CYCLIC BEHAVIOR OF ROLLED STEEL MEMBERS

by

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SYNOPSIS

The load-deflection behavior and failure characteristics of wide-flange cantilever beams and beam-columns are examined experimentally at very large amplitudes of imposed cyclic deflection. Emphasis is placed on the effects of cross-sectional dimensions, span length, and intermediate lateral bracing. For slender unbraced beams progressive web or lateral-torsional buckling is found to result in hysteresis loops which diminish with cycling. The addition of lateral bracing along one flange retards this deterioration, but may produce unsymmetrical loops. The addition of axial loading amplifies each type of buckling and sometimes produces loops with negative slopes in the yielding ranges.

SCOPE OF EXPERIMENTAL PROGRAM

Cyclic loading tests well beyond the elastic range of behavior have been conducted on individual steel members, on steel subassemblages, and on full-scale steel frames. However, in very few of these studies have the geometric properties of the members been varied. The effects of geometric variations were given special attention in the series of 50 cyclic beam and beam-column tests reviewed herein.

An idealized sketch of the experimental arrangement is shown in Fig. 1. Each as-rolled mild steel specimen was supported as a cantilever and was subjected to a slowly-varying, cyclic lateral load at the free end. Bending was about the major axis of the cross-section; boundary conditions for twist and for lateral deflection were approximately fixed-pinned. In order for member behavior to be evaluated, rather than connection behavior, the specimens were made to be continuous into a clamping fixture at the supported end.

The experimental program consisted of four sets of tests. First, two similar sets of beam type specimens were tested with and without intermediate lateral bracing, and then two sets of column type sections were tested with and without axial loading. Beam type sections chosen were the W8x13 and the W6x16; column type sections were the W6x20 and the M4x13. Of each pair, the first section has relatively thin plate elements and the second has relatively thick plate elements. Specimens of each cross-section were tested at lengths of 30 and 60 times the lateral radius of gyration. For each cross-section and length, one speci-

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men was subjected to a monotonic lateral load far beyond the elastic limit, and two were cycled inelastically between equal plus and minus end deflections.

The amplitude of cyclic deflection is represented by a "ductility factor," which is defined as the ratio of the peak deflection in each direction to the plastic moment deflection. Values of the ductility factor have been included which are greater than expected during an earthquake.

LOAD-DEFLECTION BEHAVIOR

Unbraced Beams. - For moderate amplitudes of cyclic and deflection, short unbraced beams with thick plate elements exhibited hysteresis loops which were as stable as those reported by previous investigators. However, short specimens with thin plate elements exhibited decaying hysteresis loops, as shown in Fig. 2. This figure is for a W8x13 section with a cantilever length of 24.9 in. which was cycled at a ductility factor of 7.2. The loss of load capacity represented by the decrease in loop height may be attributed primarily to web buckling, which began in the fifth half-cycle. Local flange buckling beginning in the second half-cycle did not cause a loss of strength by itself, but it did help to induce the subsequent web buckling. Figure 3 shows the hinge region of this member after 11 full cycles; despite the severe distortions shown the specimen carried 72% of the plastic moment load at this stage.

Decaying hysteresis loops were also found for long specimens with thick plate elements, but the losses of strength were due to lateral-torsional buckling rather than web buckling. For example, Fig. 4 shows a W6x16 section with a length of 57.6 in. after 20 cycles at a ductility factor of 11.1. At this stage the peak cyclic load had fallen to less than half the plastic moment load, and the elastic (unloading) stiffness was only 20% of the initial elastic stiffness. Losses of stiffness were particularly pronounced in cases of lateral-torsional buckling because of the torsional weakness of the open cross-sections considered.

As might be expected, beam specimens with larger slenderness ratios for flange, web and lateral-torsional buckling showed more rapid rates of deterioration of load capacity, stiffness, and energy dissipation per cycle. Also, a section's monotonic behavior at very large deflections proved to be a reliable indicator of the hysteretic behavior. An example of this is given in Fig. 2, where the dashed monotonic curve shows a drop in load following web buckling; the same thing happened in the corresponding cyclic tests.

Lateral Bracing Effects. - The hysteresis loops shown in Fig. 5 were obtained when lateral bracing was added to one flange of a W8x15 specimen twice as long as the one of Figs. 2 and 3. Even though lateral deformation was restrained during compression of the flange that was braced, the hysteresis loops did not remain stable because of buckling of the unbraced flange. As cycling progressed the loops became nonsymmetric, having a larger peak load when the braced flange was in compression and a greater elastic stiffness upon unloading from that peak.

