braced frames.

Keywords: Analysis, Finite element method, Strength, Ductility, Cyclic behavior.

1 INTRODUCTION

Steel-braced frames are one of the most commonly used structural systems because of their structural efficiency in providing significant lateral strength and stiffness. The steel braces contribute to seismic energy dissipation by deforming inelastically during an earthquake. The use of this type of construction indeed avoids the brittle fracture found in beam-to-column connections in moment resisting steel frames, the kind of fractures that occurred in the Northridge earthquake in 1994 and the Kobe earthquake in 1995 (ASCE 2000, IGNTSDSS 1996). However, careful design of steel-braced frames is necessary to avoid possible catastrophic failure by brace rupture in the event of a severe seismic loading. The current capacity design procedure for concentrically braced frames adopted in most seismic design steel specifications (AISC 1997, AISC-LRFD 1999, CAN-CSAS16.1 1989) requires yielding in the braces, as primary members, whereas the secondary members of the frame should remain elastic and hence carry forces induced by the yielding members. The transition from current perspective seismic codes to performance-based design specifications requires accurate predictions of inelastic limit states up to structural collapse.

The cyclic elastoplastic behavior of steel-braced frames is complex due to the influence of various parameters such as material nonlinearity, structural nonlinearity, boundary condition, and loading history. The material nonlinearity includes structural steel characteristics such as, residual stresses, yield plateau, strain hardening and Bauschinger effect.

This paper deals with the inelastic cyclic analysis of steel-braced frames. The most important parameters considered in the practical design and ductility evaluation of steel braces will be presented. The cyclic performance of steel-braced frames will be examined through finite-element analysis using the computer program ANSYS (2007). The accuracy of the analytical model employed in the analysis will be substantiated by comparing the analytical results with the available test data in the literature. The effects of some important structural and material parameters on inelastic cyclic behavior of steel-braced frames are discussed and evaluated.

2 NUMERICAL METHOD

Steel braces in braced frames are vulnerable to damage caused by the interaction between local and overall buckling during a major earthquake (Mamaghani *et al*. 1996a, 1996b, 1997). A sound understanding of the inelastic behavior of steel-braced frames is important in developing a rational seismic design methodology and in evaluating the ductility of such structures (Mamaghani 2005, Usami 1996). The finite-element analysis is carried out by using the commercial computer program ANSYS. The shell element SHELL181 is used in modeling the frame and brace members (ANSYS 2007, Zienkiewicz 1977). The details of elastoplastic large-displacement formulation and solution scheme are reported in a previous work by the author (Mamaghani 1996).

2.1 Analytical Modeling

The results for five typical examples, BFOF, BFSI, BFSO, BFDI, and BFDO, (Wakabayashi *et al*. 1980), presented hereafter are intended to verify the accuracy of the numerical method. The testing assembly is depicted in Figure 1. The frames are simply supported by three rollers at the bottom joints, see Figure 1. To prevent the out-of-plane displacement of the frames, all joints are constrained in this direction.

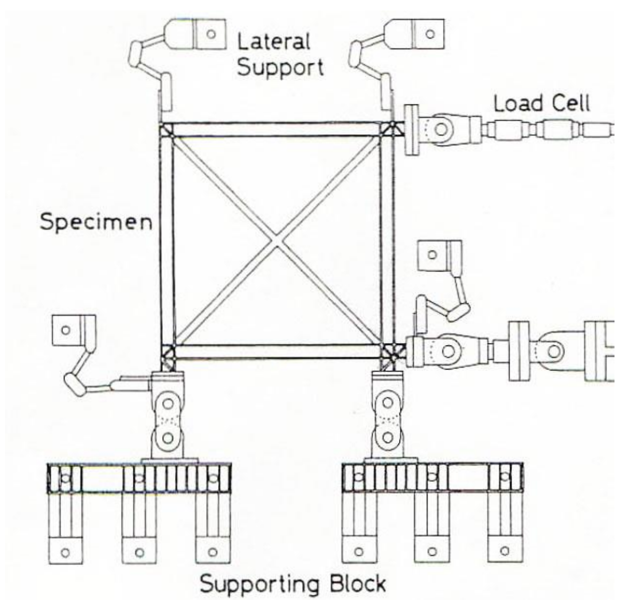
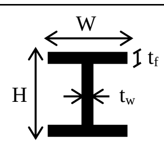


Figure 1. Brace Configuration on the testing Assembly (Wakabayashi *et al*. 1980).

