

Optical fibres — Reliability — Power law theory

ICS 33.180.10

National foreword

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**Optical fibres –
Reliability –
Power law theory**



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OPTICAL FIBRES – RELIABILITY – POWER LAW THEORY

FOREWORD

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IEC 62048, which is a technical report, has been prepared by subcommittee 86A: Fibres and cables, of IEC technical committee 86: Fibre optics.

The text of this technical report is based on the following documents:

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86A/611/CDV	86A/660/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

This document which is purely informative is not to be regarded as an International Standard.

The committee has decided that the contents of this publication will remain unchanged until 2005. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

OPTICAL FIBRES – RELIABILITY – POWER LAW THEORY

1 Scope

This is a guideline technical report that gives formulae to estimate the reliability of fibre under a constant service stress. It is based on a power law for crack growth which is derived empirically, but there are other laws which have a more physical basis (for example, the exponential law). All these laws generally fit short-term experimental data well but lead to different long-term predictions. The power law has been selected as a most reasonable representation of fatigue behaviour, by the experts of several standard-formulating bodies.

Reliability is expressed as an expected lifetime or as an expected failure rate. The results can not be used for specifications or for the comparison of the quality of different fibres. The document develops the theory behind the experimental principles used in measuring the fibre parameters needed in the reliability formulae. Much of the theory is taken from the referenced literature and is presented here in a unified manner. The primary results are formulae for lifetime or for failure rate, given in terms of the measurable parameters. Conversely, an allowed maximum service stress or extreme value of another parameter may be calculated for an acceptable lifetime or failure rate.

For readers interested only in the final results of this technical report – a summary of the formulae used and numerical examples in the calculation of fibre reliability – clauses 5 and 6 are sufficient and self-contained. Readers wanting a detailed background with algebraic derivations will find this in clauses 7 to 12. An attempt is made to unify the approach and the notation to make it easier for the reader to follow the theory. Also, it should ensure that the notation is consistent in all test procedures. Clause 13 has a limited set of mostly theoretical references, but it is not necessary to read them to follow the analytical development in this technical report.

NOTE Clauses 7 to 11 reference the B -value, and this is done for theoretical completeness only. There are as yet no agreed methods for measuring B , so clause 12 gives only a brief analytical outline of some proposed methods, and furthermore develops theoretical results for the special case in which β can be neglected.

2 List of symbols

The symbols are listed mostly in alphabetical order, within the Latin and the Greek alphabets. The symbol is first defined in the subclause (clauses 7 to 11) indicated.

NOTE The remark "dim" means dimensionless.

Symbol	Unit	Name	Clause and subclause
A	μm	Flaw depth	7.1
a_f	"	Radius of glass fibre	10.2
B	$\text{GPa}^2 \cdot \text{s}$	Crack strength preservation parameter or B -value	7.1
B_0	"	Transitional B -value at the slow-unloading/fast-unloading boundary	9.3
c	Dim	Non-linearity term for stress versus strain	7.4
C	"	Additive dimensionless proof test term or C -value	10.5
C_0	"	Transitional value of C at the slow-unloading/fast-unloading boundary	10.5
D	mm	Fibre-axe separation in two-point bending	10.2.3
E	GPa	Young's modulus	7.4
E_0	GPa	Zero-stress Young's modulus	7.4
F	dim	Fibre failure probability	11.1
$K_I(t)$	$\text{GPa} \cdot \mu\text{m}^{1/2}$	Stress intensity factor	7.1
$K_{Ic}(t)$	$\text{GPa} \cdot \mu\text{m}^{1/2}$	Critical stress intensity factor	7.1
L	μm to km	Fibre effective length under uniform stress, or equivalent tensile length	10.1.1
L_b	μm to km	Fibre length in uniform bend	10.2.2
L_p	km	Mean survival length, or survival length, during proof testing	10.5
L_0	km	Gauge length, reference length	10.1.1
m	dim	"Inert" Weibull parameter or m -value	10.1.1
m_d	dim	m -value under dynamic fatigue	10.4
m_s	dim	m -value under static fatigue	10.3
n	dim	Stress corrosion susceptibility parameter or n -value	10.1
N_p	km^{-1}	Mean breakrate per unit length during proof testing	10.5
$N(S)$	km^{-1}	Flaws per unit length not exceeding inert strength S	10.1.1
P	dim	Fibre survival probability	10.1.1
P_p	dim	Fibre survival probability after proof testing	10.5
R	mm , m	Fibre bend radius	10.2.2
$S(t)$	GPa	"Inert" strength of a crack	7.1
S_p	GPa	Strength after proof testing	9.2
$S_{p\min}$	GPa	Minimum strength after proof testing	9.3
S_0	GPa	Weibull gauge strength	10.1.1
t	s to year	Variable of time	7.1
t_d	s to year	Time to failure under dynamic fatigue, or proof testing dwelltime	8.2.1, 9.1
t_f	s to year	Lifetime (time to failure) under constant stress or static fatigue testing	7.2, 8.1
t_{fp}	s to year	Lifetime after proof testing	10.7
$t_{fp\min}$	s to year	Minimum lifetime for certain survival after proof testing	10.7
$t_f(1)$	---	Intercept on a static fatigue plot	8.1
t_l	Ms	Proof test loadtime	9.1
t_p	Ms	Effective proof time	9.2

