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Reduction factors for stainless steel bolts at elevated temperatures

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ABSTRACT

This paper presents an experimental investigation of the mechanical properties of sixty A4-70 and A4-80 stainless steel bolts under steady-state temperatures ranging from 20 to 900 °C. The material responses at elevated temperatures of the parent materials, SUS316 and SUS316Ti stainless steels (also known as EN 1.4401 and EN 1.4571 steels), and of fire-resistant bolts are included for comparisons. The tensile strength degradation of stainless steel bolts in fire are found to be reasonably close to those specified by Eurocode 3 Part 1.2 for their parent materials, but the Young's modulus degradation is not so robust. At temperatures lower than 650 °C, the stainless steel bolts retain their 0.2% proof strength better than their parent materials. Importantly, in the temperature range of 500 to 900 °C the stainless steel bolts retain their tensile strength, Young's modulus and 0.2% proof strength better than fire-resistant bolts (BOLTEN110N-FR to JSSII-09 standard). Based on the experimental data, reduction factors for tensile strength, Young's modulus and 0.2% proof strength are derived in this paper for stainless steel bolts at elevated temperatures.

1. Introduction

Stainless steel bolts are available in a variety of alloys with ultimate tensile strengths ranging from 480 to 1500 MPa (70 to 220 ksi). While high strength steel bolts with comparable tensile strengths such as Grade 8.8 bolts are available, such bolts tend to lose their tensile strength relatively quickly under high temperature compared to structural carbon steel bolts [1,2]. In addition to the high tensile strength of stainless steel bolts, the advantages of their use in building frames include the facts that no coating is required to protect against corrosion, and that a wider service temperature range may be applied compared to high strength steel bolts and structural carbon steels [3]. The potential use of stainless steel bolts in building frames is recognized by Eurocode 3 [4].

Moreno and Baddoo [5] published a technical report discussing the fire performance of M12 stainless steel bolts with a focus on its ultimate strength (tensile strength) and failure mechanisms. However, the experimental results are limited in demonstrating the strength and Young's modulus degradations of stainless steel bolts at elevated temperatures. To the authors' knowledge, little has been published in the literature regarding the strength and Young's modulus degradations of stainless steel bolts at elevated temperatures. Available data are only applicable to high strength steel bolts [1,2,6–8] and fire resistant bolts [9].

It may be noted that Hanus et al. [6] included both the heating and the cooling phases to simulate a "natural fire" condition. The cooling phase is important as it induces tensile stresses in axially restrained members of a framed structure. However, since the objective of the present work is to investigate the strength and Young's modulus degradations of stainless steel fasteners at a given temperature, only the steady-state temperature tests are involved.

This paper presents the strength and Young's modulus degradations of stainless steel bolts based on laboratory testing under steady-state temperatures ranging from 20 to 900 °C, conducted at Shenyang National Laboratory for Materials Science of the Chinese Academy of Sciences. It compares the present test results against the expected material responses of the parent materials, SUS316 and SUS316Ti steels, also known as EN 1.4401 and EN 1.4571 steels, respectively. Comparisons between the present test results and those obtained by other researchers for fire resistant bolts and Grade 8.8 bolts are also discussed. Reduction factor models for the Young's modulus, the 0.2% proof strength and the tensile strength of stainless steel bolts are proposed based on the test results.

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Table 1
Chemical composition of stainless steel bolts, fire resistant bolts and high-strength steel bolts.

Reference	Type	Chemical composition - mass fraction (%)									
		C	Si	Mn	P	S	Cr	Mo	Ni	Cu	B
This paper	A4-70	0.018	0.38	1.17	0.033	0.001	16.21	2.03	10.18	0.31	–
	A4-80	0.03	0.39	1.04	0.028	0.001	16.06	2.03	10.02	–	–
Sakumoto et al. [9]	BOLTEN110N-FR	0.224	0.249	0.790	0.023	0.023	–	–	–	–	–
Kirby [2]	Type 9	0.19	0.21	1.16	0.02	0.017	0.19	0.027	0.14	0.22	0.0051
	Grade 150 M36	0.41	0.16	1.61	0.021	0.038	0.13	0.13	0.12	0.23	<0.0005
BS EN ISO 898-1	Carbon steel with Mn & Cr	0.15–0.40	–	–	<0.025	<0.025	–	–	–	–	<0.003
	Carbon steel	0.25–0.55	–	–	<0.025	<0.025	–	–	–	–	<0.003
	Alloy steel	0.20–0.55	–	–	<0.025	<0.025	–	–	–	–	<0.003

2. Experimental program

2.1. Test specimens

This experimental program covered a total of 60 isothermal tests on two groups of stainless steel bolts belonging to the property classes A4-70 and A4-80 [10], manufactured to ISO 4014 [11]. The bolts are chiefly made from a number of iron-based alloys (e.g. austenitic steels EN 1.4401 and EN 1.4404) containing molybdenum, nickel and chromium for corrosion resistance and weldability, as shown in Table 1. The tensile strengths of the fasteners were increased through cold-forging.

