Inference of the Optical Fiber Lifetime for Mechanical Reliability

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ABSTRACT Optical fiber communication has found applications in new fields, such as fiber to the home (FTTH) optical interconnection systems and automobile communication systems. In these fields of applications, the mechanical reliability of the optical fiber is important. Since, the inference of the optical fiber lifetime has been usually discussed based on the theory of the mathematical statistics, the discussion becomes complicated. In this paper, we shall provide the statistical strength degradation map for intuitive understanding of the theory.

To avoid the serious *B*-value issue, the lifetime of the fiber has been conventionally inferred by using some approximations of the exact lifetime formula derived by Mitsunaga *et.al.*[8), 9)] However, the approximations are violated in the case of short lifetime with large stress. To avoid the difficulties, we shall develop an alternative approximation method to resolve the problem.

1. INTRODUCTION

In the new fields of the application of the optical fiber communications, such as FTTH with indoor optical wiring, automobile multimedia system and the optical interconnection, the fiber wiring is required to be coiled more compactly than ever. So far, several kinds of the novel optical fibers have been developed to reduce the bending loss [1) to 3)].

If the optical the fiber is used in the long-haul transmission systems, the accumulating transmission loss is large, therefore, the minimum bending radius of the fiber is designed as 30 mm or more to avoid the additional loss in the cable splice boxes (closures). With such loose bending, the mechanical reliability of the optical fibers is not a concern. On the other hand, in the case of the use for wiring, since the transmission distance is short, the allowable bending radius can be small. The combination of the situation, with the development of the novel, low bend-loss optical fibers as mentioned above leads to the wiring with few millimeters of bending radius in the applications. In this case, the mechanical load stress applied to the optical fiber becomes quite large therefore the conventionally neglected failure mode regarding the fracture occurring before the increment of the bending loss, should be a serious problem. This is the reason why we should pay attention to the the discussion of the reliability for the mechanical strength [4)].

The discussion of the mechanical reliability of optical fibers is also necessary for the future long-haul transmission line. Recently, given the dramatic expansion of the transmission capacity, the spatial multiplex transmission systems using the multicore optical fibers have been studied [5), 6)]. Since the mechanical structure of the optical fibers is different from the conventional one, the specific discussion will be necessary.

With respect to the lifetime expectancy of the optical fibers for mechanical strength, the IEC Technical Report (IEC/TR62048)[7)] is often referred as the typical literature. The discussion in this technical report is based on the statistical lifetime theory proposed by Mitsunaga and his colleagues [8), 9)], however the theory is mathematically complicated thus the intuitive discussion seems difficult for the general users.

In this paper, at first, we provide a technique named statistical-strength degradation map, which leads us to the intuitive understanding of the theory of the lifetime statistics of optical fibers [8), 9)]. Using the technique, we show a graphical interpretation of the discussion from Mitsunaga, *et al.*.

Secondly, we consider the *B*-value issue. The formula for the lifetime expectancy which is proposed by Mitsunaga *et. al.*[8)] includes some parameters which must be determined by the experiments. Throughout the many studies in the past, it is recognized that the determination

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of the *B*-value with sufficient accuracy is difficult. For this reason, the approximated formula of $B \to 0$ is conventionally used for the fiber lifetime expectancy. Depending on the degree of approximations, the conventional approximated formulae[8), 9)] are classified. The approximated formulae derived by Mitsunaga *et. al.* known as "Mitsunaga's Approximation" is used for the fibers for the long-haul transmission line. And the Griffioen's formula is used for the study of tight bending of the optical fiber used in wiring. We provide a novel approximation method (the parameter approximation) which is used to the exact formula with approximated (non-zero) *B*-value. We compare the above three approximations based on the measured data from the fatigue test on 1,960 pieces of an optical fiber.

In this paper, the expressions of formulae and symbols are as defined in the IEC Technical Report [7)].

