Static fatigue parameters and environmental factors effects on optical fiber lifetime

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***Abstract*—In order to study the influence of environmental factors and static fatigue parameters on the fiber lifetime, this paper adopted the two-point bending method to focus on the influence of temperature and humidity on the fiber life and fatigue parameters, on this basis, the reliability of optical fiber under the diurnal temperature difference in actual use environment is simply simulated and verified by temperature cycle experiment, and the performance of two kinds of optical fiber with obvious difference in fatigue parameters was compared under harsh conditions. Experimental results show that environmental factors have significant influence on fiber lifetime and fatigue parameters, the service lifetime and fatigue parameters of fiber will decrease sharply under high temperature and high humidity. Under the same environmental conditions, the fiber with larger fatigue parameters always has a longer life than the fiber with smaller fatigue parameters. The static fatigue parameter values tested in laboratory environment are of practical significance to judge the fiber lifetime.**

Keywords—environmental factors, fiber lifetime, static fatigue parameters

I. INTRODUCTION

As the infrastructure of the information society, optical fiber communication network has been in operation for nearly 40 years. As the transmission medium of optical signal, the main properties of optical fiber include geometric size, transmission performance, mechanical performance and environmental performance. The optical fiber geometry determines the connection loss between the optical fiber and the device. Optical fiber transmission performance limits the transmission rate and transmission distance of the system. The mechanical properties and environmental properties of optical fiber determine the service life of optical fiber. In order to ensure the long-term safe and reliable operation of the optical fiber in the actual communication network, the optical fiber must have good mechanical strength, so as to be easy to cable and lay. At the same time, the optical fiber should have good environmental performance to ensure that the optical fiber will not affect the service life of the optical fiber due to fatigue fracture in the harsh environment such as high temperature and high humidity.

Therefore, in order to improve the long-term safety and reliability of optical fiber communication network, various research institutions have not stopped the study on the influence of fatigue parameters and environmental factors on the service life of optical fiber [1-7].After more than 30 years of research, researchers put forward the brittle fracture theory of optical fiber, used fatigue parameters and environmental factors to predict the theoretical model of optical fiber life, and developed a set of test standards for evaluating the mechanical properties of optical fiber [8-9].In the study of mechanical properties of fiber, fiber fatigue parameter n is commonly used to estimate the fiber life and evaluate the strength of different types of fiber. Generally, the fatigue parameter n is divided into static fatigue parameter and dynamic fatigue parameter according to the different ways of stress application. Dynamic fatigue parameter (n_d) is required in international and domestic standards of relevant optical fiber products, while Static fatigue parameter (n_s) test is rarely reported due to its time consuming and few commercial equipment. In 2015, Lu tested dynamic fatigue parameters of optical fibers by using two-point bending method to study the influence of high humidity environment on dynamic fatigue of optical fibers [10].In 2016, Chen Liming and others of Wuhan Research Institute of Posts and Telecommunications used the life assessment model to simulate and evaluate the life of OPGW (fiber composite overhead ground wire) lines, and explored the key technologies to extend the life of OPGW link [11]. Yu analyzed and studied the two test methods of fiber dynamic fatigue parameters and their differences[12]. However, there are few reports on the influence of environmental factors on static fatigue parameters ns, fiber life and the practical significance of laboratory testing static fatigue parameters. On the basis of expounding the fiber fracture mechanism, this paper introduces the test principle and test device of two-point bending method to measure the fiber life and the principle of calculating the static fatigue parameter ns. Finally, it discusses the influence of high temperature and high humidity environmental factors on the fiber life and the practical application significance of laboratory testing static fatigue parameters. It provides theoretical support for exploring the life of optical fiber in practical use environment.

II. PRINCIPLE

A. Fiber Fracture Mechanism

The glass material of quartz fiber is brittle material. In the fabrication process of fiber preform and drawing, a large number of microcracks will occur on the surface of the fiber along the optical length. In high temperature and high humidity environment, the existence of external stress will promote the growth of microcracks. Once the external stress reaches the critical strength value or the cumulative time critical value is reached under the continuous action of small external forces (such as static stretching, static bending, etc.), the fiber will suffer fatigue fracture. The relationship between fiber crack growth rate V and time t is shown in (1) [13-14].

$$V = dL / dt = AK_{IC}^{n} \tag{1}$$

Where, L is the defect depth, that is, the defect size perpendicular to the applied stress direction; A is the material parameter related to the fracture environment; K is fiber stress intensity factor; K_{IC} is the critical value of fiber stress intensity factor; n is the fatigue (stress corrosion) parameter.