Symbol	Unit	Name	Clause and subclause
t_u	Ms	Proof test unload time	9.1
t_0		Static Weibull time-scaling parameter	10.3
V	$\mu\text{m/s}$	Crack growth velocity	7.1
V_C	$\mu\text{m/s}$	Critical crack growth velocity	7.1
x	dim	Factor relating bend length to equivalent tensile length	10.2.2
Y	dim	Crack geometry shape parameter	7.1
α	dim	Ratio of proof test unload parameters to crack parameters	9.3
β	$\text{GPa}^n \cdot \text{s} \cdot \text{km}^{(n-2)}$	Weibull β -value	10.3, 10.4
ϵ	dim	Strain corresponding to a particular stress	7.4
λ_i	$\text{km}^{-1} \cdot \text{yr}^{-1}$	Breaks/length-time (instantaneous failure rate)	11.1
λ_a	$\text{km}^{-1} \cdot \text{yr}^{-1}$	Averaged failure rate	11.2
$\sigma(t)$	GPa	Stress applied to a crack	7.1
σ_a	GPa	Applied stress under static fatigue testing and lifetime	8.1, 11.2
$\dot{\sigma}_a$	GPa/s	Applied stress rate under dynamic fatigue testing	8.2.1
σ_f	GPa	Failure stress under dynamic fatigue testing, without proof testing	8.2.1
σ_{fp}	GPa	Failure stress after proof testing	10.7
$\sigma_{fp\min}$	GPa	Minimum failure stress after proof testing	10.7
$\sigma_f(1)$	---	Intercept on a dynamic fatigue plot	8.2.1
σ_p	GPa	Proof test stress	9.1
σ_0	GPa	Dynamic Weibull stress-scaling parameter	10.4

3 General approach

First, the equivalence of the growth of an individual crack and its associated weakening is shown. This is related to applied stress or strain as an arbitrary function of time. Applied stress can be taken to fracture, from which the lifetime of the crack is calculated. Next, the destructive tests of static and dynamic fatigue are reviewed, along with their relationship to each other. These tests measure parameters useful in the theory. This also shows the difference between "inert" strength and "dynamic" strength.

The above single-crack theory is then extended to a statistical distribution of many cracks. This is done in terms of a survival (or failure) Weibull probability distribution in strength. It can allow for several deployment geometries in testing and service. The inert distribution and the distributions obtained by static or dynamic fatigue testing are derived for before and after proof testing. The latter is sometimes done with approximations that may not require knowing the B -value explicitly. Finally, the various parameters measured by the above testing are related to formulas for fibre reliability, that is, lifetime and failure rate.

Some of the main assumptions in the development are as indicated below.

- The relationship between the stress intensity factor, applied stress, and flaw size is given by equation (7.1.1), while at fracture the relationship between the critical stress intensity factor, strength, and flaw depth is given by equation (7.1.2).

