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Optical fiber mechanical testing techniques

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ABSTRACT

This paper reviews the common techniques for mechanical testing of optical fiber specimens and compares and contrasts their attributes. Any technique must be able to grip the specimens without causing failure at the grips. The techniques generally fall into two categories; uniaxial tensile testing in which the fibers must be gripped carefully, and bending techniques which reduce the local stress at the grips. The former techniques generally give results that are easier to interpret due to the homogeneous stress field but are experimentally the least convenient. In contrast, bending techniques are experimentally convenient, but due to the inhomogeneous nature of the stress field developed and the short fiber test lengths, may not be as useful as tension for some purposes.

1. INTRODUCTION

The strength of optical fiber is an important factor in the reliability of a fiber-based system since it can be degraded to the point where failure occurs in service with resulting complete loss of optical transmission. The strength of fiber can be degraded by poor manufacturing or handling techniques. Even if left undisturbed after deployment, the strength of the fiber continues to degrade due to the combined action of environmental moisture and residual tensile stresses (and even in the absence of stress in some circumstances). In order to assure reliability of the system it is necessary to characterize, and preferably understand, the strength and strength degradation (fatigue) behavior of the fiber; for this, suitable strength measurement techniques are required. This article describes the common, and some not so common, techniques for measuring fiber strength. While the emphasis is on the most widely used type of optical fiber, namely 125 μm diameter fused silica with a strength of at least 100 MPa, other optical fiber materials and diameters will also be considered; indeed, much of the discussion is relevant to strength measurement of other specimen types such as thin rods and tapes.

Several parameters need to be determined in order to characterize the mechanical behavior. These include:

1. The strength, *i.e.* the stress required to cause failure.

2. The distribution of strength. The strength of brittle materials is determined by the presence of flaws or defects; it is therefore stochastic since the flaws are distributed in position, orientation and severity. In practice, one is

interested in the weakest specimen, rather than the specimen of typical strength; thus characterization of the distribution is necessary.

3. The strength is time dependent because of the stress dependent chemical reaction between the fiber and environmental moisture. It is therefore necessary to determine how the strength degrades under various conditions. Two types of fatigue experiments can be performed to evaluate the fatigue parameters.

1.1. Dynamic Fatigue Testing

The mechanical failure strength decreases with decreasing loading rate since more time is available for the environment to degrade the strength. This type of experiment is termed "dynamic" since the applied stress varies with time. If the stress is applied linearly with time then, according to the commonly used power law subcritical crack growth model (see Ref. 1, this volume for a discussion), the failure strength, σ_f, is related to the constant loading rate, $\dot{\sigma}$, by:[2]

$$\sigma_f^{n+1} = \frac{(n+1)}{(n-2)} \frac{2}{AY^2} \left(\frac{\sigma_i}{K_{IC}} \right)^{n-2} \dot{\sigma} = (n+1) B \dot{\sigma}, \tag{1}$$

where

$$B = \frac{2}{AY^2 (n-2)} \left(\frac{\sigma_i}{K_{IC}} \right)^{n-2}, \tag{2}$$

and where K_{IC} is the critical stress intensity factor (~0.75 MPa.m$^{1/2}$ for fused silica), σ_i is the initial or inert strength of the fiber in the absence of fatigue and Y is a dimensionless parameter of order unity describing the crack geometry (Y is defined by $K_I = \sigma Y c^{1/2}$ and is 1.16 for a semicircular crack in the surface of the fiber). The fatigue parameters, n and A (or B) are determined by measuring the strength at several loading rates.

Dynamic fatigue equipment is relatively complex since it must change the loading in a controlled fashion. For this reason it is only appropriate for short term tests (up to a day or so duration) but consequently produces results correspondingly rapidly. An advantage of the technique is that the experimental duration has an upper limit that can be estimated in advance because the strength at a lower rate is always lower than that measured at a higher rate.

