Aging life evaluation of a new carbon fiber composite core wire

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Abstract. The carbon fiber composite core wire is the key component for new overhead transmission lines in the power industry. As the primary load-bearing member, the composite mandrel will produce long-term creep because of the tensile during operation. Therefore, designers need to understand the long-term deformation behaviour of the composite mandrel to assess its durability. To this end, an accelerated creep test on the composite core rod under different temperatures and stresses has been conducted in the current study. According to the time- temperature- stress superposition principle, the shift factors are calculated, and the creep under normal working condition is predicted. Results show that the carbon fiber composite core wire can satisfy the design requirements under normal working condition.

1. Introduction

The carbon fiber composite core wire is made of a highly conductive soft aluminum stranding in carbon fiber composite core. The new wire is a kind of energy saving and environmental protection new wire because of its high strength, light weight, low sag and other significant characteristics, and it has extensive application prospect in high voltage overhead conductors [1-5]. As the key load- bearing component of the wire, the carbon fiber composite core has marked advantages in short-term mechanical properties and thermal properties. During operation, the wire's weight and wind vibration will act as load putting on the composite core. This generates creep behavior for long-term of power transmission, and the process will also be affected by environment factors such as wet, heat etc [6-7].

With the rapid development of rubber and plastic industry, researchers have gradually realized the importance of the study on the viscoelasticity of substrate material. The main feature of the mechanical behavior of viscoelastic materials is time dependence. The essence is the internal clock of the material. Consequently, the analysis and the prediction of long-term mechanical behavior from short-term experiment are possible. In the literature, the time- temperature- stress superposition principle has been applied to forecasting the long-term mechanical properties of polymers by considering the effects of time, temperature and stress. The results have shown the effectiveness.

Creep of resin matrix composites is a kind of macroscopic deformation, and the creep mechanism of the composite materials is very complicated [8-13]. According to the study of Johnson [8], the creep of composite materials is caused by the viscoelasticity of the substrate material. Then the viscoelasticity and performance prediction can be connected by the time-temperature superposition principle, which states that the same mechanical behavior of polymer can be observed not only under an acute higher temperature, but also under a lower temperature condition for a much longer term. This principle has been widely adopted in corresponding polymer researches since the Ferry's pioneering work [9]. Ferry

and his colleagues proposed the Williams-Landel-Ferry (WLF) formula for shift factors to apply the time-temperature superposition principle to the study of the long-term properties of polymers.

Akinay [14] studied the creep of PLC by applying the time - stress equivalence principle. Firstly, the creep curves under 9 stress conditions were obtained by means of the time-stress superposition principle. Then, the parameters of the curve model and the shift factors were calculated. Finally, he studied how to get more accurate results with less data (2 groups and 3 groups of experimental data), and concluded that the results became more accurate when the interval between different stress levels increased. Jazouli [15] conducted an accelerated creep test on polycarbonate and applied the time-stress superposition principle to dealing with the experimental results. Brostow [16-17] proposed a new formula based on free volume and the chain relaxation capability model to calculate the temperature shift factors. In his study, a stress relaxation test involving four materials was conducted, and the characteristic parameters of the shift factor formula were obtained. Then, he applied the new formula to fitting the shift factors, and got a result with a higher precision.

Furthermore, a comprehensive time-temperature-stress superposition principle, which combines the previously mentioned time-temperature and time-stress superposition principles, has been proved effective in viscoelastic behavior analysis [18-19]. Consequently, the principle is adopted in this paper to study the long-term creep behavior of the carbon fiber composite core wire. And an accelerated creep test has been conducted on its key load-bearing component (the carbon fiber composite core) via the fatigue testing machine. Thereafter, a creep curve under normal conditions which is of engineering concerns is determined. The evaluation of aging and long-term creep properties for the carbon fiber composite core is also presented.