B. Theoretical Calculation of Static Fatigue Parameter Values

In the study of mechanical properties of fiber, fiber fatigue parameter n is commonly used to estimate the fiber life and evaluate the strength of different types of fiber. Generally, the fatigue parameter n is divided into static fatigue parameter and dynamic fatigue parameter according to the different ways of stress application. Static fatigue parameter n_s represents the fracture time of fiber under constant stress, which is mainly used to calculate the fiber life. The dynamic fatigue parameter nd represents the breaking time of the fiber under constant rate stress, which is mainly used to compare the strength of different types of fiber. In the operating environment of optical fibers, the relationship between the fiber life t_s, the stress σ applied to the fiber and the original strength of the fiber is shown in (2).

$$\lg t_s = -n \lg \sigma + \lg B + (n-2) \lg S_i \tag{2}$$

Where, B is strength retention factor, which is related to crack shape, fiber material parameter and critical value of stress intensity. n is fiber fatigue parameter; S_i is the original strength of the fiber. According to (2), when the stress on the fiber is constant, the fiber life t_s is only related to the fiber fatigue parameter n, and the greater the value of the fiber fatigue parameter n, the longer the fiber life [7].

Similarly, it can be seen from (2) that the fiber under different bending stresses σ_i corresponds to different median t_i of the fiber break time. As in (3), $\ln(\sigma_i)$ and $\ln(t_i)$are a line fitting horizontal and vertical coordinates respectively, and the fitting straight line slope is the static fatigue parameters ns.

$$-n_s In(\sigma_i) + \text{intercept} = In(t_i) \tag{3}$$

The bending stress σ_i of the optical fiber is determined by the inner diameter of the glass tube and the material properties of the optical fiber. For its calculation, see formulas (4) ~ (6).

$$\sigma_i = E_0 \times \varepsilon (1 + 0.5 \times \alpha' \times \varepsilon) \tag{4}$$

$$\varepsilon = 1.198 \times d_f / (d - d_c) \tag{5}$$

$$\alpha' = 0.75 \times \alpha - 0.25 \tag{6}$$

Where, E_0 is the Young's modulus of the fiber glass material (72 GPa), ε is the strain at the bending vertex of the fiber, α is the correction parameter of the stress/strain nonlinear deviation (typical value is 6), d_f is the diameter of the fiber glass layer, d is the inner diameter of the glass tube, and d_c is the outer diameter of the fiber (250μm)

C. Test Principle and Test Device of Static Fatigue Parameters

The standard [8] has specified in detail the testing methods for the n value of five types of fiber fatigue parameters. This paper adopts the two-point bending method to measure the static fatigue parameter ns of optical fiber, and the test device is shown in Figure 1. We select a series of precision glass tubes with different inner diameters, and send a certain number (no less than 30) of optical fibers under test into the glass tubes with different inner diameters through special tools (the glass tubes used in the test have uniform inner diameters, and the size is accurate to microns), so that the optical fibers are in two point bending state, and then the optical fibers under test obtain different degrees of bending stress σi. The glass tube is connected directly to the sound sensor. When the fiber breaks, the sound sensor sends signals to the computer through the fracture monitoring system to record the fracture time of all the fiber samples, which is the fiber life of the fiber under the action of two-point bending stress.

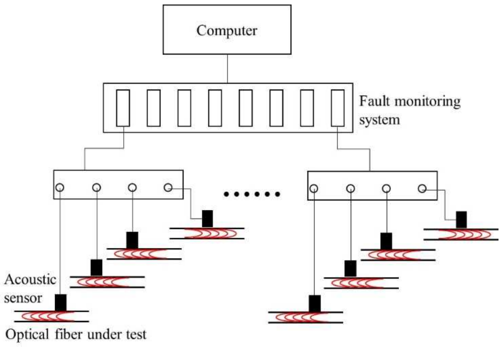

Fig. 1. Diagram of two point bending device

III. Experiment Design

In order to study the influence of ambient temperature and humidity on fiber fatigue parameters and fiber life, we used an environmental experiment chamber to obtain different temperature and humidity conditions, test the fiber life and calculate the static fatigue parameter n_s. The experimental design is shown in Table 1. The optical fiber is placed in different temperature and humidity environments and tested based on the test device in Figure 1.

