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Experimental investigation of austenitic stainless steel material at elevated temperatures

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HIGHLIGHTS

- Tensile tests of flat and corner regions under elevated temperatures were carried out.
- The accuracy of the two-stage Ramberg-Osgood model remained to be further improved.
- Mechanical properties parameters at elevated temperatures given in Eurocode were unsafe.
- The reduction factor of the plate material is lower than that of the corner material.
- Formulas of reduction factor of mechanical properties were proposed.

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ABSTRACT

Based on S30408 austenitic stainless steel, the mechanical properties of materials in flat and corner regions were investigated by steady state tests and transient state tests at elevated temperatures. The stress-strain curves of stainless steel at elevated temperatures obtained by the two test methods were compared and analysed. The results show that the mechanical properties of stainless steel obtained by the two test methods are approximately equivalent when the temperatures are lower than 700 °C; otherwise, the mechanical properties obtained by the two test methods are not completely equivalent. The formulae of the reduction coefficient of mechanical properties of stainless steel at elevated temperatures were put forward. The influences of strain hardening indices n_θ and m_θ on the stress-strain curves of stainless steel at elevated temperatures were simulated. The results show that there are large deviations in the strain hardening indices obtained by different tests.

1. Introduction

Stainless steel has a wide application in building construction owing to its attractive appearance, high level of resistance to corrosion, ease of maintenance and low life-cycle cost. Driven by construction market demand, the rapid growth in production, the increasingly wide varieties and the innovation of processing production, using stainless steel as construction material is a new trend in the field of civil engineering. In recent years, stainless steel shows broad application prospect and is favoured by many architects and structural engineers.

The design and analysis method of building structures under serviceability state is becoming more mature. Nevertheless, because of the frequent occurrence of building fires, the safety of structures under fire condition is facing unprecedented challenges. The mechanical properties of stainless steel at elevated temperatures are the important parameters of fire resistance design and numerical simulation analysis of stainless steel structure. However, compared with carbon steel, stainless steel has a stronger nonlinear stress-strain curve, a lower proportional limit, no obvious yield platform, anisotropy, significant strain hardening and higher elongation. There were significant differences of the mechanical properties between the two materials at room and elevated temperatures. Thus, it is very necessary to carry out more studies of the mechanical properties of stainless steel at elevated temperatures.

The mechanical properties of stainless steel at room temperatures and at elevated temperatures 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 temperatures: steady state tests and transient state tests [1–4]. In the steady state tests, coupons are heated to an appointed temperature according to a certain heating mode and held at a

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constant temperature for a certain amount of time. When the temperature of coupons is uniformly distributed, tensile tests are carried out. This test method has relatively low requirements for the test equipments and requires few coupons. The stress-stain curve of stainless steel at a specific temperature can be directly obtained by an experiment. In the transient state tests, the coupons are first loaded to a certain stress level and then heated according to a certain heating mode until the coupons break. This test method has higher requirements for the test equipment and requires many coupons. However, the test conditions are closer to the actual fire scene, and the results obtained by the transient state tests are more real.

