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colour
inside

Optical fibres – Reliability – Power law theory

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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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.

This second edition cancels and replaces the first edition published in 2002, and constitutes a technical revision. The main changes with respect to the previous edition are listed below:

- correction to the FIT equation in addition to all call-outs and derivations;
- insertion of a new section explaining how to numerically calculate bends and tension;
- editorial corrections of inconsistencies.

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

Enquiry draft	Report on voting
86A/1357/DTR	86A/1375/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 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
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OPTICAL FIBRES –

Reliability – Power law theory

1 Scope

This technical report provides guidelines and 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 the 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 cannot be used for specifications or for the comparison of the quality of different fibres. This 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 Symbols

Table 1 provides a list of symbols found in this document. Each symbol is first defined in the subclause or paragraph indicated in the final column of the table.

Table 1 – Symbols

Symbol	Unit	Name	Subclause or paragraph
a		Crack size (11.1)	7.1
A	µm	Flaw depth	7.1
a_f	µm	Radius of glass fibre	10.3
b	dimensionless	Bend designation	12.1.2
B	GPa^2 x s	Crack strength preservation parameter or B-value	7.1
B_0	GPa^2 x s	Transitional B-value at the slow-unloading/fast-unloading boundary	9.4
c	dimensionless	Non-linearity term for stress versus strain	7.4
C	dimensionless	Additive dimensionless prooftest term or C-value	10.6

Symbol	Unit	Name	Subclause or paragraph
C_a	dimensionless	Average additive dimensionless prooftest term or C-value	12.1.1
C_0	dimensionless	Transitional value of C at the slow-unloading/fast-unloading boundary	10.6
D	Mm	Fibre-axe separation in two-point bending	10.3.3
E	GPa	Young's modulus	7.4
E_0	GPa	Zero-stress Young's modulus	7.4
$f(h)$	dimensionless	Cumulative number of failures as a function of the number of hours h	11.4
F	dimensionless	Fibre failure probability	11.1
F_p	dimensionless	Fibre failure probability during prooftesting	12.1.2
h	dimensionless	proportionality constant	10.1.1
i	dimensionless	Rank order, sorted by increasing failure stress	5.3.2
I		Strength integral over the sample surface (assuming interior flaws are negligible)	10.2.1
$K_I(t)$	GPa x μm$^{1/2}$	Stress intensity factor	7.1
$K_{Ic}(t)$	GPa x μm$^{1/2}$	Critical stress intensity factor	7.1
L	km	Fibre effective length under uniform stress, or equivalent tensile length	10.2.1
L_b	km	Fibre length in uniform bend	10.3.2
L_p	km	Mean survival length, or survival length, during prooftesting	10.6
L_0	km	Gauge length, reference length	10.2.1
m	dimensionless	"Inert" Weibull parameter or m-value	10.2.1
m_d	dimensionless	m-value under dynamic fatigue	10.5
m_s	dimensionless	m-value under static fatigue	10.4
n	dimensionless	Stress corrosion susceptibility parameter or n-value	10.2
N	dimensionless	Total number of specimens tested	5.3.2
N_p	km^{-1}	Mean breakrate per unit length during prooftesting	10.6
$N(S)$	km^{-1}	Flaws per unit length not exceeding inert strength S	10.2.1
P	dimensionless	Fibre survival probability	10.2.1
P_i	dimensionless	Fibre survival probability of each strip	6.2.4
P_p	dimensionless	Fibre survival probability after prooftesting	10.6
R	m	Fibre bend radius	10.3.2
S	GPa	Strength	10.1.1
S_{min}	GPa	Minimum initial strength	10.5
$S(t)$	GPa	"Inert" strength of a crack	7.1
S_p	GPa	Strength after prooftesting	9.3
$S_{p\mathrm{min}}$	GPa	Minimum strength after prooftesting	9.4
S_u	GPa	Strength after unloading	9.2
$S_{u\mathrm{min}}$	GPa	Minimum strength after unloading	9.3
S_0	GPa	Weibull gauge strength	10.2.1
t	s	Variable of time	7.1
$\hat{t}$	s	Critical survival time	9.3.2
t_d	s	Time to failure under dynamic fatigue, or prooftesting dwelltime	8.2.1, 9.2

