Lifetime prediction for carbon fiber composite core wire based on accelerated degradation test

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Abstract. To reduce the huge loss caused by the failure of long-term transmission wire, proper method for the life time prediction is imminent. In this paper, to accomplish long-term service time prediction of carbon fiber composite core (CFCC) wire, an accelerated degradation test is conducted, where 15 samples are allocated to three temperature levels and the degradation data sets under different condition are obtained. Based on the test results, an accelerated degradation model is constructed where Arrhenius function is incorporated to characterize the relationship of degradation rate and temperature. Finally, the median service life and 95% reliable service life of CFCC wire for several conditions is predicted based on the test results and the accelerated degradation model.

1. Introduction

With the rapid development of society and increasing scale of urbanization and modernization, the requirements for transmission capacity have been rising. To meet this end, composite wire has been widely applied to expand the capacity of overhead transmission lines [1]. The carbon fiber composite core (CFCC) wire is a typical composite wire consisting of soft aluminium and carbon fiber. It has been widely recommended in overhead transmission lines for its environmentally friendly and energy-saving characteristics. Compared with traditional wire, CFCC has many advantages such as large current carrying capacity, high strength, light weight, low sag, and long life [2].

During operation, overhead transmission lines have two Salient features including long service time and complex and changeable working environment (greatly affected by the climate). To guarantee the safety and reliability, it is of great significance to analyse its long-term mechanical performance and evaluate its service life in general environment. To reduce the huge loss caused by the aging problem of communication wire and keep the quality in a high level, Fei [3] discussed the feasibility of X-ray real-time imaging technique or infrared imaging technique in defect inspection on carbon fiber composite core wire. Hong [4] analysed the tensile failure mode of carbon fiber composite core based on 3D drawing and finite element software. Yu [5] analysed the performance of fiber carbon composite core rod under torsion load through finite element simulation and full-scale test. [6] studied the mechanical performance of fiber carbon composite core rod under coiled condition by finite element simulation and analysed the failure modes by coiling test. Zhou [7] calculated and analysed the temperature-sag performance of carbon fiber composite core wire, and demonstrated its superior sag characteristics in the operation of the hanging net.
Generally, the design life of overhead transmission lines is very long. The biggest challenges regarding predicting their service life include how to accelerate the experiment process and how to predict the service life based on the experiment data. Zhou [8] adopted RBF neural network and BP neural network to predict the lifetime of communication wire, but how to obtain the experiment data was not discussed. Luo [9] proposed the time-temperature-stress equivalence principle, and pointed out that long-term creep behaviour of material at lower stress levels can be predicted from the short-term one at higher stress levels.

In fact, for long-service life products like CFCC, their failure modes can be regarded as degradation process, and this process can be accelerated by accelerated stress. The accelerated degradation test is to test the performance degradation in a harsher environment than working stress under the condition that the failure mechanism is kept unchanged. According to the products accelerated performance degradation data, the degradation process and failure time under working stress can be derived[10]. During this process, a proper acceleration function which constructs a relationship between degradation rate and accelerated stress is very important. For different accelerated stress, different accelerated relations have been recognized. For example, Arrhenius [11] model has been widely adopted to describe the accelerating effect of temperature, and Power law model [12] has been well accepted for the voltage accelerated stress circumstance.

The remainder of the paper is organized as follows. In Section 2, an accelerated degradation experiment for life prediction of CFCC is conducted. The temperature is set as the accelerated stress and the test arrangement and test results are illustrated. Section 3 aims at constructing a CFCC service life prediction method based on the accelerated degradation test data. The test results in Section 2 is utilized to verify the method and the service life of CFCC under different temperature are obtained. Finally, conclusions and future research discussions are summarized in Section 4.

2. Accelerated degradation test

During operation, the CFCC wire’s weight and wind vibration will act as load on CFCC. This will lead to gradual degrading process of its mechanical properties, and the deterioration can be traced by its continuously decreasing tensile intensity. In this section, an accelerated degradation test is conducted to study this deterioration process and access the service life of CFCC under working temperature considering long-term load.

2.1 Test sample

As the key load- bearing component for the carbon fiber composite core wire, tensile intensity degradation of the carbon fiber composite core is studied through a comprehensive test. Its glass transition temperature is 196℃. The tensile intensity of the carbon fiber composite core is 2262Mpa. During operation, the tensile intensity decrease gradually because of the influence of wire’s weight and wind vibration. To guarantee safety, the wire is regarded as failed when the tensile intensity drops to 60% of the initial intensity. Carbon fiber composite core rods have been produced as test sample, the diameter of the rod for testing is 8.1 mm and its length is 450 mm.