Axial Load Effects. - In Fig. 6 hysteresis loops are shown for a W6x20 specimen which carried an axial load of three-tenths the yield value in pure compression. The member was 41.7 in. long, and the amplitude of cyclic deflection was 1.5 in. Comparison to Figs. 2 and 5 shows that the axial load caused negative slopes in the yielding ranges. Also, small initial increases in load capacity with cycling were followed by more rapid decreases than for a similar specimen without axial loading. Losses in strength for this section and length were associated primarily with flange and web buckling and the axial load caused an increase in web deformation (middle beam, Fig. 7). In other cases where lateral-torsional buckling predominated, an axial load again amplified the deformation and the rate of deterioration.

FAILURE CHARACTERISTICS

In this investigation cyclic loading generally was continued until there was rupture completely through some element of the cross-section. In most cases the fracture occurred in the crease of a flange buckle, but when flange buckling was not pronounced, as for short W6x16 beams, there was fracture at the face of the support. In a few cases rupture occured between the web and one flange (see Fig. 7).

In the majority of cases the failure trends followed those cited above for load, stiffness, and energy deterioration. That is, at comparable ductility factors specimens which were more susceptible to buckling fractured earlier. However, significant exceptions occurred when the flanges buckled at a location away from the hinge region, as shown in Fig. 4. A sharing of energy dissipation between the hinge region and the region of secondary buckling allowed these specimens to endure a larger number of cycles than others which were less susceptible to buckling.

CONCLUSIONS

At very large amplitudes of cyclic deflection, cantilever beams with slenderness ratios close to the limits prescribed for ordinary plastic design may exhibit hysteresis loops which are not stable. The deterioration is severe only when local flange buckling combines with web buckling or with lateral-torsional buckling. Web buckling has a particularly adverse effect on load capacity, whereas lateral-torsional deformation tends to produce a loss of stiffness. Addition of an axial load tends to induce more rapid deteriorations. The members considered generally resisted fracture and sustained a useful amount of load capacity for a greater number of large-deflection cycles than would be expected in an earthquake. Nevertheless, the observed deteriorations should sometimes be accounted for in dynamic earthquake analyses.

