Models for fiber reliability

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ABSTRACT

Current models for optical fiber reliability are mostly based upon power law growth kinetics of sharp, stress-free cracks. The physical basis of these models is critically examined and is found to have limitations in describing the behavior of both high strength "pristine" fiber and weak fiber. In particular, the models do not account for the abrupt strength loss sometimes observed in harsh environments for both types of fiber. Recent advances in understanding the behavior of such fibers are discussed. In particular the addition of colloidal silica particles to the coating material is shown to dramatically improve reliability.

1. INTRODUCTION

The subcritical crack growth model is widely used to make quantitative estimates of optical fiber reliability. This model is comprised of two separate components or sub-models. The first sub-model, describing the micromechanics of flaws under an applied stress, assumes that the strength controlling defects are atomically sharp cracks that have an invariant tip curvature and are free of residual stresses. These cracks amplify a remotely applied tensile stress, σ_a, as quantified by the stress intensity factor, K_I:

$$K_\mathrm{I} = \sigma_a Y \sqrt{c} \tag{1}$$

where c is the crack length and Y is the crack shape parameter of order unity. When the stress at the crack tip exceeds the intrinsic strength of the material (characterized by the critical stress intensity factor, K_IC) catastrophic failure ensues. While Eq. (1) describes the ultimate strength of brittle materials, failure of many ceramic materials (and silica glass fibers in particular) shows time dependence, *i.e.*, delayed failure can occur for applied stresses much lower than are required to produce immediate catastrophic failure according to Eq. (1). The mechanism for this behavior is now understood to be due to the combined influence of stress at the crack tip and reactive species in the environment - particularly water. The strain in the bonds at the crack tip in effect reduces the activation energy for the chemical reaction between water and the silica so that silicon-oxygen bonds are slowly broken, progressively advancing the crack.[1] A power law relationship between the crack growth rate and the applied stress intensity at the crack tip is normally assumed:

$$\dot{c} = A K_\mathrm{I}^n . \tag{2}$$

Eq. (2) represents the second sub-model which describes the strength degradation kinetics. Eqs. (1) and (2) can be combined for any given loading condition to yield the fatigue life. For conditions of a constant applied stress, σ_a, the time to failure can be shown to be:[2]

$$t_f = \frac{2}{AY^2(n-2)\sigma_a^n}\left(\frac{\sigma_i}{K_\mathrm{IC}}\right)^{n\text{-}2} = B\sigma_a^{-n} \tag{3}$$

where σ_i is the intrinsic strength of the material and is related to the initial crack length. This equation forms the basis of most reliability models. Accelerated laboratory testing is used to estimate the values of B and n for the particular fiber and environment of interest. These values are then used to estimate a safe stress, σ_a,

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for a given design life, t_f. In practice, the strength of fiber shows length dependence with short lengths ($\lesssim$ 1 m) having a narrow distribution of intrinsic flaws while longer lengths are dominated by a broad distribution of occasional extrinsic defects introduced during manufacturing or handling. For this reason, a statistical distribution for the value of σ_i is used. In practice, the weakest defects are removed by proof testing the fiber to some stress level, σ_p. Recently, Griffioen *et al.*[3] reviewed several models in the literature based on the power law and showed that they reduced to one basic model but differed principally in their failure or reliability criteria. For a 30 year lifetime the models give allowed stresses typically in the range of one quarter to one half of the proof stress.

As mentioned above, the subcritical crack growth model is comprised of two sub-models, the micromechanics model which describes how a defect reduces the strength, and the kinetics model which describes the stress dependent growth of the defect. These two models will now be critically examined.

2. MICROMECHANICS MODEL

By examination of previous work on silica glass both with and without damage, one may postulate four distinct regimes which, without any other information, would be expected *a priori* to have four distinct applicable micromechanics models (Table I).

At the low strength extreme, bulk silica with macroscopic cracks is well described by Eq. (1) since the cracks are (at least while propagating) atomically sharp and only subject to externally applied stress.