2.2 Test procedure

An accelerated degradation test considering higher temperature has been conducted on an Instron fatigue test machine to test the tensile intensity degradation for the carbon fiber composite core rod. According to the Arrhenius law, the short-term test data in accelerated conditions can be utilized to analyse and predict the long-term degradation process under working temperature. The accelerated temperature levels are selected based on the principle of not only keeping the same physical failure mechanism, but also obtaining more life information in a limited test span. For the carbon fiber composite core wire, the normal operating condition is considered as 25℃. To take wire’s weight and wind vibration into consideration and get a relatively obvious degradation trend, 25% $\sigma_b$ is put on the carbon fiber composite core rods during the test where $\sigma_b$ denotes its tensile intensity. The test arrangement is listed in Table 1.
Table 1. Accelerated degradation test arrangement

| Temperature | Load condition | Sample size | Test time  |
|------------|----------------|-------------|------------|
| 170°C      | 25% \( \sigma_0 \) | 5           | 9000h      |
| 180°C      | 25% \( \sigma_0 \) | 5           | 5000h      |
| 190°C      | 25% \( \sigma_0 \) | 5           | 2500h      |

2.3 Measurements

Figures 1 shows the tensile intensity decrease of samples under different temperature. From the experiment results, it can be obviously seen that the mechanical properties of CFCC degrade gradually over time when 25% \( \sigma_0 \) are put on the wire throughout the test. In addition, the results indicate that higher temperature can significantly accelerate the degradation process. Finally, after 9000 hours under 170°C, 5000 hours under 180°C and 2500 hours under 190°C, the tensile intensity did not reach the threshold. So reasonable extrapolation is necessary to predict the service life of CFCC wire.

![Figure 1. experiment results](image1)

3. Modelling and analyzing

Based on the experiment results and results analysis above, an accelerated degradation model based on degradation path and Arrhenius function is constructed to describe the degradation process of CFCC wire under different temperature. With the aid of degradation threshold, the failure time distribution is further derived and the service time under different temperature of CFCC wire can be derived.

3.1 Accelerated degradation modelling of CFCC

To better analyse the statistical characteristics of the experiment results, the sample mean values at observational time points are obtained and illustrated in Figure 2.
From the above results, it can be seen that the temperature can accelerate the decreasing rate. In addition, the decreasing trend of mean tensile intensity follows a power function relationship with test time, for the convenience of modelling, the test time can be transformed to make sure the degradation path varies linearly with test time. The transformation can be expressed as

$$x = f(t)$$  \hspace{1cm} (1)

where $x$ is the transformed time, and $t$ is the test time. After transformation, the mean of the tensile intensity decreases linearly with the transformed time, which is intuitively showed in Figure 3.

To reasonably depict above statistical properties suggested by the experiment result, model of Eq. (1) is developed

$$y(x) = a + bx + \varepsilon$$  \hspace{1cm} (2)

where $y(x)$ denotes the true level of the key performance at transformed test time $x$; $a$ is a parameter representing the initial level of the performance index; $b$ is a parameter indicating the deterioration rate and $\varepsilon$ reflects the disparity of the degradation procedure, which obeys the normal distribution denoted as

$$\varepsilon \sim N(0, \sigma^2)$$  \hspace{1cm} (3)

where $\sigma^2$ characterizes the disparity variation of the degradation procedure.

As showed in Figure 1, the deterioration rates are different under different temperature, while the disparity keeps approximately same under different temperature. To reasonably depict the degradation trend in accelerated degradation situations, Arrhenius function is incorporated in this paper to characterize the relationship of degradation rate and temperature, and the accelerated degradation model of CFCC can be denoted as
where $\alpha$ is an unknown parameter, $T$ is stress level, $E$ denotes the activation energy to be determined and $K$ indicates the universal gas constant. Then, let $\beta = -E/K$ for expository convenience.