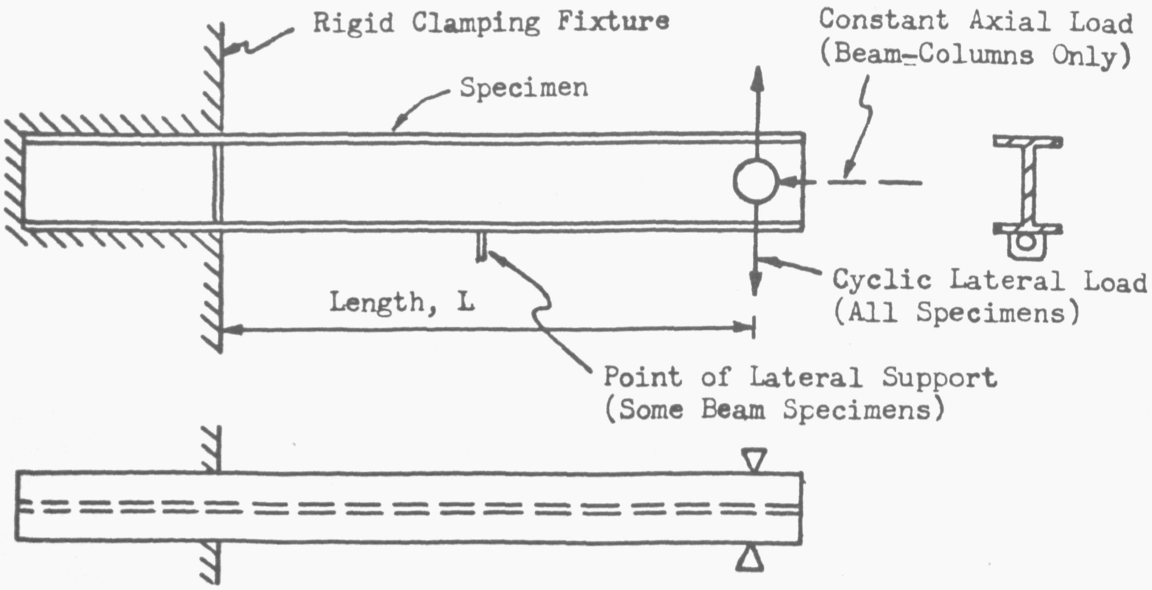

FIG. 1. CONDITIONS OF SUPPORT AND LOADING

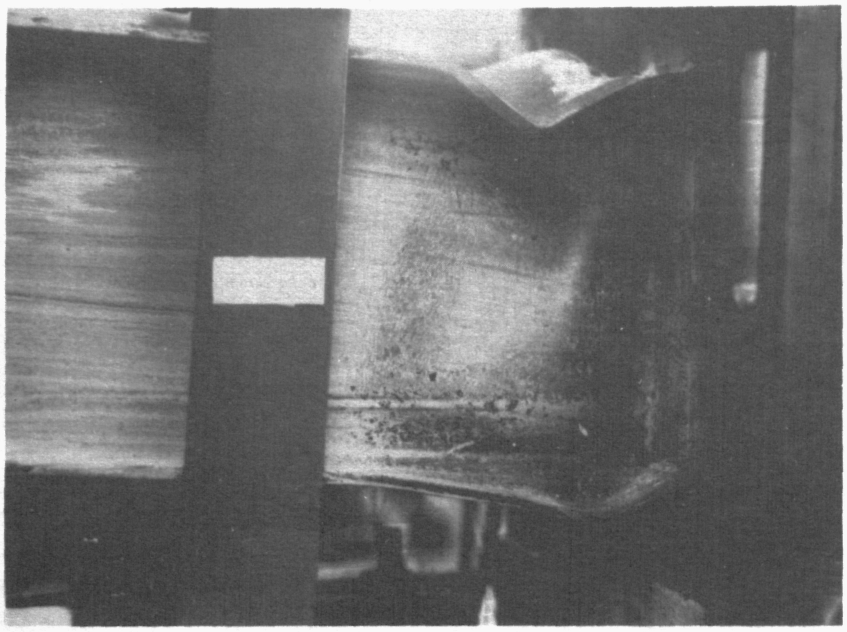

FIG. 3. SPECIMEN OF FIG. 2 AFTER 11 CYCLES OF LOADING

