OPTICAL FIBRE FATIGUE AND SUBMARINE NETWORKS RELIABILITY: - WHY SO GOOD?

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Abstract: Classical fracture-mechanics theory, applied to optical fibre in cables and submerged plant, implies that there should occasionally have been some fibre failures during installation, service or recovery. However, none have ever been reported in conforming fibre. An explanation for this is that the graduations in fibre surface crack-depth are limited by the distances between atoms in the silica lattice, so that proof-tested fibre at maximum working strain levels has a zero, and not simply 'Low', probability of fracture. This has very positive implications for allowable working strains and extension of system lifetimes.

1. HISTORY AND BACKGROUND

The replacement of a copper conductor by continuous lengths of 0.125mm diameter glass as the transmission medium in submarine networks can probably be considered to be the greatest single paradigm shift that has occurred in the 160 years of the business.

At the time of this revolutionary change there was a very understandable concern about the risk of brittle fracture of optical fibres under tensile or bending strains in service, installation or recovery. The stringent reliability requirements that have always been applied to submerged plant and cable meant that the potential mechanical failure mechanisms needed to be modelled and quantified in order to demonstrate an acceptable operational performance. This was done using fracture mechanics theory as developed for ceramics and other brittle materials.

2. THE CLASSICAL THEORY OF FRACTURE MECHANICS

The breaking strength of silica glass and similar materials is, unlike e.g. metals or polymers, not determined by the bulk properties of the material but by the size and distribution of flaws which exist on the outer surface of the material and which can grow and eventually lead to complete fracture under the influence of bulk external stress. In the absence of these flaws, fibres would only break at strains of around 6% and would be almost elastic up to break:- a performance superior to that of any metal. But the inevitable presence of surface flaws means that there will always be a significant risk of breaks at strains well below that level.

Statistical fracture mechanics theory was established for ceramic materials by the 1970's [1], and applied to optical fibres by several researchers from the 1980's onwards. The essentials of the theory are summarised very briefly here, without detailing all of the mathematical steps.

The localised stress K at the tip of a flaw is proportional to the product of the bulk applied stress σ and the square root of the flaw depth x.

$$K = Y.\sigma.x^{1/2} \qquad (1)$$

where Y is a geometric constant of about 1.5. When this stress reaches a critical level K_c a complete instantaneous fracture of the material occurs. For silica glass, K_c has been measured to be around $0.79 MPa.m^{1/2}$.

The rate of growth of a flaw at stresses below K_c is proportional to the localised stress raised to the power N, where the value of N is normally around 20:

$$dx/dt = C.K^N \qquad (2)$$

A flaw can be described in terms of its depth in nanometres and also, by inserting $K=K_c$ in equation 1, in terms of its 'Inert strength': the bulk external stress σ_c at which it would instantly fail. Using this and integrating equation 2 we obtain:

$$\sigma_{ci}^{(N-2)} - \sigma_{cf}^{(N-2)} = 1/B.\int_0^T \sigma^N.dt \qquad (3)$$

This describes the decrease in inert strength from of a flaw from σ_{ci} (initial) to σ_{cf} (final), as a result of being subjected to a stress regime σ over a period of time T. The factor B is generally referred to as the inert strength fatigue parameter, and its value for silica has been measured in a number of independent experiments.

N is generally known as the stress intensification parameter. Its value is about 20 and it can be measured by long-term fatigue measurements or, usually more conveniently, by a series of tensile tests at different strain rates.

It is frequently convenient to consider fibre strain, e, in % rather than fibre stress σ, where $e=100.\sigma/E$. Making this substitution and re-arranging, equation 3 becomes:

$$e_f^{(N-2)} = e_i^{(N-2)} - A.\int_0^T e_a^N.dt \qquad (4)$$

Where $A=E^2/10000/B$, E is the elastic modulus of the material, e_a is the bulk fibre strain, and e_i and e_f are respectively the initial and final inert strengths of the flaw, expressed in terms of percentage instantaneous breaking strain.

The sizes, and hence the strengths, of the flaws in a length of optical fibre are considered to be distributed according to the Weibull distribution, which is described by the equation:

$$F = 1 - \exp\text{-}(e_i/e_{i0})^M \qquad (5)$$

where, for a given gauge length of fibre L_g, F is the probability that one or more flaws exist with an initial inert strength less than e_i, and M and e_{i0} are constants for a given fibre type.

Equations 4 and 5 represent the complete basis of classical fracture mechanics theory as applied to optical fibre reliability. Results from manufacturing and testing then enable reliability predictions to be made.

