Reliability Analysis of Insulators for Overhead Contact System Based on Mechanical Tensile Failure

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Abstract. Insulators serve as vital component in the overhead contact system, playing their roles in mechanical support and electrical insulation. The reliability of insulator is directly related to the power supply reliability performance overhead contact system. To assess the reliability of catenary insulators in a certain coastal area, a batch of porcelain insulators with the same operating years and technical parameters are obtained from traction power supply system. Firstly, a series of strength samples of insulators are obtained by tensile failure load experiments and fitted with normal distributions. Secondly, combined with the reliability design method of insulators and the mechanical safety factor, it is assumed that the stress distribution also conforms to a normal distribution. Finally, the stress-strength interference model is applied to evaluate the reliability of insulators. This paper proposes a reliability assessment method for the insulators of overhead contact system, which significantly facilitates the development of reliability evaluation of insulator.

Keywords: Overhead contact system · Insulators · Reliability · Tensile failure load test · Stress-strength interference

1 Introduction

By the end of 2022, the total operating mileage of railway in China has reached 155,000 km, with high-speed railway exceeding 42,000 km, which firmly occupying the first position in the world. As a widely used equipment in the overhead contact system, the reliability of insulator directly affects the safety performance of system. However, given that the overhead contact system is open-air installed, the condition insulators located is extremely harsh. Due to the long-term influences of external weather factors, including rain, snow, salt fog, ultraviolet radiation, mechanical and electrical stress [1–5], it is more likely to trigger flashover, fracture and breakdown [6, 7], which can cause power outages and even train suspensions, posing a serious threat to the national economy and public safety. Therefore, it is indispensably important to evaluate the reliability for insulators of overhead contact system.

Wei et al. evaluated the reliability and average life of composite insulators by establishing a hard and soft failure model of insulators and considering their competition failure process [8]. Li et al. obtained the bending failure load data of insulators by conducting bending load tests on insulators and then analyzed the reliability of insulators [9]. Yang et al. proposed a fuzzy evaluation method for the reliability of overhead contact system based on fault tree analysis, combined with the historical failure data [10]. Liu et al. analyzed and evaluated the reliability of automobile clutch hubs by stress-strength interference model and finite element analysis method [11]. Tang et al. studied the reliability of overhead contact lines under pollution flashover and icing flashover conditions based on stress-strength interference model [12].

Currently, there are few literatures about the reliability assessment of catenary insulator. In this situation, this paper extracts ten porcelain insulators from the overhead contact system in a coastal area and conducts tensile failure load tests to analyze their aging situations. In addition, after obtaining the stress and strength distribution of insulator, the reliability is calculated by using stress-strength interference model.

2   Reliability Evaluation Methods

2.1   Safety Margin

Traditionally, product reliability has been designed or evaluated by safety margin or safety factor, that is, the stress which the product is subjected to and the product's strength are considered to be constants, as shown in Fig. 1. The difference between the product's strength and stress is the safety margin, and the corresponding ratio is the safety factor.

$$\begin{cases} M = \delta - S \\ k = \dfrac{\delta}{S} \end{cases} \tag{1}$$

where, M represents the safety margin, k represents the safety factor, S is the stress on the product, and δ is the strength of product. Moreover, S and δ have the same dimension.
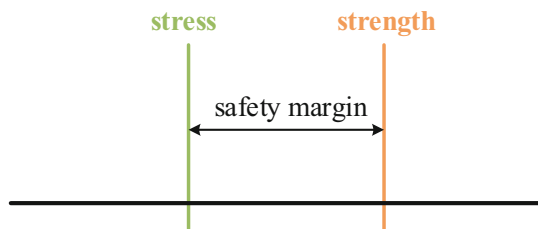

Fig. 1. Safety margin model

In Fig. 1, stress refers to all factors that cause failures of insulator, such as ultraviolet radiation, corrosion, mechanical tension, and electrical stress. Strength is the ability of

the product resisting failures caused by stress. As for insulator, this includes mechanical tensile failure load, power frequency withstand voltage, pollution withstand voltage and so on.

2.2 Stress-Strength Interference

However, due to the uncertainty in the product design and manufacturing process, and the randomness of the stress applied to the product during service, the product's stress and strength are not constant but should follow a certain probability density distribution, as shown in Fig. 2. When the stress on the product is higher than the strength, the product will fail, which is the region where the stress distribution interferes with the strength distribution in Fig. 2. The size of the interference area is negatively correlated with the reliability of the product, which represents that the larger the interference zone, the greater the failure probability and the lower the reliability. Therefore, the interference area is also called unreliable area, and the model is known as Stress-Strength Interference (SSI) model.
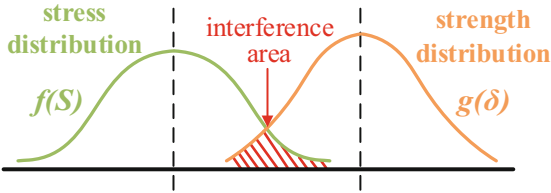

Fig. 2. Stress and strength interference model

By combining the reliability theory and the SSI model, the reliability of insulator can be obtained as follows:

$$R = P(\delta > S) = \int_{-\infty}^{\infty} f(S) \int_{S}^{\infty} g(\delta) d\delta dS \qquad (2)$$

where, R represents the reliability, P represents the probability, $f(S)$ represents the probability density function of stress, and $g(\delta)$ represents the probability density function of strength.