TABLE 1. Experimental design and test conditions

Experiment Items	Optical fiber Sample No.	Test Condition
temperature influence	H	temperature: 20°C、40°C、60°C、80°C Fixed humidity：85% RH
humidity influence	H	Humidity: 40% RH、60% RH、85% RH、 98% RH Fixed temperature: 40°C
temperature cycling	H	Range of temperature change: 0°C~50°C，humidity:40% RH Holding time at each temperature point: 1 hour Temperature change rate: 1°C/min
comparision test	H, L	temperature: 40°C, humidity: 85% RH

Note 1: Relative Humidity (RH for short), the units are %RH.
Note 2: Under laboratory conditions (23°C, 50 % RH), n_s of sample H is 28.62, n_s of sample L is 21.7.

IV. Results

A. Influence of Temperature

Figure 2 shows the test results of the influence of temperature on the fiber life. Compared with the standard laboratory environment, the fiber life decreases rapidly with the increase of ambient temperature. Under certain stress conditions (glass tube inner diameter 3670μm, bending stress 3.45Gpa), the fiber life decreases from about 1000 hours to 1.55 hours with the increase of temperature. The test results of fiber static fatigue parameter n_s also sharply decreased from 28.62 under laboratory conditions to 12.43. When the temperature exceeds 40 ℃ , n_s shows signs of accelerating decline. This experimental phenomenon shows that, under the condition that other conditions remain unchanged, the increase of ambient temperature will reduce the fatigue parameters of optical fiber, and then lead to the decrease of optical fiber life.

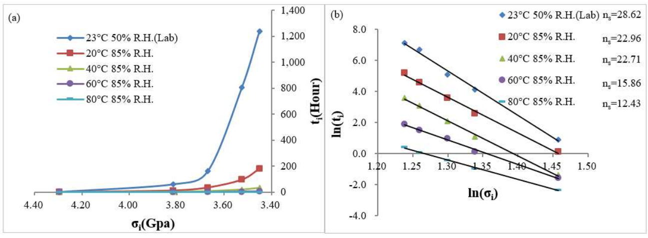

Fig. 2 Fiber lifetime under fixed humidity and different temperature conditions. (a) fiber lifetime; (b)n_s fitted line

B. Influence of Humidity

Figure 3 shows the test results of the influence of humidity on the fiber life. The fiber life decreases rapidly with the increase of ambient humidity. Under certain stress conditions (glass tube inner diameter 3670μm, bending stress 3.45Gpa), the fiber life decreases from more than 500 hours to 18 hours with the increase of humidity, and the measured static fatigue parameter n_s results also decrease from 27.95 to 20.27. This experimental phenomenon shows that under the condition that other conditions remain unchanged, the increase of humidity will also reduce the fatigue parameter of optical fiber, and thus lead to the decrease of optical fiber life.

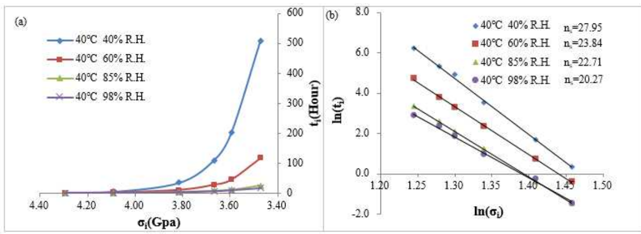

Fig. 3 Fiber lifetime under fixed temperature and different humidity conditions. (a) fiber lifetime; (b)n_s fitted line

C. Temperature Cycling

The temperature cycle experiment can simply simulate the temperature difference between day and night in the actual use environment. The temperature fluctuates back and forth between 0°C and 50°C, and the humidity is set at 40%RH. For the convenience of comparison, the test results of constant temperature of 50°C and humidity of 40%RH are taken as reference, and the test results are shown in Fig 4. It can be seen that the lifetime of the fiber with the temperature cycle of 0°C~ 50°C is much higher than that with the constant temperature of 50°C, but the n_s is close. According to the temperature test results, the life of 0°C fiber is higher than that of 50°C under specific stress. Therefore, the life of the fiber obtained by temperature cycling is between 0°C and 50°C, which is a comprehensive result of the two results. Since the constant temperature is 0°C and the humidity is 40% RH. The test conditions could not be implemented, so no actual validation was performed.

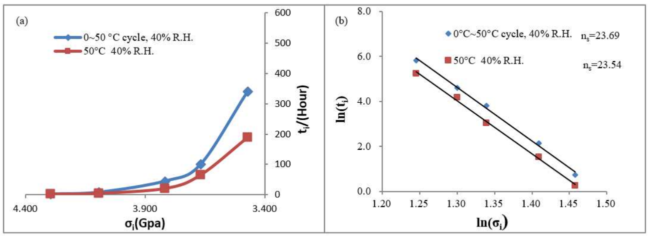

Fig. 4 Fiber lifetime under temperature cycle condition. (a) fiber lifetime; (b)n_s fitted line

D. Lifetime Comparison of Different Optical Fibers

In order to explore whether the n_s values tested in laboratory conditions are of practical significance, we selected two different optical fibers (sample H and L) to test the life and static fatigue parameters ns of these two optical fibers in laboratory environment and high temperature and humidity environment respectively. Table 2 shows the comparison of the service life and n_s test results of the two optical fibers.