- The crack growth velocity is related to the stress intensity factor by equation (7.1.4).
- The Weibull distribution of stress (before any prooftesting) is unimodal according to equations (10.1.5) and (10.1.6) or bimodal according to equation (10.1.11). The (m, S_0) pair appropriate to the desired survival probability level and length must be used. Deployment lengths will differ upon the application such as fibre on reels, in cable, splice trays, or within a connector or other component. Because of the low failure probabilities desired, however, the low-strength extrinsic mode must usually be used.
- The values of the fatigue parameters, both static and dynamic, depend upon the fibre environment, fibre ageing, and fibre preconditioning prior to testing. In theory, they are taken to be independent of time, so that some engineering judgement is needed to decide the practical values to be used in the calculations. This also implies that the corresponding static and dynamic parameters equal each other (for the same environment and time duration).
- Zero-stress ageing is not accounted for. Since the above parameters are independent of time, the strength decreases due only to stress fatigue following the power law according to 7.1.

4 Formula types

The formulae utilize parameters obtained from fatigue testing-to-failure, and from prooftesting with potential random failures. In the service condition of interest, a fibre of effective length L (dependent upon deployment geometry) is subjected to a constant applied service stress that does not change with time. (This stress is tensile, including bending stress. Torsional or compressive stresses are not covered.) The lifetime as a function of failure probability or failure rate as a function of time are given.

The formulae assume a Weibull distribution with parameters that vary among fibre types and perhaps among fibres of the same type. Moreover, they change with environment and applied stress levels. The Weibull distribution may have several nominally linear terms depending upon several levels of flaw strength. It is important that the Weibull parameters for the term of interest be used in the formulae. These are obtained from fatigue measurements. Generally, the low-strength region near the proofstress and below is of interest, and measurements must be on long fibre gauge lengths and with many samples so that the total fibre length tested is large. Parameters measured for a small number of short samples, characterizing the high-strength region, will differ from the preceding ones. They must not be used in the formulae to extrapolate to lower-strength lower-probability regions.

Within the above power-law assumptions, the equations of clauses 7 to 11 are algebraically "exact". However, in some applications, certain terms may be negligible, and more approximate and simpler algebraic equations are given in clause 12. This has the advantage that the B -value, for which there is yet no standard test method and which has been reported to span several orders of magnitude, is not required.

Even with these formulae, there is no assured way of accurately predicting fibre reliability. Some fibres may break before the most conservative of predictions, while others may last longer than the most pessimistic of predictions. After fibre manufacture, fatigue or damage may

occur due to cabling, installation, or operation; this usually cannot be accounted for in the theory. A start on estimating these effects could be made by measuring the parameters of fibres after each of these stages, but this is not commonly done.

All the equations are numbered by three digits; the first two correspond to the two digits from the subclause (for example, 5.1 for subclause 5.1), and the third is the order of the equation within the subclause (for example, equation (5.1.6) will be the sixth equation which appears in subclause 5.1. For convenience in assisting the reader to find the derivations, if desired, the formulae summarized in clauses 5 and 6 include the indication in brackets of the equations listed in clauses 7 to 12. However, it is not necessary to refer to the derivations to be able to follow clauses 5 and 6.

5 Measuring parameters for fibre reliability

This clause outlines how the parameters in the reliability (lifetime and failure rate) equations are obtained in the approximation of the small B -value. Proof test parameters are obtained from testing the full length of fibre to be deployed. By contrast, both static and dynamic fatigue procedures use many short-length test samples. These are used to obtain "linear" Weibull plots of the cumulative failure probability F scaled as $\ln\ln\frac{1}{P}$ (where $P = 1 - F$ is the survival probability) versus the $\ln$ of a suitable variable (failure time or failure stress). For situations in which the plot may be fitted to two or more straight line parts, that part closest to the anticipated service stress should be used in obtaining the needed parameters.

5.1 Length and equivalent length

The testing and service geometries may differ from each other. The symbol L_0 is the gauge length in static or dynamic fatigue testing, whereas L is the in-service length subjected to constant applied service stress. The gauge length equals the actual length only for the case of longitudinal tension. Other geometries require equivalent lengths.

For uniform bending (for example, mandrel wrap), the in-service bend length L_b is replaced by an equivalent in-service tensile length L given by

$$L \approx 0,4 \frac{L_b}{\sqrt{x}} \quad (10.2.6)$$

The same relationship holds between the gauge bend length L_{b0} and the equivalent gauge length L_0 . In this equation there is the factor

$$x = \frac{mn}{n-2} = m_s n = \frac{m_d n}{n+1} \quad (10.2.7)$$

using inert, static fatigue, and dynamic fatigue parameters, respectively, as obtained below.