Coupon test specimens were prepared from stainless steel bolts in accordance with the European standard EN 10002-5 [12] or ASTM standard E21-92 [13], as illustrated in Fig. 1. In each standard, a method is specified for tensile testing of metallic materials to determine the mechanical properties at elevated temperatures. The shape and dimensional details of the coupon are also available, where the original gauge length L_o is related to the original cross section area S_o as $L_o = 5.65S_o^{0.5}$. The geometry of the present coupons is shown in Fig. 1.

Both ends of each coupon were threaded for gripping, and the lower end was free to expand during heating before the tensile testing started.

2.2. Testing device and methodology

A 300-kN capacity INSTRON universal testing system with a heating device was used in the present work as shown in Fig. 2. Thermocouple wires were attached to the heating furnace and were used to control the heating rate inside the furnace at an increment of 50 to 80 °C per minute. While the relatively fast heating rate might result in a "temperature-overshooting" problem at the lower temperature range [14], it was prevented by slightly reducing the power input through the digital control system as the target temperature was approached.

Each tension test was performed at a stroke rate of 0.03 mm/min until the expected proof strength was reached, after which the stroke rate was increased to 0.75 mm/min until fracture. A high-temperature extensometer with a gauge length of 12.5 mm and a range limitation of ±2.50 mm was employed. In order to obtain a complete stress-strain curve, Chen and Young [14] have recommended that the extensometer be reset as the range limitation was approached during the testing.

Tensile testing of materials under elevated temperatures can be conducted under either steady-state or transient-state condition. The steady-state testing approach is commonly utilized to derive a full stress-strain curve of a metal at a given temperature, whereas the transient-state testing method is normally used to study the creep performance of a metal under temperature variation [8] including increasing and decreasing temperatures [6]. As mentioned in the introduction, since the objective of the present work is to investigate the strength and Young's modulus degradations of stainless steel fasteners at certain temperatures, only the steady-state approach was adopted, where each coupon was heated up to a target temperature that was then maintained for 15 min to establish a uniform temperature distribution before the specimen was loaded to failure. As shown in Table 2, the present target temperatures range from 20 to 900 °C.

Table 2 also shows the material properties of fire-resistant bolts and high-strength bolts tested by other researchers at elevated temperature, and their nominal properties at room temperature according to the relevant specifications.

As required by a reviewer of the original manuscript, Table 3 shows the property classes of the present specimens, the applicable manufacturing standard, the target temperatures, the tested properties and the manufacturers. For each property class and each target temperature, three specimens were tested, resulting in a total of thirty specimens for each property class since there were ten target temperatures.

In design standards, the reduction factors for strengths of stainless steels at elevated temperatures are applied to the 0.2% proof strength (yield stress) $f_{0.2,\theta}$ and to the ultimate tensile strength $f_{u,\theta}$ [15]. The 0.2% proof strength $f_{0.2,\theta}$ is defined as the intersection point between the stress-strain curve and the proportional line off-set by 0.2% strain [4].

It may be noted that the proof strengths $f_{0.5,\theta}$, $f_{1.0,\theta}$, $f_{1.5,\theta}$ and $f_{2.0,\theta}$ at the strain levels of 0.5%, 1.0%, 1.5% and 2.0%, respectively, are determined as the intersection points between the stress-strain curve and the corresponding vertical lines as shown in Fig. 3. In Eurocode 3 [15], the Young's modulus E of stainless steel is known as the slope of the linear elastic range of the stress-strain curve, as indicated in Fig. 3.

3. Test results

Fig. 4 shows the typical stress-strain curves of the present specimens for each property class and each target temperature. The resulting

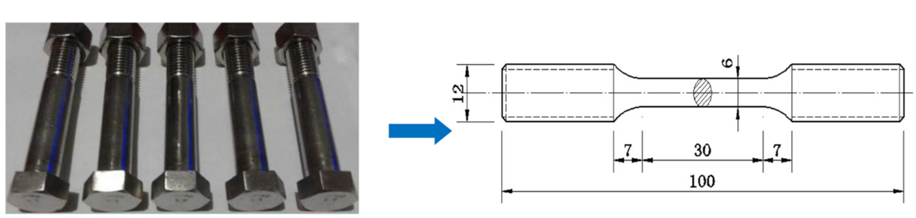

Fig. 1. Geometry of tension coupon specimens.