Localized fire tests on steel beams with different end restraints

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Abstract
Two 6.2-m span I-shaped structural steel beams were tested under combined structural and open flame localized fire loads. Two different support conditions for the beam ends were considered: (i) simple support, and (ii) double-angles bolted to laterally braced support columns. A four-point flexural loading scheme was used such that two concentrated forces were applied 2.44 m apart around midspan. The beam specimens were laterally braced at the location of concentrated forces. The midspan of each specimen, i.e. expected plastic hinge zone, was exposed to an open-flame fire using natural gas burners. The measurements included heat release rate and applied forces as well as thermal and structural responses to fire. Since the thermal gradients developed in the fire-exposed cross sections induced thermal bowing, both beam specimens exhibited similar deformational behavior and failure mode regardless of their end conditions. However, the presence of end restraint, provided through the double-angles on the second specimen, decreased its fire resistance (i.e. the failure time and failure temperature).

Keywords: Fire, End restraints, Steel beams, Experimental

1. Introduction

The current fire safety design focuses on improving the fire resistance of unrestrained structural steel members to uniform heating caused by a post-flashover fire. In open-plan compartments, however, a fire rarely develops into flashover and could be localized at a certain location. Some researchers (Zhang et al, 2014; Choe et al, 2016a; Agarwal et al, 2014) studied the effects of non-uniform heating on the fire performance of structural steel columns and discussed the effect of thermal gradients on the load-carrying capacity of columns. There is still lack of technical information needed to evaluate the behavior of restrained structural steel beams subjected to non-uniform heat possibly induced by an open flame, localized fire.

As part of commissioning the new structural fire testing capabilities of the National Fire Research Laboratory (Bundy et al, 2016), a series of localized fire tests on structural steel beams were conducted. This paper focuses on the influence of end restraints on the 6.2-m long, W16x26 structural steel beams tested under localized fire exposure. The fire performance of the beams with two different end supports were evaluated, including (a) simple support (Specimen 1) and (b) double-angle connection (Specimen 2).

2. Test Setup

Details of the test configuration and instrumentation layout are presented in Choe et al. (2016b) and are briefly summarized herein. Fig 1 shows a schematic of the test setup erected on the strong floor. The nominal length of the W16x26 beam specimens (between the centerlines of support columns) was 6.71 m. Specimens were made of ASTM A992 (ASTM, 2015b) steel with a minimum yield and tensile strengths of 340 MPa and 450 MPa, respectively. The width and thickness of flanges was 140 mm and 8.76 mm, respectively; the thickness of web was 6.35 mm; and the depth of the section was 400 mm.

As shown in Fig. 1, the beam specimen was loaded using two box-shaped steel beams placed at 2.44 m apart around mispan. To apply a bending moment to the specimen, the steel rods attached at the ends of the loading beams were pulled by hydraulic actuators placed in the basement underneath the strong floor. Specimens 1 and 2 were laterally braced at the location of the loading beams so that the unbraced length was 2.44 m. For producing a localized fire exposure to the beam specimen, a 1-m^2 natural gas burner system was placed 1.1 m below the bottom flange of the specimen at its midspan.

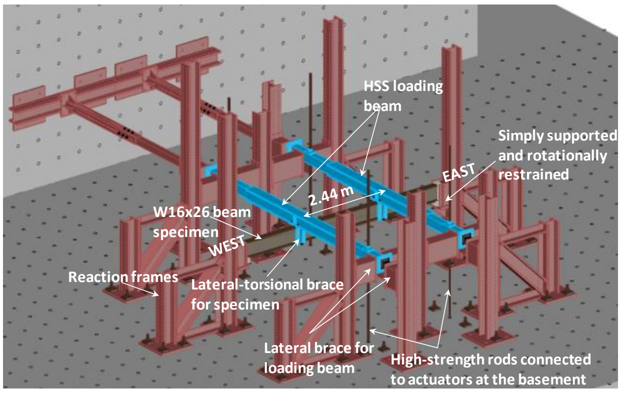

Fig. 1. A schematic of the test setup

Details of the beam end supports are shown in Fig. 2. The ends of Specimen 1 were only restrained against the rotation about the longitudinal axis of the specimen (i.e. twisting). The ends of Specimen 2 were bolted to L5x5x5/16 double angles using three 19.1 mm diameter ASTM A325 (ASTM, 2015a) bolts.