The details of steel-braced frames are listed in Table 1. The specimens are subjected to cyclic loading histories in order to better understand the cyclic behavior of steel-braced frames. The details of the test can be found in Wakabayashi *et al*. (1980).

The cross section of all columns, beams and braces in these frames is H-shaped. Stiffener plates are simple plates. The frame BFOF is a simple frame with no bracing. Frame BFSI has a single diagonal brace with its weak axis perpendicular to the frame plane. Frame BFSO also has a single diagonal brace but its weak axis is parallel to the frame plane. Frame BFDI has an X-shaped bracing system which has a weak axis perpendicular to the frame plane. Frame BFDO also has an X-shaped bracing system but its weak axis is in-plane with the frame. Dimensions of frame members are given in Table 1. Clear length of all beams and columns is 1,400 mm. Due to imperfections, the real size of these elements in the real test is a little different from these sizes but because these differences are less than one percent, these sizes are used for simplicity. The width of all stiffener plates is 7.5 mm.

Table 1. Frame dimensions*.

			Frame				
			BFOF	BFSI	BFSO	BFDI	BFDO
Member Dimension (mm)	Column 1	t_w	5.73	5.68	5.52	5.68	5.62
		t_f	7.50	7.61	7.51	7.53	7.54
	Column 2	t_w	5.73	5.68	5.52	5.65	5.60
		t_f	7.46	7.65	7.52	7.55	7.54
	Beam 1	t_w	5.78	5.62	5.63	5.63	5.78
		t_f	7.49	7.61	7.51	7.53	7.52
	Beam 2	t_w	5.75	7.65	5.62	5.93	5.57
		t_f	7.50	7.61	7.50	7.53	7.53
	Brace 1	t_w	NA	5.93	5.89	5.93	6.09
		t_f	NA	5.92	6.10	6.08	5.99
	Brace 2	t_w	NA	NA	NA	5.94	6.08
		t_f	NA	NA	NA	6.02	5.98

* Height and width of all columns and beams is 100 mm.
Height and width of all braces is 50 mm.

2.2 Material Properties

The mechanical properties of the steel used are given in Table 2. The modulus of the elasticity is E_{st} = 210 GPa and the Poisson's ratio is ν = 0.3. The columns and beams of the test specimens were made of JIS-SS41 grade hot-rolled H-shapes with a depth of 100 mm, a flange width of 100 mm, 6 mm web thickness and 8 mm flange thickness (H-100×100×6×8). The braces are built-up H-shapes. Each plate element of the brace is made of hot-rolled steel plate of JIS-SS41 grade with six mm thickness. The plates were built up to an H-shape by fillet-welding with two mm leg length. The dimensions of the cross section of the brace are 50 mm in depth, 50 mm in width (flanges) and the web and flanges both have the thickness of six mm (Built-up H-50×50×6×6).

Test frames have been annealed to remove the residual stresses of manufacturing. The mechanical properties of the steel plate and H-shapes have been obtained from tensile tests and stub column tests of the coupon specimen and are tabulated in Table 2. In the analysis, the material nonlinearity is accounted for by using the kinematic hardening rule. A tri-linear stress-strain material model adopted in the analysis. The strain-hardening modulus is assumed to be two percent of the initial Young modulus ($E_{st} = 0.02E$).

Table 2. Material properties.

