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Experimental study on stress relaxation properties of structural cables

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HIGHLIGHTS

- Stress relaxation tests on five types of structural cable were carried out.
- Three different initial stress levels and ambient temperatures were considered.
- Special onsite anchoring methods and devices for relaxation test were put forwarded.
- Relaxation rates of all cables increased with the initial stress and temperature.
- The recommended values for the 50-year relaxation rates were provided.

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ABSTRACT

Cable stress relaxation causes tension loss at high stress in high-strength structural cables, thereby influencing the stiffness and strength of cable-supported or tension structures. Previous studies have mainly focused on steel wires (SWs) and spiral strands; however, several new types of structural cable, such as semi-parallel wire strands (SPWS), Galfan spiral strands (GSSs), and steel tie rods, have emerged and have been widely applied in recent decades. The axial force during normal service state occasionally reaches 55% of the ultimate tensile strength. Relaxation data on structural cables are rare and are urgently required for structural design and lifetime safety evaluation. Therefore, experimental studies on five types of structural cable were conducted, in which the initial stress levels were 70%, 55%, and 40% of the ultimate tensile strength. Three different working ambient temperatures of 15 ± 2 °C, 20 ± 2 °C, and 25 ± 2 °C were considered. Special onsite anchoring methods and anchorage devices were established and proven effective. Results showed that logarithmic expression could well express the relationship between relaxation rate and time duration. The relaxation rates of SPWSs were larger than those of SWs. GSSs had considerably larger relaxation rates than other cable types due to their material properties and special twist characteristic. The relaxation rates of all types of cable increased with the initial stress and temperature. The recommended values for the 50-year relaxation rates for different structural cables were predicted and calculated.

1. Introduction

Cables have high longitudinal strength and minimal lateral stiffness and are widely used in various major engineering areas, such as suspension bridges, prestressed concrete structures, and cable-supported structures [1,2]. The tension-bearing and tension-holding capabilities of cables significantly influence the stiffness and strength of the entire structure because cables are key structural components designed to support high tensile load [3,4]. Most of the structures or buildings with high-strength strands or cables are public projects that are generally designed for 50–100 years (in China) and will be in service for a long period of time. Therefore, the lifetime structural working performance is closely related to the long-term characteristics of structural components. However, high-strength cables composed of steel wires (SWs) or synthetic cables are susceptible to stress relaxation due to long-term loading. The long-term rheologic properties will cause permanent strain in cable members, thereby resulting in stress relaxation and stiffness reduction, which should be considered during the design process [5].

Stress relaxation is the gradual tension loss behavior of cables with the increase of time period under constant strain and temper-

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ature condition [6]. The extent and evaluation of this degradation behavior are usually described and measured with relaxation rate $R(t)$, which can be expressed as follows:

$$R(t) = \sigma_1/\sigma_0 \times 100\%, \quad (1)$$

where $R(t)$ (%) is the relaxation rate at time t, σ_0 is the initial stress, and σ_1 is the tension stress loss caused by relaxation. Stress relaxation and creep are two reflections for the same stress-strain changing tendency caused by crystal lattice dislocation and grain boundary sliding and are associated with temperature change [7]. In 1960s, the relaxation problem of high-strength SWs and spiral strands (SSs) has attracted attention with the wide application of prestressed concrete structures in bridge engineering [8]. Magura [6] collected all the available relaxation test data in prestressing reinforcement and conducted a statistical analysis on single wire or SS by considering variables, such as test duration, initial stress, history, and temperature. Trevino [9] presented a graph and equation of the relaxation reduction coefficient and used them in the prestressed concrete design. Zeren [10] investigated the effects of temperature and stretch ratio on the relaxation behavior of 8-mm-diameter carbon SW and proposed empirical formulas from relaxation test data. Kmet [11] conducted creep tests on ropes under a constant load to validate a theoretical derivation. These valuable experimental data provided essential importance for subsequent cable relaxation studies. However, the majority of available data are about SWs or simple small-diameter strands, and the relaxation data on large-diameter cables are rare.

Subsequent studies on cable stress relaxation have gradually changed to the application analysis of stress relaxation in practical structures to investigate the degradation influence. Au [12] considered the rheologic behavior and conducted a long-term time-dependent analysis on cable-stayed bridges by time integration. Atienza [8] performed experimental and numerical studies on stress relaxation losses in steel tendons to reveal the relationship between stress relaxation and residual stress in SWs of prestressed concrete. Kmet [5,13] used modified force–density and dynamic relaxation methods to perform a time-dependent analysis on cable nets and cable dome and indicated that the relaxation behavior would alter the initial stiffness of cable structures and result in additional deflection. However, these simulations mainly determine the cable stress relaxation behavior or time-dependent properties based on the relaxation data of single wires or simple strands.

