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Post-fire mechanical properties of low-relaxation hot-dip galvanized prestressed steel wires

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ABSTRACT

Low-relaxation hot-dip galvanized prestressed steel wires are the basic component materials of high-strength steel cables, which have wide applications as key load-bearing members in prestressed steel structures. Provided that the general appearance of the prestressed steel structure is acceptable after a fire event, how the behaviors of the steel cables in these structures have been affected must be estimated accurately to ensure safety. Therefore, a series of experiments with a total of 360 specimens was conducted to investigate the post-fire mechanical properties of low-relaxation hot-dip galvanized prestressed steel wires with various grades, namely, 1670, 1770, 1860, and 1960. Tensile coupon tests were performed on specimens after exposure to 13 preselected temperatures up to 1000 °C, where two different cooling methods, namely, air cooling and water cooling, were considered. The post-fire stress–strain curves, elastic moduli, yield strengths, ultimate strengths, and ductility were obtained. Additional tests were also conducted to study the effects of cyclic heating-cooling. The post-fire mechanical properties of the studied steel wires changed significantly after exposure to temperatures exceeding 400 °C, and the change characteristics of different steel wire grades were similar. Moreover, the influences of different cooling methods were notable: the water-cooled steel wires lose most of their ductility and strength when the exposure temperature exceeded 700 °C; whereas the effects of cyclic heating-cooling were insignificant. Thus, predictive equations that incorporate the influences of different cooling methods were developed to evaluate the post-fire mechanical properties of the steel wires studied.

1. Introduction

Low-relaxation hot-dip galvanized prestressed steel wires (hereafter referred to as LG-SW) are the basic component materials of various high-strength steel cables (including steel strands, steel wire ropes, and semiparallel/parallel steel wire ropes), which have been widely used as key load-bearing members in prestressed steel structures, such as large-span prestressed space grid structures, suspended-cable structures, and cable-stayed bridge structures. Compared with the steel wires commonly used in prestressed concrete structures, LG-SW possesses such characteristics of higher strength (with a characteristic strength higher than 1670 MPa), lower relaxation, and better corrosion resistance. Fire represents one of the extreme conditions that may be encountered by structures and structural members. During fire hazards, steel materials, including both structural steels and steel wires, are inevitably exposed to elevated temperatures and lose strength and stiffness quickly. Hence, the performance of steel materials at elevated temperatures is critical for the safe design and evaluation of the fire resistance of prestressed steel structures. Extensive studies have been conducted to investigate the high-temperature mechanical properties of various grades of structural steels [1–6] and steel wires [7–11]; moreover some design guides, such as British Standard (BS) 5950-8 [12] and EC3 [13], also provided recommendations. Nevertheless, for safety purposes, prestressed steel structures are commonly designed conservatively and bear considerable redundancy (e.g., large-span prestressed space grid structures exhibit a high degree of statistical indeterminacy). Although the material performance decreases remarkably in a fire, the entire structural collapse may not happen because of significant internal force redistribution. Under such circumstances, the residual performance of the load-bearing structural members such as steel cables must be evaluated accurately to determine whether the structures should be dismantled, repaired, or reused directly. Therefore, studying the post-fire mechanical properties of steel wires, which are the basic component material of steel cables, is of great significance.

To date, existing studies on post-fire mechanical properties mainly focused on various structural steels, such as hot-rolled mild steels

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[14,15], cold-formed steels [15,16], and high-strength structural steels [17–20]. Other studies have also focused on reinforcing steel bars [21,22] and stainless steels [23]. Moreover, Appendix B of BS 5950-8 [12] also provides some recommendations for the reuse of mild steels and reinforcing steels after fire exposure. However, relative studies on the post-fire mechanical properties of steel wires are limited, and almost all of them focused on the steel wires used in prestressed concrete structures [24–26]. Comprehensive research on the post-fire mechanical properties of LG-SW of various grades used in prestressed steel structures has not been reported. Furthermore, no current design guide has provided applicable recommendations for the reuse of LG-SW after fire events. Given the considerable differences in both chemical compositions and manufacturing processes, the outcomes generated from other materials, such as structural steels, reinforcing steel rebars, and steel wires for prestressed concrete structures in previous literatures should not be applied directly to estimate the post-fire performance of LG-SW used in prestressed steel structures.

