Journal of Constructional Steel Research 99 (2014) 129–139

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Stress–strain model of austenitic stainless steel after exposure to elevated temperatures

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ARTICLE INFO

Article history:
Received 16 January 2014
Accepted 3 April 2014
Available online xxxx

Keywords:
Stress–strain relations
Stainless steel
Post-fire
Damage evaluation
Temperature effects

ABSTRACT

With the increasing use of stainless steel in structures, there is a research need to evaluate the post-fire behaviour of this structural material. An experimental research was conducted to investigate the mechanical properties of austenitic stainless steel of grade 1.4301 after heating and cooling down to room temperature. Three types of stainless steel coupons were tested, including flat and corner coupons cut from a square hollow section and curved coupons extracted from a circular hollow section. The post-fire stress–strain curves of stainless steel exposed to various temperatures (200–1000 °C) and heat soak times (0–135 min) were measured. The influence of different parameters on the elastic modulus, yield strength, ultimate strength and ultimate strain is discussed in this paper. Based on the test results, a stress–strain model is proposed for austenitic stainless steel after exposure to fire.

1. Introduction

Compared with carbon steel, stainless steel is of increasing interest to structural engineers because of its additional benefits, such as corrosion resistance, ease of maintenance and aesthetic appeal [1]. The high amount of chromium present makes stainless steel different from carbon steel. Some stainless steel grades also contain certain amount of nickel, molybdenum and/or titanium.

Due to the high alloy content, the shape of the stress (σ)–strain (ε) curve of stainless steel can be described as "roundhouse" type, and the pronounced yield plateau widely observed in mild steel σ–ε curves does not exist for stainless alloys [2]. Plenty of research has been done before to capture the σ–ε relationship of stainless steel at room temperature, and a number of σ–ε models have been proposed accordingly by Rasmussen [2], Gardner and Nethercot [3], and Quach et al. [4]. To investigate the mechanical properties of duplex stainless steel grade 1.4462 and austenitic stainless steel grade 1.4301 at elevated temperatures, Chen and Young [5] conducted steady and transient tensile coupon tests at different temperatures ranging from 20 to 1000 °C. A σ–ε relationship for stainless steel at elevated temperatures was then proposed by Chen and Young [5], which was a revised version of the Rasmussen's σ–ε model [2] for stainless steel at room temperature. Using available test data in literature, Gardner et al. [6] proposed a modified compound Ramberg–Osgood model to predict the elevated temperature material properties of stainless steel alloys. It is worth noting that EN 1993-1-2 (2005) [7] also provides a two-stage model to describe the elevated temperature σ–ε response of stainless steel.

For the evaluation of damage to a structure after exposure to fire, post-fire stress–strain models are required to conduct an accurate structural analysis [8]. For stainless steel material, Felicetti et al. [9] tested stainless steel bars (austenitic grade 1.4307) after being heated up to 850 °C. Both hot-rolled (ϕ12 mm in diameter) and cold-worked (ϕ24 mm in diameter) stainless steel bars were tested. For hot-rolled stainless steel bars, degradation in the yield strength (f_y) was observed if the temperature was higher than 500 °C. But the strength loss was only 6.5% for f_y at a given temperature of 850 °C, and the fire exposure had no apparent influence on the ultimate strength of the hot-rolled bars. On the contrary, cold-worked stainless steel bars had a totally different behaviour with a slight strength increase up to 400 °C and a strong decay at higher temperatures. A decrease of 80% in f_y was found for the cold-worked stainless steel bars heated up to 850 °C and cooled to room temperature. To the best knowledge of the authors, no research has been conducted to investigate the mechanical behaviour of structural stainless steel after fire exposure.

In this paper, tensile tests were conducted to investigate the post-fire properties of austenitic stainless steel of grade 1.4301 after heating up to 1000 °C. A simplified stress–strain model is then proposed for the post-fire austenitic stainless steel, which is based on Rasmussen's σ–ε model for stainless steel at ambient temperature.

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http://dx.doi.org/10.1016/j.jcsr.2014.04.020

2. Experimental investigation

2.1. Preparation of steel coupons

Since austenitic stainless steel 1.4301 is the most common grade for structural applications, it is selected for study in this paper. Different steel coupons, including flat, corner and curved coupons, were cut from structural hollow sections made from hot-rolled steel strips by cold forming. The flat coupons were cut from the middle of the flat surfaces of a square hollow section (SHS, 200 × 200 × 6 mm). To investigate the corner effect, corner coupons were cut from the corners of the same SHS tube as shown in Fig. 1b. Meanwhile, curved coupons were cut from a circular hollow section (CHS, 260 × 3 mm). All coupons were cut along the longitudinal direction of the steel tubes. The coupon dimensions are shown in Fig. 1, which were determined according to the Australian Standard AS 1391 [10].

2.2. Heating and cooling

A temperature-controlled furnace was used for the heating of the stainless steel coupons. The coupons were heated from ambient temperature to the predetermined target temperature (T) at a heating rate of 20 °C/min, and then the temperature was kept stable at T until the pre-selected soak time was reached. The target temperatures (T) ranged from 200 °C to 1000 °C, as shown in Table 1. For the majority of the steel coupons, the heat soak time (t_s) was chosen to be 30 min shown in Fig. 2, which was longer than the minimum soak time of 20 min specified in ASTM E21-09 [11] to ensure the equilibrium of temperature in the coupon. To investigate the influence of the heat exposure time on the post-fire behaviour of stainless steel, four different soak times (0, 45, 90 and 135 min) were chosen for the flat coupons tested at 800 °C. After a coupon soaked in the furnace for the designated time, the coupon was cooled down to room temperature in the furnace naturally. It should be noted that all coupons were free from loading during the heating and cooling.