TABLE 2. TEST RESULTS COMPARISON OF LIFETIME AND NS FOR TWO KINDS OF FIBER

Testing environment	n_s		**Fiber Lifetime (under 3.524 Gpa)/hour**	
	fiber sample H	**fiber sample L**	**fiber sample H**	**fiber sample L**
laboratory conditions (23°C, 50% RH)	28.6	21.7	804.6	7.5
hot and humid environment (50°C, 85% RH)	20.7	11.5	22.0	0.1

As can be seen from Table 2, in the laboratory environment, the fiber life of the fiber sample H with high ns value is much higher than that of the fiber sample L with low n_s value. When placed in a high temperature and high humidity environment, the n_s value and life of the two disks of fiber decreased a lot, but the ns value and life of fiber sample H were still much higher than that of fiber sample L. Therefore, it is of practical significance to test n_s value in laboratory environment. Generally speaking, the fiber with a higher n_s value in the laboratory environment still has a longer service life in the actual use environment.

V. CONCLUSION

In this paper, the static fatigue parameters of fiber are measured by two-point bending method, and then the influence of high temperature and high humidity environment on the fiber life is studied. Our experiments verify that the increase of ambient temperature and humidity can significantly reduce the fiber life and fatigue parameters. At the same time, the results of temperature cycle experiment show that the fiber life and fatigue parameters are a result of the long-term comprehensive action of various environments in the unsteady environment, and the specific principle needs further study. The experimental results of fiber lifetime comparison under different environmental conditions prove that testing ns value in laboratory environment is of practical significance for evaluating fiber lifetime.

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REFERENCES

[1] Kurkjian C R, Krause J T, Matthewson M J. Strength and Fatigue of Silica Optical Fibers [J]. Journal of Lightwave Technology, 1989, 7(9):1360-1370.

[2] Hakan H, Kapron F P. Use of fatigue measurement for fiber lifetime prediction[J]. SPIE, 1990, 1366:144-156.

[3] Zhu Y N. Theory and method for calculating the lifetime of fiber under stress [J]. Optical Fiber & Electric Cable and Their Applications. 1992, (4):17-19.

[4] Zhu Y N. Fatigue mechanism of high strength silica glass fiber [J]. Optical Fiber & Electric Cable and Their Applications. 1997, (04):3-6, 11.

[5] Bhaumik S. Effect of humidity of drawing environment on dynamic fatigue of high strength optical fiber [J]. Study on optical communicaitons. 2005, (03):49-52.

[6] Matthewson, M.J. Strength-probability-time diagrams using power law and exponential kinetics models for fatigue. [J]. Proceedings of SPIE Photonics Europe, 2006, 6193.

[7] Hu X Z, YU S H. Optical Fiber Performance Measurement [M].Beijing: Electronic Industry Press, 2013.

[8] "Optical fibers - Part 1-33:Measurement methods and test procedures - Stress corrosion susceptibility "[S]. IEC 60793-1-33, Edition 2.0, International Electrotechnical Commission, (August, 2017)

[9] China Communication Standardization Association. Specification for test methods for optical fibres - Part 33: Methods of measurement and test procedures for mechanical properties - stress corrosion sensitivity parameters; CSBN: GB/T 15972.33-2008 [S]. Beijing: Standards Press of China, 2008.

[10] Lu Y Q, Lu Y, Wang J. Influence of high humidity environment on dynamic fatigue of optical fiber [J]. Study on optical communicaitons. 2015(5):29-31

[11] Chen L L, Liu C, Hou J Y. Mechanical reliability and life evaluation of optical fibers[J]. Study on optical communicaitons. 2016(4):36-47

[12] Yu L J, Hu P, Peng L H. Two kinds of Test-Method for fiber Dynamic Fatigue Parameter and Their Difference Analysis [J]. Study on optical communicaitons. 2016(6):39-41.

[13] International electrotechnical commission. 2014. IEC TR 62048 Optical Fibers-Reliability-Power law theory [S].

[14] Yu L J. Study on Reliability and Lifetime of optical fiber machinery [D]. Wuhan: Wuhan Research Institute of Posts and Telecommunications, 2017