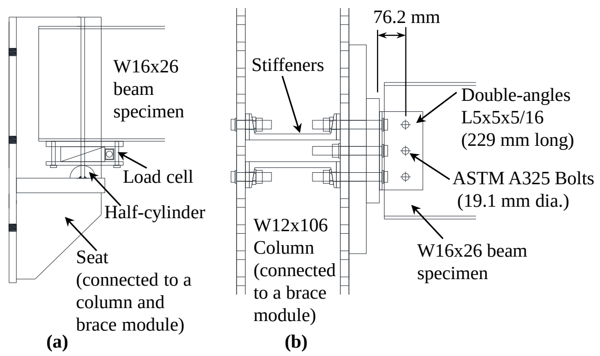

Fig. 2. Details of the support of (a) Specimen 1 (b) Specimen 2

Fig. 3 shows the instrumentation layout used in the tests. Type-K thermocouples were installed at sections 1 through 5 in the fire-affected zone. The temperature-compensated string potentiometers were installed to measure the vertical and lateral displacements at midspan. The conventional string potentiometers were used to measure the vertical displacements of the bottom flanges at the two loading points.

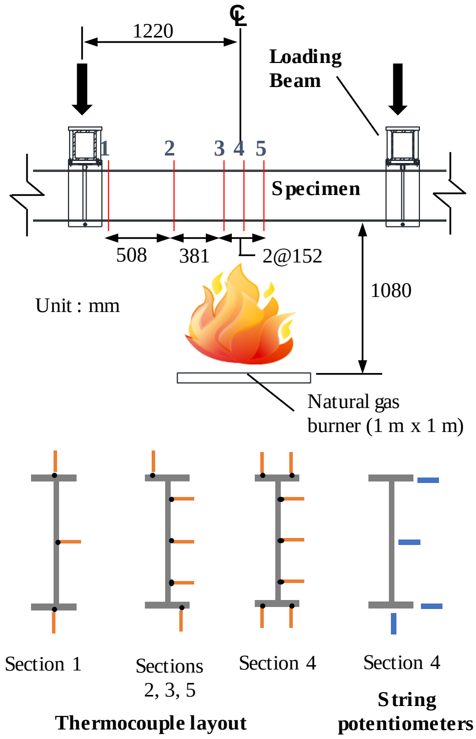

Fig. 3. Thermocouple and displacement sensor layout

3. Results and Discussion

Fig. 4 shows the average point load (P_y) applied on the beam specimen at the location of box-shaped loading beams and the heat release rates (HRR) of the natural gas burner over the test duration. Prior to fire loading, each point load on the beam specimen was increased to 89 kN, approximately 67% of the measured ambient capacity, and this load was maintained throughout the test. The specimen was exposed to an open flame fire controlled by regulating the flow of natural gas. The t-square fire was applied using a pre-programed quadratic function of HRR $= 4.5 \cdot t^2 + 250$, where t is fire exposure time in minutes and HRR is in kW. Fig. 5 shows a photograph of Specimen 1 during the test. When the specimens could no longer support the imposed loads, the specimens were immediately unloaded, and the burner was shut off. The figure shows that Specimen 1 failed at 37.9 minutes (i.e., 17.5 minutes from ignition of a fire); Specimen 2 failed at 30.5 minutes (i.e., 14.2 minutes from ignition of a fire).

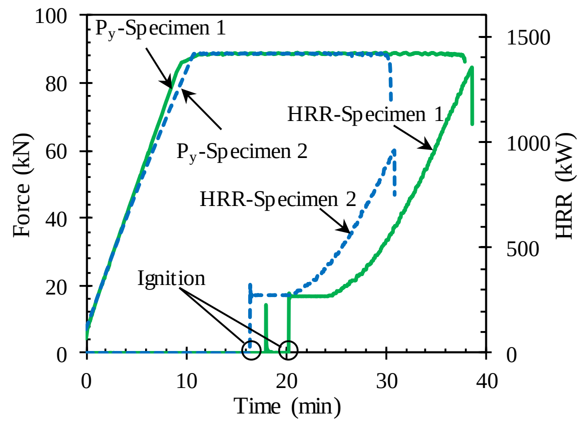

Fig. 4. Measured HRR and average point load (P_y)