Frame			σ_y (MPa)	σ_u (MPa)	ε_{st}	ε_u
	BFOF BFSO BFDI	Flange	254	430	.023	0.26
		Web	281	432	.028	0.31
	BFSI	Flange	274	455	.032	0.32
		Web	291	435	.023	0.28
	BFDO	Flange	247	420	.023	0.36
		Web	282	429	.023	0.38

2.3 Loading

A displacement-controlled load is imposed at the top-right joint of the frames. This load is based on the story drift angle (R), which is equal to the ratio of the story drift (δ) to the clear height of the column. The cyclic loading program is shown in Figure 2.

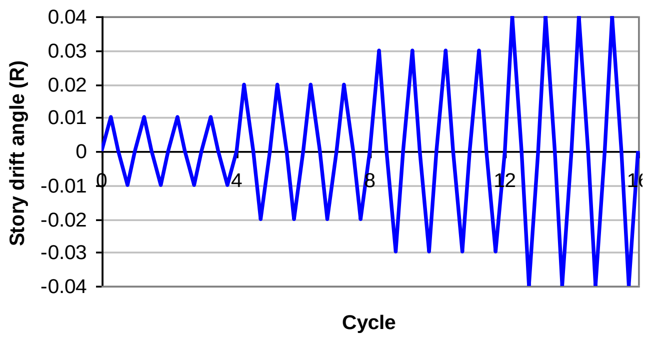


Figure 2. Loading pattern.

3 ANALYTICAL RESULTS

The outputs of the analysis, the force-displacement curve at the tops of the frames, are presented in Figures 3. It has been revealed from these results that the numerical method and finite-element modeling employed in the numerical analysis can predict with a reasonable degree of accuracy the experimentally observed cyclic behavior of steel-braced frames. The additional outputs of the analysis, including the shear and axial forces in columns, deformed shapes and Von-Mises stress at the final stage of the loadings are not presented in this paper due to space limit and they will be presented in the conference.

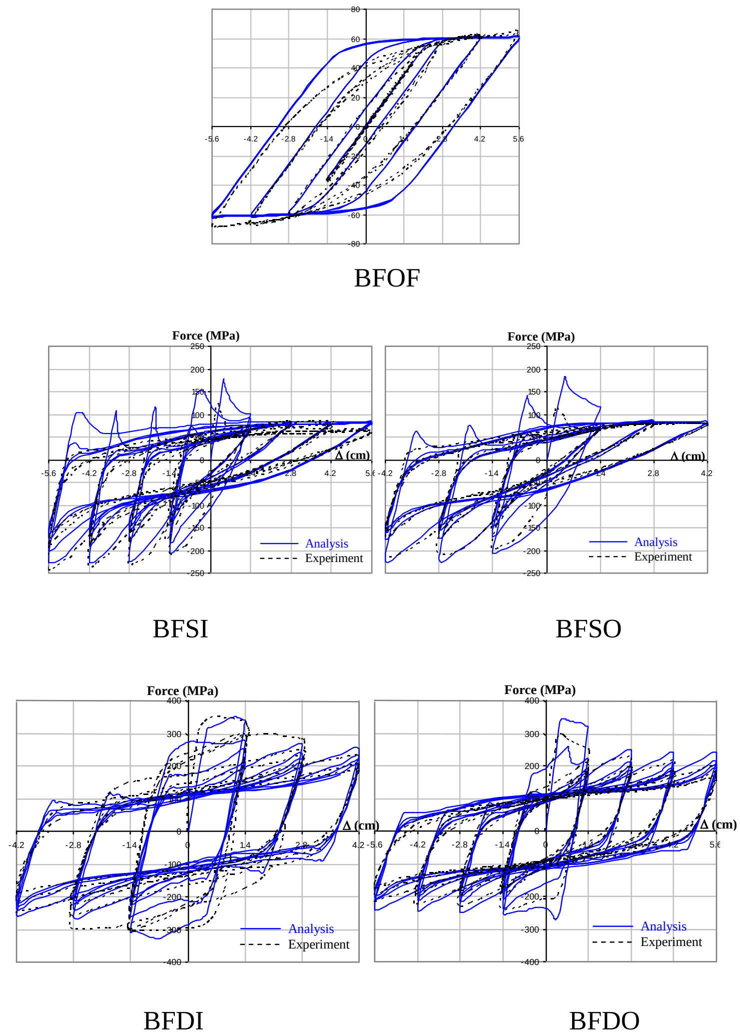


Figure 3. Lateral force-displacement at top of the frames.