At the opposite end of the strength range is short length, "pristine" silica fiber. Under inert conditions (*e.g.* liquid nitrogen) such fiber exhibits a single valued strength close to the theoretical strength of the material.[4] Any defects are of atomic dimension and, while atomically sharp, are also atomically wide and can be considered blunt and so are not described by Eq. (1). Additionally, Eq. (1) is a continuum model that does not describe the discrete nature of small flaws and the discreteness might have a major influence on the fatigue.[5]

In between these two strength extremes are strengths of the order of the proof stress. Such strengths result from extrinsic effects such as abrasion damage or particles adhering to the fiber surface. Vickers indentation by a diamond pyramid is a useful model for these defects since it generates both surface damage and a residual stress field akin to those formed by abrasion. Dabbs, Marshall and Lawn[6] found that indentation defects exhibited two types of behavior. Below a certain indentation load threshold the resulting flaws (named "subthreshold") exhibit a plastic indent without well defined cracks. Above the indentation load threshold the "postthreshold" flaws show well defined radial cracks emanating from the indentation site. Subthreshold defects are not described by Eq. (1) since no well defined cracks are present. Postthreshold cracks are also not described by Eq. (1) without modification since residual stresses around the indentation site modify the behavior of the cracks.

Table I. Types of defect and strength ranges for silica.

Defect Type	Effective n	Inert Strength	Comments
Pristine	20	> 7 GPa	Surface phenomenon. Pits.
Subthreshold	10-20	0.7 – 7 GPa	Crack initiation by residual stresses.
Postthreshold	30	1 – 100 MPa	Crack propagation dominated by residual stresses.
Macroscopic Crack	40	< 1 MPa	Well defined, residual stress free cracks.

To summarize, of the four types of defects in silica, the only one expected to be correctly described by Eq. (1) is the macroscopic crack; the only type of defect of no relevance to optical fiber reliability. Therefore, doubt is cast on the applicability of Eq. (3). Eq. (3) is found to fit fatigue data for t_f and σ_a quite well under many circumstances and this has been cited for its validity. However, in reliability models, Eq. (3) is used to extrapolate to lower values of σ_i, as well as large values of t_f, and it is this extrapolation that depends on the micromechanics model. Extrapolation on σ_i has not been tested empirically in detail and may well be invalid since it is often extrapolating from pristine fiber behavior to the behavior of sub- or postthreshold defects.

2.1. Reliability concerns

In practice, a long (> 10 m) length of optical fiber may be considered to be composed almost entirely of high strength pristine material but with occasional low strength defects distributed along the length. In practice both types of fiber cause concern for overall reliability. A stressed fiber will fail at the severest defect so the behavior of weak fiber is important. This is especially the case when optical fiber is deployed in fiber-in-the-loop and cable TV systems since the fiber will be handled more extensively by less skilled personnel and be exposed to more aggressive environments.[7] However, weak defects are, at least in principal, controllable by more careful manufacturing and handling techniques and by using higher proof stresses. Also, the fiber is under (supposedly) zero stress in many optical cable designs and the defects do not cause failure in the absence of stress. Failure at a weak spot is simply repaired by splicing.

A minimum strength of ~3 GPa is required in order to be able to handle a fiber for making interconnects. This is substantially higher than typical proof stress levels of 0.7 GPa.[8] Since the strength of pristine fiber can degrade to this level in harsh environments *even in the absence of applied stress*, the behavior of high strength fiber is also important to system reliability, despite claims to the contrary.[7] If severe degradation occurs it may arise that the fiber is too weak to handle but is still substantially stronger than the proof stress. In this circumstance, repair may involve replacement of long lengths of cable.

The fatigue and aging behavior of both strong and weak fiber both impact reliability. In view of the nature of the flaws being quite different in these two types of fiber, they will be discussed separately in detail in the subsequent sections.

2.2. Fatigue and aging behavior of weak fiber

Reliability predictions for weak fiber can be made without extrapolating from pristine fiber behavior if weak fiber is studied directly. Naturally occurring defects can be studied by examining very long lengths[9] but this is inconvenient since it is achieved by testing many short lengths consecutively; long duration experiments are not practical. As an alternative, fiber can be deliberately weakened by various techniques including blowing steam over[10] or rubbing[11,12] the bare fiber during drawing, abrading the fiber[12] or by incorporating hard particles in the polymer coating.[13] These techniques are useful but it is difficult to reproducibly damage the fiber. Additionally, each technique produces only one characteristic strength and can not explore the complete strength range of interest. This is an important limitation because of the complex behavior of the glass in the region of typical proof stress levels.