2. DEVELOPMENT OF THE STATISTICAL STRENGTH DEGRADATION MAP FOR AN INTUITIVE UNDERSTANDING OF THE THEORY OF LIFETIME

2.1. The Statistical Theory of the Optical Fiber Lifetime

At first, we outline the standard theory for the crack growth in the fibers. It is known that the stress corrosion cracking (SCC) is the physical origin of the crack growth and the fracture of the brittle materials. For simplicity, we solely conceive the type-I fracture that is the traverse fracture through the longitudinal direction of the fiber [10)]. The conventional optical fiber lifetime theory is based on the power-law theory [8), 9)] of crack growth and the Weibull statistics of the inert strength distribution.

According to the power-law theory, the crack growth is governed by the equation $da/dt = K_I^{\,n}$, where *a* is the size of the crack in glass, K_I is the stress intensity factor and *n* is the stress corrosion factor. Here, *t* is time and *A* is the proportional coefficient. This relation is confirmed by the experiments [8), 9)]. K_I increases with the growth of the crack, and the fracture occurs in the case where K_I coincides with the fracture toughness K_{Ic}.

If the strength of the fiber is defined as *S*, K_{Ic} is represented in $K_{Ic} = YSa^{1/2}$ where *Y* is a proportional coefficient and K_I is represented in $K_I = Y\sigma_a{}^{1/2}$ where the load stress is σ.

Using the relations above, the equation of the crack growth is rewritten as the equation of the strength degradation as follows:.

$$\frac{dS^{n\text{-}2}(t)}{dt} = \frac{\sigma^n(t)}{B}, \tag{1}$$

Here, $B=2/\{AY^2(n\text{-}2)K_{Ic}{}^{n\text{-}2}\}$ is called the *B*-value. The equation (1) represents the deterministic nature. If the values of *n* and *B* are determined by measurements, the temporal degradation of the strength $S(t)$ under load stress $\sigma(t)$ can be calculated by using the initial strength $S(0)$ at $t=0$. In this case, the condition of the fracture $K_I = K_{Ic}$ is rewritten as $S(t) = \sigma(t)$ and the time taken to the fracture is called the fiber lifetime. Figure 1 shows the conceptual schematic of the process of the fatigue fracture of the brittle materials according to the power-low theory using the conventional strength degradation map[11)]. In the map, the horizontal axis represents the elapsed time and the vertical axis represents the stress or strength. $t = t_c$ in the Figure 1(b) corresponds to the lifetime.

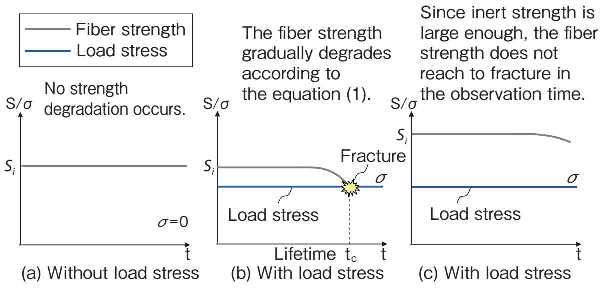

Figure 1 Conceptual schematic of the process of the fatigue fracture of the brittle materials according to the Power-Low theory using the strength degradation map.

It is apparent that the optical fiber lifetime strongly depends on the initial condition $S_i = S(0)$, however, the destructive inspection is necessary to know S_i. It implies that we cannot exactly know the lifetime of particular products. This leads us to, the probabilistic discussion. The strengths of the optical fibers, which are manufactured from the same materials and the same process, are assumed as belonging to the same population. The probabilistic distribution of the population is estimated by fatigue tests from a random sampling. From the past studies, it is known that the strength distribution of optical fibers can be described by the Weibull distribution [8), 13)], The set of "formulae" for lifetime statistics is derived by combining the power-law theory of the fracture and the Weibull distribution of inert strength [7)].

That is, if each failure probability *F* is defined as $F=1-\exp(-H)$, the cumulative hazard function[12)] *H* becomes as following.