With the emergence and rapid development of prestressed cable structures, many new types of high-efficient steel cables, such as steel tie rods (STR), parallel/semi-parallel wire strands (SPWS), and Galfan spiral strands (GSS), have emerged and have been widely used. The stress relaxation properties of these cables are different and are not the same with SWs or simple strands due to different manufacturing methods, constituent wires, and spiral constructions. Relaxation tests on large-diameter cables or wire strands require solid anchorage conditions, precise tension control, and high-tension loading capability of the testing machine. Thus, relevant tests on SPWS, STR, and GSS are rare, and no specific data are available. In actual engineering projects, the cable forces during service state are generally controlled within 55% of the ultimate tensile strength [14], which is not the normally considered stress level in stress relaxation tests. Therefore, the real cable relaxation behavior under practical working stress state and environment is unavailable.

In this study, an experimental investigation was conducted on the stress relaxation properties of structural cables under practical working stress state and environment. The research objects were single SW, SS, STR, SPWS, and GSS, which are cables widely used in structural engineering. Three initial stress states in the test were 70%, 55%, and 40% of the ultimate tensile strength, and three different working ambient temperatures of 15 ± 2 °C, 20 ± 2 °C, and 25 ± 2 °C were also considered. No relaxation tests on SPWS and GSS have been performed previously. Thus, special anchoring devices and testing methods were proposed and applied in the test. The relaxation rates of the tested cables under different initial stress levels and temperatures were derived, and long-term relaxation rates were calculated, which could be used in the design of bridges and cable-supported structures for stress degradation evaluation.

2. Overall description and testing devices of cable stress relaxation test

2.1. Testing plan and method

Five different types of cable commonly used in civil engineering, namely, single SW and SS normally used in prestressed concrete structures; STR and SPWS normally used in beam string structures, cable-stayed bridges, cable-supported structures; and GSS normally used in cable domes and suspension curtain walls, were selected. Detailed information on the tested cable specimens are listed in Table 1. Standards on cable relaxation test suggest an initial stress state of 70% of the ultimate tensile strength [15,16]. Moreover, the designed tension force was controlled within 55% of the ultimate tensile strength in cable-supported structures or tension structures. The real tension state occasionally surpassed the level under additional loads or accidental conditions. Therefore, three different initial stress levels with the same gradient interval were adopted, that is, 70%, 55%, and 40% of the ultimate tensile strength.

Stress relaxation rate is closely related to ambient temperature. The surrounding temperature was also selected as a determining factor in the test to consider the practical temperature change during working conditions. A normal room temperature of 20 ± 2 °C was selected, as specified in the relaxation test standard, and 15 ± 2 °C and 25 ± 2 °C were also adopted as temperature variables to consider practical working temperature states. A detailed testing plan is shown in Table 2. In the test, each case had two specimens and was repeated twice, in which the first specimen was tested for 120 h and the second specimen was tested for 60 h. The 60-h test reduced a considerable amount of time, as well as verified the 120-h test results. A 1000 h relaxation rate was then derived based on the measured stress relaxation behavior. Each specimen was named as "cable type_ stress state_ temperature" mode for identification. "SW-70-20" represented "SW type with initial stress state within 70% of the ultimate tensile strength at 20 ± 2 °C surrounding temperature." In addition, suffix *a* or *b* was included to identify the 120-h or 60-h testing case, respectively.

2.2. General testing device and apparatus

All tests were conducted based on the requirements and criteria of the relaxation test standards [15,17] using a 10–500 kN range computer-controlled stress relaxation testing machine (TYPE WSC-500) in Tianjin University, as shown in Fig. 1(a). The testing machine was placed in an individual testing room with an air con-

Table 1
Detailed information on the specimens used in the test.

Cable type	Diameter (mm)	Construction	Cross-sectional area (mm^2)	Tensile strength (MPa)
SW	5.0	Single	19.6	1670
SS	15.2	1×7	140.0	1860
STR	25.0	Single	490.9	650
SPWS	25.0	1×19	373.0	1670
GSS	20.0	1×19	233.0	1670