Construction and Building Materials 143 (2017) 259–271

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental investigation of the residual mechanical properties of cast steels after exposure to elevated temperature

Jie Lu [b], Hongbo Liu [a,b,c,*], Zhihua Chen [a,b], Luke Bisby [c]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
[b] Department of Civil Engineering, Tianjin University, Tianjin 300072, China
[c] School of Engineering, University of Edinburgh, Edinburgh EH93JL, UK

HIGHLIGHTS

- Test on cast steels G20Mn5N and G20Mn5QT after exposure to elevated temperature.
- Mechanical properties obviously changed when exposure temperature exceeded 700 °C.
- The influences of two different cooling methods were remarkable.
- The effects of cyclic heating–cooling were insignificant.
- Proposed predictive equations to estimate the post-heating mechanical properties.

ARTICLE INFO

Article history:
Received 3 April 2016
Received in revised form 4 November 2016
Accepted 13 March 2017

Keywords:
Cast steels
Fire
Cooling method
Residual mechanical properties
Predictive empirical equations

ABSTRACT

Cast steel is extensively used in civil engineering, especially for complex joints in spatial steel structures. Provided that local or global structural collapse of structures that incorporate cast steel structural elements and joints does not occur during or immediately after a fire event, the post-heating residual behavior of the steel castings in steel structures must be accurately characterized to estimate the remaining structural capacity and resulting safety. An experimental investigation was undertaken to explore the post-heating residual mechanical properties of two widely used structural cast steels, namely G20Mn5N and G20Mn5QT. Tensile coupon tests were performed on specimens after exposure to one of 13 preselected maximum temperatures (up to 1000 °C). Both air cooling and water cooling methods were considered, and residual mechanical properties, such as stress–strain curves, elastic modulus, yield strength, ultimate strength, and fracture strains were obtained for both types of cast steel. Additional tests were undertaken to investigate the effects of cyclic heating and cooling. The mechanical properties of both cast steels began to change after exposure to temperatures exceeding approximately 700 °C. With increasing exposure temperatures, up to 1000 °C, G20Mn5N showed maximum variations of approximately 28.6%, 14.8%, and 57% in yield strength, ultimate strength, and fracture strains, respectively; while the corresponding variations for G20Mn5QT were less severe at 16.8%, 7.6%, and 45%, respectively. The influence of different cooling methods was considerable, particularly when the exposure temperature exceeded 700–750 °C, whereas the effects of cyclic heating and cooling appeared to be insignificant. Predictive empirical equations to evaluate the post-heating mechanical properties of the two cast steels studied herein are proposed for both air and water cooling.

1. Introduction

Cast steels are extensively used in civil engineering, especially for complex joints of spatial steel structures both in China and internationally. Compared with regular welded joints, cast steel joints possess several advantages, including: streamlined shape for minimum stress concentrations, good fatigue life, a good degree of design freedom, and the absence of welding residual stress and deformation. Cast steel structural elements are thus employed in numerous large-span complex steel structures [1]. Steel structures using steel castings (i.e. structural parts made from cast steels) may be exposed to elevated temperatures in the event of a severe building fire, and such fires must typically be considered as credible threats during design of such buildings. Nevertheless, provided

* Corresponding author at: State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China.
E-mail address: hbliu@tju.edu.cn (H. Liu).

http://dx.doi.org/10.1016/j.conbuildmat.2017.03.118
0950-0618/

that a sufficiently high design safety factor and/or proper fire insulation are provided, structural collapse of the entire structure is unlikely to occur in a real fire. If the response of the structure is satisfactory during (and immediately following) a fire event, the residual post-heating performance of its important load-bearing elements, including any steel castings, must be properly assessed to determine whether the structure should be dismantled, repaired, or reused without repair. As an important basis for assessing the performance of steel castings after a fire event, the post-heating mechanical properties of cast steels must first be investigated.

Extensive studies have been undertaken focusing on the high-temperature behavior of structural steels of varying types and grades [2–10], and various design guides, such as British Standard (BS) 5950-8 [11] and EC3 [12] also provide design recommendations for specific types and grades of steel. At present, increasing attention [13–25] has been given to the post-fire mechanical properties of various structural rolled steels, such as hot-rolled mild steels [14,15], cold-formed steels [15–17], and high-strength structural steels [18–21]. Recent studies have also focused on high-strength steel tie rods [22], reinforcing steel bars [23,24], and pre-stressing steel [25,26]. However, to the knowledge of the authors, no studies specifically focusing on the mechanical properties of cast steels after high temperature exposure are available in the literature. Furthermore, only limited design guidance documents have provided information applicable to this field; for example, only brief recommendations based on experience in real fires rather than experimental results is provided by BS 5950-8 [11]. Considerable differences in the chemical composition and manufacturing processes between cast steels and rolled steels mean that applying conclusions based on tests of rolled steels directly to cast steels is not appropriate.

