Paper No. 202, Bull. ISET, Vol. 17 No. 1, March 1980 pp. 11–18

STATIC AND DYNAMIC CYCLIC BUCKLING OF STEEL MEMBERS

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Introduction

The number of tall steel buildings in seismic regions has increased rapidly in recent years. As the building increases in height the need to ensure sufficient lateral strength and stiffness becomes more acute. It has been realized that inelastic deformations can be and need to be permitted in such structures in order to produce better designs. The inelastic dynamic response of a braced frame structure is obtained by using the hysteretic force-deformation relationship for columns, girders and bracing members. This paper is concerned with the hysteretic behaviour of steel bracing members which are obtained from two distinct orientations : analytical methods (1, 2, 3, 4, 5, 6) and experimental tests on small specimens (7, 8, 9, 10, 11). These approaches must be applied conservatively because of the lack of sufficient data on the cyclic dynamic characteristics of structural steel loaded alternatively into buckling and yielding.

The experimental studies have pointed out that compressive strength of steel bracing members decreases with number of cycles which was not predicted by analytical methods. The purpose of this paper is to compare the reduction in maximum compressive loads obtained statically and dynamically. Such comparison will help in determining the validity of using the static hysteresis behaviour of bracing members to predict the inelastic dynam c response of braced steel frames.

Experimental Programme

Small scale specimens are easier to fabricate and test in the laboratory but have the disadvantage of introducing the scale effects into the results. These results must be used cautiously when extrapolated to practical applications. The size of specimens was dictated by the capacity of the loading equipment. It was decided to use displacement control rather than force control on all tests. Displacement control was preferred because at larger displacement levels the change in force is small for relatively large displacement increments making force control less accurate.

Tube Specimens

Eight tube specimens were made from 1-inch × 1-inch cold-rolled steel tubes. The tubes were stress relieved by heating at 1200°F followed by slow cooling. Average yield stress of annealed tube was 38.1 ksi and average ultimate strain was 25% over a gage length of 9 inches. Details of tube specimens are given in Table 1. Four specimens were tested statically and four identical specimens were tested dynamically. Rectangular gusset plates were placed in slots at the end of each tube. Welds were made all around the slot. Each gusset plate was welded to a 12-inches × 6-inches × 0.75-inch end plate as shown in Figure 1.

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Table 1 Details of Tube Specimens

Specimen No.	Gusset Plate Size L×W×Th (inch)	Length of Tube (inch)	L/r	KL/r
1	3×2.5×1/2	18.16	60	34
2	3×2.5×1/2	31.60	100	54
3	3×3×1/8	31.60	100	92
4	3×3×1/8	48.00	149	134

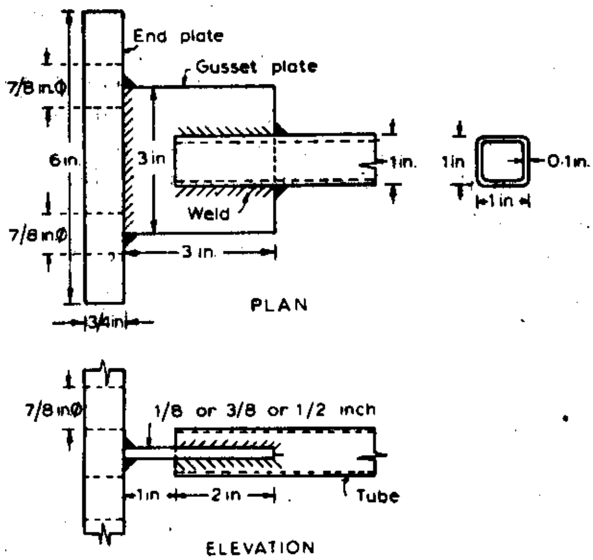

FIG 1 _ CONNECTION DETAILS OF A TUBE SPECIMEN (1inch = 25.4mm)

Angle Specimens

Eight angle specimens were made from M1020 hot rolled single angle sections. Size of these angles varied from 1-inch × 1-inch × $\frac{1}{4}$-inch to $1\frac{1}{2}$-inch × $1\frac{1}{2}$-inch × $\frac{1}{8}$-inch. Their average yield stress was 50 ksi and average ultimate strain was 19% over a gage length of 9-inches. These specimens had no gusset plates and were directly welded to the end plates. Details of angle specimens are given in Table 2. Four specimens were tested statically and four identical specimens were tested dynamically.

End plates of both tube and angle specimens were bolted to the support blocks of test apparatus by means of eight $\frac{3}{4}$-inch diameter high tensile strength bolts.

Test Procedure

Static and dynamic tests employed different load sequences. Loading history used in static tests is shown in Figure 2. The specimens were compressed upto a predetermined displacement level and then pulled in tension upto yield load P_y. Compression displacements were expressed in terms of tension yield displacement Δ_y. Each cycle was completed in six or seven steps in about three minutes by manually adjusting the voltage control. Axial load and axial displacement were recorded on a X-Y plotter.