For two-point bending, the equivalent length depends upon the applied stress in a complex way. Computation of the equivalent in-service length for an arbitrary applied service stress is difficult. The equivalent gauge length is approximately 10 μm to 30 μm , depending upon the failure stress.

5.2 Reliability parameters

This subclause outlines methods that are commonly used to derive these parameters.

5.2.1 Proof testing

- Obtain the composite proof test parameter $\sigma_p^n t_p$, where σ_p is the actual proof test stress during dwell, and n is the stress-corrosion susceptibility parameter (or n -value). The effective proof time is given by

$$t_p = t_d + \frac{t_l + t_u}{n + 1} \quad (9.2.2)$$

obtained from the load time t_l , the dwell time t_d , and the unload time t_u .

- (Optional): If from proof testing the mean number of breaks N_p per length or the mean survival length L_p during proof testing is known, calculate

$$\beta = \frac{\sigma_p^n t_p}{N_p^{\frac{n-2}{m}}} = \sigma_p^n t_p L_p^{\frac{n-2}{m}} \quad (12.1.12)$$

where

$$\frac{m}{n-2} = m_s = \frac{m_d}{n+1} \quad (12.1.13)$$

If this is not possible, obtain β as a fit parameter in 5.2.2, 5.2.3, or 5.3.

5.2.2 Static fatigue

- Obtain the static Weibull plot of scaled probability versus $\ln$ of failure times t_f for any particular constant applied stress σ_a :

$$\ln \frac{1}{P_p(t_f)} = \left[(t_f \sigma_a^n + t_p \sigma_p^n)^{m_s} - (t_p \sigma_p^n)^{m_s} \right] \frac{L}{\beta^{m_s}} \quad (12.1.14)$$

Determine parameters m_s and β from the characteristics of the plot.

- Obtain the best-fit straight line to the $\ln$ of failure times versus the $\ln$ of applied stresses:

$$\log t_f(\sigma_a) \approx \log t_f(1) - n \log \sigma_a \quad (8.1.4)$$

Measure the static stress-corrosion susceptibility parameter as the negative slope $-n$ of this line. The term $t_f(1)$ is the "intercept" of this line on the ordinate axis, that is, the value of failure time where the applied stress is unity. (This value will depend on the units used, and may require a straight-line extrapolation beyond the data points. It does not have the dimension of time.)

5.2.3 Dynamic fatigue

IEC 60793-1-31¹ describes how to measure both short-length and long-length strength distributions of optical fibres.

- Obtain the dynamic Weibull plot of scaled probability versus $\ln$ of failure stresses σ_f for any particular constant applied stress rate $\dot{\sigma}_a$:

$$\ln \frac{1}{P_p(\sigma_f)} = \left\{ \left[\frac{\sigma_f^{n+1}}{(n+1)\dot{\sigma}_a} + \sigma_p^n t_p \right]^{\frac{m_d}{n+1}} - (\sigma_p^n t_p)^{\frac{m_d}{n+1}} \right\} \frac{L}{\beta^{\frac{m_d}{n+1}}} \quad (12.1.15)$$

Determine parameters m_d and β from the characteristics of the plot.

- Obtain the best-fit straight line to the $\ln$ of failure stresses versus the $\ln$ of applied stress rates:

$$\log \sigma_f(\dot{\sigma}_a) \approx \log \sigma_f(1) + \frac{\log \dot{\sigma}_a}{n+1} \quad (8.2.5)$$

Measure the dynamic stress-corrosion susceptibility parameter from the slope $\frac{1}{n+1}$ of this line.

The term $\sigma_f(1)$ is the "intercept" of this line on the ordinate axis, that is, the value of failure stress where the applied stress rate is unity. (This value will depend on the units used, and may require a straight-line extrapolation beyond the data points. It does not have the dimension of stress.)

5.3 Parameters for the low-strength region

This subclause describes the way to measure the strength distribution at sufficiently low probability to represent the distribution of failure strengths near the proofstress level for the second mode of the Weibull distribution (shown as the extrinsic region in figure 14). Normally, the fibre population has been proofstested once according to clause 9.