1.2. Static Fatigue Testing

In a static fatigue experiment, a constant (hence "static") stress is applied to the fiber and the time to failure is measured; this is the time required for the intrinsic strength of the fiber to degrade until it equals the applied stress. The fatigue parameters can be determined by fitting the power law subcritical crack growth model to measurements of the failure time, t_f, as a function of applied stress, σ_a:[2]

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

The apparatus for applying a static stress to the fiber is usually considerably simpler than that required for a dynamic fatigue test. It can therefore be replicated so that long duration experiments of up to a year or more can be conducted. Unlike dynamic fatigue, however, the experimental duration is not predictable in advance and sometimes can lead to open ended experiments that can keep equipment busy for unexpectedly long duration. Static fatigue more closely models the practical situation of failure times exceeding (hopefully) many years.

1.3. Gripping Considerations

Optical fibers are almost exclusively made of glasses which, unlike polycrystalline materials, normally fail from surface defects rather than internal flaws. The strength therefore not only depends on the environment at the surface, but also on the complete manufacturing and handling history the surface has experienced. For this reason, the fiber itself must be directly studied, rather than model specimen geometries, such as "dog-bone" specimens widely used for testing metals and polycrystalline ceramics. Gripping the fiber is therefore a problem that any testing technique must address. Consider the conceptually simplest situation of a fiber pulled axially in uniform tensile stress. Since the fiber has a uniform section (unlike the dog-bone specimen) this stress must be transferred out of the specimen at its ends into the loading apparatus without perturbations at the grips that would increase the local stress. This is in order to avoid failures at the grip which are not characteristic of the tested section. The problem of achieving smooth stress transference to the grips is aggravated by two properties of fused silica fiber. Firstly, the scatter in the fiber strength can be very low (Weibull moduli, m, well in excess of 100 have been observed with corresponding scatter of less than 1%). If the scatter were large it is very likely that the weakest defect is found in the long tested section rather than the short gripped section. Secondly, silica fiber is relatively durable in a wide range of environments, so that the grip may also need to be durable. There are three strategies to avoid gripping problems. The first two are relevant to uniaxial tension:

1. The grips are immersed in the test environment. They must be at least as durable as the fiber, which must be gripped very carefully to avoid stress concentrations.

2. The grips are held outside the test environment. The grips do not need to be durable but the tested section must be weaker than the gripped section. If the test environment is very aggressive then gripping need not be as careful as in the first strategy.

3. It is arranged for the intensity of the applied stress to be smaller in the

gripped region than in the test section. This is achieved by employing bending techniques. The gripping system is usually immersed in the test environment and therefore must be at least as durable as the fiber.

2. TEST TECHNIQUE CONSIDERATIONS

There are many factors to be considered when selecting a test technique and they will be discussed here. It will be seen that many are conflicting so that no single test technique is appropriate for all, or indeed for most, circumstances. A well equipped laboratory will therefore have a range of techniques available.

2.1. Types of Fiber

There are several broad types of fiber that might require different testing techniques. Fiber is generally coated with one or more polymer layers to protect from damage during handling; such fiber is relatively easy to grip. However, it can be useful, principally for research purposes, to determine the strength of fiber in the absence of the coating. Bare fiber is severely damaged by even the slightest contact with solid objects and requires special handling and gripping techniques. Optical fiber cables are often made from ribbons of fibers that have been joined side by side. It can be useful to examine the strength of ribbons to determine how the fiber strength is modified.[3]

The above types of fiber can be assumed to have a distribution of flaws that is uniform over the fiber surface. If this is not the case, the test technique must be chosen with care. For example, a fiber containing a fusion splice only suffers strength degradation near or at the splice; a fiber end, stripped in preparation for making interconnects, will have localized damage. In these situations it is desirable to employ a test technique that has a uniform stress distribution so that the positioning of the defects in the apparatus is not critical.

2.2. Test Environments

Test techniques must be compatible with a wide range of possible test environments. Typical vapor environments extend from ambient up to 85°C, 85% humidity[4] or beyond. Fibers are often tested in liquids that might be encountered in service: strong acids and bases, biological liquids (*e.g.* blood or urine) and organic liquids including solvents, lubricants, fuels and hydraulic fluids. High temperatures are frequently used to accelerate testing; 90°C aqueous environments are common.