Symbol	Unit	Name	Subclause or paragraph
t_f	s	Lifetime (time to failure) under constant stress or static fatigue testing	7.2, 8.1
t_{fp}	s	Lifetime after prooftesting	10.8
$t_{fp\text{min}}$	s	Minimum lifetime for certain survival after prooftesting	10.8
$t_f(1)$	dimensionless	Intercept on a static fatigue plot	8.1
t_l	ms	Prooftest loadtime	9.2
t_p	ms	Effective prooftime	9.3
t_u	ms	Prooftest unloadtime	9.2
t_y	years	Service time in years	6.1
$t0$	dimensionless	Static Weibull time-scaling parameter	10.4
V	µm/s	Crack growth velocity	7.1
V_C	µm/s	Critical crack growth velocity	7.1
w_i	dimensionless	Weibull cumulative probability ordinate scale	5.3.2
$wout_i$	dimensionless	Median Weibull cumulative probability ordinate scale	5.3.2
x	dimensionless	Factor relating bend length to equivalent tensile length	10.3.2
Y	dimensionless	Crack geometry shape parameter	7.1
z	dimensionless	Length factor	11.1
α	dimensionless	Ratio of prooftest unload parameters to crack parameters	9.4
β	GPa^n-s-km$^{(n-2)/m}$	Weibull β-value	10.4, 10.5
β_i	GPa^n-s-km$^{(n-2)/m}$	Weibull β-value for each failure stress	5.3.2
ε	dimensionless	Strain corresponding to a particular stress	7.4
λi	km^{-1}-yr.$^{-1}$	Breaks/length-time (instantaneous failure rate)	11.1
λa	km^{-1}-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_b	GPa	Maximum bend stress	6.3.4
σf	GPa	Failure stress under dynamic fatigue testing, without prooftesting	8.2.1
σfp	GPa	Failure stress after prooftesting	10.8
σfp_{min}	GPa	Minimum failure stress after prooftesting	10.8
$\sigma f(1)$	dimensionless	Intercept on a dynamic fatigue plot	8.2.1
σp	GPa	Prooftest stress	9.2
σ_{max}	GPa	(Non-failing) maximum stress	5.3.2
σ_u	GPa	Applied stress during unloading	9.2
$\dot{\sigma}_u$	GPa/s	Positive unloading stress rate	9.2
$\sigma 0$	GPa	Dynamic Weibull stress-scaling parameter	10.5

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 prooftesting. 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 formulae 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 (29); while at fracture, the relationship between the critical stress intensity factor, strength, and flaw depth is given by Equation (30).
- The crack growth velocity is related to the stress intensity factor by Equation (32).
- The Weibull distribution of stress (before any prooftesting) is unimodal according to Equations (85) and (86), or bimodal according to Equation (91). 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 utilise 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 prooftest stress 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.

For convenience in assisting the reader to find the derivations of equations, 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

5.1 General

This clause outlines how the parameters in the reliability (lifetime and failure rate) equations are obtained in the approximation of the small B-value. Prooftest 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 $\ln\text{-}\ln\frac{1}{P}$ (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.

5.2 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 approximate equivalent in-service tensile length L given by Equation (97).

$$L \approx 0{,}4\frac{L_b}{\sqrt{x}} \qquad (1)$$

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 Equation (98).

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

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.

5.3 Reliability parameters

5.3.1 General

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

5.3.2 Prooftesting

- Obtain the composite prooftest parameter $\sigma_p^n t_p$, where σ_p is the actual prooftest stress during dwell, and n is the stress-corrosion susceptibility parameter (or n-value). The effective prooftime is given by Equation (64).

$$t_p = t_d + \frac{t_l + t_u}{n+1} \tag{3}$$

  obtained from the loadtime t_l, the dwelltime t_d, and the unloadtime t_u.

- (Optional) If from prooftesting the mean number of breaks N_p per length or the mean survival length L_p during prooftesting is known, calculate Equations (172) and (173).

$$\beta = \frac{\sigma_p^n t_p}{N_p^{\frac{m}{n-2}}} = \sigma_p^n t_p L_p^{\frac{m}{n-2}} \tag{4}$$

where
$$\frac{m}{n-2} = m_s = \frac{m_d}{n+1} \tag{5}$$

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

5.3.3 Static fatigue

- Obtain the static Weibull plot of scaled probability versus the natural log of failure times t_f for any particular constant applied stress σ_a (Equation (174)).

$$\ln\frac{1}{P_p(t_f)} = \left[\left(t_f\sigma_a^n + t_p\sigma_p^n\right)^{m_s} - \left(t_p\sigma_p^n\right)^{m_s}\right]\frac{L}{\beta^{m_s}} \tag{6}$$

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

- Obtain the best-fit straight line to the log of failure times versus the log of applied stresses (Equation (48)).

$$\log t_f(\sigma_a) \approx \log t_f(1) - n \;\log\sigma_a \tag{7}$$

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.)

5.3.4 Dynamic fatigue

IEC 60793-1-31[1] describes how to measure both short-length and long-length strength distributions of optical fibres.

- Obtain the dynamic Weibull plot of scaled probability versus natural log of failure stresses σ_f for any particular constant applied stress rate $\dot{\sigma}_a$ (Equation (175)).

$$\ln\frac{1}{P_p(\sigma_f)} = \left\{\left[\frac{\sigma_f^{n+1}}{(n+1)\dot{\sigma}_a} + \sigma_p^n\, t_p\right]^{\frac{m_d}{n+1}} - \left(\sigma_p^n\, t_p\right)^{\frac{m_d}{n+1}}\right\}\frac{L}{\beta^{\frac{m_d}{n+1}}} \tag{8}$$

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

- Obtain the best-fit straight line to the log of failure stresses versus the log of applied stress rates (Equation (53)).

$$\log\sigma_f(\dot{\sigma}_a) \approx \log\sigma_f(1) + \frac{\log\dot{\sigma}_a}{n+1} \tag{9}$$

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.)

5.4 Parameters for the low-strength region

5.4.1 General

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

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

5.4.2 Variable prooftest stress

This method (briefly mentioned in 9.5) subjects a full length of fibre to a certain prooftest stress, another length to a higher prooftest stress, and so on for several increasing levels of prooftest stress. 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 prooftest stress 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 5.3.

First, consider the case in which there is no initial prooftest at manufacture. From Equations (171) and (173) one has

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