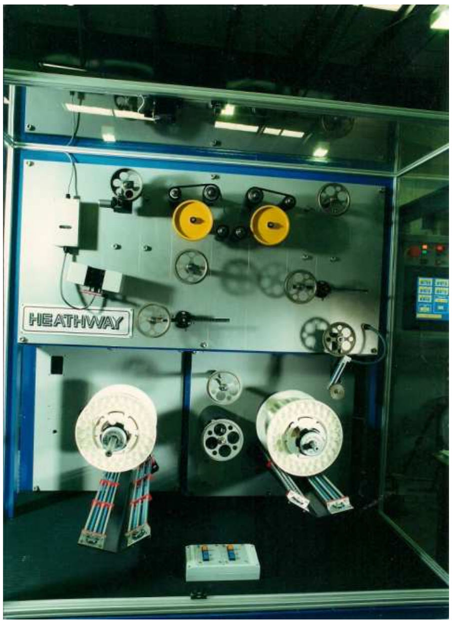
3. FIBRE TENSILE TESTS TO BREAK

The Weibull parameters M and e_{i0} in equation 5 can be determined from tensile tests to break at a constant rate of increasing strain on a large number of individual fibre lengths L_g (typically 10m or 20m), after manufacture but before the usual proof-testing is carried out.

A plot of ln(ln(cumulative failure)) against ln(breaking strain) at a given strain rate enables the basic Weibull parameters e_{i0} and M in equation 5 to be determined from the tensile test results by applying the crack growth law as described by equation 4 with some straightforward integration and algebraic manipulation, and making valid approximations when necessary.

4. FIBRE PROOF TESTING

After manufacturing, and coating with a polymeric material, all optical fibres are subjected to a proof-test at a specified strain level. The primary effect of this process is to eliminate all flaws weaker than a certain strength, by simply breaking them. A typical proof-test machine is shown in this photograph:



The fibre is fed around 3 pulleys running at the same angular speed, where the centre pulley (the lower one in the photograph) has a larger diameter, by the same percentage as the proof test, compared to the outer two. For the submarine application over approximately the last 20 years, this proof-test level has been 2% strain for about 1 second. This typically leads to around one fibre break every 40 to 50km during proof-testing, a quite acceptable yield.

It needs to be stressed that fibre proof-testing, unlike some other situations where the expression 'Proof-test' is also used, is an intrinsic part of the manufacturing process, essential for the elimination of the weakest flaws.

According to the classical fracture mechanics theory as described by equation 4, proof-testing will also weaken of all the fibre flaws which are not sufficiently weak to break during the proof-testing itself. This effect therefore needed to be quantified in order to make reliability predictions.

5. RELIABILITY ALGORITHMS DERIVED FROM TESTING AND THEORY

Making the assumptions that B, N and the Weibull parameters are all constants for a given fibre type and under all conditions of interest, it is possible to use the classical theory to predict the probability of fibre failure due to fracture under any given set of operational or test conditions.

Essentially, the probability that a fibre will fail in service is the probability that it initially contained a flaw strong enough to survive proof testing but not strong enough to survive the combination of proof testing followed by service. Any flaws weaker than that can be discounted because they will be eliminated by proof-testing, and flaws stronger than that can of course be discounted because they will survive.

This probability can be calculated for any given set of proof-testing and service conditions by applying equations 3 and 4 and by making appropriate and valid approximations. For example, the probability F_{SL} that a length L of fibre will fail under a constant service strain e_s during a service lifetime t_s can be shown to be:

$$F_{SL} = L.M.A.t_s.e_s^N/(A.t_p.e_p^N)^{(N-2-M)/(N-2)}/(N-2)/e_{i0}^M/L_g$$

where t_p and e_p are respectively the time duration and strain level of the proof test.

Work in the early 1980s by Mitsunaga et. al. [2] demonstrated that a simplification is possible by considering the break-rate N_p per unit length during proof testing, resulting in the following expression:

$$F_{SL} = L.N_p.M.(t_s/t_p).(e_s/e_p)^N/(N\text{-}2) \quad (6)$$

This elegant formula has the advantage of not involving the value of B (or A), or the Weibull parameter e_{i0} explicitly, though tensile test information is still required in order to determine the parameter M.

Equation 6 has sometimes been criticised as being an over-simplification and also as being overly pessimistic under some conditions, and overly optimistic under other conditions, in the failure predictions it makes. But for all situations in which B, N and the Weibull parameters are constant, and for working strains up to about 30% or less of the proof-test level, it is perfectly valid, and generally the best and most useful algorithm derived from the classical theory.

6. THE SPECIFIC SUBMARINE RELIABILITY CONCERNS

A concern of several materials reliability experts in the field of submarine networks was that crack growth rates under service conditions might be different (and possibly worse) than those encountered in proof testing or in tensile tests. In mathematical terms, this means that the values of B (and hence A) and N in equations 3 and 4 would not always be constant.