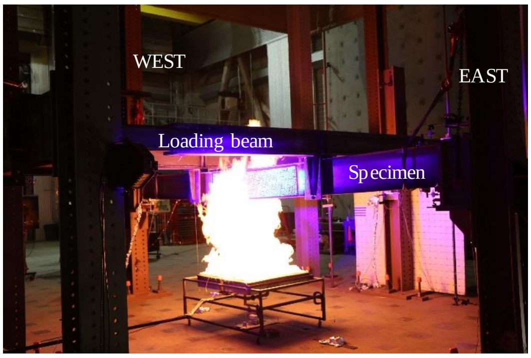

Fig. 5. Specimen 1 under structural and thermal loading

Figs. 6(a) and 6(b) show steel temperature-time curves measured in the fire-exposed cross-sections of Specimens 1 and 2, respectively. The magnitudes of temperatures in those figures are averaged values of temperatures in sections 3, 4, and 5 at each thermocouple location shown in Fig. 6(c). As shown, non-uniform temperature distribution was developed through the section depth. The temperature of the exposed bottom flange was directly affected by the HRR versus time relationship. However, the temperatures in the other locations, i.e., the upper portion of the cross section, were similar, and no severe thermal gradient was developed.

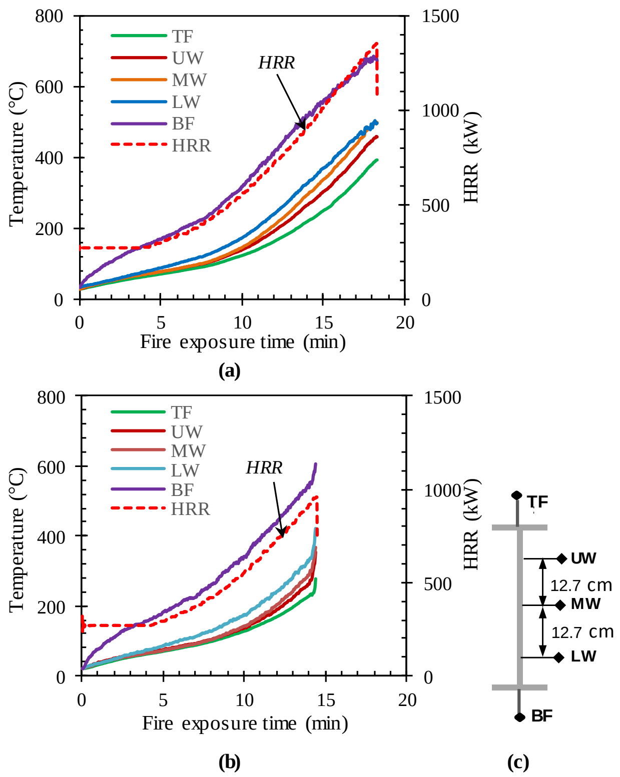

Fig. 6. Thermal response of (a) Specimen 1 and (b) Specimen 2; (c) locations of temperature measurements

Figs. 7(a) and 7(b) show the displacement versus the bottom temperature responses of Specimens 1 and 2, respectively, where the displacement data includes the vertical displacements at midspan and at the loading points as well as the lateral displacements at the top and bottom flanges. In those figures, the positive values indicate the vertical displacement in the downward direction and the lateral displacement in the south direction. It should be noted that, the discontinuity of the plotted displacement data indicates the sensor failure.

As shown in Figs 7, both Specimens 1 and 2 started sagging as soon as a fire was ignited. Regardless of the beam end conditions, the thermal gradient developed through the section depth, as shown in Fig. 6, caused bowing of the specimen. During a fire, the lower portion of the cross section subjected to an intense heat from fire expanded greater than its upper portion which remained at lower temperature. This nonuniform thermal expansion led the beam specimen to deflect toward the hotter side.

As the critical temperatures were reached, the beam specimens behaved in a complex way such that combined flexural bending (about the strong axis) and lateral torsional buckling occurred simultaneously. The midspan lateral displacements of Specimens 1 and 2 gradually increased when the bottom flange temperature reached about 550 °C and 500 °C, respectively. At those temperatures, the vertical displacements were continuously increasing.