NOTE These implementations are used only for characterization and not for specification.

5.3.1 Variable proofstress

This method (briefly mentioned in 9.4) subjects a full length of fibre to a certain proofstress, another length to a higher proofstress, and so on for several increasing levels of proofstress. The mean survival length L_p (or number of breaks N_p per unit length) is counted for each length and stress level. This resembles a static fatigue test in which the failure stress (the proofstress σ_p) varies. However, the failure time does not exceed the fixed prooftime t_p . The n -values are obtained by the fatigue measurements of 5.2.

¹ IEC 60793-1-31:2001, *Optical fibres – Part 1-31: Measurement methods and test procedures – Tensile strength*

First consider the case in which there is no initial proof test at manufacture. From equations (12.1.11) and (12.1.13) one has

$$\ln L_p + m_s(n \ln \sigma_p + \ln t_p - \ln \beta) = 0 \quad (5.3.1)$$

so a logarithmic plot of mean survival length versus proof test stress should be close to a straight line. The slope is $-nm_s$, while the stress and length “intercepts” are $\frac{1}{n}(\ln \beta - \ln t_p)$ and $m_s(\ln t_p - \ln \beta)$, respectively.

In reference [11], fibres with a 400 μm jacket and initial lengths of 10 km to 15 km were used, with five proof strains of 0,8 % to 3,5 %. There was no other initial proof test. Equation (5.3.1) is equivalent to equations (18) to (20) of reference [11] with $C = \beta^{-m_s}$. With a duration time t_d of 1 s, it was found that $nm_s = 2,07$, so that with $n = 20$, one has $m_s = 0,1035$. Also, $m_s \ln t_p + \ln C = -2,09$, so that $\beta^{m_s} = 8,085 \text{ GPa}^{nm_s} \cdot \text{s}^{m_s} \cdot \text{km}$.

More common is the case in which there is an initial proof test at manufacture. If the second proof test stress is significantly above the first, then equation (5.3.1) can still be used.

In reference [12], the proof test stress level at manufacture was not stated. A minimum sample length of 10 km or 20 km was used, and each sample was subjected to a different one of five proof test stress levels between 1 GPa and 4 GPa. The proof test speed was reduced to minimize breakage during the start-up acceleration period, so the duration time t_d was normalized to 1 s using $n = 23$. The failure probabilities F per meter were calculated for each stress and plotted to fit the straight line of the form

$$\ln\left(\frac{1}{1-F}\right) = M \ln \sigma_p + \ln K \quad (5.3.2)$$

With another “ln” on the left (apparently missing), this is equivalent to equation (10.3.2) for static fatigue (ignoring the initial proof testing) if

$$M \equiv nm_s \text{ and } K \equiv \left(\frac{t_d}{\beta}\right)^{m_s} \quad (5.3.3)$$

From this it was determined that $M = 1,69$, so we find $m_s = 0,0735$, and $K = 0,000418$, so that $\beta^{m_s} = 2,392 \text{ GPa}^{nm_s} \cdot \text{s}^{m_s} \cdot \text{km}$.

5.3.2 Dynamic fatigue

This is a form of dynamic testing with censoring, as mentioned in 8.2.2, and with more details on the apparatus given in reference [5].

A specimen is a single gauge length L_0 of fibre. (A recommended gauge length L_0 is longer than 1 m; for example, 10 m to 20 m.) A sample is a group of specimens from a given population of fibres.

Each specimen is loaded to a failure stress σ_f , or, with censoring, to a (non-failing) maximum stress $\sigma_{\max}$ (for example, 2,4 GPa, about 3,2 % strain from equation (7.4.2)). The recommended strain rate $\dot{\sigma}_a$ is fast (for example, greater than 200 %/min, about 2,6 GPa/s, from equation (7.4.1)). The sample size should be large enough to provide an adequate representation of the second Weibull mode (for example, so that 1 km of the total specimens fail).

The following data are recorded:

- the total number of specimens tested: N , whether or not failure occurred;
- the failure stress values of those specimens that failed: σ_{fi} in GPa. Here i is the rank order, sorted by increasing failure stress.
- the stress rate (converted from strain rate): $\dot{\sigma}_a$ in GPa/s.
- the gauge length of the specimens: L_0 in km.