Table 2 Details of Angle Specimens

Specimen No.	Section Size (inch)	Length (inch)	L/r	KL/r	b/t
1L	1 × 1 × 1/4	33.3	170	85	4
2L	1 × 1 × 1/4	47.0	240	120	4
3L	1½ × 1½ × 1/8	51.0	170	85	12
4L	1½ × 1½ × 1/8	58.5	240	120	10

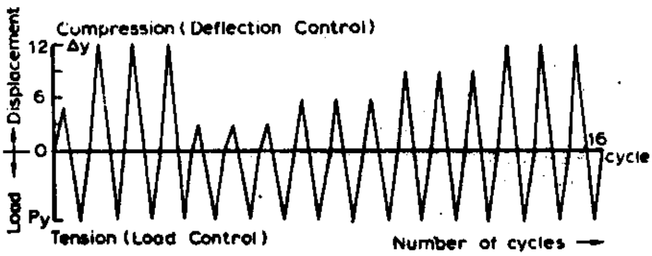

FIG. 2 – LOADING HISTORY FOR STATIC TEST

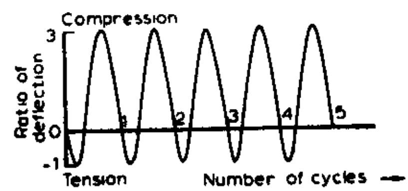

FIG. 3 – LOADING HISTORY FOR DYNAMIC TEST

Loading history used in dynamic tests is shown in Figure 3. This curve was mounted on a curve follower. A typical set of five cycles was completed in one continuous sequence. The specimens were cycled between fixed displacement levels. By adjusting the voltage control it was possible to change the displacement amplitude for next set of cycles. With the available curve follower it was possible to obtain a maximum loading rate of 1/16 cps whose output signals could be directly recorded on the X-Y plotter.

The research reported in this paper was part of a large testing programme (10, 11). Each specimen was subjected to same order of load or deflection level in static and dynamic tests. Therefore, it is believed that change of loading histories did not have any effect on the accuracy of the results reported herein.

Analysis of Results

Hysteresis loops of tube specimen 2 (effective slenderness ratio $KL/r = 54$) obtained at 1/16 cps are shown in Figure 4. It can be seen that there is a gradual reduction in its tensile and compressive strengths. After the first cycle a permanent plastic deformation, a kink, was observed at the midspan and in the gusset plates of each tube specimen. These kinks did not disappear completely even when the specimen was pulled in tension upto yield load. At the end of each cycle there was a net increase in length of a specimen. This increase

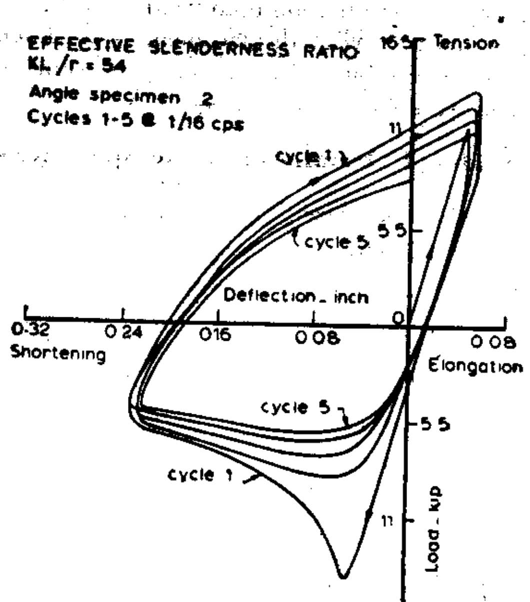

FIG. 4 _ HYSTERESIS BEHAVIOR OF TUBE SPECIMEN 2
(1 kip = 4.45 kN, 1 inch = 25.4 mm)

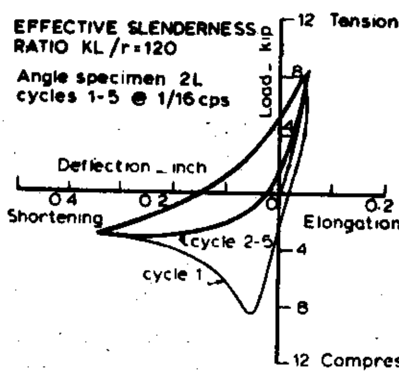

FIG. 5 _ HYSTERESIS BEHAVIOR OF ANGLE SPECIMEN 2L
(1 kip = 4.45 kN, 1 inch = 25.4 mm)

in length is defined as column growth or residual elongation. Bairstow (12), Benham (13), Jain (14), Kahn and Hanson (7), and Royles (15) also noted this observation. The reduction in maximum compressive loads may be due to the presence of kinks and the residual elongation which never let the specimen become fully straight. The reduction in tensile strength may be due to the residual elongation because, for the same displacement level in tension, the specimen is not as straight as it was in the previous cycle.

Hysteresis loops of angle specimen 2L (effective slenderness ratio KL/r = 120) are shown in Figure 5. It can be seen that there is a sudden drop in maximum compressive loads between first and second cycles. The hysteresis loops became repeatable after first two cycles. A typical set of next five cycles is shown in Figure 6 for angle specimen 1L. It shows that if the displacement level is changed the hysteresis loops become repeatable after one or two cycles. Similar observation was made in the tube specimens.