Moreover, when prestressed steel structures are exposed to fire, fire nozzles are commonly used to extinguish flames. Under such situations, steel cables will cool down from an elevated temperature by water spraying at a much higher rate than when they are cooled down in air, thereby leading to a difference in post-fire mechanical properties of the structural material. Thus, different cooling methods should be considered to simulate actual fire events in the study of post-fire mechanical properties of structural materials. In addition, given that some structures may have been exposed to fire events recurrently without collapsing, the residual performance of the key members of these structures, such as steel cables, must be assessed with greater caution. Therefore, the effects of cyclic heating-cooling on the mechanical properties of steel wires should also be adequately considered in the evaluation of the post-fire performance of steel wires. Nevertheless, the influence of either different cooling methods or cyclic heating-cooling has not been considered even in the study of steel wires commonly used in prestressed concrete structures, let alone LG-SW.

In general, without comprehensive knowledge of the post-fire mechanical properties of LG-SW, the residual behavior of the steel cables that act as the key load-bearing members in prestressed steel structures cannot be evaluated convincingly after fire events. The results of such an unreliable evaluation may lead to an uneconomical consequence or a potential safety problem. This paper presents the details of a comprehensive experimental investigation on the post-fire mechanical properties of four widely used LG-SW grades, namely, 1670, 1770, 1860, and 1960. Tensile coupon tests were conducted on specimens cooled down from 13 predetermined elevated temperatures up to 1000 °C. Both the air cooling and water cooling methods were considered. Associated mechanical properties, including stress–strain curves, elastic moduli, yield strengths, ultimate strengths, and ductility, were obtained. The influences of exposure temperatures, steel wire grades, and cooling methods on the post-fire mechanical properties were discussed. The effects of cyclic heating-cooling were also investigated through additional tests. On the basis of the experimental results, predictive equations that considered the influences of different cooling methods are developed to estimate the residual behavior of the steel wires that were studied.

2. Experimental investigation

2.1. Test materials and specimens

The LG-SW specimens were cut from longer 5.0-1670-II, 5.0-1770-II, 5.0-1860-II, and 5.0-1960-II low-relaxation hot-dip galvanized prestressed steel wires ordered for this study with a nominal diameter of 5 mm. The steel wires satisfied the requirements of GB/T 17101-2008 [27]. The naming method for steel wires specified in this standard is also adopted, where 5.0 means that the nominal diameter of the steel wires is 5.0 mm; 1670, 1770, 1860, and 1960 refer to characteristic strengths of 1670, 1770, 1860, and 1960 N/mm^2, respectively; and II indicates that they are low-relaxation steel wires. All four grades of steel wires were manufactured with hot-rolled wire rod 82MnA, and different cold draw and heat treatment processes were adopted for each steel wire grade. 82MnA is the grade designation abbreviation of this hot-rolled wire rod, where 82 refers to an average carbon content of 0.82%; Mn indicates that the major alloy element is Mn; and A refers to its quality grade. The chemical composition of 82MnA, which is in accordance with GB/T 24238-2009 [28], is shown in Table 1.

Table 1
Chemical compositions of hot-rolled wire rod 82MnA material (%).

Chemical element	C	Si	Mn	P	S	Cr	Ni	Cu	Fe
	0.82	0.25	0.74	0.016	0.005	0.18	0.015	0.11	Bal.

The actual diameters 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 LG-SW.

2.2. Test equipment and procedure

The entire experiment procedure 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, tensile coupon tests were conducted on the specimens at ambient temperature. The heating process was accomplished by a temperature-controlled electric furnace (Fig. 1). The thermocouple located inside the furnace measured the air temperature in the furnace and fed back the information to the control system to facilitate the adjustment of the heating rate; thus, a closed control loop was formed. In this study, the 13 elevated temperatures were 100, 200, 300, 400, 500, 600, 650, 700, 750, 800, 850, 900, and 1000 °C. In the heating process, the furnace temperature was initially increased at a rate of 15 °C/min to a temperature 50 °C less than the target temperature and then 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. Adopting heating process like this ensures a uniform temperature distribution in the specimens and prevents the actual temperature from exceeding the target temperature.

Fig. 1. Electric furnace.