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Experimental study on the post-fire mechanical properties of high-strength steel tie rods

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ABSTRACT

High-strength steel tie rods have been increasingly used as important load-bearing members in building structures. During fire hazards, building structures are inevitably exposed to elevated temperatures. If the general appearance of the structure is satisfactory after a fire event, how the performance of steel tie rods in these building structures has been affected should be accurately estimated. Hence, an experimental investigation was conducted to reveal the post-fire mechanical properties of four widely used high-strength steel tie rod grades, namely, GLG460, GLG550, GLG650, and GLG835. Specimens were heated to 13 various preselected temperatures up to 1000 °C and subsequently cooled down to ambient temperature via two different methods: air cooling and water cooling. Tensile coupon tests were conducted, and the post-fire stress–strain curves, elastic modulus, yield strengths, ultimate strengths, and ductility were obtained. Additional tests were also conducted to investigate the effects of cyclic heating and cooling. The post-fire mechanical properties of high-strength steel tie rods significantly changed after exposure to temperatures exceeding approximately 650 °C, and the change characteristics were much different from that of hot-rolled steels and cold-formed steels. The influence of different cooling methods was notable, whereas the effects of cyclic heating and cooling were insignificant. Thus, new predictive equations, where the influence of different cooling methods was incorporated, were proposed to evaluate the post-fire mechanical properties of steel tie rods.

1. Introduction

High-strength steel tie rods (hereafter referred to as steel tie rods) possess such advantages as light weight, high specific strength, and good toughness. Thus, they are increasingly utilized as load-bearing members in building structures, particularly large-span steel structures, such as large-scale stadiums, airports, and convention centers. For instance, National Exhibition and Convention Center (Shanghai) has used steel tie rods GLG345, GLG460, GLG650, and GLG835 in its roof bracing structures; Kunming Changshui International Airport has also used GLG460 as its lower chord bracing members. Among the disasters causing damages to building structures, fire hazards are among the most common and dangerous. During a fire, building structures are inevitably exposed to elevated temperatures. When exposed to elevated temperatures, steel members heat up quickly and lose strength and stiffness, so the fire design of steel structures including interaction between structural members is highly important. Hence, the high-temperature performance of steels of varying grades has been studied extensively [1–7], and corresponding recommendations have been provided in design guides, such as BS5950-8 [8] and EC3 [9]. Nevertheless, for conservative consideration in design, building structures commonly bear considerable redundancy (e.g., large-span steel structures have high degree of statical indeterminacy). Although steel performance decreases markedly in a fire, the collapse of the whole structures may not occur because of internal force redistribution. Considering that structural collapse does not occur after fire events, the residual performance of important load-bearing members must be evaluated accurately to determine whether the structures should be dismantled, repaired, or reused directly. As important load-bearing members increasingly used in building structures, whether steel tie rods have sufficient load-bearing capacity after fire should be estimated accurately in case of safety accidents and uncommercial consequence. Therefore, as an important basis of assessing the steel tie rod performance after fire, to study its post-fire mechanical properties is of considerable significance.

To date, increasing attention [10–19] has been given on the post-fire mechanical properties of commonly used structural steels (hot-rolled or cold-formed), specifically in Europe, USA, Australia, and China. Moreover, in British standards BS5950-8 [8], some recommendations for the reuse of steel after fire are available. However, nearly no available study in previous literature has focused on post-fire mechanical properties of steel tie rods, and no current design guide has provided applicable recommendations. With the large difference in chemical compositions

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Table 1
Chemical compositions of alloy structural steel 35CrMo material (%).

Chemical element	C	Si	Mn	P	S	Cr	Ni	Cu	Ti	Mo	V	B	Al
	0.35	0.20	0.56	0.014	0.011	0.94	0.02	0.01	0.007	0.164	0.004	0.0003	0.014

and manufacture process between steel tie rods and commonly used structural steels, to apply the outcomes of steels to steel tie rods directly is obviously inappropriate.

In addition, when building structures are exposed to fire, extinguishing the flames involved the use of fire guns. Under such situations, steel tie rods will be cooled down from elevated temperature by water spraying at a much higher rate than cooling down in air. Different cooling methods may lead to difference in post-fire mechanical properties of the structural material, and thus different cooling methods should be considered to simulate the actual fire events in the study of post-fire mechanical properties of structural material. However, the influence of cooling methods has been barely considered even in the study of commonly used structural steels, let alone steel tie rods.

Furthermore, given the structures that have experienced fire events before and been reused were exposed to fire again and still do not collapse, the residual performance of their important members, such as steel tie rods, must be assessed more carefully. Therefore, the effects of cyclic heating and cooling should also be considered in the evaluation of post-fire performance of steel tie rods.