The remainder of the paper is organized as follows. The experiments including the material selection and the experimental methods are introduced in Section 2. The long-term creep property analysis and evaluation process are discussed in Section 3. A two-step method is presented to treat the accelerated test (short-term) data by shifting the creep curves for two times. First, 25 ℃ is set as a reference temperature state. The creep strain-logarithmic time curves under other temperatures are shifted according to the reference curve, and the time-temperature shift factors are calculated. Second, 500 MPa is supposed as a reference stress state. The creep strain-logarithmic time curves under other stresses are shifted according to the reference curve, and the time-stress shift factors are calculated. Then the main creep curve of the carbon fiber composite core is obtained. Finally, the aging life and long-term creep properties are evaluated and predicted. Then a summary and conclusion is given in Section 4.

2. Experiments

2.1. Material selection
As the key load- bearing component for the carbon fiber composite core wire, creep performance of the carbon fiber composite core is studied through a comprehensive test. Carbon fiber composite core rods have been produced as test sample, as shown in figure 1. Its glass transition temperature (T_g) is 196 ℃. The diameter of the rod for testing is 8.1 mm and the length is 450 mm.

2.2. Characterization methods
An accelerated tensile creep test considering higher temperature and higher load conditions has been conducted on an Instron fatigue test machine to test the tensile creep properties for the carbon fiber composite core rod. According to the time-temperature-stress superposition principle, the short-term test data in accelerated conditions can be utilized to analyze and predict the long-term behavior in normal condition. The severe temperatures and stresses are chosen based on the principle of both maintaining the same physical failure mechanism and obtaining more life information in a limited test interval.

For the carbon fiber composite core wire, the normal operating condition is given as 25℃ and 500 MPa. Through testing, the intensity of the carbon fiber composite core is 2000Mpa, and as we know

that its physical failure mechanism can be maintained at any temperature lower than its glass transition temperature (T_g). Consequently, the accelerated stress levels are preset as 1800 MPa and 1000 MPa, and the higher temperatures are taken as 160 ℃ and 140 ℃. The normal operating condition of 25℃ and 500 MPa are also considered as a reference in the test. Thereafter, the fatigue machine is set to conduct a 24-hour creep testing. Then creep strain data sets are collected under the preset temperatures and stress levels, as shown in Figure 2.
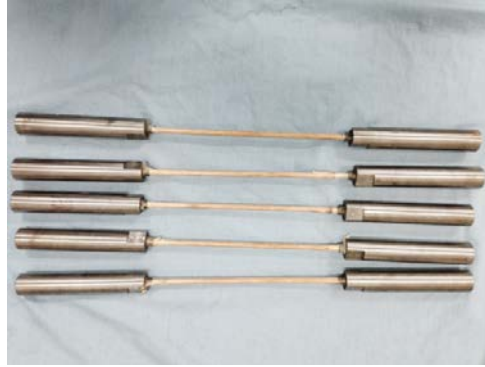

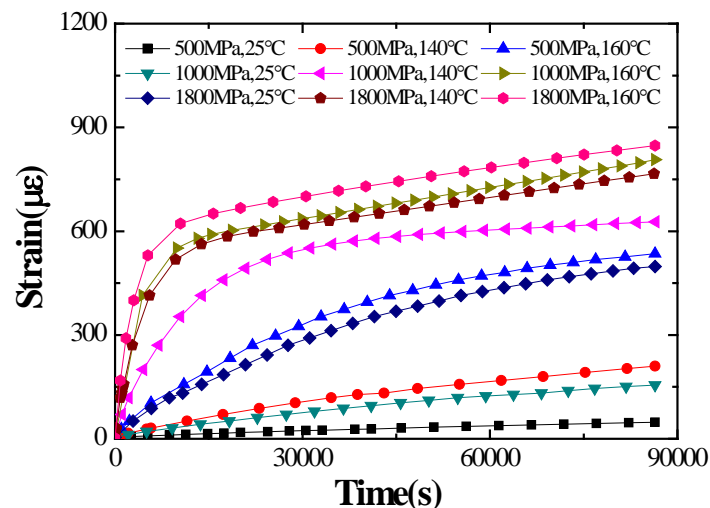**Figure 1.** The carbon fiber composite core specimen.