To evaluate the overall fire resistance of the steel beams on a consistent basis, the temperature at a certain vertical displacement limit can be compared. In this study, the vertical displacement of 76 mm was considered as the displacement limit at failure since it was the maximum displacement recorded for Specimen 1. As shown in Fig. 7, the bottom flange temperature of Specimen 1 corresponding to this displacement limit was (663 ± 85) ºC and that of Specimen 2 was (552 ± 21) ºC.

Given that the same structural and fire loading were applied, Specimen 1 failed at higher bottom flange temperature than Specimen 2. The lower failure temperature observed in Specimen 2 is attributed to the effects of axial restraints (against thermal expansion) provided by double-angle connections attached to laterally rigid columns.

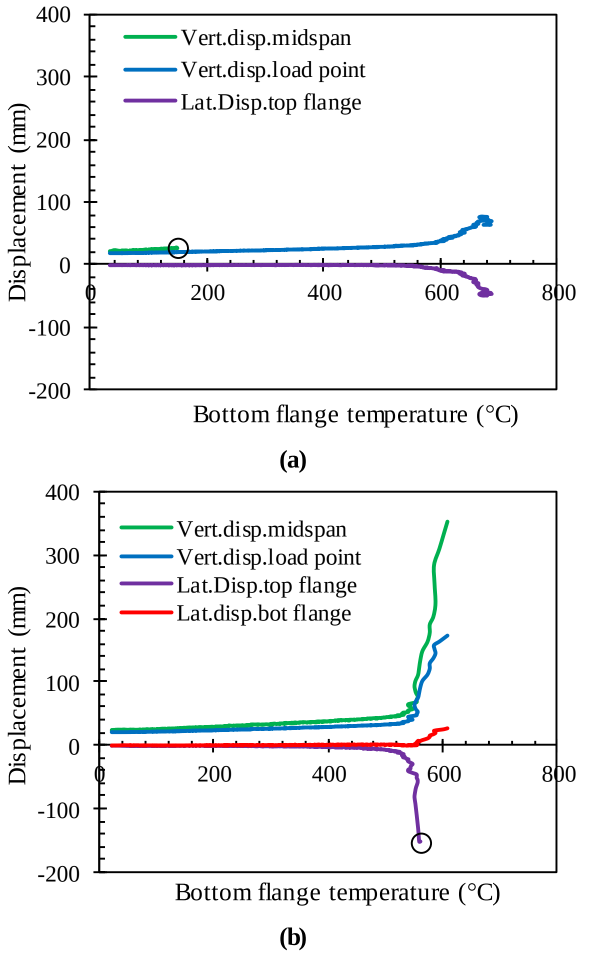

Fig. 7. Deflection responses of (a) Specimen 1 and (b) Specimen 2

It should be noted that the estimated standard uncertainty in temperature data reported in Fig. 6 was 42.5 ˚C. The estimated expanded uncertainty in the displacement measurement was 0.3 mm with a coverage factor of 2.

Figs. 8(a) and 8(b) show the deflected shapes of

Specimens 1 and 2, respectively, after the cool-down phase. The steel beam specimens exhibited permanent deformations in the combination of the strong-axis bending and the lateral-torsional buckling. In both specimens, local buckling modes were observed at the compression flange (i.e., the top flange at midspan).

(a)

(b)

Fig. 8. Deflected shapes of (a) Specimen 1 and (b) Specimen 2

4. Summary and Conclusions

Two 6.17-m long W16×26 steel beams were tested under combined structural (flexural) and open-flame localized fire loads. Specimen 1 was simply supported; Specimen 2 was supported by rigid columns via double angle connections. The specimens were loaded using a four-point loading scheme to apply a uniform bending moment between two point loads. The midspan of each specimen was directly exposed to an open-flame natural gas fire. Regardless of the beam end conditions, a thermal bowing was observed due to the thermal gradient developed in the fire-exposed cross sections. Both specimens showed combined flexural and lateral torsional behavior at failure. Under the same t-square fire, however, Specimens 1 and 2 failed at a bottom flange temperature of 663 °C and 552 °C, respectively. This discrepancy in the failure temperature was caused by axial restraints (against thermal expansion) provided by double-angle connections.

6. References

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