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# Experimental investigation into the post-fire mechanical properties of hot-rolled and cold-formed steels

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ABSTRACT

Hot-rolled Q235, Q345, and Q420 steel members and cold-formed Q235 hollow sections are widely used in building structures. During fire hazards, steel structures are inevitably exposed to elevated temperatures; provided that structural collapse does not occur after fire events, the residual performance of such structures must be estimated accurately to determine whether they should be dismantled, repaired, or directly reused. Therefore, an experimental investigation was conducted to reveal the post-fire mechanical properties of hot-rolled Q235, Q345, and Q420 steels as well as of cold-formed Q235 steels that underwent different levels of cold working. Specimens were heated to various preselected temperatures up to 1000 °C and subsequently cooled down to ambient temperature via two different methods, namely, air and water cooling. Tensile coupon tests were performed to obtain the post-fire stress–strain curves, elastic moduli, yield strengths, ultimate strengths, and ductility. Additional tests were also conducted to investigate the effects of cyclic heating–cooling. The post-fire mechanical properties of hot-rolled steels changed significantly after exposure to temperatures exceeding approximately 700 °C; the corresponding temperature for cold-formed steels was 300 °C. The influences of different cooling methods were notable, whereas the effects of cyclic heating–cooling were insignificant. Thus, new predictive equations that incorporated the influences of various cooling methods were developed to evaluate the post-fire mechanical properties of both hot-rolled and cold-formed steels studied.

## 1. Introduction

Hot-rolled Q235, Q345, and Q420 steel members have been applied extensively as load-bearing members in building structures. For instance, the beams, columns, and joints in most steel residential and industrial buildings in China are currently made of either Q235 or Q345 steel; meanwhile, Q420 is mainly used extensively in high-rise buildings. Q235 cold-formed hollow sections of different shapes (square, rectangular, or circular) possess advantages such as low cost and a simple production process; these sections are also increasingly employed in both high-rise and large-span building structures. Inevitably, building structures made of steels may be exposed to elevated temperatures during fire hazards, which constitute one of the most common and dangerous disasters that damage building structures. Unlike structures composed of reinforced concrete, steel structures are weakly resistant to fire, i.e., their performance drop significantly within a short time when exposed to elevated temperatures. Thus, the fire design of steel structures is highly significant. Extensive studies have been conducted to investigate the high-temperature performance of steels of various grades and types [1–9], which revealed that in general the strength and stiffness of steels significantly reduced with increasing temperature; furthermore, corresponding recommendations have been provided in design guides, such as British Standard (BS) 5950-8 [10] and EC3 [11]. Nevertheless, building structures are commonly designed conservatively for safety and bear considerable redundancy (e.g., large-span steel structures exhibit high degree of statical indeterminacy). Although the performance of steel decreases remarkably in a fire, entire structures may not collapse due to internal force redistribution. Provided that structural collapse does not occur after fire events, the residual performance of entire structures and of important load-bearing members must be evaluated accurately to determine whether the structures should be dismantled, repaired, or reused directly. Therefore, the post-fire mechanical properties of steels must be studied to provide an important basis for assessing the performance of steel structures after fire events.

At present, increasing but limited studies [12–21] have been conducted on the post-fire mechanical properties of steels, mainly in Europe, USA, Australia, and China. Outinen and Makelainen [12,13] presented an experimental study to determine the mechanical properties of S355 cold-formed steels at elevated temperatures and after cooling. Qiang et al. [14,15] conducted experimental studies to estimate the mechanical properties of high-strength structural steels S460, S690,

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and very high-strength steel S960 after cooling down from elevated temperatures up to 1000 °C. A similar experimental study was performed by Gunalan and Mahendran [16] to identify the post-fire mechanical properties of cold-formed steels G300, G500, and G550 after exposure to temperatures up to 800 °C. Chiew et al. [17] investigated the mechanical properties of reheated, quenched, and tempered high-strength steel plates (grade S690) at elevated temperatures and after cooling down. Wang et al. [18] conducted an experimental research on the mechanical properties of high-strength Q460 steel after exposure to temperatures up to 900 °C and considered both natural air and water cooling methods. Other works focused on the post-fire mechanical properties of prestressing steel wires [19], reinforcing steels [20], and stainless steels [21]. Moreover, in Annex B of BS 5950-8 (2003) [10], some recommendations are available for the reuse of mild steels after fire exposure.

According to the brief review of existing literatures, few studies have explored the post-fire mechanical properties of the extensively used hot-rolled Q235, Q345, and Q420 steels and of the cold-formed Q235 steel. Furthermore, no current design guide has provided applicable recommendations for the reuse of these materials after fire events. Given the considerable differences in chemical compositions and manufacturing processes, the results of previous studies on other steels cannot be applied directly to estimate the post-fire performance of structures made of hot-rolled Q235, Q345, and Q420 steels and of cold-formed Q235 steel.

In addition, fire guns are employed to extinguish flames when building structures are exposed to fire. Under such situations, steel members are cooled down from an elevated temperature by the spraying of water at a much higher rate than by cooling down in air. Different cooling methods may induce variations in the post-fire mechanical properties of steels; thus, various such techniques should be considered in simulating actual fire events in the study of the post-fire mechanical properties of steels. Nonetheless, the influence of cooling methods has rarely been accounted for in previous studies. Furthermore, the residual performance of the structures must be assessed with great caution given that a few structures may have been exposed to fire events recurrently without collapsing. Therefore, the effects of cyclic heating–cooling should be adequately considered when evaluating the post-fire performance of steels; nevertheless, this factor has never been accounted for in previous works.