Extremes of temperature may be encountered; the strength measured in liquid nitrogen can be used to determine the inert strength of the fiber (σ_i in Eq. (1)) which is an important parameter in reliability models. Embrittlement of the coating usually requires its removal prior to testing. Polyimide coatings can withstand temperatures of up to 400°C and their performance at elevated temperatures can be assessed.[5]

Clearly, the test technique must be compatible with the appropriate test environment. The test equipment, and the fiber grips in particular, must either be stable in that environment or adequately insulated from it.

2.3. Fiber Diameter

While optical fiber for communications applications is almost exclusively 125 μm in diameter, other diameters are encountered in other applications. Optical fibers can range from ~10 μm diameter for imaging applications to ~1000 μm for power delivery. Since the force required to break a fiber (whether in tension or bending) depends on the square of its diameter, forces spanning several decades can be encountered.

2.4. Tested Length

The tested length is the length of the specimen that is subjected to significant stress. When a fiber is loaded in bending, only the outside of the bend is in significant tension so that the effective tested length may be substantially shorter than the specimen length. The strength of a fiber specimen depends on its length; a longer specimen is more likely to contain a large flaw and is therefore weaker. If the purpose of the strength testing is to determine the strengths expected in practice, it is desirable to match the tested specimen length with the length used in a given application. This is not always possible since lengths of practical interest can vary from about 10^{-1} to 10^{6} m. For other testing purposes, such as evaluating the influence of different coatings or environments on the fatigue, matching the tested length to the application length is less important.

The strength of long fiber lengths (greater than a few meters) is usually determined by the occasional extrinsic defect introduced during processing (manufacture, cabling, installation, repair, reconfiguration) while short lengths have strengths characteristic of the intrinsic properties of the fiber material. Long length strength therefore characterizes processing quality while short length strength indicates how much impact improvements in processing can potentially have on the long length strength. It can therefore be useful to measure the strength of short specimens, even for long-length applications.

2.5. Specimen Length

The specimen length is related to the tested length, but includes the additional length of fiber required for gripping. Clearly, if only short lengths of fiber are available then both the tested length and gripped length must be short and this can constrain the choice of test method.

2.6. Range of Loading Rates

When determining fatigue parameters by dynamic fatigue, it is generally considered that spanning at least three decades of loading rate is necessary to determine the fatigue parameter, n. Most test techniques can achieve this range of loading rates so that this consideration is not normally important.

2.7. Range of Failure Times

Static fatigue testing is normally used to determine fatigue behavior over very long duration. While most techniques can achieve several decades range in failure time, it is very useful to be able to conduct extended experiments for up to years or beyond.

2.8. Strength Range

Fiber strengths of interest generally extend from around 0.1% strain to failure (~50 MPa for silica) to 20% strain to failure (~14 GPa for silica). Below the lower limit the fiber is so fragile it can not be handled; the upper limit represents the theoretical strength of the material which can not be exceeded. Most techniques can not conveniently access the complete strength range. For such experiments to be feasible, compact and inexpensive equipment is required.

2.9. Precision

The precision of the test should match the scatter in the results. Scatter is usually characterized by the Weibull modulus, m, which is a measure of the width of the Weibull distribution;[6] the cumulative probability of failure by the stress σ is given by:

$$F(\sigma) = 1 - \exp\left[\left(\frac{\sigma}{\sigma_0}\right)^m\right]. \tag{4}$$

The dispersion of the data, defined as the ratio of the standard deviation to the mean, is related to the Weibull modulus by the approximation:

$$\nu = \frac{1.283}{m}, \tag{5}$$

which is adequate for $m \gtrsim 5$. Typical values of the Weibull modulus for fiber strength range from ~5 for weak fiber to 100 or more for pristine silica. Highly precise techniques are therefore required in order to accurately quantify the scatter in the strength (dynamic fatigue) of the high strength material.

The scatter in the time to failure in static fatigue experiments is known to be amplified over the scatter in strength by a factor approximately equal to the stress corrosion susceptibility parameter, n, whether the scatter comes from the fiber strength[7] or fiber radius fluctuations.[8] Since n is about 20 for silica, large scatter is encountered in static fatigue experiments and so high precision in timing is not required.