- The initial strength distribution of optical fiber (Weibull distribution)

$$H_i(S_i) = \frac{L}{L_0}\left(\frac{S_i}{S_0}\right)^m, \tag{2}$$

- The strength distribution after screening by prooftest

$$H_p(S_p) = \frac{L}{\beta^{m_s}}\left\{(BS_p^{n\text{-}2} + \sigma_p^n t_p)^{m_s} - (\sigma_p^n t_p + BS_{p\min}^{n\text{-}2})^{m_s}\right\}, \tag{3}$$

- The lifetime distribution

$$H(t_{fp},\sigma_a) = \frac{L}{\beta^{m_s}}\left\{\left[\sigma_a^n\left(t_{fp} + \frac{B}{\sigma_a^2}\right) + \sigma_p^n t_p\right]^{m_s} - (\sigma_p^n t_p + BS_{p\min}^{n\text{-}2})^{m_s}\right\}, \tag{4}$$

Here H is the cumulative hazard function [12] and is related to the failure probability by the relation $F=1-\exp(-H)$. Since the failure probability needs to be in the range of $0 \leqq F \leqq 1$, $H \geqq 0$ is required.

In the formula (2), L_0 is called the gauge length, m and S_0 represents the shape parameter and the effective scale parameter of the Weibull distribution respectively.

The formula (3) represents the strength distribution of an optical fiber that passed the screening test of strength S_p.

$S_{p\min}$ is the minimum strength of the optical fiber. $m_s=m/(n-2)$ and $\beta=BS_0^{n-2}L_0^{1/ms}$. It was pointed by Miyajima and Tachikura that the fiber parameter k is essential in the theory [4), 14)]. According to the IEC Technical Report expression, the parameter k corresponds to β in the above formula, σ_p is the proof stress which is the maximum value of the stress applied at the prooftest. t_p is the proof time in which the proof stress σ_p is effectively applied during the test.

Eq. (4) is the commonly used formula and provides the failure probability F after the time t_{fp} is elapsed under the load of the application σ_a. These are the typical theories of lifetime statistics, however, given in mathematically complicated form, and it is difficult to see the physical meaning intuitively.

2.2. Graphical Interpretation of the Theory Using Statistical-Strength Degradation Map

In this section, we attempt a visualization of the physical contents of the formulae (2) to (4) by introducing the statistical-strength degradation map which is the statistical extension of the conventional strength degradation map of Figure 1. Here, the initial strength is assumed to be the same as its inert strength. To visualize the theory, we represent the probability distribution of the initial strength in the strength degradation map. In this paper, we refer to the map made in such way as the statistical strength-degradation map and its conceptual schematic is shown in Figure 2.

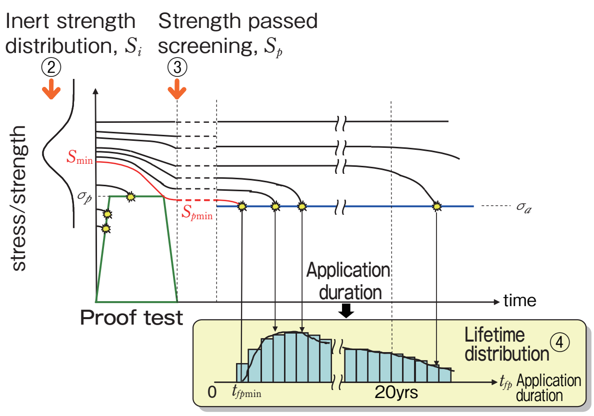

Figure 2 **Conceptual Schematic of the statistical meanings of the lifetime distribution using the statistical strength degradation map.**

The horizontal axis in Figure 2 represents the elapsed time from the drawing of the optical fiber and the vertical axis represents the strength or the load stress of the optical fiber. The initial strength distribution of optical fiber represented by formula (2) is shown on the extreme left in Figure 2. This can be interpreted as the probability of the existence of the inert strength of one optical fiber with length L or as the fiber strength distribution of a manufactured lot of optical fibers. For the screening, the drawn optical fiber is forced to be examined through the prooftest. This prooftest stress profile is shown as the trapezoidal shape which consists of the processes of load, dwell, and unload. Under the stresses, the optical fiber strength degrades according to the formula (1) of the power-law theory and the relatively weak parts of the optical fiber fractures at the point where $S(t)=\sigma(t)$. Since the portions of the optical fiber with large strength have no fracture, they survive, and passes the screening. The red line in the map shows the minimum strength of the optical fibers that passed through the screening. Since the strength degrades during the process, the minimum strength $S_{p\min}$ is smaller than the corresponding initial strength $S_{\min}$. It should be remarked that the fiber is also fatigued during the unloading process, therefore generally $S_{p\min} < \sigma_p$. If the fatigue during the unloading process is large and the $S_{p\min}$ is much smaller than the proof stress σ_p, the unexpectedly weak optical fiber will be admitted to the field. In this case, the proof test is inappropriate. The design of the appropriate prooftest condition was precisely studied by Mitsunaga, *et.al.* [8)]. They found the condition of $\alpha=\sigma_p^2 t_u/((n-2)B)<1$ for appropriate prooftest, with t_u as unloading time.

