Experimental study of the performance of structural steel members subjected to multi-dimensional ground motion

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Abstract

This paper presents an experimental investigation of the inelastic behavior of wide-flange structural steel members under combined time-dependent bending and torsional loading. A quantitative evaluation of energy dissipation capacity after occurrence of local buckling was made. Test results show that a W6x15 section with a d/bf ratio equal to one performed better than a W8x10 section, which has a larger d/bf ratio, in resisting combined bending and torsion. Test results also show that the presence of torsion significantly affects a member's bending-moment carrying capacity.

Introduction

Current design philosophy for structural systems requires that structures must be sufficiently ductile to prevent collapse during major earthquakes. Steel structures have been widely used in building and bridge construction because of their high ductility performance during earthquake ground motion [1]. The success of a structure in absorbing severe earthquake ground motion without collapse depends largely on each member's ability to absorb excessive energy through inelastic deformation.

Loading induced by an earthquake is usually complicated and time-dependent. Therefore, members designed for safety under static loading must still be checked for instability-failure potential under cyclic and earthquake loading[2]. The most important design concept in earthquake engineering is recognizing that the buckling of a structural member does not end that member's service life. However, there will be a reduction in the member's strength and energy dissipation capacity[3]. Therefore, it is essential to investigate the post-
buckling behavior of steel members subjected to multi-dimensional earthquake ground motion, qualitatively and quantitatively.

Theoretical analyses of structural responses to combined dynamic loading are usually complicated and difficult [4-10]. This paper is focused on the performance of steel members subjected to combined time-dependent bending and torsional loading induced by multi-dimensional earthquake ground motion. The performance of various steel members is compared according to their strength, and deterioration in energy dissipation capacity during the post-buckling stage.

Test set-up

The test set-up was designed as a closed loop with respect to force equilibrium during testing. Two strong base beams connected by three tie beams formed the frame base, which was then stiffened and bolted to the test floor. Test specimens were mounted on one of the base beams in the vertical direction. The configuration is shown in Fig. 1.

The reaction frames were composed of two W14x135 wide-flange columns with 1/2 inch-thick stiffeners added where the actuators were mounted, and two bracing members with 1/2 inch-thick end plates. Loading was transmitted to the test specimens through a strong loading beam from two actuators (one for bending and one for torsion). By varying the displacements of each actuator, a combination of bending, shear and torsional loading was generated. Two one-inch-thick end plates were welded to the specimens and attached to the frame base and the loading beams. The details are shown in Fig. 1.

The hydraulic actuators used were MTS models 244.41 and 244.52. Load capacities for the actuators were 100 kips and 200 kips, respectively, and strokes for both were 10 inches. Actuator piston rods movements were monitored and recorded by internally mounted Linear Variable Differential Transformers (LVDTs).

Experimental procedures and results

In order to determine the effect of torsion on the performance of steel members with various cross-sectional dimensions, two A-36-grade wide-flange steel members, W6x15 and W8x10, were selected for testing. Four loading combinations including bending, shear and torsion were chosen to study the effect of torsion on a member’s bending-moment capacity. They were:
(1) cyclic bending and shear,
(2) cyclic torsion,
(3) cyclic bending and shear with minor constant twist,
(4) cyclic bending and shear with moderate constant twist.
Displacement at the top of the specimen was used as the control parameter in all tests.

W6x15 Series Tests

The first series of tests was conducted on W6x15 members. The sectional area of these members was 4.43 inch$^2$ and the moment of inertia about the strong axis ($I_x$) was 29.1 inch$^4$. The width/thickness ($b/2t_f$) ratio was equal to 11.5 and the $d/b_f$ ratio was one.

Cyclic bending and shear

This specimen was subjected to periodically increasing bending and shear forces until local buckling occurred. Then, the member was subjected to repeated loading by keeping the displacement amplitude at the value at which local buckling occurred. Loading history was sequentially composed of three cycles of 0.25, 0.5, 0.75 and 1 inch displacements at the top of the specimen, followed by 10 cycles of 1.25 inches of displacement amplitude. Displacement history for both actuators is shown in Fig. 2. The relation between load and displacement is shown in Fig. 3.