In general, if the post-fire mechanical properties of hot-rolled Q235, Q345, and Q420 steels and of cold-formed Q235 steel are not reliably evaluated and if the influences of the aforementioned factors are not considered, then the behavior of the structures composed of these steels after fire events cannot assessed convincingly. The results of such an evaluation may generate an uneconomical consequence or a potential safety problem. The current paper presents the details of an experimental investigation into the post-fire mechanical properties of hot-rolled Q235, Q345, and Q420 steels as well as those of cold-formed Q235 steels cut from both the flat and corner regions of square hollow sections. Tensile coupon tests are conducted after these specimens are cooled down from predetermined elevated temperatures up to 1000 °C (800 °C for cold-formed steels). Both the air and water cooling methods are considered here. Associated mechanical properties are obtained, including stress–strain curves, elastic moduli, yield strengths, ultimate strengths, and ductility. The influences of the manufacturing processes (with or without cold working), exposure temperatures, steel grades, and cooling methods on the post-fire mechanical properties are also discussed. The effects of cyclic heating–cooling are investigated through additional tests. Predictive equations that incorporate the influences of different cooling methods are proposed based on the experimental results to evaluate the residual behavior of the studied steels.

## 2. Experimental investigation

### 2.1. Test materials and specimens

The hot-rolled Q235, Q345, and Q420 steel specimens considered in this test were cut in the longitudinal direction from hot-rolled steel sheets of grades Q235, Q345, and Q420, respectively. The steel sheets utilized comply with GB/T 700 [22] and GB/T 1591 [23]. Q235, Q345, and Q420 are the abbreviations of the grade designations of these steels; Q refers to yield strength (in Chinese Pinyin) and 235, 345, and 420 denote the corresponding minimum nominal yield strengths of 235, 345, and 420 N/mm$^2$. The cold-formed Q235 steel specimens were cut in the longitudinal direction from the flat region (hereafter referred to as CFS-F) and the corner region (hereafter referred to as CFS-C) of Q235 cold-formed square hollow sections (SHS, 800× 800×20mm). These sections are produced in accordance with GB/T 6725-2008 [24]. CFS-C evidently has a higher level of cold working than CFS-F does.

The shapes and dimensions of the test specimens accord with GB/T 228.1-2010 [25] and GB/T 4338-2010 [26], as shown in Fig. 1, Table 1, and Fig. 2. The dimensions of each specimen were measured with a vernier caliper at three points within the gauge length. The average values of the measured dimensions were used to calculate the mechanical properties of the steels.

### 2.2. Test equipment and procedure

The entire procedure of the experiment mainly comprised two steps. In the first step, the specimens were initially heated to the preselected elevated temperatures and subsequently cooled down to ambient temperature. In the second step, a tensile coupon test was conducted on the specimens at ambient temperature. The heating process was accomplished by a temperature-controlled electric furnace (Fig. 3). The thermocouple located inside the furnace measured the air temperature in the furnace and relayed this information to the control system to facilitate the adjustment of the heating rate; thus, a closed control loop was formed. In this study, 10 elevated temperatures were set for the Q235, Q345, and Q420 specimens, i.e., 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C, and 1000 °C. Owing to the limited material, four elevated temperatures were selected for the CFS-F and CFS-C specimens, i.e., 300 °C, 500 °C, 700 °C, and 800 °C, which could also basically meets the demand of engineering application because in general, the elevated temperatures steel members may experience during a fire hazard will not exceed 800 °C though some local members may suffer higher temperatures. In the heating process, the furnace temperature was initially increased at a rate of 15 °C/min to a temperature of 50 °C less than the target temperature; this temperature was maintained for 10 min. Subsequently, the furnace temperature was raised to the target temperature at a rate of 5 °C/min and held for another 20 min. This heating process ensures the uniform temperature distribution in the specimens and avoids the exceeding of actual temperature from the target temperature. The influence of heating duration can be ignored according to [20,27]. Subsequently, the specimens were removed from the furnace and cooled down to ambient temperature. Both air and water cooling methods were considered; the specimens for the air cooling method were exposed to air and allowed to cool down at their own rates to simulate the situation in which a fire dies out naturally. The specimens for the water cooling method were cooled down by water spraying using a water jet to simulate the scenario in which fire is extinguished by fire guns. The entire heating–cooling procedure is plotted in Fig. 4. The water volume adopted in the experiment

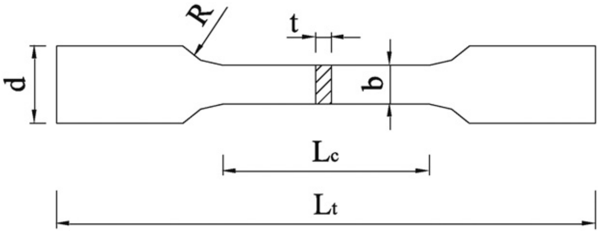

**Fig. 1.** Shapes of the hot-rolled Q235, Q345, and Q420 steel specimens.