Figure 2. The creep strain curves in different test conditions.

3. Results and discussion

Creep process can generally be divided into three stages: 1) the attenuation creep, where the strain rate decreases with the increase of time; 2) the steady creep, where the strain rate can almost be assumed as a constant value; 3) the accelerate creep, where the strain rate increases gradually over time, and finally results in creep rupture. Since the test in the current study regards short-term creep, only the first two stages can be observed.

3.1. The influence of temperature

The time-temperature superposition principle establishes an equivalent relationship between temperature and the effective time of creep response by a conversion factor. According to its basic theory, mechanical properties of viscoelastic materials are equivalent under a high temperature for a short period of time and a low temperature for a long time span. That is, the increase of temperature is

equivalence to the decrease of the time scale. This kind of equivalence can be accomplished by translating logarithmic coordinate axis. Then creep compliance function[10] can be represented as:

$$J(T,t) = J\left(\frac{T}{\phi_T^\sigma}, t_0 \right) \tag{1}$$

where ϕ_T^σ is the time-temperature shift factor at a fixed stress. The creep- log time curves for different conditions are obtained and shown in Figure 3(a).

In the current study, the reference temperature state is taken as 25 ℃, the creep strain - log time curves under other temperatures shown in figure 3(a) are shifted to the reference curve, and the shift distance is the corresponding temperature shift factor $\log \phi_T^\sigma$. The obtained creep strain - log time curves are shown in figure 3(b), and the shift factors are listed in Table 1.
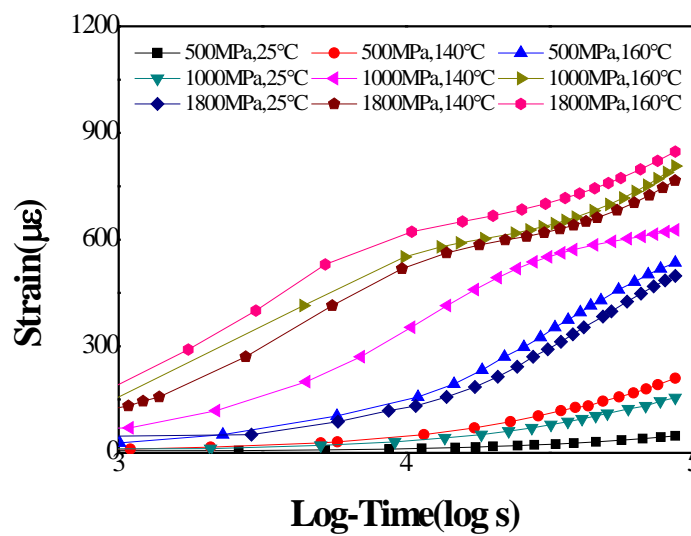
(a)
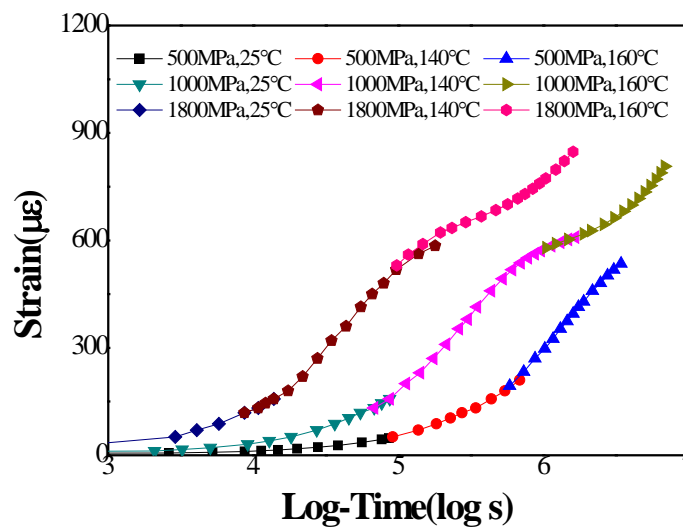
(b)

Figure3. The creep strain- log time curves of composite rods at different temperatures(a) and the superposed creep curves at T_{ref}=25℃(b).