The strength distribution of the optical fiber which passed the screening is the strength distribution at the point shown as ③ in Figure 2 and is represented by the formula (3). These optical fibers are weakened in accordance to the Eq. (1) under the load stress σ_a in the field. The fiber is fractured at the point where $S(t_{fp})=\sigma_a$. The failure probability in operation is calculated by the Baye's formula considering the optical fiber which passed screening as a new population. In accordance with the initial strength distribution, the lifetime is also distributed probabilistically as shown in the lower right ④ of Figure 2. This corresponds to the lifetime probability distribution of the formula (4). As shown in the schematic, the no failure time $t_{fp\min}$ exists in association with the existence of the finite minimum strength $S_{p\min}$.

The above schematic discussion is exactly the same as the original theory of the lifetime statistics. By using only the formula (1) of the strength degradation and the Weibull distribution (2), we could provide the more intuitive interpretation of the theory from Mitsunaga *et. al.* [8)] (or equivalently IEC/TR62048).

2.3. High Strength Region and Low Strength Region of the Fiber

The Weibull plot of the strength distribution is shown in Figure 3. The results was obtained by the tensile test which we have examined on 1,960 pieces of the 10m-length optical fiber.

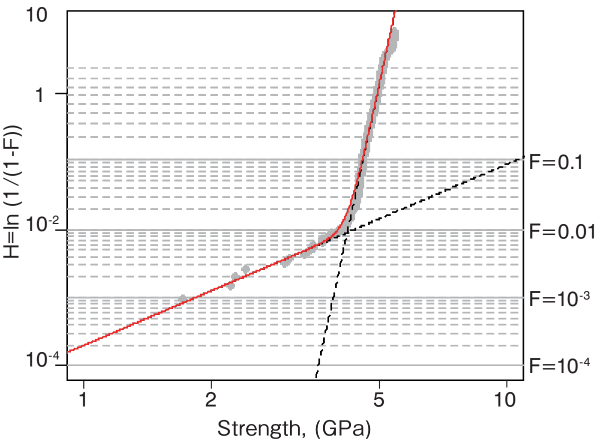

Figure 3 Weibull plot of the tension test on the 1,960 fibers.

From the result of Figure 3, it is found that the strength distribution of the optical fiber in practice is not a simple Weibull distribution but it consists of two Weibull distributions. The high strength region is the inherent strength of glass and the low strength region is attributed to defects in the optical fiber or cracks developed at manufacturing [8), 13)]. In spite of the complex fact, it is not necessary to change the discussion of the lifetime statistics except for rewriting the initial strength distribution to the extended distribution shown in ② of Figure 2. Concretely, we conceive the whole cumulative Weibull hazard $H=H_1+H_2$ where H_1 and H_2 are the cumulative Weibull hazard of the high strength region and low strength region respectively.

3. THE LIFETIME FORMULAE WITH AVOIDING THE B-VALUE ISSUE AND THEIR COMPARISON

3.1. The B-value Issue and Approximated Formulae with $B\to 0$

Since the B-value is related to the inert strength, to estimate this parameter, the tensile test should be examined in an ambient of liquid nitrogen or in an extremely high speed. It is known that in spite of the efforts by many researchers, the reported B-value of the conventional single-mode fibers vary in the range of eight-digit as $2\times 10^{-8}\mathrm{GPa}^2\cdot \mathrm{s}\leqq B\leqq 0.5\ \mathrm{GPa}^2\cdot \mathrm{s}$. This is known as the B-value issue[17)]. To avoid the issue, the approximate equation of $B\to 0$ is conventionally used instead of the exact lifetime formula (4). Depending on the degree of approximations, there are two types of approximations: the Griffioen's formula and the Mitsunaga's approximation.