The approach used at Rutgers is to use Vickers indentation to model weak defects.[14] The residual strength of the fiber can be accurately controlled by varying the indentation load. By using fibers of various diameters and appropriate strength measurement techniques (two-point bending[10] for stronger fibers and a novel four-point bend technique for weaker fibers[15,16]). Fig. 1 (from Ref. 17) shows the inert (liquid nitrogen) strength of indented fiber as a function of indentation load. In the subthreshold region strengths of up to 3.7 GPa (5% strain to failure) have been measured. It is noted that the two- and four-point bending results overlay each other in the region of overlap. The threshold region is extensively explored and in the indention load range of 2 to 5 N bimodal behavior is observed - some indentations have no radical cracks while others have well defined cracks and are substantially weaker. In fatiguing environments even more complex behavior is expected in the threshold region with bimodal strength distributions - subthreshold indents may fail by two modes; radical cracks "pop-in" during loading and can either propagate to cause immediate failure or can arrest and then grow stably until later catastrophic failure.[18,19] Therefore, the uncontrolled weakening techniques, such as abrasion, while extremely useful, are not sufficient to map out the full behavior near the threshold since they effectively take a "snap-shot" of the behavior at one strength.

Also shown in Fig. 1 are data of Jakus *et al.*[20] for measurements of "inert" strength made in room temperature dry nitrogen. The latter measurements are significantly lower than in liquid nitrogen and dry nitrogen therefore does not give inert conditions (the difference can not be explained by the temperature dependence of elastic modulus which only differs by ~10% between −196°C and 25°C).

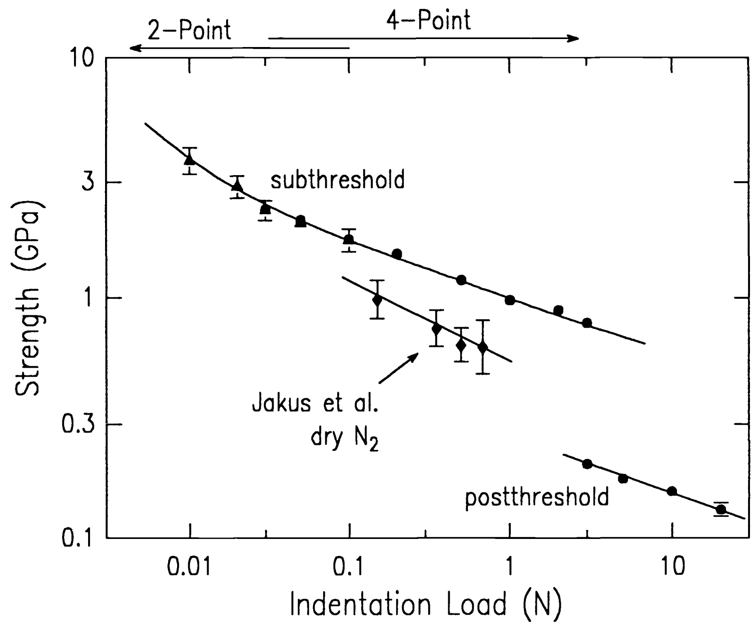

Fig. 1. Inert (liquid nitrogen) strength of indented fiber as a function of indentation load as measured by two and four point bending (after Ref. 17).

While Glaesemann[12] found no evidence for crack "pop-in" for fiber abraded both during and after drawing, recent results indicate that crack pop-in may indeed be a problem.[17] Fig. 2 shows how the strength of fiber varies with aging time for 0.5 N indents aged under zero stress in 90°C pH 7 buffer.[17] Damaged specimens show unimodal strength behavior in the subthreshold region. However, on aging for just a few hours, the residual strength becomes bimodal, with the high strength mode gradually increasing in strength. However, the low strength mode initially shows a dramatic loss of strength to ~40% of the initial value, followed by a gradual recovery. Clearly, this behavior has serious reliability implications since a fiber that passes the proof test may later become weaker than the proof stress. The 0.5 N indents have an inert strength of 1.2 GPa (Fig. 1) and so would readily pass a 0.7 GPa proof test. If crack pop-in reduces the inert strength to 40% of the initial value (0.5 GPa), the fiber would no longer pass that proof test. Therefore, proof testing ***does not*** guarantee the strength if the fiber is exposed to aggressive environments. This behavior is not accounted for by present reliability models.

