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Mechanical properties of high tensile steel cables at elevated temperatures

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HIGHLIGHTS

- A full range of temperature dependent stress-strain relationship of high tensile steel cable is proposed, which considers the stress hardening path.
- The reduction factors of proportional limit, elastic modulus, yield strength and ultimate strength of high tensile steel cables are proposed.
- The coefficient of thermal elongation of high tensile steel cable as a function of temperature is proposed for design implementation.

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ABSTRACT

This study is motivated by increasingly prevalent use of cable-tensioned spatial steel structures and suspension bridges. Fire is one of the extreme conditions that need to be taken into consideration in the design of such structures. In this paper, steady-state tests have been conducted on steel cables with tensile strength of 1860 MPa, which consist of a group of 7-wire twisted strands, to study their full range of stress strain relationships at elevated temperature. Thermal elongation test of steel cables has also been conducted. A charge-coupled device camera (CCDC) system is used to capture the full range of stress-strain relationship of high tensile strength steel cables till rapture at elevated temperature. The reduction factors of proportional limit, elastic modules, effective yield strength and rupture strength at different temperature were obtained from the steady state tests and compared with that proposed by EN 1992-1-2. The experimental work discovered that EN 1992-1-2 overestimated effective strain up to 2% and ignored the stress-hardening phase for high tensile strength cables within the full temperature range. The effective yield strength with 1.25% strain and a full range of stress-stain model considering stress-hardening phase are proposed. Finally, several sets of reduction factors and thermal elongation coefficient as a function of temperature have been proposed by fitting the test results. The reduction factors of pre-stressing strands proposed by EN 1992-1-2 for pre-stressing concrete is found not suitable for steel cables which are widely used for pre-tensioned steel structures. The reduction factors proposed in the present paper are found to be reasonable for steel cables. The experimental work also shows that the mechanical properties of steel cables at elevated temperature depends on whether the cable is made from straight wires or twisted wires.

1. Introduction

With the similar mechanical behaviors as the pre-stressed tendons used in the pre-stressing of concrete structures, high tensile steel cables have been widely used in tensile steel construction for long span structures such as cable-net structures, beam string structures, suspension domes and suspension bridges etc. [1] as shown in Fig. 1. Fire is one of the extreme conditions that need to be taken into account in the design of such structures. Therefore, the mechanical properties of high tensile steel cables at elevated temperature should be accurately determined to study the fire safety of tensile steel structures. The mechanicalal properties at elevated temperature, such as the effective yield strength, elastic modulus, ultimate strength and strain etc., are the important parameters for non-linear analysis of tensile structures study their response behavior in various fire scenarios.

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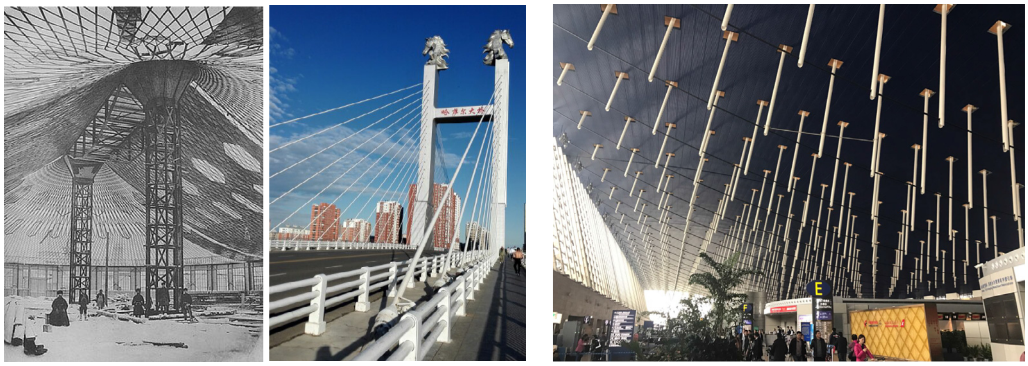

(a) The first tensile steel cable net roof in the world, established in 1896, Russia (b) A suspension bridge in China (c) Beam string structure roof, Pudong International Airport, Shanghai, China

Fig. 1. Tensile cables involving in tensile structures.

At present, the mechanical properties of cold worked wires and strands are specified in the concrete design guidelines, such as EN 1992-1-1 [2], BS 5896:2012 [3] and ASTM A416/A416M-02 [4]. Abrams et al. [5], investigated the behavior of steel strands for pre-stressing concrete at high temperature. ACI 216.1-14 [6] and PCI [7] provide some guidance for the fire resistance of pre-stressing concrete. Accordingly, the high temperature mechanical properties of wires and strands are given in EN 1992-1-2 [8].