According to the proposed accelerated degradation model, for the $i$ th temperature level, $j$ th sample and $k$ th measurements, the true level of the key performance follows the normal distribution:

$$y_{ijk} \sim N\left(a + \alpha \exp\left(\frac{\beta}{T}\right)x, \sigma^2\right)$$

Thus, logarithmic maximum likelihood function $\ln L$ throughout all samples under all stress levels can be written as

$$\ln L = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=2}^{p} \left\{ -\frac{1}{2} \ln(2\pi\sigma^2) - \frac{\left[ y_{ijk} - \alpha - \alpha \exp\left(\beta / T\right)x_{ijk}\right]^2}{2\sigma^2} \right\}$$

The maximum likelihood estimations of parameters $a, \alpha, \beta, \sigma$ can be derived based on $\ln L$. These parameters can be further adopted in service life prediction.

According to the accelerated degradation model constructed above, the distribution function of the performance index subject to working temperature $T_0$ at a certain transformed test time $x$ can be given by

$$F_x(y | x) = \Phi\left(\frac{y-a - \alpha \exp(\beta / T_0)x}{\sigma}\right)$$

As mentioned before, the wire can be regarded as failed when the tensile intensity drops to 60% of the initial intensity. This definition provides a bridge linking the degradation process and the service life prediction of CFCC wire. Consequently, the distribution of time-to-failure $T$ can be defined as

$$F_T(x | D_f) = P\{T \leq x | D_f\} = P\{y(x) \leq D_f\}$$

where $D_f$ denotes the threshold of the degradation performance. For CFCC wire, it is 0.6.

As important characteristics, FTD percentiles are elemental in reliability and safety analysis. Let $t_p$ be the 100$p$th FTD percentile, i.e., an average of 100$(1-p)$% of the population of the product will not fail before $t_p$. According to this definition, $t_p$ can be derived by solving

$$F_T(t_p | D_f, x_p = f(t_p)) = p$$

In this paper, $t_p$ can be expressed as

$$t_p = f^{-1}\left(\frac{D_f - a - \alpha \sigma}{\alpha \exp(\beta / T_0)}\right)$$

where $u_p$ is the standard normal offset of $p$. Taking $p = 0.5$ for example, the median life, the most common statistic associated with the FTD in practical applications can be derived by
\[ t_{0.5} = f^{-1} \left( \frac{D_f - a}{\alpha \exp \left( \frac{\beta}{T_0} \right)} \right) \] (11)

3.2 Service life prediction for CFCC

According to experimental results, the tensile intensity of CFCC wire would gradually degrade over time when 25% \( \sigma_s \) is consistently put on it. In the experiment, we incorporated temperature as accelerated stress to better observe this phenomenon and figure out the relationship between degradation and service life faster. Then the key issue is to extrapolate the service life of CFCC wire under working temperature. In the previous section, we constructed an accelerated degradation model to accomplish this goal. Based on the experiment results, the model parameter is estimated and the median life of CFCC wire is obtained and listed in Table 2.

As we know, the dispersion has to be considered in engineering practice. In the current study, the dispersion of the experiment data is characterized by \( \sigma \), during life prediction process, the concept of FTD percentiles are introduced to consider the dispersion, which has been illustrated in the previous section. To illustrate the influence of dispersion, \( t_{0.05} \) of CFCC wire is also calculated listed in Table 2, which means an average of 95% of the population of the product will not fail before \( t_{0.05} \).

In addition, during the long-term service time, the temperature of the wire may be different due to different amount of current flowing through it or climate change. Accordingly, life prediction results for several conditions are calculated and summarized in Table 2.

| Temperature/°C | 25   | 70   | 100  |
|----------------|------|------|------|
| \( t_{0.5} \) /year | 5.71 | 3.11 | 3.09 |
| \( t_{0.05} \) /year | 5.08 | 3.07 | 2.99 |

4. Conclusion

The accelerated degradation test of CFCC wire, accelerated degradation model construction and service life prediction are focused in this paper. According to the experiment results, one can conclude that the tensile intensity of CFCC wire degenerates gradually with a tensile stress of 25% \( \sigma_s \) put on it. Besides, this degradation process can be accelerated by temperature. The relationship between the degradation and temperature, time is constructed by an accelerated degradation model, and the service life of CFCC wire under working temperature and several conditions are evaluated.

In the experiment of this paper, it is worth mentioning that 25% \( \sigma_s \) is put on the sample so that we can observe the degradation process more easily. However, in real situation, the load on the wire is much lower than 25% \( \sigma_s \), thus the real service life of CFCC wire can be longer than the predicted results. To get the service life of the wire under the real stress level and temperature, method to cope with multiple accelerated stresses need to be developed. We are working on this problem and hope to obtain valuable findings.

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