The cumulative hazard of the Griffioen's formula is given as follows [4), 16)].

High strength region

$$H_1=\frac{L}{L_0}\left(\frac{\sigma_a^n t_{fp}}{BS_{01}^{n-2}}\right)^{m_{s1}}=\frac{L}{\beta_1^{m_{s1}}}(\sigma_a^n t_{fp})^{m_{s1}}, \quad (5)$$

Low strength region

$$H_2=N_pL\left\{\left(\frac{\sigma_a^n t_{fp}}{\sigma_p^n t_p}+1\right)^{m_{s2}}-1\right\}=\frac{L}{\beta_2^{m_{s2}}}\left\{(\sigma_a^n t_{fp}+\sigma_p^n t_p)^{m_{s2}}-(\sigma_p^n t_p)^{m_{s2}}\right\} \quad (6)$$

Here, $m_{s1}=m_1/(n\text{-}2)$ and $m_{s2}=m_2/(n\text{-}2)$. The two regions correspond to the two strength distributions which compose the Weibull distribution. S_{01} appearing in the formula (5) is the Weibull effective scale parameter of the high strength region. N_p is the break rate and the value which represents the number of fiber fractures per unit length during the prooftest. The Griffioen's formula (6) for the low strength region is usually understood as the approximation as $B\to 0$ in the formula (4) but it could be also interpreted as the approximation for the case when $S_{p\min}\to 0$ and the fatigue in operation $\sigma_a^n t_{fp}$ is sufficiently large. Likewise, the formula (5) is almost the same form as the eq. (6) with the subscript of the parameters changed from 2 to 1 and also $\sigma_p^n t_p\to 0$, and it is assumed that the high strength region is subjected to a small fatigue from the prooftest. It is an appropriate assumption, considering that the prooftest as the test that removes the defect part at the manufacturing. If the parameters except B, such as n, β_1, β_2, m_{s1}, and m_{s2}, are determined from the experiments, it is possible to infer the lifetime prediction by the Griffioen's formula. In fact the n-value is determined from the dynamic fatigue tests and the other parameters are defined from the tensile test as shown in Figure 3 [7)].

It is known that the Mitsunaga's approximation is the approximation of the low strength region and is derived from the eq.(6) of the Griffioen's formula by assuming the fatigue in operation is sufficiently small, that is, the formula (7) as $\sigma_a^n t_{fp} << \sigma_p^n t_p$ in the formula (6).

$$H=H_2=m_{s2}N_pL\frac{\sigma_a^n t_{fp}}{\sigma_p^n t_p}, \quad (7)$$

Since the Griffioen's formula is the approximation in the case where $\sigma_a^n t_{fp}$ is large, the approximation will be violated if the time t_{fp} is short even if σ_a is large. Usually, the discussion for the lifetime expectation of the optical fiber is used for evaluating the lifetime after the optical fiber installation for a period duration over 10 years. On the other hand, considering the fracture during fiber assembly operation, the lifetime expectancy during short period of assembly operation is necessary. In this case, as discussed above, the Griffioen's formula will not be applicable. This is the serious problem of the conventional approximation of $B\to 0$.

3.2. Introduction of the Parameter Approximation

We will provide an alternative approximation method to resolve the problem associated with the approximation $B\to 0$. As discussed in the section 2.2, the condition of the appropriate prooftest is given by $\alpha=\sigma_p^2 t_u/((n\text{-}2)B)<1$. Using this relation, the lower limit for B-value can be derived as follows:

$$B = B_{min} = \frac{\sigma_p^2 t_u}{n\text{-}2}, \qquad (8)$$

According to the studies by Mitsunaga and colleagues, the lifetime formula (4) indicates that the more the B-value becomes large, the more the estimated failure probability becomes as small [8), 9)]. So the lifetime expectancy with large safety factor is achieved when using approximate value of $B=B_{min}$ together with the exact formula. The accuracy of the approximation is improved compared to the approximation $B \rightarrow 0$. In using the exact formula, σ_a and t_{fp} will have no limitation for the domain of applicability.