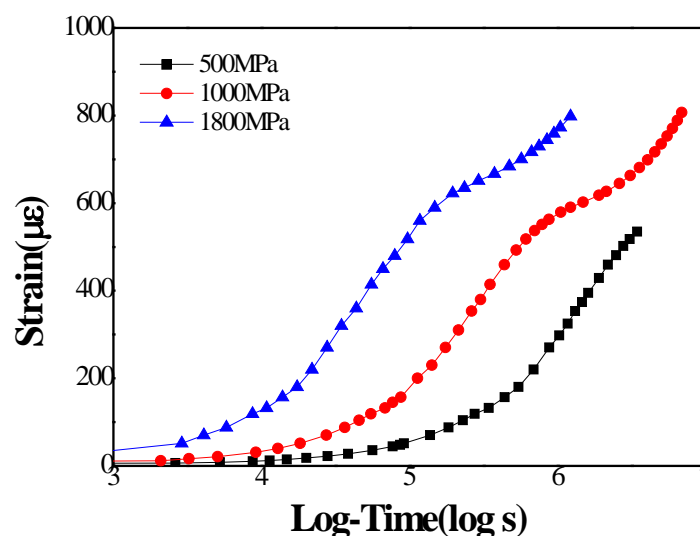**Table 1.** the time-temperature shift factors under different stresses.

Temperature	Stress（MPa）		
（℃）	500	1000	1800
25	Ref.	Ref.	Ref.
140	-0.18	-1.7	-1
160	-1.58	-2.1	-1.04

Relative to the reference temperature of 25 ℃, the temperature shift factors under 160 ℃ are $\log \phi_T^{(500)} = -1.58$, $\log \phi_T^{(1000)} = -2.1$, $\log \phi_T^{(1800)} = -1.04$, respectively. Since the temperature shift factor differs from stresses, superscripts for shift factors are used to represent the stress conditions. It can be seen that the equivalent test time span shown by the master curve increases significantly compared to the initial 24 hour accelerated test time. According to the time-temperature superposition principle, the 24 hour creep data under 160 ℃ contains almost 4 year creep information under 25 ℃. Then the time-temperature superposition principle provides an accelerated characterization method for long-term mechanical properties of materials.

3.2. The influence of stress

Similar with temperature, stress also has an impact on material internal clock. Mechanical properties of viscoelastic materials under high stress in a short time period are equivalent to that under low stress in a long time span. According to the time-stress superposition principle, the long-term performance under low stress can be accessed from short-term experimental data by calculating the shift factor ϕ_σ.

The reference stress state is taken as 500 MPa. The creep strain - log time curves shown in figure 3(b) can be shifted to the reference curve, and the shift distance is the corresponding stress shift factor $\log \phi_\sigma$. The creep strain - log time curves before and after shifting are shown in Figure 4, and the shift factors are summarized in Table 2.
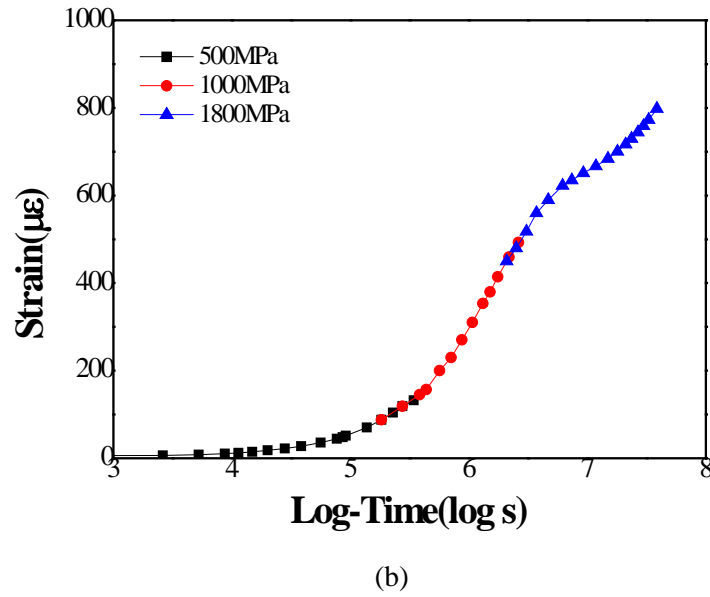

(a)

(b)

Figure 4. The creep strain- log time curves of composite rods under different stresses(a) and the superposed creep curves under σ_{ref}=500MPa(b).