A Weibull plot in the form of figure 1 may also be presented (without the curve fits). The points are measurements from about 0,8 GPa to 2,4 GPa, for an acrylate-coated fused silica fibre with a cladding diameter of 125 μm .

Calculation of Weibull parameters

Here the data of the measurement is analysed. According to equation (10.1.6), the Weibull cumulative probability ordinate scale is of the form

$$\ln \left[\ln \left(\frac{1}{1-F} \right) \right],$$

where $F = 1 - P$ is the cumulative failure probability.

Hence compute

$$w_i = \ln \left[-\ln \left(1 - \frac{i}{N+1} \right) \right] \quad (5.3.4)$$

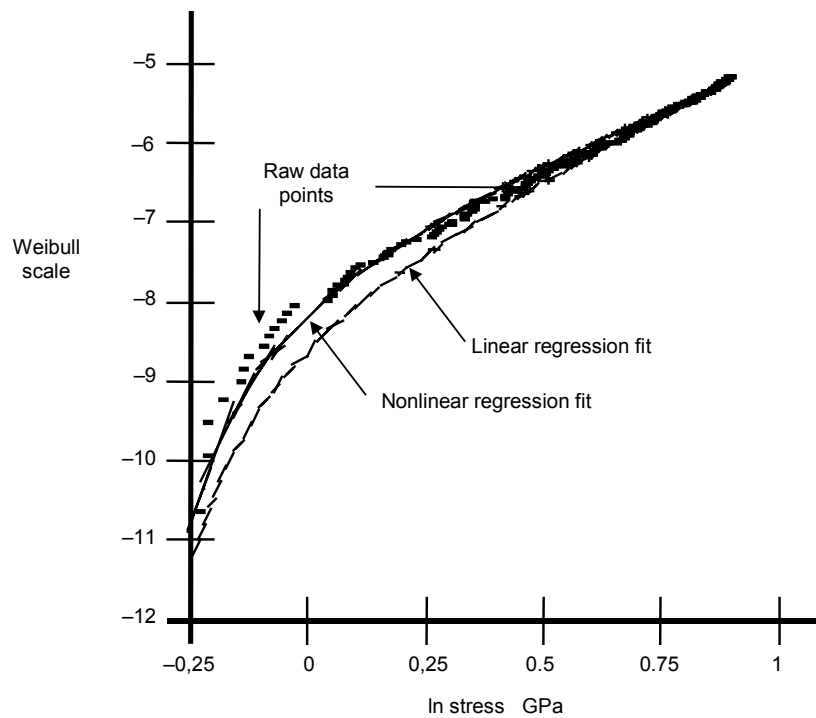


Figure 1 – Weibull dynamic fatigue plot near the proofstress level

Exponentiate this and use a rearranged form of equation (10.7.2):

$$\exp w_i = \frac{\sigma_{fi}^{m_d} L_0}{[\dot{\sigma}_a(n+1)\beta]^{\frac{m_d}{n+1}}} \times \left\{ 1 + \frac{\dot{\sigma}_a(n+1)\sigma_p^n t_p}{\sigma_{fi}^{n+1}} \right]^{\frac{m_d}{n+1}} - \left[\frac{\dot{\sigma}_a(n+1)\sigma_p^n t_p}{\sigma_{fi}^{n+1}} \right]^{\frac{m_d}{n+1}} \right\} \quad (5.3.5)$$

Here the length L becomes the testing gauge length L_0 .

Two fits are used on this equation.

Linear regression fit

For large failure stresses, the term in equation (5.3.5) that is enclosed in curled brackets $\{ \}$ approaches one. The equation approaches the "linear" form of the usual equations (10.4.2) and (10.4.4) without prooftesting:

$$w_i = A + m_d \ln \sigma_{fi} \quad (5.3.6)$$

where

$$\ln \beta = \frac{n+1}{m_d} (\ln L_0 - A) - \ln[(n+1)\dot{\sigma}_a] \quad (5.3.7)$$

Hence for failure stress greater than some selected value, find m_d and A such that the least squares error of w_i is minimized.

This procedure produces the linear regression fit in figure 1. Clearly, it would be better to have a closer fit at the left side of this data set, where the values are closer to the applications of interest.

