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Study on the creep performance of steel wire ropes

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Abstract
The cable-strut structure will creep in the service life and the structural stiffness and safety performance will be degradated. In this article, the long-term creep experiment on steel wire ropes was carried out, and more than 20,000 hours of creep data were obtained. The experimental data were fitted based on the viscoelastic theoretical equation to obtain the general creep constitutive equation of the steel wire rope, which could be used to quickly estimate the creep of the steel wire rope under different stresses and diameters. And a Levy cable dome was taken as a numerical example to illustrate the application of the creep constitutive equation. The result shows that the structural performance could be well predicted by the creep constitutive equation, and the structure needs to be monitored and maintained as necessary.

Keywords:creep, cable-strut structure, long-term, constitutive equation, steel wire rope

1. Introduction
Cable-strut structures are widely used in various large public buildings all over the world. During the long-term service, the creep will inevitably occur in cables, which will lead to the degradation of performance and the large displacement of nodes [1]. This will have a negative impact on the structural usability and safety performance. Therefore, it is meaningful to conduct research on this phenomenon. For structural creep, it is necessary to study the creep performance of steel cables from a macroscopic and long-term perspective.

Research on creep in metals began in the 1990s, primarily focusing on prestressed concrete tendons or steel wires in concrete structures [2,3]. However, the composition and processing technology of steel wires differ from those of steel cables in tensile structures. Therefore, the results and properties of these studies cannot be directly applied to tensile structures unless their applicability to such structures is verified. Luo and Huo [4] proposed a generalized creep constitutive model with two critical creep time points and six stress-dependent parameters to describe typical creep curve styles. However, this model is only applicable to high-temperature conditions and provides little assistance in calculating the creep of steel cables at normal temperatures. Lin [5] investigated the creep behavior of prestressed steel wires used in forging press frames and obtained 140 hours of creep data under two sets of stresses at normal temperatures. Although a corresponding prestress relaxation model was proposed, the short test duration prevented the obtained model from being used to predict the creep of structural steel cables. While there have been numerous studies analyzing steel creep through experiments, there is a lack of research focusing on the long-term behavior of structural steel cables at normal temperature.

In this paper, long-term creep experiments were conducted on steel wire ropes at normal temperature. These experiment data served as the basis for deriving the creep constitutive equation. According to the viscoelastic theory, the form of the constitutive equation is determined, and then the specific equation expression is determined through data fitting. After comparison, the calculated results obtained by the constitutive equation showed a better fit with the measured results in the experiment. In addition, a Levy cable dome was taken as a numerical example to illustrate the application of the creep constitutive equation.

The result shows that he structural performance could be well predicted by the creep constitutive equation. Therefore, the concise constitutive equation can be wildly used in actual engineering for calculating the creep strain of wire ropes.

2. creep experiment of wire ropes

The development of creep is influenced by the stress and the diameter of the steel wire rope. Therefore, the experiment should include groups with different diameters and stresses. The test specimens were 6×7+IWS steel wire ropes with a diameter of 4mm and 6×19+IWS steel wire ropes with a diameter of 6mm. The material of the steel wire ropes is SUS316, and the density is 7800kg/m^3. A universal testing machine was used to measure the performance of the steel wire ropes. The ultimate tensile strength of the 4mm steel wire rope was 9.01kN, and the ultimate tensile strength of the 6mm steel wire rope was 18.76kN. The elastic modulus of the two diameters of steel wire ropes is 107GPa, with the inner steel wires having a modulus of 195GPa.

In practical applications, the stress of steel wire ropes generally does not exceed 60% of the ultimate stress. This experiment includes groups with different stresses for two types of steel wire ropes, as shown in Tab. 1. Here, "WR" is the abbreviation for wire rope, and the numbers following "WR" as well as "-" indicate the diameter of the steel wire rope (in mm) and the stress percentage, respectively. Each group of wire ropes was pre-stretched before the experiment. And the experimental apparatus is shown in Fig. 1.

Tab. 1 Information of steel wire ropes in the creep experiment

Group of wire rope	initial stress / Mpa	Measuring length / m
WR4-30	338.70	3
WR4-40	463.23	3
WR4-50	575.30	3
WR6-30	327.61	5
WR6-40	435.30	5
WR6-50	543.00	5

Loading the apparatus and waiting for the wire ropes' elongation to stabilize can be considered as the starting point. This indicates that the elastic strains of the wire ropes have stabilized, and subsequent elongations are solely due to creep. The elongation of each group of wire ropes can be determined by reading the upper and lower scales on the experimental apparatus. Data was recorded every half hour for the first 2 hours, and then every hour for the next 6 hours. After 8 hours, data was recorded every 2 hours, and then every 24 hours, weekly, or biweekly when the data stabilized. Due to the impact of COVID-19, some data from 5000 to 7000 hours is missing, but this has little impact on the experiment's results. A thermometer was also set on the apparatus to simultaneously record the ambient temperature and eliminate temperature variation errors [6]. This experiment was conducted for more than two years, and over 20,000 hours of data were obtained.