3.3. The Lifetime Expectancy of the Optical Fiber and Comparison of Each Approximations

In this section, we discuss the lifetime expectancy using the parameters evaluated from the actual test of optical fibers. Using the method mentioned in the section 3.1, we evaluated the parameters required for the calculation of the lifetime formula from the test result. Using these parameters, the failure probability is calculated. In general, we wish to know the followings. The first (a) is the allowable load stress(or equivalently the bending radius) in the operation that does not have a fiber fracture until a specified lifetime. The second (b) is the time until the fracture occurs with a specified load stress for the application.

$$\sigma(R) = E_0 \frac{a_f}{R_0}\left(1 + \frac{9a_f}{4R}\right), \qquad (9)$$

Here, the bending stress formula (9) represents the effective maximum stress and for the sake of calculation, the effective length is used instead of the actual practical fiber length[7)]. In eq. (9), E_0 is the Young's modulus of the optical fiber, a_f is the radius of the glass region of the optical fiber and R is the bending radius.

Figure 4 shows the comparison of the inferred failure probabilities with respect to the bending radius R after time in the operation t_{fp}=over 15 years. We assume the optical fiber has 2.5 turns of the bend around each radius. As discussed in section 3.1, the Mitsunaga's approximation shown in dark solid line coincides with to the Griffioen's formula (dashed blue line) when the stress is small in the application as R is about 15 mm. On the other hand, the difference between parameter approximation (red solid line) and the Griffioen's formula appears in case $R>R_{max}$~16 mm. In this region, the failure probability of the parameter approximation becomes F=0. The smaller the load in the application σ_a becomes, the longer the no failure time t_{fpmin} shown in section 2.2 becomes. The facts lead us to the result that the radius $R=R_{max}$ which satisfies t_{fpmin}=15 years exists. In other words, the failure probability becomes zero with bending stress of $R>R_{max}$ during the 15 years operation time.

In the region where the $\sigma_a^n t_{fp}$ is large, the Griffioen's formula coincide with the parameter approximation. It is found that the high strength region is dominant up to $R<2.4$ mm. In this region, since the part of optical fiber is short, and the probability that cracks and others caused by manufacturing exist in the bending section becomes low. On the other hand, the increase of the load stress makes the fracture of glass (in the high strength region) dominant. The above characteristics are the particulars when considering the tight bending radius as shown in the Tomita and Kurashima's result[3)]. If the required failure rate is about 0.1 FIT, the minimum bending radius is defined at the high strength section.

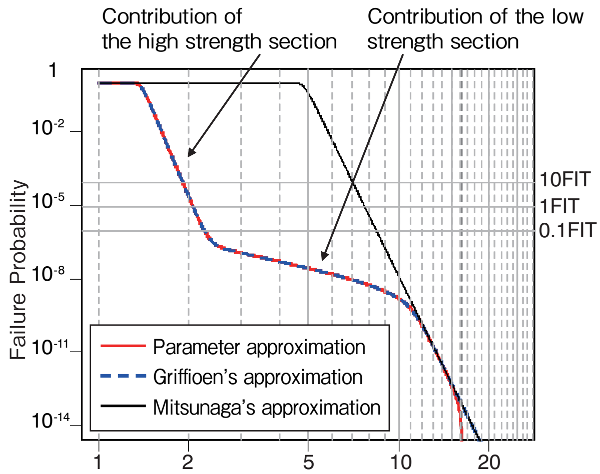

Figure 4 Inferred relations between the bend radius and the failure probability after 15 years in the application.

The results of the failure probability calculation for some proof-strain ε_p($\varepsilon_p = \sigma_p/E_0$) values are shown in Figure 5. When the required failure rate is assumed about 0.1FIT or more, the large proof strain is not significant for the assurance of the mechanical reliability of the fiber. This result is consistent with the result in the literature [3)].

