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Experimental investigation of eccentrically compressed stainless steel columns with constraints in fire

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ABSTRACT

To study the behaviour reaction and failure mechanism of stainless steel columns in fire, a series of fire tests were performed on the eccentrically compressed columns with constraints, based on S30408 stainless steel. 7 specimens were used to investigate the effects of the load ratio n, eccentricity e and axial constraint stiffness ratio β on the fire-resistance performance of eccentrically compressed stainless steel columns. The failure process and failure modes of stainless steel columns in fire were revealed. The test phenomena, heating curve, deformation curve and buckling temperature were obtained. The test results show that the load ratio n ($n = 0.22–0.35$), eccentricity e and axial constraint stiffness ratio β ($\beta = 0.0458$ and 0.0495) are the key factors that determine the fire-resistance performance of eccentrically compressed stainless steel columns with constraints. The larger the load ratio n, eccentricity e and axial constraint stiffness ratio β are, the lower the buckling temperature of the specimen. There are two main types of failure modes of eccentrically compressed stainless steel columns with constraints in fire: the first is the overall buckling mode and the second is the local-overall interaction buckling mode. The failure modes depend mainly on the section dimensions and the section type of the stainless steel column. The process of bearing capacity of eccentrically compressed stainless steel columns with constraints in fire goes through two stages: the prebuckling stage and the post-buckling stage. It takes times for the specimen to progress from the buckling state to the ultimate failure state. The bearing capacity of the post-buckling stage can effectively improve the fire-resistance performance of the stainless steel column with constraints.

1. Introduction

The design and analysis of structures under normal service conditions are relatively mature, but because structure fires occur frequently, the safety of building structures has unprecedented challenges under fire conditions. Therefore, the behaviour reaction and properties of structures in fire have attracted much attention around the world [1,2]. Stainless steel as a building structural material that has the advantages of an attractive appearance, good corrosion resistance, easy maintenance and low cost over a full life-cycle; therefore, it has wide applicability in building construction [3]. However, compared with carbon steel, stainless steel materials have a strong non-linear stress-strain curve with a lower proportional limit, an unapparent yield platform, anisotropic behaviour, significant strain hardening and higher elongation. There are many differences between carbon steel and stainless steel with respect to their mechanical properties. Therefore, the fire-resistant design methods of stainless steel columns are different from those of carbon steel columns. At the same time, due to an attractive appearance, stainless steel structures always lack fire prevention measures, making the study of the mechanical properties of structures in fire particularly important.

There have been many studies on the design method and theory of stainless steel members under normal service conditions. However, few studies have been conducted on the fire-resistance performance of stainless steel structures in fire, especially the fire-resistance performance of stainless steel columns with constraints. Ala Outinen and Oksanen [4,5] investigated the influence of multiple parameters on the performance of compressed stainless steel members and presented relevant design methods and suggestions. Gardner and Ng [6] carried out the numerical simulations on the temperature fields of stainless steel members in fire, analysed the thermal response factor of stainless steel material by sensitivity, and proposed the surface emissivity value and convective heat transfer coefficient. Gardner and Baddoo [7] conducted a full-scale fire test on six axially compressed stainless steel columns

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and four stainless steel beams with concrete ribbed plates to obtain the mechanical properties, failure modes, fire-resistant times and critical temperatures; then the relevant design suggestions and methods were proposed by finite element numerical simulation and parametric analysis. Uppfeldt et al. [8,9] performed fire tests on six axially compressed short stainless steel box columns with fixed supports at both ends, and the numerical simulations of the stainless steel columns were carried out; then a type of calculation method of the fire-resistant design of stainless steel columns was proposed. Ng and Gardner [10] investigated the effect of parameters (such as the slenderness ratio and load level) on the fire-resistance performance of stainless steel members, and the results showed that the slenderness ratio and load level were the main determinants of the critical temperature of stainless steel columns in fire. To and Young [11] evaluated the fire-resistance performance of rectangular and circular hollow section stainless steel columns with fixed supports at two ends; then the failure modes and the load curves of stainless steel columns at elevated temperature were determined, and two fire resistant design methods were proposed for the stainless steel columns. Gardner [12] summarized the existing research results of the stainless steel members at elevated temperatures and analysed the influence of the thermal expansion on stainless steel beams and columns with constraints. Lopes et al. [13] conducted a numerical simulation analysis of the mechanical properties of welded H-section stainless steel beams and columns, considering the influence of the steel material quality, residual stress, slenderness ratio and load model on the fire-resistance performance of the members; then the fire-resistant design methods of stainless steel beams and columns were locally adjusted in the European Codes (EN1993-1-2/EN1993-1-4) [14,15]. Ding and Fan [16–18] carried out fire tests on eight axially unrestrained stainless steel columns with square hollow sections, considering the influence of the load ratio, section dimensions and eccentricity on mechanical performance of stainless steel in fire, and the numerical simulations and parametric analyses were carried out; then the design method of stainless steel columns without constraints in fire was presented. Tondini et al. [19] conducted fire tests and load tests at room temperature on the columns with EN 1.4003 stainless steel, and the results showed that the temperature gradient along the longitudinal direction was the key factor for failure modes of stainless steel columns in fire. Fan et al. [20] carried out parametric analyses on the ultimate bearing capacity of H-section stainless steel columns with axial compression in fire, and the results showed that the slenderness ratio and section dimensions were the key factors that determine the ultimate bearing capacity of the H-section stainless steel columns with axial compression in fire.