A number of approaches were adopted to model this risk, and in western Europe (UK and France) the method used was to allow for the possibility that the N-value might be lower in service due to higher humidity, resulting in a higher risk of fracture. This seemed to be a sensible approach, since failure risk is much more strongly dependent on N than it is on A or B.

Writing the N-value in service as n (different from N in proof-testing or tensile tests), the equation for F_{SL} becomes:

$$F_{SL} = L.N_p.M.(A.t_s.e_s^2)^{(N-2)/(n-2)}e_s^{(N-2)}/A/t_p/e_p^N/(N\text{-}2)$$

This is clearly a more complicated expression, and the version using e_{i0} is more complicated still, but it is still a one-line algorithm that can be solved with a spreadsheet, and writing n=N reduces it to the Mitsunaga formula, equation 6.

If a very conservative or worst-case reliability prediction needed to be made, this formula would be used with N=20 and n=15.

7. RESULTS FROM MEDIUM-TERM LABORATORY TESTS

As part of the development of optical cable and submerged plant in the 1980's, a number of medium-term laboratory tests and trials were set up on lengths of fibres under known tensile and bending strains and the results of these were compared with the predictions of fracture-mechanics theory.

There was good agreement between these results and the predictions of the theory for higher strain values that resulted in fractures over periods of hours, days and up to a few weeks. But as these trials were extended to periods of the order of months or longer the theory, whether using the same or different values of n and N, always made pessimistic predictions. In other words, at relatively low levels of strain there were significantly fewer fibre breaks in the tests than the numbers predicted by the theory.

The classical theory therefore seemed to be reasonably accurate in its short-term, i.e. high-strain, predictions, and to make pessimistic predictions for working (lower) strains and longer timescales. So it was used to specify the acceptable strains under long-term operational conditions, and under the shorter-duration installation and recovery conditions, with justifiable confidence that these would be more than adequate for acceptable system reliability.

8. FIBRE BREAKS IN WORKING NETWORKS

Early optical submarine cable systems sometimes incorporated fibre that had been proof-tested to only around 1% or even lower, and these cable designs frequently incorporated tight-construction fibre packages in which long lengths of fibre could be at significant positive levels of long-term residual strain, as well as at higher strain levels during installation and recovery.

Additionally, short lengths of fibre in cable joints, couplings and submerged plant were coiled at bending strains corresponding to up to 30% of the proof-test level.

Under these conditions, it would be expected that there might have been a few, though not many, fibre breaks under service conditions.

In reality, there have not been any failures at all in the million-plus kilometres of properly proof-tested conforming optical fibre installed throughout the world over the last 30 years, as far as I am aware. There have been a few failures, but in all but one of those cases the fractures were very clearly due to damage inflicted on the fibre after proof testing had been carried out, and this damage was clearly visible on the fibre coating. For the one remaining case, the most likely explanation was that the particular length of fibre involved had never in fact been proof-tested.

These results from service over the last 30 years have therefore been consistent with the findings from the medium-term laboratory tests described earlier, confirming that the predictions made using the classical fracture-mechanics theory are indeed pessimistic when applied to operational conditions.

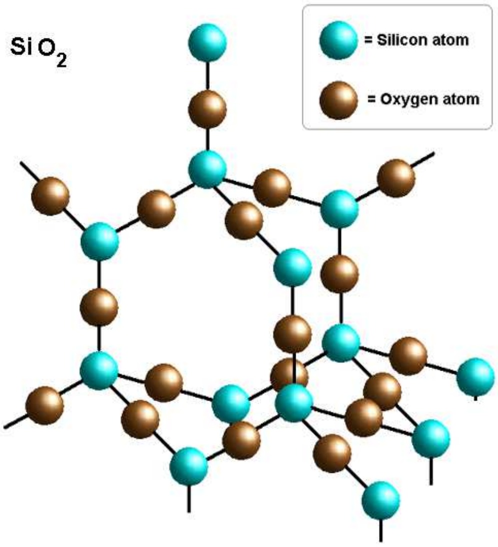
9. PERMISSIBLE CRACK-DEPTH VARIATION, AND RESULTING RELIABILITY

It might be argued that it simply does not matter that the predictions of the classical fracture mechanics theory are wrong, since they clearly err on the side of caution and it has proved possible to manufacture and install networks throughout the world for the last 30 years with no problems, provided that the fibre is undamaged and conforms to requirements. But it would nevertheless be satisfying to have an explanation for this discrepancy and to see what implications it might have.

