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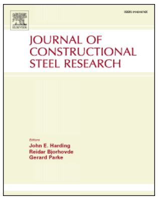

Behaviour of restrained high strength steel columns at elevated temperature

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ABSTRACT

High strength steel has been widely used in various types of structures due to its merits of high strength and good ductility. However, high strength steel structures are vulnerable to fire hazards as the strength and stiffness of the steel deteriorate rapidly at elevated temperature. Presented in this paper are the investigations on the behaviour of restrained high strength steel columns at elevated temperature obtained from full-scale fire tests and finite element analyses. In the fire tests, applied load and restraint stiffness are two key factors to be examined. Column responses such as the axial displacement, deflection at column middle height and axial force induced by thermal expansion associated with temperature evolution were reported. Column buckling and failure temperatures were determined based on the criteria of the axial displacement and lateral deflection of the specimens at elevated temperatures. The test results show that both the applied load and restraint stiffness have considerable influences on fire resistances of high strength steel columns. It was observed that the columns with only axial restraints failed by flexure buckling about the weak axis whereas the columns with both axial and rotational restraints and subjected to large magnitude of the applied load failed by flexural torsional buckling. Finite element analyses were conducted to simulate the fire responses of the test specimens and the obtained numerical results are found to be reasonably agree with the test data. Parametric studies via finite element analysis were carried out to quantitatively determine the effect of applied load, restraint stiffness and slenderness ratio on fire resistance of high strength steel columns.

1. Introduction

In recent years, high strength steels (HSS) are widely used in long-span structures and high-rise buildings primarily due to its merits of high yield strength and good ductility. For example, more than 400 tons of high strength steel are used in the construction of China National Stadium (so-called "Bird Net"), where the opening ceremony of 2008 Olympic Games was held [1]. As there is no a general consensus on the definition of HSS around the world, the yield limits adopted for categorizing HSS are different in various design standards. Generally, a type of steel is referred as high strength steel if its yield strength is not less than 460 MPa. In fact, one most common product of high strength steel in Far East is Q460 steel with the nominal yield strength of 460 N/mm^2.

In fire conditions, buckling of steel columns can occurs at a lower magnitude of load than that of at ambient temperature as the result of degradations of strength and stiffness at elevated temperatures [2,3]. In the case of local fire, the fire response or behaviour of a steel column with end restraints is quite different from that of a steel column without end restraints since the thermal expansion in the restrained steel column would result in an additional axial force in the heating phase [4]. In the cooling phase, the load applied on the restrained column may be transferred to the adjacent columns which have not experienced elevated temperature. Literature review [5] demonstrates that there are some fundamental researches on fire response of restrained steel columns, not only by testing, but also by finite element modelling. Li et al. [6,8] conducted a series of investigations on behavior of restrained steel column in fire with carrying out fire tests, finite element simulation and development of a practical design approach. It was found from the investigations that the axial restraint resulted in a lower buckling temperature for the restrained steel columns and the effects of axial restraint to the failure temperature were also related to the load ratio and the axial restraint stiffness ratio. Correia and Rodrigues [9] conducted fire tests on restrained steel columns and the results showed that increasing the stiffness of the adjacent structure members might not lead to a reduction of the critical temperature of a restrained steel column. Correia et al. [10] subsequently proposed a simple approach for fire design for steel columns with thermal elongation being restrained based on the results obtained from a parametric study using

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finite element software ABAQUS. Yang and Yang [11] carried out fire tests for ten unprotected restrained column specimens. The specimens were loaded by steady-state method and heated up to 500 °C. Craveiro et al. [12] conducted a series of experiments to investigate the behavior of restrained cold-formed steel built-up columns for both closed and open sections at elevated temperature. The results showed that the magnitudes of restraining stiffness and applied load are the important parameters influencing the fire behavior of the columns. In addition, it was found that the 350 °C of limit temperature for class 4 cross-sections stipulated in European code [13] is conservative.

From the aforementioned literature review, it was found that almost all the tests were carried out for mild steel or cold-formed steel columns. There are few publications reported on the investigation of the axially and rotationally restrained high strength steel columns at elevated temperature. It needs to point out the structural properties adopted for fire resistance design of steel structures in current design standards and specifications are not applicable for high strength steel structures since the deterioration of steel properties are different between mild and high strength steel [14]. To address this knowledge gap, a recent investigation, which includes an experimental test program and the corresponding finite element analysis, on the behaviour of high strength Q460 steel columns subjected to both fire and applied loading is presented in the following.

2. Experimental program

In order to investigate the fire response of restrained high strength steel columns, fire tests were carried out for the high strength steel columns with axially and rotationally end restraints in a fire furnace.