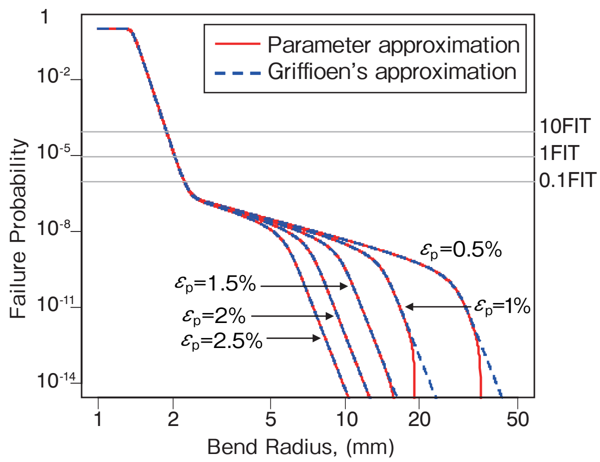

Figure 5 Inferred results of the failure probability after 15 years in the application. 2.5-turn bending around the bend radius is considered. Some proof-strain cases are shown.

The results about (b) in the section 3.3 are shown in Figure 6 and 7. These are the results with 2.5 turns of bending with radius R=6 mm. As discussed at the end of section 3.1, the difference of Griffioen's formula and the parameter approximation is large if the short time in the field t_{fp} is short as t_{fp} is about 3days. The difference in the failure probability seems small, however it appears as large in the discussion about failure rate. From this result, it is considered that using Griffioen's formula for the discussion of the failure rate in short-time, such as fiber assembly operation or cable installation underestimates the lifetime of the fiber, and possibility influences the design of the process or the products including optical fibers.

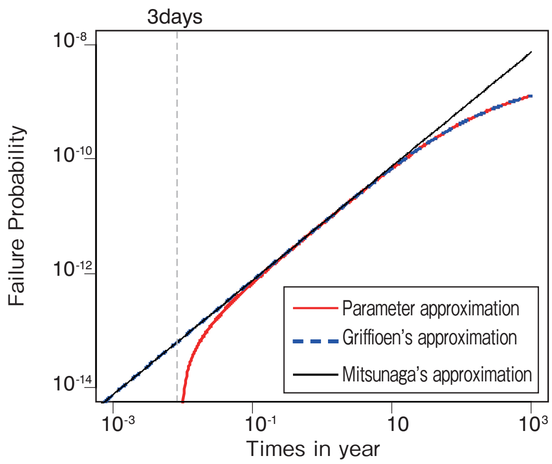

Figure 6 Inference of the temporal growth of the failure probability under the condition of the 2.5-turn bending of the bend radius *R*=6 mm.

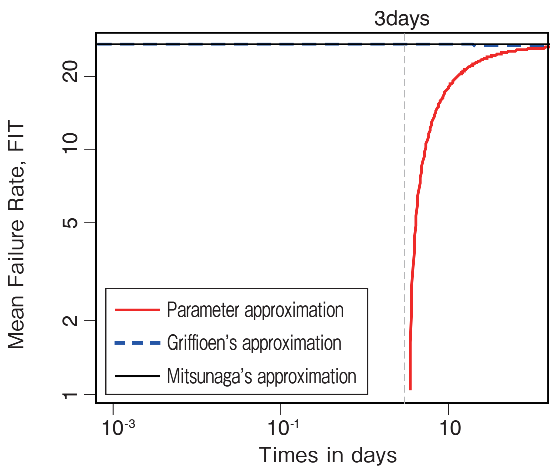

Figure 7 Inference of the temporal growth of the mean failure rate under the condition of the 2.5-turn bending of the bend radius *R*=6 mm.

4. CONCLUSION

We shall summarize the discussion of this paper. First, in Chapter 2, we provided the statistical strength degradation map for the intuitive understanding of the theory of the lifetime statistics. The statistical strength-degradation map would enable us to see intuitively, not only the result of the lifetime statistics but also the processes to the failure without using mathematics. In Chapter 3, we explained that the difficulties of the B-value issue, and the Mitsunaga's approximation and the Griffioen's formula were introduced to avoid this problem. And then, from the condition of no over-fatigue during unloading at the proof-test, we provided a novel parametric approximation method where the appropriate B-value is evaluated by $B=B_{min}$.

Also, in the discussion of the lifetime reliability in short-time which ensures the reliability during the optical fiber installation, there is a possibility of underestimation of the reliability when using the Griffioen's formula. It becomes more pronounced especially at the discussion using the failure rate. In such case, it can be considered that the parametric approximation is effective.

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