The classical theory assumes a continuous range of possible crack depths, and hence strengths, as represented by equation 5. It therefore follows that even after proof-testing there is always a finite possibility that a flaw may exist which will be weak enough to fail at the relatively low tensile or bend strains which may be encountered in service.

Using the measured value for K_c of $0.79\text{MPa.m}^{1/2}$ quoted earlier, it is possible to calculate the actual crack depths corresponding to a given instantaneous bulk breaking stress or strain. The standard 1 second/2% proof test will eliminate all flaws with a strength less than 4.2GPa or 5.8%, and this corresponds to a crack depth of 15.9nm. Considering then the additional effect of a 25-year working lifetime at a residual strain of 0.5% (far higher than generally likely), we arrive at a crack depth only very slightly smaller than that, with a difference between these two crack depths of $1.3X10^{-12}$m.

A consideration of the inter-atomic spacing in silica leads us to the conclusion that such a small difference in crack depth cannot be possible in practice. The picture below shows the structure of the silica lattice.



The length of the atomic bonds in this structure is ~$150X10^{-12}$m: two orders of magnitude higher than the crack depth difference required for the situation to arise where a fibre can survive proof-testing but then subsequently fail under service conditions. Since what 'Crack growth' means in reality is the breaking of these bonds, it is clear that such a small difference in crack depth is not possible, and so the classical theory as represented by equation 5 is not applicable.

An accurate quantitative estimate of what the smallest difference in crack depth can be would require a detailed consideration of the geometry of the lattice and the inter-atomic bond energies. But an order-of-magnitude estimate can be made by simply taking the bond length as the minimum crack depth difference: this will be an under-estimate but reliability and lifetime estimates based on it will be also be under-estimates, though not as pessimistic as those derived from the classical theory.

We therefore make the assumption that the deepest, and hence the weakest, flaw remaining in a fibre after proof test corresponds to an initial crack depth of that of a flaw just weak enough to fail the proof test, minus the bond length. By manipulating equations 1 and 4 we can then calculate the bulk external strain below which there is zero probability of failure in a specified time. For the 2% proof test level and typical fracture mechanics constants, these times and strains are tabulated below.

Time Duration	Maximum Strain Level For Guaranteed Survival
1 Hour	1.18%
48 Hours	0.97%
25 Years	0.63%
1000 Years	0.53%

The strain levels quoted are those below which the failure probability is zero for the given time duration, and are independent of the fibre length. At higher strains and/or longer timescales there would be a finite possibility of a break, but that might still be very low, the actual probability depending on the length involved and on the flaw distribution.

10. SUMMARY AND LIMITATION OF THIS ANALYSIS

An explanation has been presented as to why the classical fracture mechanics theory always makes pessimistic predictions of fibre breaks at low strains and longer durations. The analysis concludes that because of the quantisation of flaw sizes resulting from the finite silica bond length, that there are levels of strain (or stress) below which the probability of fibre fracture in a given time is zero, and not simply ‘very low’.

It needs to be remembered, though, that this analysis is based on the requirement that all of the fibre under consideration has been properly proof-tested, and that no damage occurred to the fibre at any point between proof-testing and service. If either of these factors did not apply, then there certainly would be a significant risk of failure under service, installation or recovery conditions. The probability of such a failure could be estimated, provided that there was sufficient information available about the nature and distribution of any flaws induced.

11. IMPLICATIONS FOR LONG-TERM PERFORMANCE OF SUBMARINE NETWORKS

The table at the end of section 9 gives the strains up to which conforming fibre could be subjected with zero risk of fracture for the periods stated. All of those strains are well in excess of the levels which any fibre in submerged plant or cable might be expected to experience, even under the most extreme installation or recovery conditions. The risk of failure in any properly-manufactured and tested fibre under practical working conditions is therefore zero, and this is consistent with the results of laboratory tests and system performance.

Professor Charles Kao, who received the 2010 Nobel Prize for Physics for his work on the invention and development of optical fibre transmission, stated at the time that he could not conceive of any better practical transmission medium likely to emerge over the next 1000 years. The last figure in the table confirms that the mechanical reliability of optical fibre would indeed be consistent with such a timescale!

12. REFERENCES

[1] A G Evans and S M Weiderhorn, ‘Proof Testing Of Ceramic Materials – An Analytical Basis For Failure Prediction’, Int. J Fracture, 10 3 (1974) pp. 379-392.

[2] Y Mitsunaga, Y Katsuyama, H Kobayashi and Y Ishida, ‘Failure Prediction For Long Length Optical Fibre Based On Proof Testing’, J Applied Physics, vol. 53 no. 7, pp4847-4853, July 1982.