Without comprehensive knowledge of the post-fire mechanical properties of cast steels, assessing the residual performance of steel castings after fire exposure impossible. This paper presents an experimental investigation into the post-heating mechanical properties of two widely used (in China) cast steels, namely: G20Mn5N and G20Mn5QT steel, tested accordance with DIN EN 10293 [26].

Tensile coupon tests were performed on cast steel specimens that had cooled after being exposed to one of 13 preselected elevated temperature exposures (up to 1000 °C). Both air cooling and water cooling were considered, to elucidate cooling rate effects on residual mechanical properties. The associated mechanical properties, such as stress–strain response, elastic modulus, yield strength, ultimate strength, and fracture strain, are all discussed, and the effects of cyclic heating and cooling are also investigated. The results are compared with data found in the existing literature on rolled steels, as well as with the recommendations of BS 5950-8 [11]. Furthermore, predictive empirical equations, based on the experimental results and wherein the influences of different cooling methods are considered, are proposed to estimate the post-heating mechanical properties of cast steels after exposure to elevated temperatures.

2. Experimental investigation

2.1. Test materials and specimens

Test specimens used were cut from G20Mn5N and G20Mn5QT steel castings ordered specifically for the current study. The steel castings were manufactured according to DIN EN 10293 [27], which is recognized as amongst the strictest standards for steel castings and adopted by several countries. Both G20Mn5N and G20Mn5QT are heat-treated cast steels. G20Mn5 refers to the designation of cast steel grade, N refers to a heat treatment of normalizing, and QT refers to a heat treatment of quenching and tempering. G20Mn5QT has higher strength, undergoes a more complex manufacturing process (the process of QT requires an extra step of tempering compared to that of N), and costs more than G20Mn5N. Thus, G20Mn5N is widely used in larger steel castings and thicknesses, whereas G20Mn5QT is preferentially used in high-performance steel castings.

The principal chemical components of the steels used in the current study are given in Table 1. The test specimen shapes and sizes, which are all in accordance with GB/T 228-2010 [28] and GB/T 4338-2010 [29], are shown in Fig. 1. A vernier caliper was employed to measure the diameter of each specimen at three points along the gauge length, and the average values of these were used in calculating the mechanical properties during testing.

2.2. Test equipment and procedure

The experimental procedure comprised two steps: first, the specimens were initially heated to the preselected elevated temperatures, and then cooled to ambient temperature; second, tensile tests were performed on specimens at ambient temperature. A temperature-controlled electric furnace was employed for heating the samples, as shown in Fig. 2. The control thermocouple inside the furnace measured the gas temperature in the furnace, and fed back to the thermal control system which adjusted the heating rate accordingly. The 13 preselected exposure temperatures were 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, 600 °C, 650 °C, 700 °C, 750 °C, 800 °C, 850 °C, 900 °C, and 1000 °C. Higher temperatures were not considered because cast steels become extremely soft above 1000 °C, rendering study of their post-heating performance effectively meaningless. During heating, the furnace temperature was initially raised to 50 °C lower than the target temperature at an essentially arbitrary rate of 10 °C/min, and then maintained for 10 min. The temperature was then raised to the target temperature at a rate of 5 °C/min and maintained for another 20 min. This heating process was adopted to promote a uniform temperature distribution the specimens and to accurately hit the target temperature. When the heating process was completed, the specimens were removed from the furnace and cooled to ambient temperature. Both air and water cooling methods were considered in this study. For the air cooling method, the specimens were exposed to ambient air and cooled down under free convective conditions to simulate the situation wherein fire is not manually extinguished. For water cooling, the specimens were cooled by water spraying using a jet to simulate the situation wherein fire is manually extinguished. The entire heating–cooling procedure is shown in Fig. 3. The water volume used for water cooling was based on the idea that the water volume sprayed on each unit area of the specimen surface should be proportional to the water volume expected in an actual fire extinguishment. The following equation was proposed to calculate the time of spraying based on the fire-fighting parameters and the water jet flux:

$$T_2 = \frac{Q_1 T_1 A}{Q_2 \pi R^2} \tag{1}$$

where T_1 is the fire-extinguishing time in a real fire event (s); Q_1 is the water flux for fire extinguishment (m^3/s); R is the cover radius

Table 1
Principal chemical components of G20Mn5N and G20Mn5QT materials (%).

Chemical element	C	Si	Mn	P	S
G20Mn5N	0.196	0.29	1.23	0.016	0.014
G20Mn5QT	0.193	0.28	1.23	0.017	0.013