Fig .1 Creep experimental apparatus of steel wire ropes

Based on the recorded data of the wire ropes' elongation, the creep strain of each group can be calculated. Using the temperature linear expansion coefficient and the temperature data, the creep strain at normal temperature was then revised. The normal temperature in this paper is set to 25℃, and the "creep strain – time" curve of the wire ropes is shown in Figures 2 and 3.

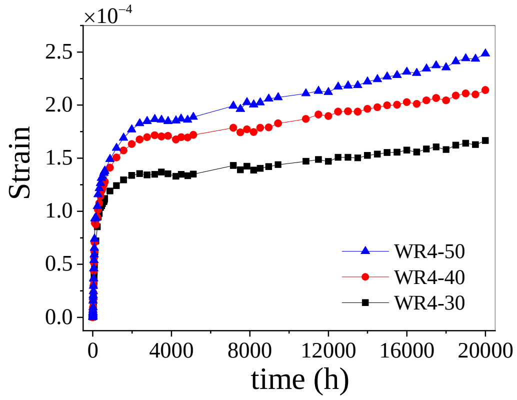

Fig. 2 Creep strain – time curve of 4mm steel wire rope

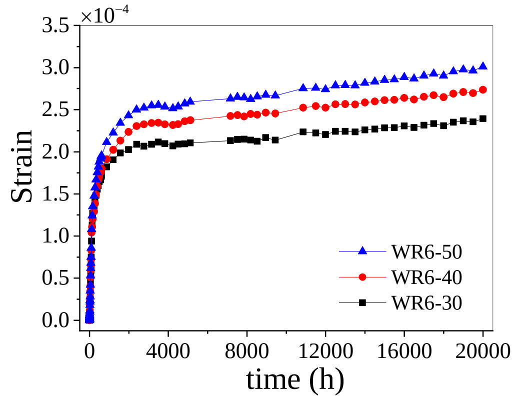

Fig. 3 Creep strain – time curve of 6mm steel wire rope

From above figures, it can be observed that the creep strain of wire ropes with different diameters and stresses generally exhibit similar development trends and patterns, which can be divided into three periods. Initially, the creep strain shows an approximately linear growth in the first 100 hours, followed by a gradual slowdown in growth over the next 4100 hours. After 4200 hours, the creep strain grows steadily at a small rate. The results also indicate that the stress level and the diameter of the wire ropes have a significant influence on the creep performance. Specifically, for steel wire ropes of the same specifications, a higher stress level leads to a greater creep strain, and a larger diameter wire rope will have a greater creep strain under the same load.

3. Derivation of creep constitutive equation

In viscoelastic theory, the Kelvin model is a common model consisting of parallel spring and dashpot elements, often used to describe materials with asymptotic elastic properties. It can explain the deceleration of E_t in the second period. However, there were some strains in the initial moments of the second period, representing a transient elastic response. The Kelvin model alone cannot adequately describe this phenomenon unless another spring element is added in series. This modified model is known as the standard linear solid model.

After Laplace transforming and deriving this model, the equation for strain change with time can be expressed as follow [7]:

$$\varepsilon_{cr}=\left(\frac{E_1+E_2}{E_1E_2}-\frac{1}{E_2}e^{-\frac{E_2}{\eta}t}\right)\sigma_0 \tag{1}$$

where E_1 is the elastic modulus of the spring element in series, E_2 is the elastic modulus of the spring element in parallel and η is the damping coefficient of the dashpot element.

According to the functional form of eq. (1), the exponential function in the form of $y = Ae^{R_0 x} + y_0$ is selected in Origin for fitting to the second period creep strain data of each experimental group. Where x is the independent variable, representing for the time t in this fitting; y is the dependent variable, representing for the creep strain in the second period ε_{cr2}, and A, R_0 as well as y_0 are the parameters that need to be fitted [8].

The parameters in each of the above fitting equations are related to the stress σ and the diameter d, so the creep strain in second period ε_{cr2} can be expressed as follow:

$$\varepsilon_{cr2} = A(\sigma, d)e^{R_0(\sigma, d)x} + y_0(\sigma, d) \tag{2}$$

where $A(\sigma, d)$, $R_0(\sigma, d)$, $y_0(\sigma, d)$ are the parameters related to stress and the diameter, and they are uniformly written as $f(\sigma, d)$. Based on observing the change in the pattern of the $f(\sigma, d)$ with respect to stress and diameter and the comparison of fitting results of different forms of functions, $f(\sigma, d) = C_1 \sigma_0^{C_2} d^{C_3} + C_4$ gives a better fit to the data. And the constitutive equation can be obtained based on the above derivation. The comparison of the calculated values based on constitutive equation and the measured values in experiment are shown below, and the error is relatively small.