At present, many experimental studies [5–12] have investigated the mechanical properties of stainless steel at room temperatures. However, there are not many studies on mechanical properties of stainless steel at elevated temperatures. In the relevant specifications, only European code (EN1993-1-2) [13] and the Euro Inox/SCI. Design manual for structural stainless steel (2006) [14] give the calculation methods of mechanical properties of stainless steel at elevated temperatures. The relevant experimental reports on the mechanical properties of stainless steel are mainly from studies as follows. Ala-Outinen [15] performed the fire tests of mechanical properties on flat and corner area of stainless steel type EN1.4301 and EN1.4571 cold-formed stainless steel components, and obtained the variation law of the elastic modulus, yield strength and tensile strength of stainless steel with temperatures. Sakumoto et al. [16] carried out the tensile tests of mechanical properties of stainless steel at elevated temperatures, and gained the mechanical property parameters, stress-strain curves and creep-time curves of stainless steel. Chen and Young [17] performed a series of tests of mechanical properties on stainless steel type EN1.4301 and EN1.4571 at elevated temperatures, and established the calculation formulae of the mechanical property parameters and the stress-strain model of stainless steel at elevated temperatures. Gardner and Baddoo [18] conducted the fire tests of the mechanical property on five grades of stainless steel at elevated temperatures, and proposed the formulae for calculating the reduction factors of strength and stiffness at various temperatures. Montanari and Zilli [19] carried out transverse and longitudinal tensile tests, and the results showed that the stainless steel also has anisotropy at elevated temperatures. Abdella [20] proposed a more accurate stress-strain relationship of stainless steel at elevated temperatures based on the Ramberg-Osgood model. Gardner et al. [1] numerically simulated the calculation of the reduction coefficient of strength and elastic modulus at elevated temperatures through the comprehensive summary of the existed test data of mechanical property at elevated temperatures and put forward the stress-strain model of stainless steel at elevated temperatures by the modified R-O equation. Xia [21] carried out the tests of mechanical properties of stainless steel at elevated temperatures, including 18 coupons for the steady-state tests and 26 coupons for the transient-state tests, which were from the flat regions of the austenitic S30408 stainless steel members, and provided the relevant parameters for the mechanical properties of stainless steel at elevated temperatures, and modified the hardening coefficients in the stress-strain relationship of stainless steel. Raghuram et al. [22] carried out tensile tests of the mechanical properties of stainless steel based on austenitic 304 L and 316 L under the temperatures from 50 °C to 650 °C (intervals of 50 °C). The coupons were stretched three times at 0.0001 s^{-1}, 0.001 s^{-1}, 0.01 s^{-1} strain rate under each temperature condition. At elevated temperatures, the reduction coefficient of mechanical properties parameters (such as ultimate tensile strength, yield strength, elongation and strain hardening index of stainless steel at various strain rates) were compared. The results showed that there was no significant difference in the reduction coefficient of mechanical properties parameters at various strain rates.

In the above experimental studies of the mechanical properties of stainless steel at elevated temperatures, most of the test methods were steady state tests and transient state tests, and the maximum value of tests control temperature reached 1000 °C. The austenitic stainless steel type EN1.4301, EN1.4401, EN1.4541 and EN1.4571, ferritic stainless steel type EN1.4003 and duplex stainless steel type EN1.4462 were adopted in the above tests. The results showed that the mechanical properties obtained by the two test methods were similar when the temperatures were low, and the difference of results between the two test methods increased with the rising of the test temperatures. Based on the test results of mechanical properties of stainless steel at elevated temperatures, the numerical simulation analysis on constitutive model of stainless steel was carried out and proposed the stress-strain models for austenitic stainless steel type EN1.4301 and duplex stainless steel type EN1.4462 were proposed.

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 elevated temperature. As a result, for now a unified material model for stainless steel at high temperature has not been put forward. Meanwhile, the comparative analysis of results obtained by steady state tests and transient state tests was not sufficient in the existed experimental researches. First, in these experimental studies, the elastic modulus at elevated temperatures obtained from the two test methods was just compared, but the specific calculation method of that was not given. Besides, in the transient state test, there were big deviation on the elastic modulus at elevated temperatures. Secondly, the reduction factors of yield strength obtained from the two methods were not compared and analysed. Particularly, at elevated temperatures without conversion error, the mechanical properties of stainless steel, such as ultimate tensile strength, ultimate strain and stress-strain curve, were not given in the transient state test. At the same time, most stainless steel pipes (such as rectangular section, square section, etc.) are made by rolling or extruding stainless steel plates, and the evident strain-hardening effects of mechanical properties were produced in the bending zone of the stainless steel plate, which can lead to a large difference in the mechanical properties between the stainless steel in plates and corner areas at room and elevated temperatures [3,4].

Therefore, based on the steady state tests and the transient state tests, the tensile tests of the mechanical properties on austenitic S30408 (EN 1.4301) stainless steel in flat and corner regions at elevated temperatures were carried out to study the stress-stain curve, elastic modulus, yield strength and ultimate tensile strength. The test contents include the tensile tests at room temperatures, steady state tests and transient state tests at elevated temperatures. There are 61 coupons of stainless steel in this test, including 33 coupons from flat region (4 coupons for the room temperatures tests, 9 coupons for the steady state tests, and 20 coupons for the transient state tests), and 28 coupons from corner region (4 coupons for the room temperatures tests, 9 coupons for the steady state tests, and 15 coupons for the transient state tests). The mechanical properties parameters of stainless steel at elevated temperatures were obtained by experimental study and the differences of results between the steady state tests and transient state tests were analysed. At last, the calculation formulas of the reduction factors of the initial elastic modulus, yield strength, tensile