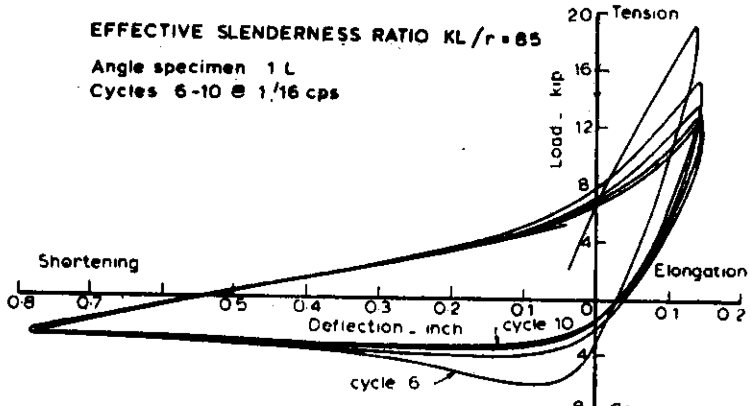

FIG. 6 – HYSTERESIS BEHAVIOR OF ANGLE SPECIMEN 1L
(1 kip = 4.45 kN, 1 inch = 25.4 mm)

Maximum compressive loads obtained in the first cycles of static and dynamic tests are shown in Table 3. These loads are expressed as percentage decrease between those obtained in static and dynamic tests with respect to those in static test. It can be seen in column 3 that compressive loads are lower in static tests than those in dynamic tests in all the tube specimens. This effect may be attributed to the inertia of the loading and recording systems. However, in angle specimens it can be noted that maximum compressive loads in first cycle are higher in static tests than those in the dynamic tests. Therefore, it can be concluded that the difference in static and dynamic compressive loads may not be due to the inertia effects.

Width-thickness ratio (b/t) of the tube sections is 7.5. Maximum permissible b/t ratio in accordance with American Institute of Steel Construction Specifications (AISC, 16) are 39 and 31 in elastic and plastic designs. Although all tube specimens satisfied b/t requirements, tube specimen 1 still developed local buckling at midspan and fractured in the 7th cycle. No local buckling was observed in tube specimens 2, 3 and 4. Width-thickness ratios of angle sections are shown in Table 2. For angle sections with a yield stress of 50 ksi maximum permissible b/t ratios are 10.6 and 6.8 for elastic and plastic design in accordance with AISC Specifications (16). Specimens made from 1-inch × 1-inch × $\frac{1}{8}$-inch angle sections showed no local buckling, whereas, all other angle specimens developed local buckling. Local buckling developed identically in each specimen tested statically or dynamically. Therefore, it can be expected that local buckling equally affected the compressive loads in static and dynamic tests.

Reduction in maximum compressive loads between first and second cycles with respect to the first cycle, and between second and sixteenth cycles with respect to second cycle of static test as well as of dynamic test are also shown in Table 3. These values are reported separately for static and dynamic tests so as to exclude the inertial effects of the test system, if any. It can be seen that rate of loading has a significant effect on the rate of reduction. This Table also shows that the rate of reduction is different for tube and angle specimens.

Therefore, hysteresis models of axially loaded steel members which are based on the static test data should be used with caution in the dynamic analysis of braced frame structures.

Table 3 Reduction in Compressive Loads

Specimen	KL/r	Reduction Between (in percent)				
		First static & dynamic cycles	1 & 2 cycles of		2 & 16 cycles of	
			Static Test	Dynamic Test	Static Test	Dynamic Test
TUBE						
1	34	−20.4	5.7	20.0	28.0	—
2	54	−10.0	29.7	40.5	28.8	43.5
3	92	−18.8	42.8	51.0	24.0	39.5
4	135	−18.5	38.8	48.0	31.0	—
ANGLE						
1L	85	14.5	55.0	59.0	61.5	40.0
2L	120	3.5	31.4	64.6	46.6	16.7
3L	85	27.6	45.6	68.5	57.0	56.7
4L	120	16.7	33.4	60.0	35.0	50.0

Conclusions

While this experimental programme was limited in scope, the following conclusions were reached on the basis of the results concerning the cyclic buckling of axially loaded steel members :

1. The rate of loading significantly influences the reduction in maximum compressive loads in axially loaded steel members.
2. The rate of reduction in compressive loads is different for different cross-sectional shapes.
3. The work presented herein points out the need for more information in the following areas : (a) A comparison of static and dynamic hysteresis behaviour should be extended to additional excitation frequencies and cross-sectional shapes ; and (b) large size specimens should be tested to investigate the scale effects.

Acknowledgements

The research reported in this paper was supported by the National Science Foundation while pursuing graduate studies at the University of Michigan, Ann Arbor, Michigan, U.S.A. However, the results and conclusions are those of the writer and donot necessarily reflect the views of the sponsor. The writer is grateful for the guidance and help of Professors Subhash C. Goel. and Robert D. Hanson during these studies.

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