The specimen buckled when displacement amplitude at its top reached 1.25 inches. Energy absorption was obtained by calculating the work bounded by the hysteresis loop. The energy dissipated during each cycle was divided by the energy absorbed during the first cycle after buckling occurred to obtain the normalized energy dissipation factor.

Normalized capacity to absorb energy during the cycles after buckling occurred was reduced from 1 to 0.992, 0.956, 0.932, 0.915, respectively. These values were linearly curve-fitted to obtain the deterioration rate, which represents the average drop per cycle in energy dissipation capacity. The deterioration rate for this test was 1.9%

Cyclic torsion

This specimen was subjected to periodically increasing torsion. Pure Cyclic torsion was applied by fixing the center actuator and cyclically moving the actuator at the end to generate torsion. The applied torsion was obtained by multiplying the load measured by the load transducer with the distance between the two actuators. The relation between torsion and twist angle is shown in Fig. 4. Buckling occurred, due to pure torsion, when twist angle reached 0.133 radians. At this stage, noticeable distortion of the section was observed during the test. The deterioration in energy dissipation capacity was small for this
cyclic torsion test. Normalized energy dissipation factors for the cycles after buckling occurred were 1, 0.998, 0.984, 0.966, respectively. The deterioration rate for this test was 0.75%.

**Cyclic bending and shear with minor constant twist**
Combined bending, shear and torsion was achieved by first controlling the displacements of both actuators to maintain a constant twist angle, then cyclically moved both actuators at same amplitude. A 0.01 radians constant twist angle was applied to this specimen. Local buckling occurred at the same displacement amplitude as that in the bending and shear test, 1.25 inch. Normalized energy dissipation factors for the cycles after buckling occurred were 1, 0.956, 0.916, 0.89, 0.871, respectively. These values represent a deterioration rate of 2.76%.

**Cyclic bending and shear with moderate constant twist**
This specimen was subjected to periodically increasing bending and shear with a constant 0.03 radians twist angle. The loading sequence was the same as that used in the cyclic bending and shear test. Local buckling occurred when the displacement at the top of the specimen reached 1.25 inches. Normalized energy dissipation factors for the cycles after local buckling occurred were calculated as 1, 0.91, 0.87, 0.83, respectively. The deterioration rate in energy dissipation was 4.1%. Comparisons of initial buckling strength and normalized energy dissipation factors for W6x15 sections with various degrees of torsion applied are shown in Figs. 5 and 6.

**W8x10 Series Tests**
The second series of tests was conducted on W8x10 specimens. The moment of inertia about the strong axis \( I_x \) was 30.8 inch^4 and the sectional area of these member was 2.96 inch^2. The width/thickness \( (b_t/2t_f) \) ratio was equal to 9.6 and the d/bf ratio was two.

**Cyclic bending and shear**
The loading sequence was composed of three cycles of 0.1, 0.25, 0.5, 0.75 inches and five cycles of 1 and 1.25 inches. Initial buckling occurred when the amplitude reached 1 inch. At this stage, noticeable deterioration in energy absorption and strength was observed. When the displacement amplitude was increased to 1.25 inches, a further reduction in strength was clearly detected. Detailed relation between load and displacement is shown in Fig. 7.

Initial buckling strength during the first cycle of 1 inch amplitude was 15.12 kips for the positive side and 14.95 kips for the negative side. Strength for the cycles after initial buckling was 14.57, 13.38, and 12.38 kips, respectively. Normalized energy dissipation factors for each cycle when the
displacement at the top of the specimen equaled 1 inch were reduced from 1 to 0.966, 0.919, 0.862, respectively. A deterioration rate of 2.85% was calculated by linearly curve-fitting these values.