Abrams et al. [5] reported in their tests that the ultimate strength of 7 wire strands at 204 °C is reduced by 10%, while it loses 50% of the ultimate strength at 427 °C. The test was also conducted on the strands of 1/4 and 7/16 in. diameter at elevated temperature; it was found that within the small strand size, the percent loss of ultimate strength is not significant. In their tests, the pre-stressed force has been applied on the specimen to conduct the transient-state test at elevated temperature to capture the rupture temperature. Thus, the thermal creep strain has been included in the total strain. Abrams's test also discovered that the rupture temperature is almost the same from transient-state test or steady-state test. The test heating rate is 2.8, 5.5 and 8.3 °C/min, which was not correspond with the heating rate proposed by EN 10002-5, to simulate the heating rate of pre-stressed strands imbedded in concrete. Thermal expansion elongation also cannot be eliminated from the steady-state test. Therefore, heating rate and thermal expansion elongation should be considered properly in the experimental study of steel cables.

In 1970, Harmathy et al. [9] investigated the mechanical properties of A421 pre-stressing steel wires at elevated temperature. The steady-state tests captured the full-range stress-strain curves and it was observed that there is no significant loss in ultimate strength before 217 °C, but a sharp decrease beyond 400 °C. The decreasing tendency of yield stress and elastic modulus also have been investigated. Harmathy et al. were the first to report that the high temperature mechanical properties of strands were dependent on the microstructure of the materials, which changed at elevated temperature. The mechanical properties of high tensile steel cables made from a group of twisted wires would be difference from that of A421 pre-stressing steel wire at elevated temperature.

In 1982, Holmes et al. [10] conducted three series of steady-state test for strands to determine the yield strength, ultimate strength and elastic modulus at elevated temperature. In the transient-state test, the specimen was pre-stressed to 70% minimum ultimate tensile strength and then heated until rupture temperature. Similar to Abrams et al. work [5], the rupture temperature of the strands under pre-stressed load includes the thermal creep effect. However, the specimens were manufactured according to British Standard specifications BS 2691 and BS 3617 for steel wire and steel strand. Due to the different in material, the steady-state test conducted by Holmes can only be taken as reference in the present study.

Fan et al. [11] and Zhou et al. [12] carried out steady-state test on 1860 MPa strand at elevated temperature. The necking of specimen and ductile failure behavior weer observed for temperature heated beyond 500 °C. However, the full stress-strain relationship cannot be captured in their experiments.

Hertz et al. [13] not only proposed a simple mathematical model to predict the reduction in mechanical properties for several steel types at elevated temperature based on the test data resulted from previous studies by other researchers, but also described the crystalline structure for cold worked bars loosens above 300 °C. The residual properties of cold worked steel suffer irrecoverable losses if subject to temperature over 400 °C. However, this simple mathematical model cannot predict the mechanical properties of high tensile steel cables at elevated temperature.

Due to the complex surface of strands and the difficulty of gripping the a group of strands in a tensile test, Zhang et al. [14] chose the single wire of 1860 MPa strand to conduct tensile test at elevated temperature. Comparison of the results from testing a group of strands made of straight wires and twisted wires; it was found that the twisting configuration of the strands affected the thermal mechanical properties of strands made from a group of wires.

In recent years, Conor [15] and Shakyo et al. [16] studied the mechanical properties of seven-wire pre-stressing strands by fire test. Their studies indicated that the mechanical model of cold worked strands specified by EN 1992-1-2 could not accurately describe the stress-strain relation at elevated temperature as it ignored the stress hardening with a continuous increase in strain till failure even for temperatures in the range between 200 °C and 500 °C.

Xiong et al. [17] tested heated-treated high tensile structural steel at elevated temperature to study the mechanicalal properties and the microstructure of high tensile steels at elevated temperature. They discovered from the testing that the thermal creep becomes noticeable when the steel temperature exceeds approximately one third of the steel melting temperature, thus, the steady-state test method is merely suitable to measure the elastic modulus of high tensile steel up to 400°. It also noted that there - was no significant discrepancies between the steady-state and transient-state test for effective yield strength when the temperature is below 500 °C. In the present study, the steady-state test method is employed to investigate the mechanical properties of