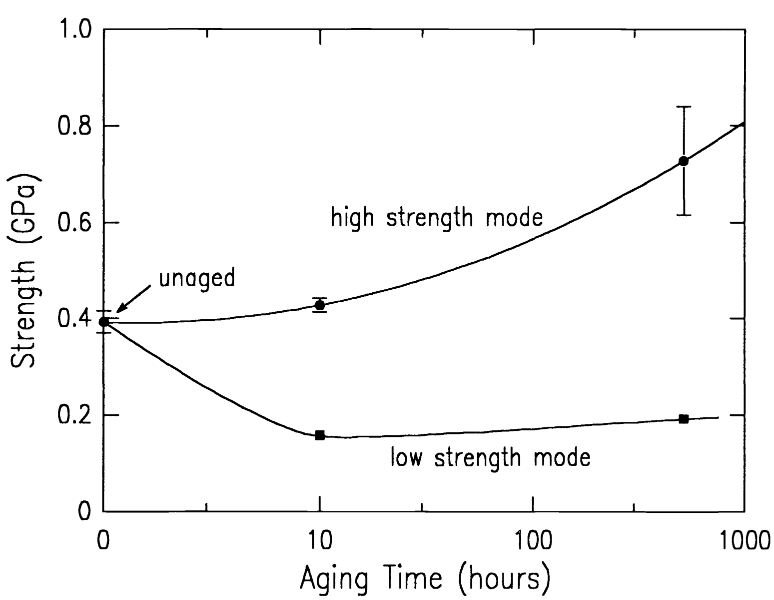

Fig. 2. Residual strength (measured by two-point bending in 27°C pH 7 buffer) of fiber indented at 0.5N, as a function of aging time in 90°C pH 7 buffer.[17]

2.3. Fatigue and aging behavior of pristine fiber

Under many circumstances the fatigue behavior of pristine fiber is found empirically to fit Eq. (3) quite well, in at least the dependence of time to failure on applied stress. However, under many circumstances, and particularly in harsh environments, important deviations are observed. For example, the short-term strength of fiber in aqueous solutions has been found to be dependent on ionic species, not just on temperature, pH and water availability.[21-23] In particular, it has been found that the dependence of the fiber strength on the presence of group I alkali metal ions[21] correlates with silica dissolution rate data[24] but no similar dependence has been observed for macroscopic crack growth.[25] These results imply that fatigue of high strength fiber is caused by surface effects rather than processes occurring inside cracks below the surface.

Of more serious concern is the now well-established fatigue "knee". This effect, an abrupt decrease in the fatigue parameter, *n*, at long times to failure, results in a fatigue life which is very much shorter than indicated from short-term fatigue data. While originally observed in data for static fatigue in humid air,[26] the presence of the fatigue knee has not been unequivocally confirmed in vapor environments. Its presence, however, has been well established in harsher, liquid environments for both bare fiber and many types of coated fiber. Matthewson and Kurkjian[27] observed that the dramatic strength loss in fiber aged under zero stress occurred on a similar time scale to the fatigue knee, and postulated that both effects were due to the same phenomenon, namely the etching of surface pits. The presence of these pits has been directly confirmed by both scanning tunneling microscopy[28] and atomic force microscopy (AFM).[29] While a variety of coated and bare fibers show quite different zero stress aging strength loss behavior, it has been shown that the residual strength and surface roughness (measured by AFM) have a unique relationship.[30] This strongly suggests that the fatigue and aging knees are caused by initiation of new surface flaws by surface dissolution rather than by propagation of preexisting defects. Recognition of this mechanism has allowed us to produce fibers with additives in the polymer coating that dramatically improve the long term reliability of the fiber in harsh environments.