2.3. Testing

After cooling to ambient temperature, the coupons were taken out from the furnace and tensile tests were conducted afterwards using an Instron testing machine. Strain-controlled method was used and the coupons were tested to failure in accordance with AS1391 [10]. Two extensometers were placed on both sides of the flat and curved coupons to measure the extension. For corner coupons, only one extensometer was mounted onto the specimens due to the difficulties in installing another one on the concave side of the coupons. During the testing, the full-range σ–ε curve was recorded for the coupon, and the modulus of elasticity (E_{sT}), 0.01% proof yield strength ($f_{0.01T}$), 0.2% proof yield strength (f_{yT}), ultimate strength (f_{uT}), and corresponding ultimate strain (ε_{ut}) were obtained. These parameters with a subscript T indicates that they are for heat-treated coupons. The strain hardening exponent (n_T) can then be calculated by the following equation [2]:

$$n_T = \frac{\ln(20)}{\ln\left(f_{yT}/f_{0.01T}\right)}. \tag{1}$$

It should be mentioned that tensile tests were also conducted on coupons which had not been exposed to elevated temperatures. The obtained results ($T = 20$ °C) were used for reference to evaluate the fire exposure effect.

Table 1
Mechanical properties of austenitic stainless steel after exposure to elevated temperatures.

T (°C)	E_{sT} (MPa)	$f_{0.01T}$ (MPa)	f_{yT} (MPa)	f_{uT} (MPa)	ε_{uT}	n_T	Coupon type
20	210,190	219.1	305.5	655.5	0.440	9.02	Flat
200	202,748	208.1	298.9	650.9	0.496	8.27	
300	177,659	258.5	353.2	655.5	0.441	9.59	
400	203,543	191.6	294.6	646.2	0.491	6.96	
500	184,590	218.6	299.8	651.3	0.458	9.49	
700	197,188	191.6	266.8	647.0	0.479	9.04	
800 ($t_s = 0$)	196,214	209.0	290.8	640.2	0.461	9.08	
800 ($t_s = 45$ min)	224,600	201.5	298.5	651.0	0.456	7.62	
800 ($t_s = 90$ min)	210,164	215.5	300.6	656.8	0.486	9.01	
800 ($t_s = 135$ min)	218,569	195.8	291.2	644.5	0.489	7.54	
1000	173,054	191.7	271.8	641.5	0.502	8.59	
20	171,120	404.4	622.9	765.2	0.176	6.93	Corner
300	174,224	367.3	534.6	720.0	0.216	7.98	
500	184,947	403.1	557.7	734.7	0.207	9.22	
700	194,660	300.4	436.1	675.0	0.250	8.03	
1000	–	147.8	226.4	622.2	0.391	7.03	
20	200,192	214.6	318.9	670.2	0.489	9.00	Curved
300	188,840	221.6	316.6	676.6	0.505	8.40	
500	187,480	220.1	305.8	666.6	0.471	9.11	
700	205,389	195.3	263.6	662.3	0.467	9.99	
1000	221,041	176.3	250.4	664.1	0.476	8.54	

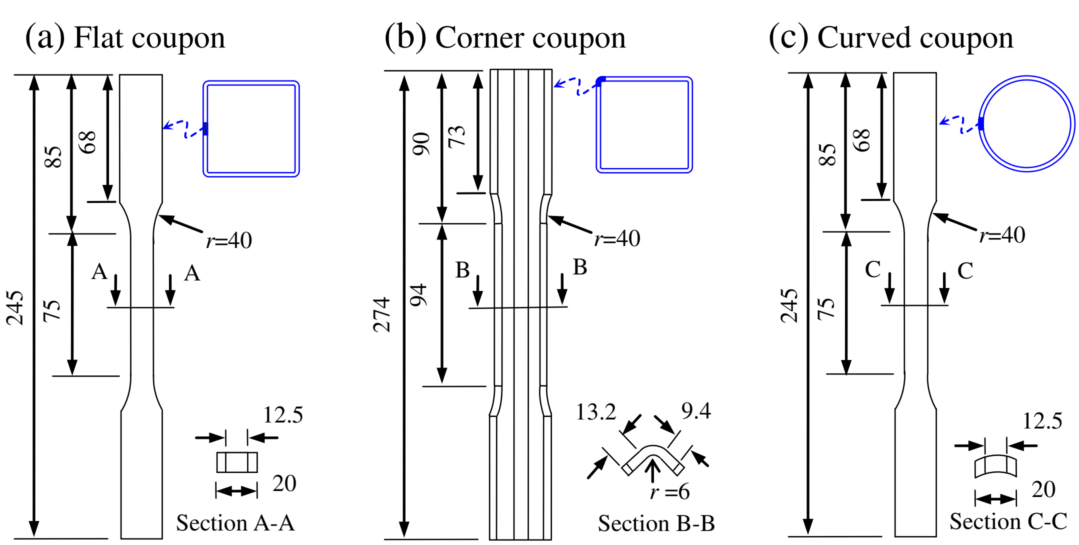

Fig. 1. Dimensions of steel coupons (unit: mm).