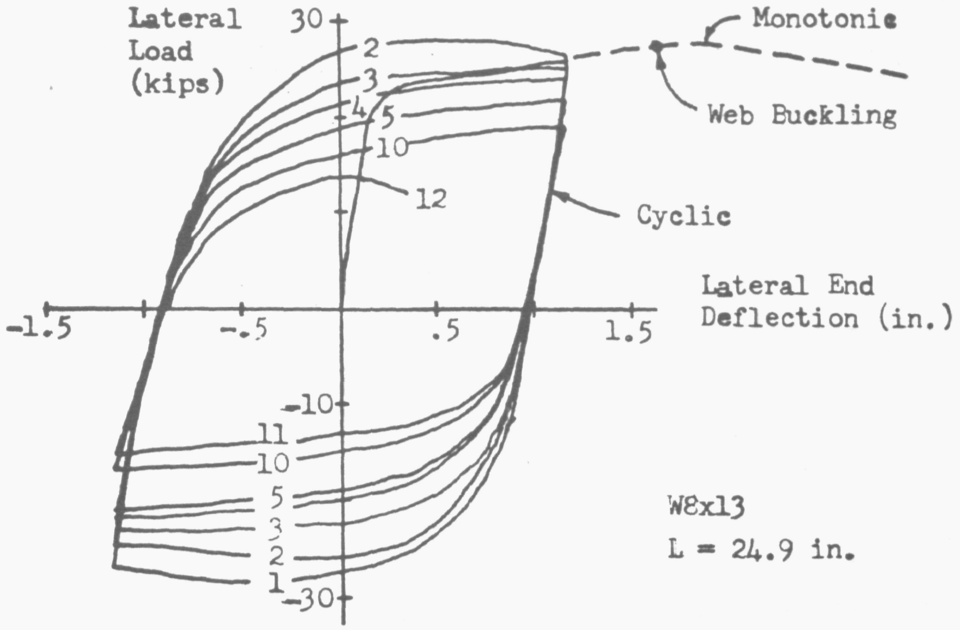

FIG. 2. HYSTERESIS LOOPS FOR UNBRACED BEAM

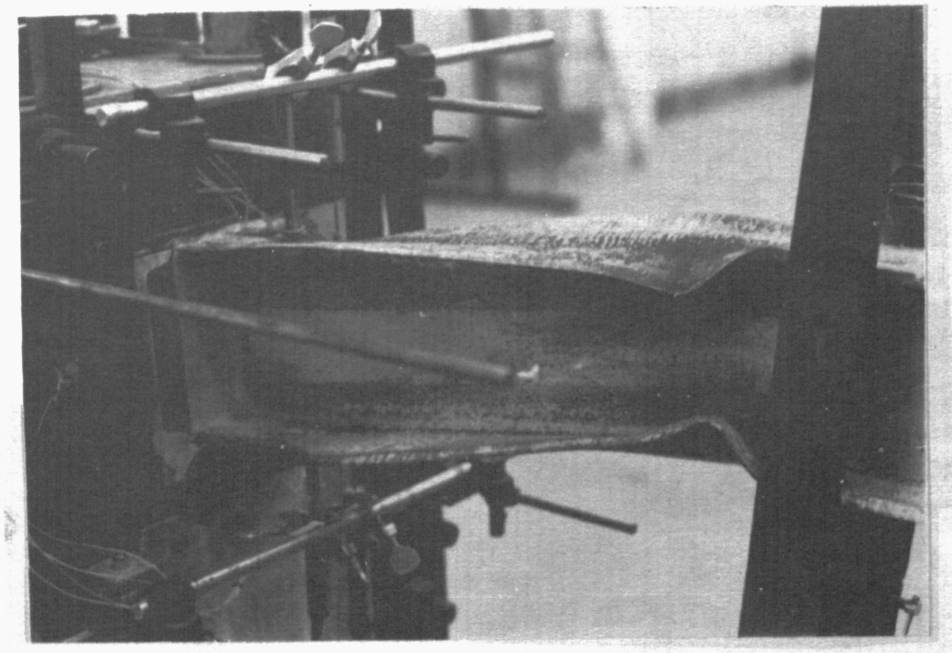

FIG. 4. SPECIMEN WITH SEVERE LATERAL DISTORTION (W6x16, L = 57.6 in., 20 cycles of loading)