In an attempt to slow down surface etching of silica fibers, Matthewson and coworkers[31-33] incorporated 0.7 wt% of 20 to 30 nm diameter colloidal silica particles in the liquid prepolymer prior to coating the fiber. The coating additive was found to inhibit strength loss under zero stress aging, delay onset of the fatigue knee by two orders of magnitude in time and to increase lifetime beyond the knee by factors of up to 30 in 90°C pH 7 buffer environments. The coating additive has also been found to be effective in vapor environments; in 85°C, 85% relative humidity, the additive improved fatigue life by factors of up to ten, and reduced the strength loss after 30 days of zero stress aging from 15% to 5%.[33] Fig. 3 shows static fatigue results for fibers with a coating without any additive and two coatings with a higher concentration (3 wt%) of Cab-O-Sil[34] grade M5 (specific surface area 200 $m^2.g^{-1}$) and grade EH5 (320 $m^2.g^{-1}$). Lifetime improvements of over 100 times have been observed for the EH5 additive. The M5 additive delays the fatigue knee even further in time and lifetime improvements by factors of over 400 have been observed.

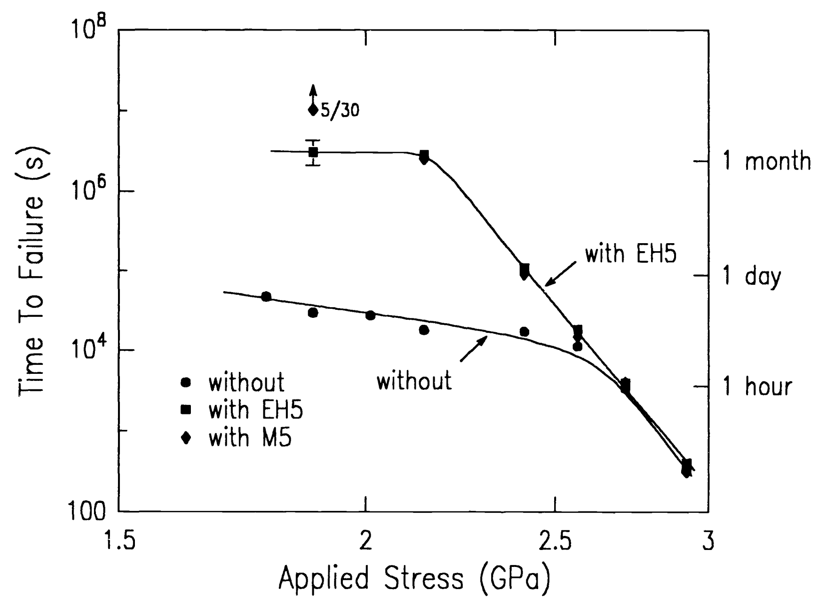

Fig. 3. Static fatigue in 90°C pH 7 buffer solution of fiber without any coating additive and with 3 wt% of grades M5 and EH5 colloidal silica particles in the coating.[33]

The above results were obtained using two-point bending.[35] Tensile results, however, showed a low strength mode, presumably due to μm sized particulate contaminants introduced while incorporating the colloidal silica in the liquid prepolymer.[31,32] This represents an impediment to any practical application of the coating additives, however, this problem can be solved (or potentially solved) in either of two ways. Fig. 4 shows a Weibull plot showing the effect of filtering the coating prepolymer after incorporating the colloidal silica particles.[33] Without any additive the distribution is unimodal with a Weibull modulus, $m = 170 \pm 60$. Without filtering, 3 wt% of M5 gives 8 of 30 specimens with a degraded strength, while after filtering through a 20 μm membrane only two specimens show degradation. Filtering through sub micron membranes should remove this low strength mode entirely. An alternative strategy is to only incorporate the silica particles in the outer coating of a dual coated fiber. No low strength mode has been observed in tensile testing of such fiber, but similar improvements in fatigue life are still observed.[33]

