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Fire resistance of stainless steel beams with rectangular hollow section: Experimental investigation

Shenggang Fan [a,*], Binbin He [a], Xinfeng Xia [a], Heyang Gui [a], Meijing Liu [b]

[a] Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, School of Civil Engineering, Southeast University, Sipailou #2, 210096 Nanjing, China
[b] Department of Civil Engineering, Southeast University Chengxian College, 210088 Nanjing, China

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ABSTRACT

To study the bearing capacity and failure mechanism of rectangular stainless steel beams in a fire, a series of tests were performed on S30408 stainless steel, including 3 material mechanical property tests at room temperature, 45 material mechanical property tests at elevated temperature and fire experiments of 6 rectangular hollow section stainless steel beams with two simply supported ends. Both steady tests and transient tests at elevated temperature were used to investigate the mechanical properties of stainless steel. The stress–strain curve, elastic modulus, yield strength and reduction factor of ultimate strength of stainless steel at elevated temperature were found, and the test results were compared with the results of the European Codes. The experiments studied the mechanism properties of a rectangular hollow section stainless steel beam in fire, and the failure phenomenon, heating curve, deformation curve and critical temperature of the test specimens were obtained. The effects of the sectional dimension and load ratio on the critical temperature and fire-resistance performance of the stainless steel beam were also studied. The test results show that the load ratio and section depth are the key factors for the critical temperature of a stainless steel beam in fire.

1. Introduction

As a construction material, stainless steel offers great applicability due to its attractive appearance, strong corrosion resistance, easy maintenance and low life cycle cost. In addition, booming growth in the production of stainless steel along with its many varieties and continuing improvements in processing methods have paved the way for its increased use in building structures in recent years. Under the strong urge of the construction market, stainless steel as an architectural material is the new trend of civil engineering and is welcomed by many architects and structural engineers.

The design specifications for structures at normal service conditions are relatively mature, but because structure fires frequently occur, the security of the architectural structure is facing unprecedented challenge under fire conditions. Therefore, the behaviour reaction and properties of structures in fire have gained attention in all countries, especially the new materials (such as stainless steel, aluminium alloy and glass) that are without any fire prevention measures for their aesthetic appearance, making the study of the mechanical properties of these structures particularly important.

Many studies have investigated the material properties at elevated temperatures and the fire resistance of stainless steels. Baddoo and Burgan [1] analysed the test results of two austenite 304 stainless steel composite beams at elevated temperature, and the results showed that a stainless steel composite beam is superior to a carbon composite beam. Zhao and Blanguemon [2] carried out mechanical property tests of stainless steel beams and column components and proposed the fire resistance design method for stainless steel columns in fire. The simplified calculation methods for the bearing capacity of a stainless steel beam in fire were proposed in European Codes (EN1993-1-2/EN1993-1-4) [3,4]. Gardner and Baddoo [5] conducted full-sized fire tests on 6 stainless steel axial compression columns and 4 stainless steel beams with concrete ribbed plate for stainless steel type EN1.4301 and obtained the related design guidance and methods. Uppfeldt et al. [6] conducted finite element analysis for the fire resistance performance of box section stainless steel columns at elevated temperature and locally adjusted and modified the methods of the design code, thus proposing a new method suitable for fire resistance design of a stub column. Gardner and Ng [7,8] studied the effect of different parameters on the fire resistance of stainless steel components, and the results showed that the slenderness

* Corresponding author.
E-mail address: 101010393.@seu.edu.cn (S. Fan).

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ratio and load level were the decisive factors affecting the critical temperature of stainless steel columns in fire. Christophe [9] conducted fire tests on two stainless steel composite beams, and the results showed that the stainless steel composite beam without fire resistance measures can satisfy at least 60 min of fire resistance time within certain limits of load ratio. Ernest and Young [10] evaluated the fire resistance performance of rectangular and circular section stainless steel columns and proposed two methods suitable for fire resistance design of stainless steel columns. Vila Real et al. [11] calculated the bearing capacity of a stainless steel beam with the lateral displacement and lateral torsion constrained using the programme SAFIR [12] and proposed a simplified calculation formula. Ellobody [13] used a nonlinear 3D finite element model to conduct a parametric analysis of the bearing capacity of a stainless steel composite beam at elevated temperature. Lopes et al. [14] evaluated the accuracy and safety of the bearing capacity of a stainless steel beam in fire and proposed a new design method. Ding [15] carried out fire experiments on 8 square hollow section stainless steel columns without longitudinal restraint and investigated the effects of the load ratio, section size, eccentricity and other parameters on the bearing capacity. Xia [16] performed fire experiments on 6 rectangular hollow section stainless steel beams and proposed calculation methods for the bearing capacity and critical temperature of a stainless steel beam in fire based on the design method in the European Codes.