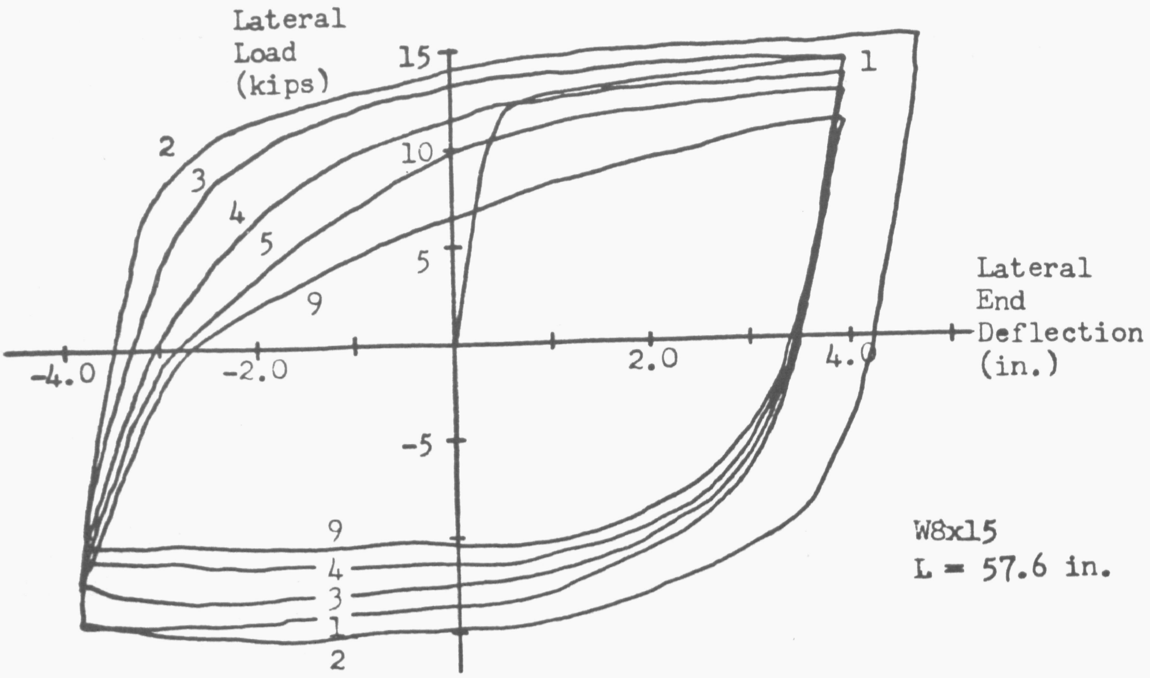

FIG. 5. HYSTERESIS LOOPS FOR BRACED BEAM

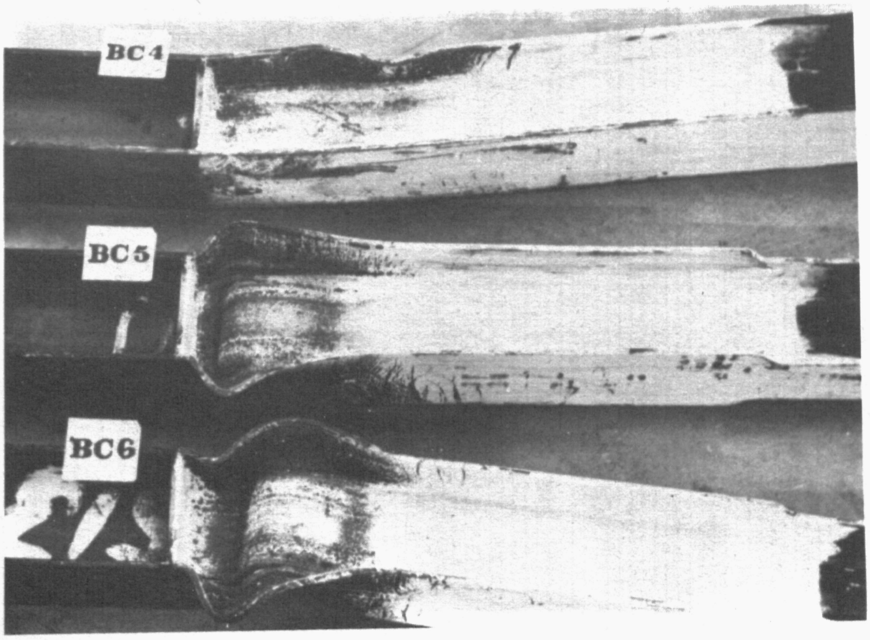

FIG. 7. SPECIMEN OF FIG. 6 (MIDDLE BEAM) AT RUPTURE

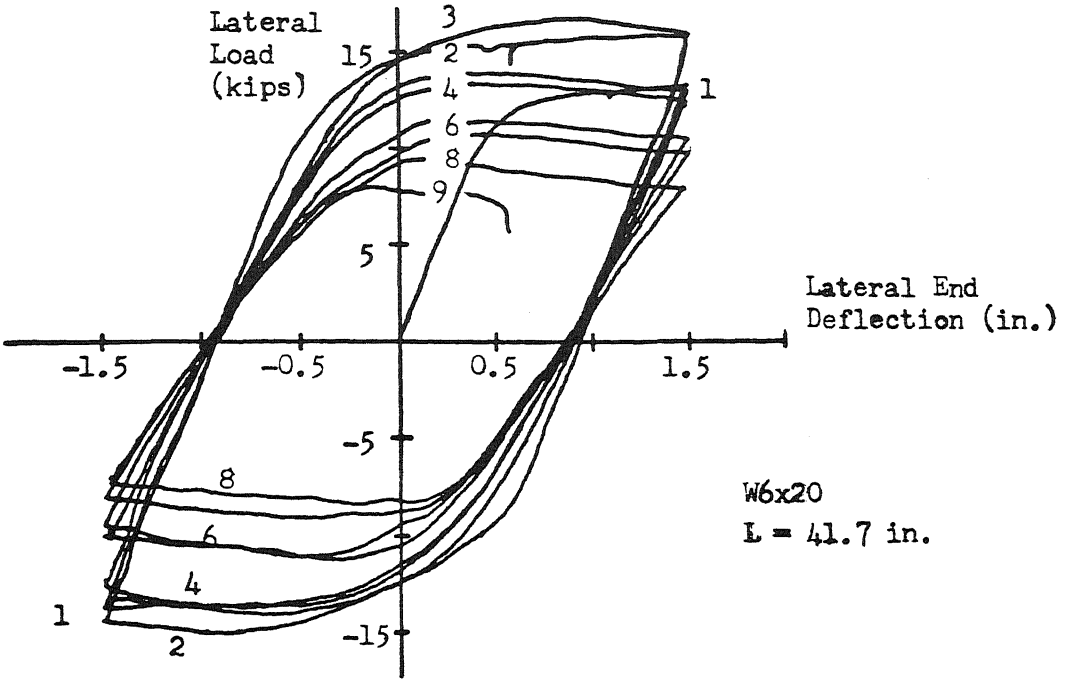

FIG. 6. HYSTERESIS LOOPS FOR UNBRACED BEAM-COLUMN