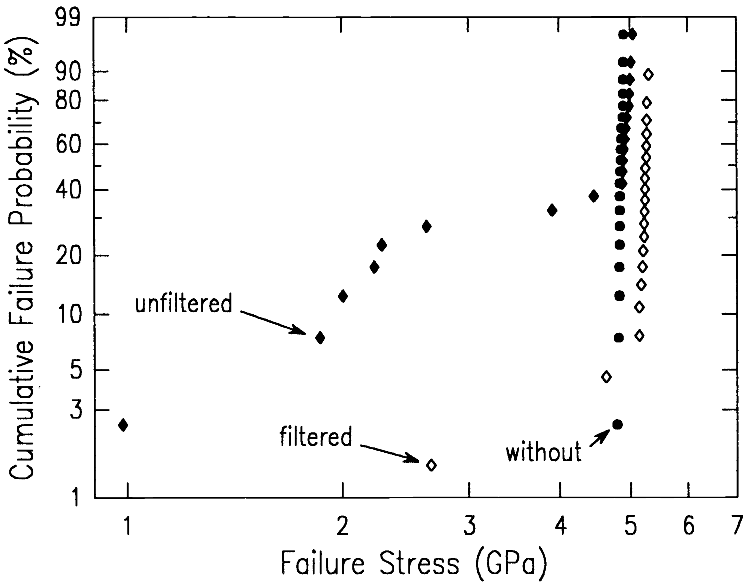

Fig. 4. Weibull probability plot of the tensile strength (300 mm gauge length) of fiber without silica particles in the coating, and fiber with 3 wt% of M5 particles in the coating when the liquid prepolymer has been both unfiltered and filtered through a 20 μm membrane (after Ref. 33).

While the mechanisms leading to the aging and fatigue knees are now reasonably well understood qualitatively, it is not possible to make quantitative predictions of their occurrence. However, the addition of silica particles to the polymer coating promises to be a simple and inexpensive modification to existing coating technology that can substantially delay the knee, perhaps to a time when it has little or no significance for fiber reliability.

3. DEGRADATION KINETICS MODEL

The power law model for the kinetics of strength degradation, Eq. (2), is widely used for its mathematical simplicity; firstly because it is readily integrable for a wide variety of loading schemes (dynamic fatigue in particular) and because it is mathematically similar to (and hence compatible with) the Weibull distribution often used to describe the variability in strength. However, the power law form is not based on any physical model and in fact leads to inconsistencies when trying to incorporate the effect of temperature on fatigue.[36] It has been shown that lifetime predictions can be very sensitive to the form of the degradation kinetics model.[37] This is somewhat mitigated by the observation that if one simultaneously extrapolates to lower applied stresses and lower initial strengths, the sensitivity to the model is reduced due to the scaling with these two parameters.[36] In effect, the crack velocity, c, is similar for strong specimens tested rapidly and for weak specimens tested slowly.[38] However, as discussed above, since the safest strategy is not to extrapolate to lower strengths, but to directly determine the behavior of defects in the strength range of interest, it is still important to know how to extrapolate to longer times and hence it is necessary to use the correct kinetics model.

Kinetics models examined in the literature are generally similar to one of three basic forms; the power law, Eq. (2), or one of two exponential forms:

$$\dot{c} = A_1 \exp(n_1 K_\mathrm{I}) \tag{4}$$

$$\dot{c} = A_2 \exp\left(n_2 K_\mathrm{I}^2\right) \tag{5}$$

The first exponential form is based on a simple chemical kinetics model.[1] Michalske *et al.*[39] show that if crack growth does follow Eq. (4) then this can explain why the power law fatigue parameter, n, has typical values of 20 for high strength fiber and 40 for weak silica containing macroscopic cracks. However, they then incorrectly conclude that this gives some evidence for the validity of the sub-critical crack growth model (it only is evidence for the degradation kinetics model and not the micromechanics model). They also suggest that since an exponential form appears curved on a log-log fatigue plot, this might explain the fatigue knee (however, fatigue knees are usually too abrupt to be explained by any smoothly varying kinetics function).

The second exponential form, Eq. (5), is deduced from a simple atomistic model for fracture.[40] The two exponential forms, Eqs. (4) and (5), effectively differ by whether the stress is incorporated into the activation energy for the silica-water reaction as a linear or quadratic term.

It has been shown that the power law always gives the most optimistic lifetime predictions while the second exponential form gives by far the most pessimistic lifetime mediations.[37] For example, Fig. 5 extrapolates fatigue data taken on a time scale of 3 s to 5 days to a lifetime of 25 years. The different models give maximum allowed service stresses for a 25 year life that span a decade in stress.