Through the above process, the relationship among reliability, stress and strength is established. Thus, if the stress and strength distribution of insulator are obtained, its reliability can be effectively evaluated.

3 Experiment

3.1 Materials

Extract 10 porcelain insulators with the same technical parameters and manufacturer, the insulators have been in the overhead contact system for approximately 5 years in a certain coastal region. Its structure is depicted in Fig. 3, and Table 1 lists some technical parameters of the insulator.
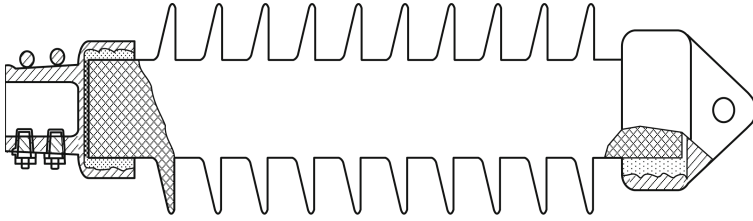
Fig. 3. The structure of insulator

Table 1. Technical parameters of insulator

Voltage class (kV)	Specified mechanical load (kN)	Creepage distance (mm)	Height (mm)	Shed diameter (mm)
25	120	1200	760	180

3.2 Experiment Process

To find out the tensile load strength of this batch of insulators, mechanical tensile failure load tests are executed according to TB/T 3199.1-2018. The experimental device is shown in Fig. 4.
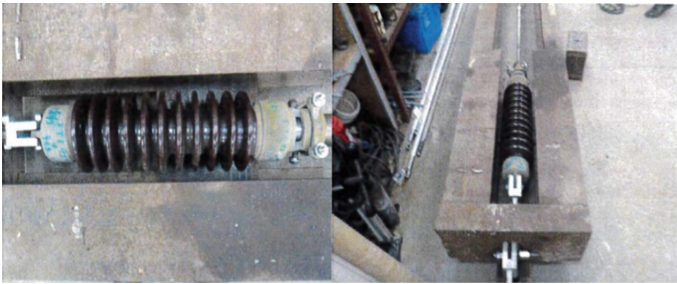

Fig. 4. Insulator tensile experimental device

When the insulator in the experiment appears end damage or rod fracture, it is considered to have failure. During the test, fix both two ends of insulator to the device, then a tensile load is applied along the axial direction of the insulator.

Specific steps are as follows. (1) Firstly, applying a tensile load of 40 kN to the insulator and hold it for 1 min. (2) Then, in the event of non-failure of the insulator, escalating the applied tensile load to 80 kN and sustaining it for a duration of 1 min. (3) If the insulator experiences failure during this interval, the experiment is ceased. However, if the insulator remains non-failure, it is proceeded to incrementally augment the tensile load until the insulator eventually fails. Figure 5 shows that the insulator has tensile fracture.
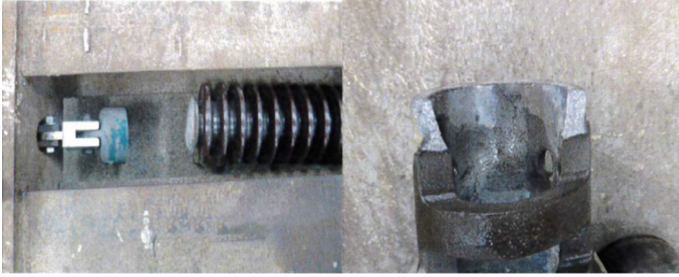
Fig. 5. Insulator tensile fracture

3.3 Experiment Results

During the experiment, the mechanical tensile damage load is recorded when the insulator failed, and the concrete results are shown in Table 2.

Table 2. Results of insulators tensile load failure

Number	Failing load (kN)	Meet the requirement
1	126.3	Yes
2	95.5	No
3	151.6	Yes
4	139.0	Yes
5	173.7	Yes
6	156.4	Yes
7	134.8	Yes
8	152.5	Yes
9	150.9	Yes
10	176.1	Yes

Analysis of the test data shows that basically all the porcelain insulator samples meet the specified requirements for tensile strength, with an average value of 145.68 kN and a maximum tensile failure load of 176.1 kN. There is a large safety margin between the strength of insulators samples and the specified tensile failure load (120 kN), so its reliability is great.

4 Reliability Evaluation

4.1 Strength Distribution

Assume that the tensile stress applied to the insulator follows a normal distribution. As a matter of fact, in engineering practice, the stress S and strength δ mostly obey the Gaussian distribution, that is $f(S) \sim N(\mu_S, \sigma_S^2)$ and $g(\delta) \sim N(\mu_\delta, \sigma_\delta^2)$.