There is a greater difference between the existing test results and the calculations according to the relevant codes. The largest difference between the mechanical properties of axially compressed stainless steel columns with constraints and without constraints is the following: the thermal expansion of restrained columns results in an additional axial force inside the members during heat; thus, the fire-resistance performance of the members is reduced. At present, the fire-resistant design methods of stainless steel members have been proposed in European Codes (EN1993-1-2/EN1993-1-4) [14,15] and Euro Inox/SCI [21]. However, those design methods are based on the fire test results of unrestrained stainless steel members, which could not reflect the actual mechanical properties of the restrained stainless steel members.

Therefore, to investigate the mechanical properties of eccentrically compressed stainless steel columns with constraints in fire, a series of fire tests were carried out based on S30408 according to the fire-resistant test-elements of building construction (GB/T 9978.1–2008) [22]. The effects of the load ratio n, the eccentricity e and the axial stiffness ratio β on the fire-resistance performance of eccentrically compressed stainless steel columns with constraints were investigated. The test phenomena, temperature-time curves of the furnace, temperature-time curves of specimens, deformation-time curves, buckling temperature and failure modes were obtained.

2. Fire tests

2.1. Test equipment and loading device

In general, fire tests on columns or walls are conducted with a vertical fire furnace test system. Because of the dimensions and end constraints of the eccentrically compressed stainless steel columns, it is difficult for this fire test to be accomplished using a vertical fire furnace test system. Therefore, according to the fire test method of the carbon steel columns with constraints in the existing literature [23,24], the fire tests on the eccentrically compressed rectangular-section stainless steel columns with constraints were conducted using a horizontal fire furnace test system. The system mainly includes three parts: the horizontal fire furnace, the loading system and the data acquisition control system.

The dimension of the furnace chamber was $2.4\,m \times 3.4\,m \times 4.25\,m$. 8 craters and eight thermocouples were set up in the furnace chamber, which were used to heat and control the temperature of the fire furnace. The furnace chamber was heated according to the ISO-834 standard heating curve. It was necessary to design and produce a set of horizontal loading systems for the eccentrically compressed stainless steel columns with constraints before the fire tests. The horizontal loading system mainly includes a horizontal loading reaction frame and a restrained steel beam. The horizontal loading reaction frame provided the main support point for the test loading and was needed to meet the force self-balance. The restrained steel beam provided axial restraint stiffness for the test specimen. In the fire test device, the horizontal loading reaction frame was placed on the top steel beam of the horizontal fire test furnace. The restrained steel beam and the test specimen were placed horizontally in the horizontal load reaction frame. The test load was applied to the restrained steel beam using a hydraulic jack. The plane layout of the horizontal loading system is shown in Fig. 1.

There was a circle of H-section steel beams around the top of the horizontal fire test furnace, and the top flange of the steel beam was flat with the top of the furnace. The horizontal load reaction frame was placed on the top flange of the steel beam. Along the inner surface of the furnace, the fire mortar was used to build the 120-mm-thick fire brick wall from the bottom of the furnace to 600 mm above the furnace roof, as shown in Fig. 2 (a). The cover plate with furnace chamber above the test furnace was placed on the fire brick wall. There was enough clearance between the bottom of the cover plate and the upper surface of the test specimen to ensure that the eccentrically compressed stainless steel column specimens had four faces exposed to fire. At the same time, to ensure the sealing of the test furnace during the fire test, fire rock wool was spread on the inner surface of the fire brick wall, as shown in Fig. 2 (b).

2.2. Test specimens

2.2.1. Section dimensions of specimens

When determining the length and the section dimensions of the eccentrically compressed stainless steel columns with constraints, the following factors were considered: (1) the length of the compressed members should not be less than 3.0 m in accordance with the fire-resistant test elements of building construction (GB/T9978.1–2008) [22]; (2) the dimensional requirements of the horizontal fire test furnace; (3) the ratio of the axial constraint stiffness between the restrained steel beam and test specimens should not be too large or too small, and the axial restraint stiffness ratio should be controlled in 0.02–0.10 according to the existing researches [23–25]; and (4) the section dimensions of the test specimens shall meet the standard for the classification of column sections in European Codes [14,15]. Considering the above factors, seven specimens were used in the fire tests; the length of the stainless steel columns was set at 3300 mm; and the section dimensions of specimens were set as $120\,mm \times 120\,mm \times 5\,mm$, $140\,mm \times 120\,mm \times 5\,mm$ and