Cyclic torsion
This specimen was initially subjected to three cycles of 0.01 radians twist angle, followed by a series of increasing twist angles up to 0.125 radians. Local buckling occurred when the twist angle reached 0.136 radians. The buckling zone was small and only occurred at the ends of the specimen. The result of the interaction between torsion and twisting angle is shown in Fig. 8. Normalized energy dissipated in each cycle with respect to that of the first cycle after local buckling was reduced from 1 to 0.996, 0.989, 0.979, respectively. The deterioration rate obtained by curve-fitting these values was 0.8%.

Cyclic bending and shear with minor constant twist
This specimen was subjected to periodically increasing bending and shear with a constant 0.0085 radians twist angle. The loading sequence for the actuator that generated bending was the same as that used in the bending and shear test. Significant local buckling occurred when the displacement amplitude at the top of the specimen reached 1 inch. The energy dissipated in each cycle was normalized with respect to that of the first cycle when local buckling of the member occurred. The normalized energy dissipation factors were reduced from 1 to 0.929, and 0.866. The deterioration rate for this test specimen was 3.35%.

Cyclic bending and shear with moderate constant twist
This specimen was subjected to periodically increasing bending and shear with a 0.03 radians twist angle. The twisting angle was kept constant throughout the loading history. Local buckling occurred when the displacement at the top of the specimen reached 1 inch. Due to the larger twist angle, the normalized energy dissipation capacity dropped from 1 to 0.896, 0.839 and 0.789 for the cycles after the member had locally buckled. The deterioration rate calculated from these values was 5.32%. Comparisons of initial buckling strength and normalized energy dissipation factors for W8x10 sections with various degree of torsion applied are shown in Figs. 9 and 10.

Comparison of test results
In order to identify the effect of torsion on the reduction of load-carrying capacity as well as rate of deterioration in load-carrying capacity after the member buckled, a comparison of test results between members with and without torsion was made.

For all W6x15 sections tested with bending, local buckling occurred at the same displacement amplitude regardless of whether the twist angle was included.
The same phenomena were observed in the W8x10 sections. However, the initial buckling strength and deterioration of energy dissipation capacity after the members had locally buckled showed significant differences. This can be clearly seen in Figs. 5, 6, 9 and 10. The W6x15 section test results show that members subjected to minor and moderate degrees of constant twist angles deteriorated in energy dissipation capacity 1.45 and 2.15 times faster than that without torsion. The W8x10 sections showed average deterioration rates of members with minor and moderate constant twist angles were 3.35% and 5.32%, respectively. These values are larger than those of the W6x15 sections with the same order of torsion.

Summary and conclusion

In this paper, two wide-flange structural steel members were tested to study their performance during multi-dimensional earthquake ground motion. Information obtained from this investigation is of two-fold benefit. It clearly shows, by comparing the performance of members with and without torsion, that the presence of torsion can significantly reduce a member's energy dissipation and bending-moment carrying capacity. Therefore, the torsional effect should be included in the design considerations for earthquake-resistant structural systems. The experimental study mentioned above also showed that the effect of torsion increases when degree of torsion and d/bf ratio increase, which can be useful in the selection of member sections for design and construction.

References


Figure 1: Configuration of test frame

Figure 2: Loading history for W6x15 with cyclic bending and shear
Figure 3: Load-displacement relation for W6x15 with cyclic bending and shear

Figure 4: Torsion-twist angle relation for W6x15 with cyclic torsion

Figure 5: Comparison of strength for W6x15 sections with various degrees of torsion

Figure 6: Comparison of normalized energy dissipation factor for W6x15 sections with various degrees of torsion
Figure 7: Load-displacement relation for W8x10 with cyclic bending and shear

Figure 8: Torsion-twist angle relation for W8x10 with cyclic torsion

Figure 9: Comparison of strength for W8x10 sections with various degrees of torsion

Figure 10: Comparison of normalized energy dissipation factor for W8x10 sections with various degrees of torsion