2.1. Specimen preparation

Eight column specimens were made of Q460 steel plate welded to a H-shape section of H200x195x8x8, in which four specimens were designed with axial end restraints with the length of 4.3 m, whereas the others are designed with both axial and rotational end restraints with the length of 4.48 m. The restraining stiffness at each end was provided by two H-shaped steel beams made of Q235 steel with the length of 3.2 m. Two cross-sections, namely H200x150x6x9 and H300x150x6.5x9 were fabricated for the beam to generated two different restraining stiffness. The mechanical properties of the test specimens and the restraining beams are obtained by the standard tension coupon test according to the ASTM A370 test protocol [15]. The test results are tabulated in Table 1.

For the specimens with the axial end restraints, the end conditions are hinge connected to the restraining beam to ensure the specimen ends can freely rotate about its weak axis. The end conditions of strong axis are seen as fixed and cannot rotate. For the specimens with both axial and rotational end restraints, extended end-plate connections were used to connect the column ends to the restraining beam in such a way both axial and rotational deformation at column ends are prevented. The aforementioned two types of end connections are illustrated in Fig. 1.

Different magnitudes of the applied load and restraining stiffness were considered in the tests. The axial restraint ratio β_a is defined as:

$$\beta_a = \frac{K_b}{K_c} = \frac{48E_bI_b}{l_b^3} / \frac{E_cA_c}{l_c} \tag{1}$$

Table 1
Material properties of steels by coupon tests.

Steel	Thickness	Yield strength	Ultimate strength	Elastic modulus
Q235	9 mm	285 MPa	415 MPa	2.10×10^5 MPa
Q460	8 mm	585 MPa	660 MPa	2.12×10^5 MPa

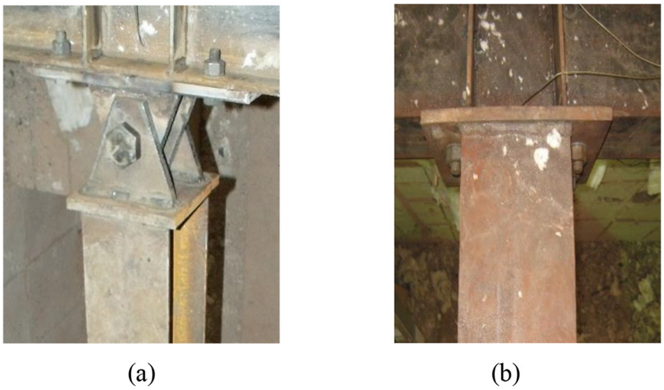
(a) (b)

Fig. 1. Connection between column specimen and restraining beam. (a) Hinged connection (b) Extended end-plate connection.

where K_b is the flexural stiffness associated with the mid-span deflection of the restraining beam; K_c is the axial stiffness of the column; I_b is the moment of inertia of the beam; A_c is the column cross sectional area; and l_b and l_c are the length of the beam and column, respectively.

The rotational restraint ratio is defined as:

$$\beta_r = \frac{K_{rb}}{K_{rc}} = \frac{12E_bI_b}{l_b} / \frac{3E_cI_c}{l_c} = \frac{4E_bI_bl_c}{E_cI_cl_b} \tag{2}$$

where K_{rb} is the rotational stiffness associated with the mid-span rotation of the restraining beam; K_{rc} is the end rotational stiffness of the column;

The load ratio R is expressed as:

$$R = N/N_{cr} \tag{3}$$

where N is the applied load placed on the column top end and N_{cr} is the ultimate load capacity of the column evaluated based on GB50017-2017 [16] at ambient temperature.

The detail information about the specimens is tabulated in Table 2.

2.2. Test set-up and measurements

The test specimens are heated in a fire furnace. The dimension of the furnace is 3.6 m wide, 4.6 m long and 3.3 m high. The maximum heat power generated by the furnace is 5 MW. Eight natural gas burners are installed in the furnace, and the furnace temperature was recorded by ten thermocouples placed in the test chamber over a fire test. The plan view of the furnace is shown in Fig. 2. During the fire test, the temperature readings in thermocouples (noted as FT1 ~ FT8) are used to compare with that of ISO-834 heating curve and the control system automatically adjusts corresponding fuel supply to maintain the furnace temperature with that of the heating curve.

A horizontal self-reaction loading system, consisting of a steel frame and two steel restraining beams (top beam and bottom beam), was designed to apply loading on the test specimen and provided desirable

Table 2
Parameters of the specimens.

Specimen No.	End restraint	Load (ratio)	β_a	β_r
S-1	Axial	0.25	0.45	0
S-2		0.40	0.45	0
S-3		0.25	0.17	0
S-4		0.40	0.17	0
S-5	Axial and rotational	0.20	0.45	36
S-6		0.20	0.17	14
S-7		0.36	0.45	36
S-8		0.38	0.17	14