4 CONCLUSIONS

This paper deals with the cyclic elastoplastic analysis and stability (strength and ductility) evaluation of steel-braced frames. The most important parameters considered in the practical seismic design and ductility evaluation of steel-braced frames, such as brace slenderness, cross-section slenderness, material behavior, and loading history, were presented. The cyclic elastoplastic performance of steel-braced frames was examined through finite-element analysis using the commercial computer program ANSYS and employing a tri-linear kinematic strain-hardening model to account for material nonlinearity. The details of finite-element modeling and numerical analysis were described. The accuracy of the analytical model employed in the analysis was substantiated by comparing the analytical results with the available test data in the literature. The effects of some important structural, material, and loading history parameters on cyclic inelastic behavior of steel-braced frames were discussed and evaluated with reference to the experimental and analytical results. It has been shown that the numerical method and finite-element modeling employed in the numerical analysis can predict with a reasonable degree of accuracy the experimentally observed cyclic behavior of steel-braced frames.

References

American Institute of Steel Constructions (AISC), Seismic Provisions for Structural Steel Buildings, Chicago, llinois, 1997.

American Institute of Steel Constructions (AISC-LRFD), Load and Resistance Factor Design Specification for Structural Steel Buildings, 3rd Edition, Chicago, 1999.

ANSYS, *Elements Reference*, Release 11.0, ANSYS Inc, 2007.

ASCE, Steel Moment Frames After Northridge. *J. Struct. Eng.*, 126(1) (special issue), 2000.

Canadian Standards Associations (CAN-CSA S16.1), Steel Structures for Buildings, Limit State Design, 1989.

Interim Guidelines and New Technologies for Seismic Design of Steel Structures (IGNTSDSS), In Usami, T. (eds), Committee on New Technology for Steel Structures, Japan Society of Civil Engineers (JSCE), Japan, (in Japanese), 1996.

Mamaghani, I.H.P., Cyclic Elastoplastic Behavior of Steel Structures: Theory and Experiments, *Doctoral Dissertation*, Department of Civil Engineering, Nagoya University, Nagoya, Japan, 1996.

Mamaghani, I.H.P., Usami, T. and Mizuno, E., Inelastic Large Deflection Analysis of Structural Steel Members Under Cyclic Loading, *Engineering Structures*, UK, Elsevier Science, 18(9), pp. 659-668, 1996a.

Mamaghani, I.H.P., Usami, T., and Mizuno, E., Cyclic Elastoplastic Large Displacement Behaviour of Steel Compression Members, *Journal of Structural Engineering,* JSCE, Japan, Vol. 42A, pp. 135-145, 1996b.

Mamaghani, I.H.P., Usami, T., and Mizuno, E., Hysteretic Behavior of Compact Steel Box Beam-columns, *Journal of Structural Engineering*, JSCE, Japan, Vol. 43A, pp. 187-194, 1997.

Mamaghani, I.H.P., Seismic Performance Evaluation of Thin-walled Steel Tubular Columns, *Structural Stability*, Structural Stability Research Council, Montreal, Quebec, Canada. pp. 1-10, 2005.

Wakabayashi, M., Nakamura, T., and Yshida, N., Experimental Studies on the Elastic-Plastic Behavior of Braced Frames under Repeated Horizontal Loading, 1980.

Zienkiewicz, O.C., *The Finite-element Method* 3rd Ed., McGraw-Hill, New York, 1977.