The strength distribution of insulator can be obtained by the mechanical tensile failure load test results. Through the Lillietest function in MATLAB to test the data, the results back $h = 0, p = 0.39$, indicating that the data conforms to the normal distribution, as shown in Fig. 6, the strength distribution function is as follow:

$$g(\delta) = \frac{1}{\sigma_\delta \sqrt{2\pi}} \exp[-\frac{(\delta - \mu_\delta)^2}{2\sigma_\delta^2}] \tag{3}$$

where, μ_δ is the mean tensile strength, 145.68 kN; σ_δ is the standard deviation of tensile strength, 23.55 kN.
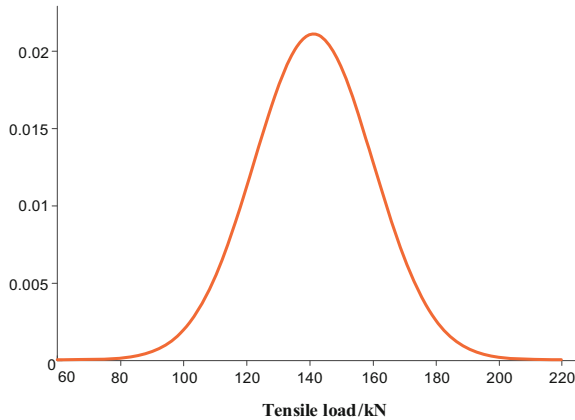

Fig. 6. Tensile strength distribution of insulator

4.2 Stress Distribution

For rod cantilever insulator, it will be subjected to the force between its own gravity and the stress between cantilever and the messenger wire. In addition, it is necessary to consider the impact of environmental factors such as wind load and icing load. The strength distribution of insulators has been obtained by mechanical tensile failure experiments, and the stress distribution can be acquired by directly measuring the tensile load of insulators in the field. However, in many cases it is difficult to directly measure the stress of insulators on the overhead contact system.

In view of the above-mentioned reasons, this paper assumes that the tensile load of insulators meets their safety margin requirements from the insulator reliability design under different working conditions.

According to the insulators service characteristics and long-term operation experience, it is required that the annual average load on the rod-shaped porcelain insulator meets the requirement of a mechanical strength safety factor of not less than 4.0 in normal operating conditions. Moreover, when exposed to the utmost load capacity, the

insulator's mechanical strength safety factor must remain at a minimum of 3.0, guaranteeing its durability and structural integrity. Combined with the rated tensile failure load (120 kN) and the safety factors, the stress distribution function is as follow:

$$f(S) = \frac{1}{\sigma_S \sqrt{2\pi}} \exp[-\frac{(S - \mu_S)^2}{2\sigma_S^2}] \tag{4}$$

where, μ_S is the mean tensile stress, 30 kN, and σ_S is the standard deviation of tensile stress, 15 kN.

4.3 Reliability Evaluation

After obtaining the probability functions of tensile stress and strength of insulators, the reliability can be calculated by Eq. (2). Figure 7 shows the tensile stress-strength interference model of insulators. Taking into account that the tensile stress and strength of insulators follow normal distributions, Eq. (2) can be simplified as follow:

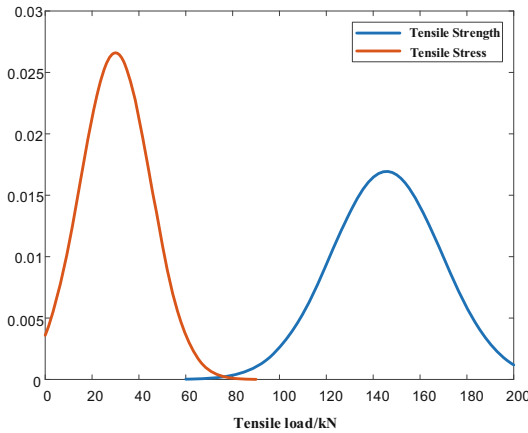$$R = \Phi(\frac{\mu_\delta - \mu_S}{\sqrt{\sigma_\delta^2 + \sigma_S^2}}) \tag{5}$$

Fig. 7. Insulators tensile stress-strength interference model

We can obtain the reliability by querying the standard normal distribution table. By substituting the data and performing calculations, the reliability of insulators is $R = 0.999983$. Generally, the reliability requirement for in-service insulator is above 0.99, so the reliability of this batch of insulators meets the requirement.

5   Conclusion

In response to the current reliability assessment issue concerning catenary insulators, this paper conducts mechanical tensile experiment on insulators and finds that there is a significant safety margin between the test tensile failing load and the rated tensile

failing load. Moreover, suppose that the tensile stress and strength of insulators follow Gaussian distribution, and the reliability of insulators is calculated by the stress-strength interference model, exhibiting a high level of reliability. This research method does not require the statistical failure rate of insulators, it only necessitates obtaining the stress and strength distribution of insulators to effectively determine the reliability, offering a suitable approach to carry out reliability assessment for catenary insulators.

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