Table 2. the time-stress shift factors at reference temperature.

Stress（MPa）	Time-stress shift factor
500	Ref.
1000	-0.78
1800	-1.52

3.3. Time - temperature - stress superposition principle

Time - temperature - stress superposition principle concludes that level of stress and temperature have an effect on the material free volume. An assumption can be given as:

$$\eta\left(T,\sigma\right)=\eta\left(T_0,\sigma_0\right)\phi_{T\sigma} \tag{2}$$

Then according to Doolittle equation, one can get

$$\log\phi_{T\sigma}=\frac{-B}{2.303f_0}\left[\frac{\alpha_T\left(T-T_0\right)+\alpha_\sigma\left(\sigma-\sigma_0\right)}{f_0+\alpha_T\left(T-T_0\right)+\alpha_\sigma\left(\sigma-\sigma_0\right)}\right]=-C_1\left[\frac{C_3\left(T-T_0\right)+C_2\left(\sigma-\sigma_0\right)}{C_2C_3+C_3\left(T-T_0\right)+C_2\left(\sigma-\sigma_0\right)}\right] \tag{3}$$

Supposing there are stress shift factor under constant temperature ϕ_σ^T and temperature shift factor under constant stress ϕ_T^σ, which can hold:

$$\eta\left(T,\sigma\right)=\eta\left(T,\sigma_0\right)\phi_\sigma^T=\eta\left(T_0,\sigma_0\right)\phi_T^{\sigma_0}\phi_\sigma^T=\eta\left(T_0,\sigma\right)\phi_T^\sigma=\eta\left(T_0,\sigma_0\right)\phi_\sigma^{T_0}\phi_T^\sigma \tag{4}$$

Then,

$$\log\phi_\sigma^T=-C_1\frac{C_2}{C_2+\left(T-T_0\right)}\bullet\left[\frac{C_2\left(\sigma-\sigma_0\right)}{C_2C_3+C_3\left(T-T_0\right)+C_2\left(\sigma-\sigma_0\right)}\right] \tag{5}$$

$$\log\phi_T^\sigma=-C_1\frac{C_3}{C_3+\left(\sigma-\sigma_0\right)}\bullet\left[\frac{C_3\left(T-T_0\right)}{C_2C_3+C_3\left(T-T_0\right)+C_2\left(\sigma-\sigma_0\right)}\right] \tag{6}$$

The following relationship can be given according to Eqs. (5)-(6).

$$\phi_{T\sigma} = \phi_T^{\sigma_0}\phi_\sigma^T = \phi_\sigma^{T_0}\phi_T^\sigma \tag{7}$$

Then from the results in Table 1 and Table 2, the temperature stress joint shift factors for the reference temperature T_0 and stress σ_0 are shown in Table 3. And the following results for the unknown parameters can be determined according to Equation. (3).

$$\begin{cases} C_1 = -0.083 \\ C_2 = -162.83 \\ C_3 = -4.97 \times 10^3 \end{cases} \tag{8}$$

Table 3. the temperature-stress joint shift factors.

Temperature (°C)	Stress（MPa）		
	500	1000	1800
25	Ref.	-0.78	-1.52
140	-0.18	-2.48	-2.52
160	-1.58	-3.62	-2.56

There are two ways to accomplish the shift of material's mechanical properties from a certain condition of temperature T and stress σ to the reference condition of temperature T_0 and stress σ_0. One is a one-step method, which can be realized by a temperature stress joint shift factor. The other one is a two-step approach, which is accomplished by a stress shift factor under constant temperature and a temperature shift factor under constant stress.