2.10. Number of Specimens Tested Simultaneously

Fatigue measurements require spanning decades in experimental duration so that the overall time taken for a fatigue measurement is dominated by the longest experiment. Industry standards typically require 25 to 30 specimens to be tested at each rate; it is therefore very useful to be able to test several specimens simultaneously in order to obtain data quickly and cost effectively. Additionally, if several specimens are tested simultaneously they experience identical loading and environmental conditions. Provided certain criteria are met, this means the scatter in the results is an intrinsic property of the fiber from which useful information can be extracted.[9]

2.11. Convenience and Simplicity

Convenience and simplicity are obviously desirable attributes of any test technique. They are particularly important in applications where equipment is used by unskilled operators.

2.12. Cost

Recent trends have been towards more extensive and detailed mechanical testing of optical fibers in order to justify reliability claims. The financial cost of such testing can be significant compared to overall costs and so should be minimized. Costs are associated with both equipment and personnel. Capital equipment costs may be high, particularly if equipment is not available commercially; in-house development can entail considerable cost, time and inconvenience. Operating costs are mostly associated with personnel. Since fatigue experiments can last days or more, it is necessary to automate the test so that minimal operator attention is required. Thus the ability to test many specimens simultaneously is also important for reducing costs.

2.13. Break Detection

Automatic detection of the time or load at which the fiber fractures is key to automating mechanical testing. There are several break detection techniques available and many testing techniques can use more than one. An important consideration is whether, when testing several fibers simultaneously, individual breaks can be resolved (*i.e.* whether two breaks close together in time produce two break signals) and identified (*i.e.* whether a break signal can be associated with a particular specimen). The philosophy of several test techniques is that specimens tested simultaneously are subjected to essentially identical loading so that it is not necessary to know which particular specimen broke.

Optical Break Detection

Fracture of optical fibers can be detected by determining when optical transmission is lost. This is perhaps the most versatile but least convenient technique. Individual breaks can be both resolved and distinguished. However, the technique can be costly since individual circuitry is required for each specimen (though either or both the light source and detector can be shared between several specimens); it is also inconvenient since long tails of fiber need to be taken from the test equipment to the optical source and detector. While suitable components for constructing such a system are available, a complete system is not commercially available.

Acoustic Break Detection

The release of elastic energy when the fiber breaks produces a pulse of acoustic energy. Often the most convenient break detection system is based on detecting this acoustic energy by placing a suitable transducer close to the fibers.[10,8] The acoustic signal typically peaks in the 10 kHz to 1 MHz band (depending on the acoustic sensor, the test environment and the fiber strength and diameter) so that filtering the acoustic signal reduces sensitivity to ambient noise. Suitable purpose-designed instruments are available commercially.

The acoustic signals of two fibers breaking overlap if they are less than a few tens of ms apart so that acoustic detection is not suitable for testing multiple specimens simultaneously at high loading rates; though the technique is useful at low loading rates (*i.e.* the overall rate controlling experiments). However, the inconvenience of having to test specimens individually when using high loading rates is more than offset by the overall convenience of the technique.

A particular specimen can not conveniently be identified by its acoustic signal so that all specimens must be under effectively identical load when testing several simultaneously. Acoustic break detection is not suitable when the acoustic signal strength is at or below ambient noise levels: it is therefore not suitable for testing in vacuum, or when testing very weak (< 20 MPa) or very thin (< 20 μm diameter) fibers.

Force Break Detection

The force applied to a fiber falls to zero at fracture; this can be employed to detect failure by monitoring the output of a force transducer (strain gage) attached to the loading system. Alternatively, failure can release a weight which stops a clock.[11] The limitations of this technique are similar to those of acoustic detection. Force detection, except for tensile testing, is less convenient than acoustic detection.

Visual Break Detection

The above break detection techniques may not be suitable for very thin, very weak or optically opaque fibers. Under these circumstances fiber breaks can be detected visually, but this requires considerable operator alertness. Limited automation can be achieved by videotaping an experiment. Visual inspection is extremely useful, however, in very long term static fatigue experiments. As described above, time to failure need not normally be accurately determined and an error of a day in experiments lasting months is adequate. For such experiments it is only necessary to count the number of surviving specimens on a daily basis. A single acoustic detection system can monitor many experiments simultaneously. When a break occurs, the operator need only determine from which batch the failure originated.