Generally, without the reliable post-fire mechanical properties of steel tie rods considering the influence of factors stated above, the evaluation on the behavior of these critical load-bearing members after fire is not convincing. Such results will lead to an uneconomical consequence or potential safety problem. This paper presents the detail of an experimental investigation on the post-fire mechanical properties of four commonly used steel tie rods grades, namely, GLG460, GLG550, GLG650, and GLG835. The standard specimens studied in this experiment were cut from the products of steel tie rods ordered for this study. The specimens were heated to 13 preselected elevated temperatures up to 1000 °C and subsequently cooled down to ambient temperature in air or by water spraying. After that tensile coupon tests were conducted on these specimens and then associated mechanical properties, such as stress–strain curves, elastic modulus, yield strength, ultimate strength, and ductility, were obtained. The influences of exposure temperatures, steel tie rod grades, and cooling methods on the post-fire mechanical properties were studied. The effects of cyclic heating and cooling were also investigated by additional tests. Predictive equations were proposed based on the experimental results to evaluate the residual behavior of steel tie rods, in which the influence of different cooling methods was considered. The outcomes of this research are expected to assist engineers to evaluate the residual performance of steel tie rods after fire events accurately.

2. Experimental investigation

2.1. Test method

The most commonly used method to investigate the mechanical properties of metallic structural material, such as steel and aluminum alloy, in fire conditions is to conduct tensile coupon tests under transient or steady state. Compared with the steady-state test method, the transient-state test method is considered more precise in studying the mechanical properties of metallic structural material at high temperatures because it simulates the actual fire [1,2]. However, the steady-state test method is more commonly used and adapted to study the post-fire mechanical properties because it is easier to conduct and can provide stress–strain curves directly. Thus, in this experimental study, the steady-state test method was used after the specimens were cooled down from various elevated temperatures.

2.2. Test material and specimens

The test specimens were cut from products of steel tie rod GLG460, GLG550, GLG650 and GLG835 ordered for this study with the nominal diameter of 25 mm. In this paper, the naming method of steel tie rods suggested in GB/T 20934–2007 [20] is adopted, where GLG is the abbreviation of steel tie rods (in Chinese Pinyin); 460, 550, 650, and 835 means their minimum nominal yield strengths are 460 N/mm^2, 550 N/mm^2, 650 N/mm^2, and 835 N/mm^2, respectively. All of these four grades of steel tie rods were manufactured with alloy structural steel 35CrMo using different quenching and tempering methods. 35CrMo is the grade designation abbreviation of this alloy structural steel, where 35 means that the average content of carbon element is 0.35%, and CrMo means that its major alloy elements are Cr and Mo. Table 1 shows the chemical composition of 35CrMo, which is in accordance with GB/T 3077–1999 [21]. Table 2 presents the nominal mechanical properties of these four grades of steel tie rods specified in GB/T 20934–2007 [20].

The shapes and sizes of the specimens tested in this study are in accordance with GB/T 228–2010 [22] and GB/T 4338–2010 [23] (Fig. 1). The diameter of each specimen was measured at three points within the gauge length using a vernier caliper. The average values of the measured dimensions were used to calculate the mechanical properties of the steel tie rods.

2.3. Test equipment and procedure

The entire procedure of the test mainly contains 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, the tensile coupon test was conducted on the specimens at ambient temperature. The specimens were heated by a temperature-controlled electrical furnace (Fig. 2). The thermocouple located inside the furnace measured the air temperature of the furnace and fed back to the control system, which thereby adjusted the heating rate; thus, a closed control loop was formed. In this test, the 13 preselected 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. Temperatures higher than 1000 °C were not considered because steel tie rods become very soft at such temperatures. In the heating process, the furnace temperature was initially raised at 15 °C/min to a temperature of 30 °C less than the target temperature and held for 10 min, after which the furnace temperature was set to the target temperature and held for another 20 min. Because the influence of heating duration can be ignored according to previous literature [24], such heating process could be adopted to ensure the uniform temperature distribution of the specimens as well as to avoid the exceeding of actual temperature from the target temperature. Subsequently, the specimens were removed from the furnace and cooled down to ambient temperature. Both air and water cooling methods were considered. For

Table 2
Nominal mechanical properties of steel tie rods.

Grade	Yield strength (MPa)	Ultimate strength (MPa)	Elongation after fracture (%)
GLG460	≥460	≥610	≥19
GLG550	≥550	≥750	≥17
GLG650	≥650	≥850	≥15
GLG835	≥835	≥1030	≥13