Non-linear regression fit

This uses lower-stress data, where the curvature is apparent. Given a value of m_d , a value of β is computed for each failure stress, and a value from the middle of the data of interest produces a curve that goes through that area. The result produces a sum of squared errors for the entire curve, and m_d is varied to minimize the sum. The steps are indicated below.

- Define a range of data in which the fit is to be forced. Here it is constructed using $\ln \sigma_{fi}$ values between 0 and 0,5.
- Select a value of m_d .
- Compute $\ln \beta_i$ for each failure stress in the defined region using equation (5.3.5).
- Set $\ln \beta$ equal to the median of the computed $\ln \beta_i$ values.
- Compute $wout_i$ using equation (5.3.5) and the above value of β .
- Compute the squared errors $(w_i - wout_i)^2$, and then compute the sum of squared errors.
- Vary m_d as in the second step, and repeat the remaining steps to minimize the sum.

The procedure produces the non-linear regression fit in figure 1.

5.4 Measured numerical values

In this subclause, experimental values resulting from the measurements of 5.3.2 are obtained. They will be used in the calculations of clause 6.

In 5.2.1, the composite proofstress parameter is $\sigma_p^n t_p = 8,8849 \times 10^{-5} \text{ GPa}^n \cdot \text{s}$, with a nominal proof stress of $\sigma_p = 0,69 \text{ GPa}$ ($\ln \sigma_p = -0,37$ in figure 1). From 5.2.3 $n = 20$ is obtained, and in 5.3.2 the stress rate is $\dot{\sigma}_a = 4,59477 \text{ GPa/s}$ for a gauge length $L_0 = 20 \text{ m}$. The non-linear fit gives

the values $m_d = 2,359$ and $\ln \beta = 25,499$. Note that β has the unit $\text{GPa}^n \cdot \text{s} \cdot \text{km}^{\frac{n+1}{m_d}}$.

The static value will also be needed in the following subclause

$$m_s = \frac{m_d}{n+1} \quad (10.4.8)$$

which according to the above subclause equals 0,11233. Note too that β now has the unit $\text{GPa}^n \cdot \text{s} \cdot \text{km}^{\frac{1}{m_s}}$ and that $\beta^{m_s} = 17,538 \text{ GPa}^{nm_s} \cdot \text{s}^{m_s} \cdot \text{km}$.

The two values are in reasonable agreement with those of 5.3.1.

6 Examples of numerical calculations

The numerical values experimentally obtained in 5.4 are used in the calculations below. The results will be conservative since the explicit B -value is neglected; lower failure rates and longer lifetimes would be obtained if this value were included. (The degree of improvement increases as B increases.) The results of the calculations can be quite sensitive to the choice of parameter values. These values are related to each other, and a change in one parameter will affect the values of other parameters. Ideally, the parameter values should be obtained on the basis of experimentation.

If the failure probability $F = 1 - P$ is 10^{-3} or less (generally the region of practical interest), the term $\ln \frac{1}{P}$ in the formulae below may be replaced by F to an accuracy of 0,5 % or better, but this has not been done in the numerical results given here. Set

$$t_f(\text{sec}) = 31\,577\,600\, t_y(\text{yr}) \quad (11.4.5)$$

Finally, the notation "5,45 E-10" means " $5,45 \times 10^{-10}$ ".

6.1 Failure rate calculations

Compute the failure rates λ that would occur at various static stress levels σ_a as a function of service time t_y in years.

6.1.1 FIT rate formulas

The instantaneous failure rate is

$$\lambda_i(t_f) = 3,6 \times 10^{12} m_s \left(\frac{\sigma_a}{\beta} \right)^{m_s} \left[t_f + t_p \left(\frac{\sigma_p}{\sigma_a} \right)^n \right]^{m_s-1} \quad (12.2.2)$$

The averaged failure rate is

$$\lambda_a(t_f) = \frac{3,6 \times 10^{12}}{t_f L} \left\langle 1 - \exp \left[\left[\left(t_p \sigma_p^n \right)^{m_s} - \left(t_f \sigma_a^n + t_p \sigma_p^n \right)^{m_s} \right] \frac{L}{\beta^{m_s}} \right] \right\rangle \quad (12.2.3)$$

6.1.2 Long lengths in tension

Use several applied stresses, as a fraction of the nominal proofstress, in the above equations for a fibre length $L = 1$ km. As a function of time out to 50 years, these give the instantaneous and averaged failure rate plots of figures 2 and 3, respectively. The corresponding values are given in table 1. (Zero time is avoided because of the singularity shown there of the averaged failure rate.)