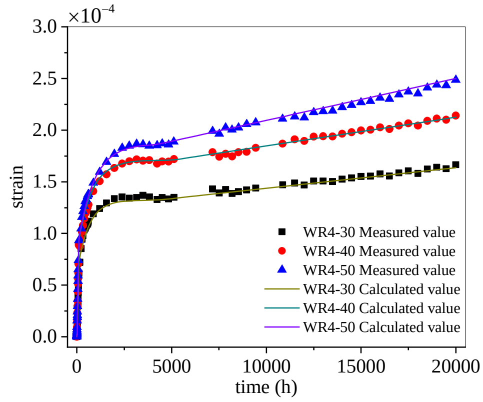

Fig. 4 The comparisons of measured and calculated value for a diameter of 4mm

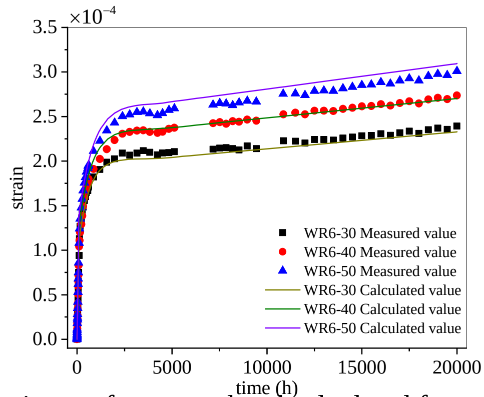

Fig. 5 The comparisons of measured and calculated for a diameter of 6mm

4. Numerical example

A Levy cable dome was taken as an example, it is divided into 12 sections circumferentially, each spanning 18 meters. Steel wire ropes are used as tension member with an ultimate tensile strength of 1670 MPa, and the elastic modulus of wire ropes marked as E_s is 1.1×10^5 MPa. The steel bars are used as members in compression with the yield strength of 345 MPa, and the elastic modulus of steel bars marked as E_b is 2.06×10^5 MPa. The dead load is taken as $0.3\,\mathrm{kN/m^2}$ and the live load is taken as 0.5

kN/m^2. The outermost nodes are constrained by the displacement in the *x*-, *y*-, and *z*- directions. The geometric parameters and labels are shown below.

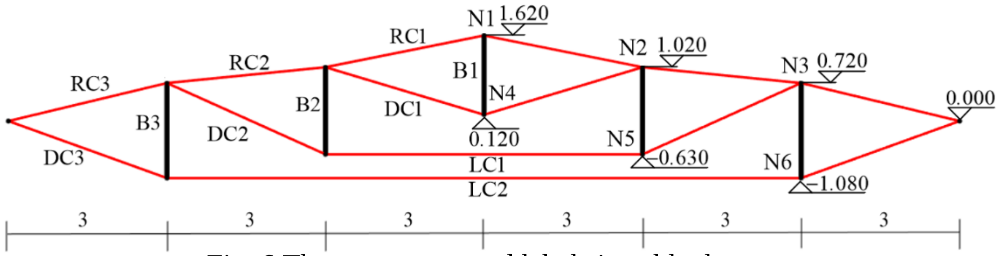

Fig. 6 The parameters and labels in cable dome

Takes 1 years as a basic timespan (except for the first year, which shoulu be smaller) to calculate the creep strain and the stresses reduction of members. The specific result is shown in the figure below.

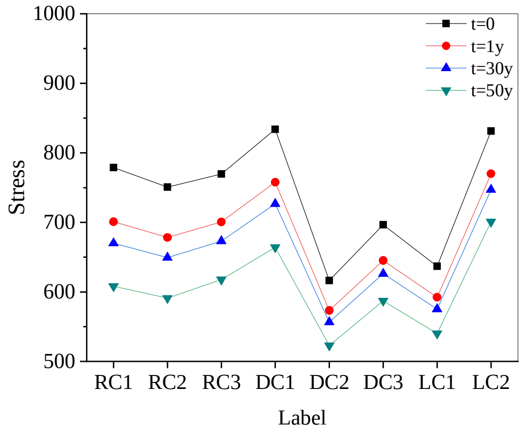

Fig. 7 The parameters and labels in cable dome

It can be known that the stress of each cable decreases over time. Therefore, It is essential to monitor the health of the structure and ensure that maintenance is carried out as necessary.

5. Conclusion

The creep experiment was carried out in this paper, and the constitutive equation was obtained based on viscoelastic theory and the data fitting. The errors between calculated values obtained by the constitutive equation and measured value in experiment are relatively small. And the example show that the method can effectively calculate the degree of creep of the structure, the stress will decrease over time. It is essential to monitor the health of the structure and ensure that maintenance is carried out as necessary.

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