Subcritical crack growth data in the literature usually show too much scatter to determine which kinetics model best fits the data, but very slow crack speed measurements by Helfinstine and Gulati[41] favor the second exponential form, Eq. (5). In contrast, measurements on optical fiber usually show the power law dependence or sometimes the first exponential form. In static and dynamic experiments, Matthewson[42] found that one fiber gave a best fit to the first exponential form when tested in ambient air, but fitted the power law best when tested in 25°C pH 7 buffer solution (whether tested coated or stripped of the coating) indicating that there is no unique kinetics model applicable to all environments. Ironically, when reviewing power law based reliability models, Griffioen *et al.*[3] proposed the models were only valid in vapor environments but not in liquid environments (in order to avoid having to consider the fatigue knee). While conducting the experiments described above, Matthewson[42] found a small but statistically significant discrepancy between the static and dynamic results. While estimates of n measured by static and dynamic fatigue showed overlap, estimates of the fatigue parameters A and n as

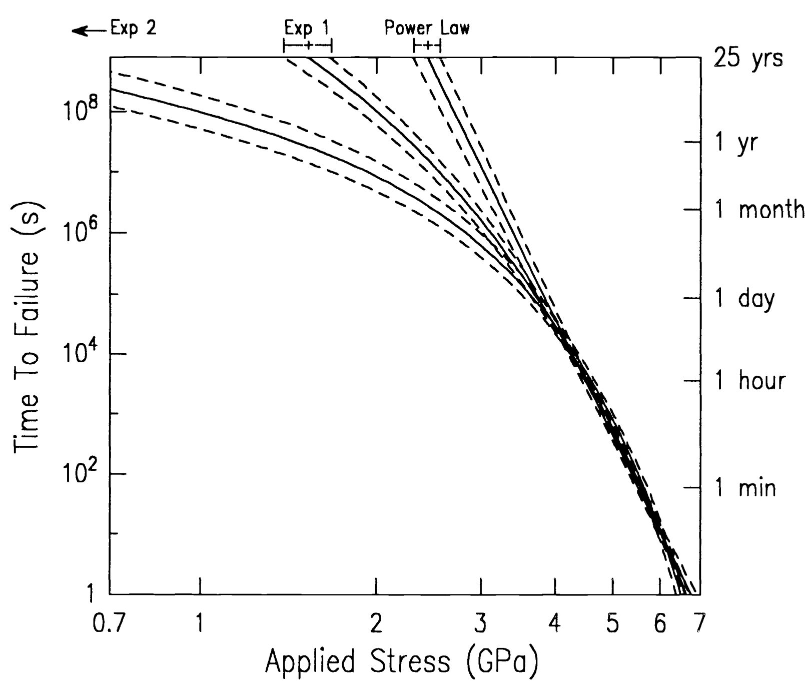

Fig. 5. Extrapolation of short term fatigue data to a 25 year lifetime for measurements made in 25°C air.[42]

defined in Eq. (2), showed substantial differences when their correlation is taken into account. These results are not sensitive to the kinetics model assumed but cast doubt on the validity of the micromechanics model.

In the absence of any clear evidence for which kinetics model to use, a suitably conservative approach to design should be adopted. The power law kinetics model is therefore unsatisfactory. The second exponential form is probably too conservative, since it has not been observed for fiber. The first exponential form, Eq. (4), is therefore the most reasonable candidate. While this form results in quantitative reliability models that are mathematically intractable, solution of the equations can be performed numerically and so should not be a lasting inconvenience once suitable general purpose computer codes are developed.

4. CONCLUSIONS

Reliability models are actually based on two sub-models - the micromechanics model describing the strength degrading effects of defects, and the kinetics model describing how defects evolve with time and stress in a reactive environment. Serious doubt is cast on the validity of current models since both the micromechanics and kinetics models are inappropriate. In particular, the micromechanics model does not adequately describe the various types of defect present in the fiber and does not successfully describe their behavior in harsh environments. The power law degradation kinetics model most widely used, while convenient, is not as conservative as more physically meaningful models. However, the models can be successfully fitted to most fatigue data for relatively benign environments but this just means the models are useful for *semi empirical* scaling laws.

Abrupt loss of strength has been observed in harsh environments for both pristine (the fatigue "knee") and weak fiber (crack "pop-in"). The former effect has been shown to be due to surface etching of the fiber and can be controlled by adding colloidal silica particles to the polymer coating. The latter effect is due to crack pop-in caused by the combined influence of residual stresses and the environment. This can be controlled to some extent by improved manufacturing and handling procedures and by increased proof stress levels. Current reliability models ignore this type of behavior and are therefore inadequate for assuring reliability in harsh environments.

5. ACKNOWLEDGMENTS

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