Two points are worth noting. First, all the failure rates are almost constant over time, especially at the lower stresses. This indicates an almost linear increase in total cumulative failures with time. Secondly, and because of this, there is little practical difference in the values between the instantaneous and averaged failure rates.

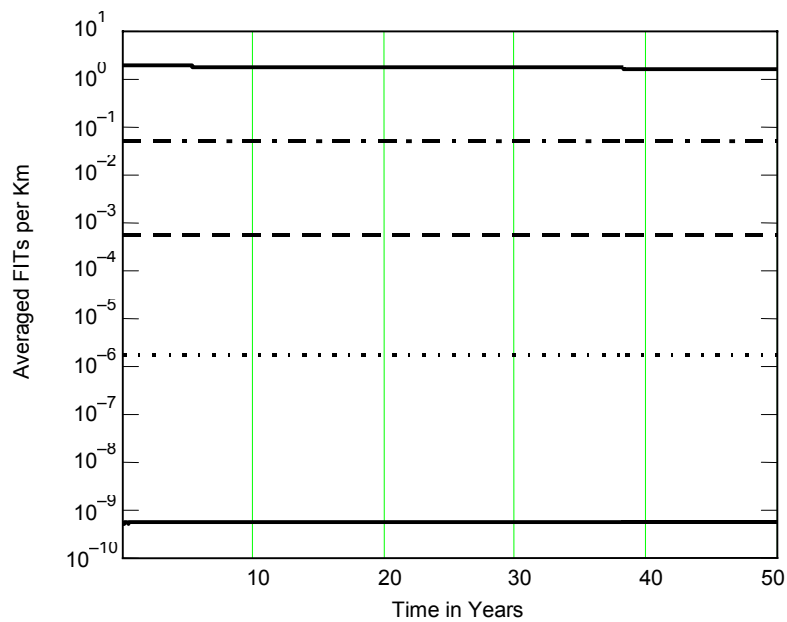


Figure 2 – Instantaneous FIT rates per fibre km versus time for applied stress/proof test stress percentages (bottom to top): 10, 15, 20, 25, 30 %

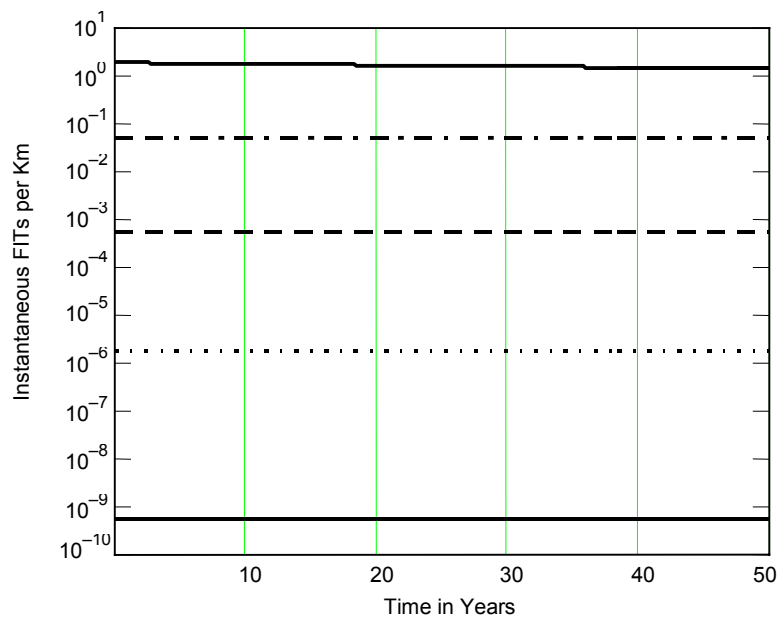


Figure 3 – Averaged FIT rates per fibre km versus time for applied stress/proof test stress percentages (bottom to top): 10, 15, 20, 25, 30 %