3.4. Long-term creep prediction
The carbon fiber composite core wire is designed to serve 30 years. During this long time span, various external forces and environmental factors will influence the creep process. Therefore, it is necessary to explore the long-term creep performance. The master creep strain curve obtained based on the previous procedure is adopted to evaluate the long-term creep behaviour.
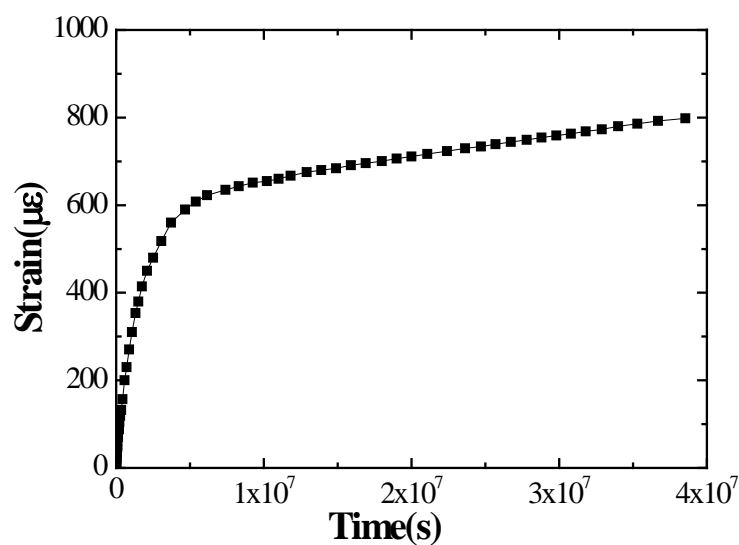

Figure 5. The creep strain-time curves of the composite rods.

The creep strain-time curve under 25 ℃ and 500 MPa is shown in Figure 5. The improved Findley model is adopted for fitting.

$$\varepsilon = a_1 + a_2(1 - e^{-\frac{t}{a_3}}) + a_4 t \tag{9}$$

The results of the parameters are as follows:

$$\begin{cases} a_1 = 9.62 \\ a_2 = 584.93 \\ a_3 = 1.03 \times 10^7 \\ a_4 = 3.58 \times 10^{-6} \end{cases} \tag{10}$$

According to experimental results, creep rupture will appear when the creep strain develops to 20000με for the carbon fiber composite core. From the creep strain-time curve and the corresponding fitting function in Equation (1) under normal condition in Figure 5, it can be known that the creep strain of the material will reach 20000με in about 175 years.

As we know, the dispersion has to be considered in engineering for materials and components. In the current study, the dispersion is considered via a safety factor for the carbon fiber composite core, which is predefined as 1.5. Then the extreme strain changes to 14000με. Therefore, the service life of the carbon fiber composite core is about 117 years for the normal condition.

In addition, the long-term creep behaviour and service life can also be assessed in other conditions with different temperatures and stress levels. Results for several conditions are analysed and summarized in Table 4. Accordingly, it can be concluded that the carbon fiber composite core wire can still satisfy the 30-year design requirement under conditions more severe than normal service.

Table 4. the service life of the composite rods under different working conditions (unit: year)

Temperature	Stress level			
(℃)	25%	30%	35%	40%
70	109	108	107	106
150	63	59	54	48
160	47	43	36	32

4. Conclusion

- To study the long-term creep behaviour of a new carbon fiber composite core wire, an accelerated creep test is conducted on their key load-bearing component, the carbon fiber composite core. 9 data sets regarding different conditions are obtained.
- The time-temperature-stress superposition principle is adopted to analyse and predict the long-term creep behaviour. A 24-hour creep test span for accelerated condition is equivalent to a nearly 4-year period for normal service condition according to the theory.
- The relationship between creep and temperature, stress, time is determined, and the service life of the carbon fiber composite core under normal service condition and several conditions are evaluated. The results show that the service life of the carbon fiber composite core can satisfy the design requirements.

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