The stainless steel material takes on a complicated stress–stain relation according to its strong nonlinearity, low proportional limit, unapparent yield platform, anisotropy and strain hardening property in normal temperature. The elastic modulus, the nominal yield strength and the hardening index are the three influence factors on stainless steel stress–strain relation at room temperature. However, differences in processing technique, production site, and test method for stainless steel may lead to great variation in the mechanical property test results at high temperature. As a result, for now a unified material model for stainless steel at high temperature has not been put forward. In the meantime, the essential behaviour of a structure in fire is that the rise of temperature and heat transfer result in the decay of material performance. Parts of the members are damaged and cannot support the structure any more, and the balance of the structure system is broken, with internal force redistribution. As the fire spreads from the centre, the damage range of structure extends continuously. As a result, the main structure may lose its bearing capacity or collapse in a wide range.

Based on steady tests and transient tests at elevated temperature, material mechanical property tensile tests on S30408 stainless steel were conducted to study the stress–strain curve, elastic modulus, yield strength and ultimate strength. Fire experiments on 6 rectangular hollow section stainless steel beams with two simply supported ends investigated the effects of the sectional dimension and load ratio on the critical temperature and fire-resistance performance of a stainless steel beam, and the failure phenomenon, heating curve, deformation curve and critical temperature of the test specimens were obtained. The results show that the load ratio and section depth are the key factors affecting the critical temperature of a stainless steel beam in fire.

2. Mechanical property tests

The mechanical properties of stainless steel at room temperature and at elevated temperature are the basis for analysing and designing a structure or component. Two major test methods exist for finding the mechanical properties of stainless steel at elevated temperature: steady tests and transient tests [17,18]. In steady tests, coupons are heated to an appointed temperature according to a certain heating model and then held at a constant temperature for a certain amount of time. When the temperature of the coupons is uniformly distributed, tensile tests are carried out. In transient tests, the coupons are first loaded to a certain stress level and then heated according to a certain heating model until the coupons break.

To study the mechanical properties of stainless steel at both room temperature and elevated temperature, the flat tensile coupon tests were performed on the test material of S30408 stainless steel. The flat tensile coupon tests include a test at room temperature, steady test and transient tests at elevated temperature and a free expansion test, with a total of 48 test coupons (3 coupons at room temperature, 18 steady test coupons, 2 free expansion test coupons and 26 transient test coupons). The experiment equipment was an MTS810 material test system including loading equipment, heating equipment (high temperature furnace), and temperature controlling equipment and measuring equipment.

2.1. Tests at room temperature

The flat tensile coupons of stainless steel were cut from the flat regions of the rectangular hollow section stainless steel beam specimen, and the dimensions are detailed in Fig. 1. In Fig. 1, b is the width of the tensile coupon, t is the thickness of the tensile coupon and L_0 is the standard distance. In order to effectively control the smoothness and cutting speed of the coupons, a laser cutting machine was employed to cut all the coupons from 5 mm parent material. After cutting out the specimens, the cut edges were polished and the dimensions of each specimen were measured. The specimen code and dimensions are detailed in Table 1.

The flat tensile coupon tests of stainless steel at room temperature were loaded in displacement-controlled mode and consist of two periods. The first loading period was intended to measure the initial elasticity modulus and nominal yield strength of the stainless steel. Tensile load was applied to the coupons at the deformation rate of 0.3 mm/min until the deformation reached 6 mm. The second loading period was mainly intended to measure the ultimate tensile strength, for which the deformation rate was 3 mm/min until the coupons broke.

According to the data fitting method of the mechanical property test results of stainless steel proposed by Gardner [19] and the formula for the stress–strain curve of stainless steel put forward by Rasmussen [20], the basic parameters of the mechanical properties of stainless steel at room temperature were obtained, and the detailed test results are shown in Table 2.

2.2. Tests at elevated temperature

The dimensions of the flat tensile coupons at elevated temperature are detailed in Fig. 2, where b is the width of the tensile coupon, t is the thickness of the tensile coupon and L_0 is the standard distance. In order to fix the elevated temperature extensometer and prevent it from slipping in the tensile process, grooves were set on both ends of the standard distance of the tensile coupons, shown in Fig. 2.

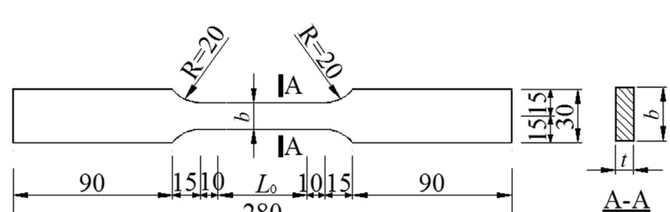

Fig. 1. Specimen dimensions in tensile test at room temperature.