2.14. Modeling Practical States of Stress

In practical use, fiber can experience a variety of states of stress including pure tension, bending and torsion. The strength of a specimen depends on the state of stress because it is controlled by flaws distributed in size, but of more relevance here, distributed in orientation and position. Test techniques that closely model practical states of stress provide direct functional data. The results from techniques that have a different state of stress need to be corrected before they can be interpreted.

3. UNIAXIAL TENSION

The conceptually simplest, and perhaps most common test technique, is uniaxial tension in which the ends of the fiber are pulled in a direction coaxial with the fiber. The state of stress on the fiber is uniform simple tension. Gripping is a major concern to this technique and some common methods are shown in Fig. 1. The most reliable and widely used technique is to wrap two or three turns of fiber around a capstan (Fig 1a). The capstans are covered in a compliant rubber layer which smoothes any stress discontinuities and gradually transfers stress from the fiber. The capstan diameter should be large enough so that bending stresses are negligible. Slip necessarily occurs between the capstan and the fiber during loading so that only fiber coated with a reasonably strong polymer can be successfully tested. Typically, approximately 0.5 m of fiber is needed to wrap around both capstans so that short specimens can not be tested with this gripping system.

A variety of techniques can be employed for gripping short specimens (Figs. 1b to 1d). Rubber faced pneumatic grips can be used with coated fiber (Fig. 1b) but strong fiber can only be tested if the coating is strong and if there is

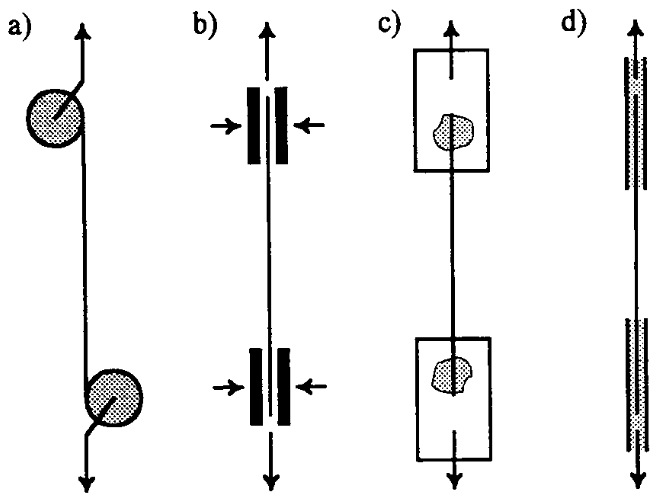

Fig. 1. Common methods for gripping tensile test specimens.

sufficient friction to avoid slipping. Alternatively, specimens can be glued to card tabs (Fig. 1c); the tabs can then be held in conventional grips. Finally, the fiber can be glued inside hypodermic needles which protect them from the gripping forces (Fig. 1d). For all these techniques it is important that the load train and fiber be accurately aligned in order to avoid preferential failure in bending where the fiber enters the glue or grips. All the fixtures in Fig. 1 are available commercially or are readily constructed.

For strength (dynamic fatigue) measurements, the load can be applied to the fiber by attaching the grips to the crosshead of a tensile test machine that is commercially available from several sources. The failure stress is calculated from the failure load which is measured by a load cell. Alternatively the failure stress can be calculated form the elastic modulus and the failure strain. Note, however, that the failure strain should ***never*** be deduced from the crosshead movement since the load train and grips have significant compliance. If required, the failure strain should be measured directly using displacement transducers attached to the specimen.

The tensile test is relatively inconvenient for several reasons. Only one specimen can be tested at a time using commercially available equipment though systems testing up to ten simultaneously have been constructed. This effectively limits the failure times to hours for dynamic tests and days for static tests. Application of the test environment can be a problem since the severest environment in which the apparatus can be immersed is a humid non-condensing atmosphere of moderate temperature (≲50°C). Alternatively, the central test section can be sealed in the test environment, as shown in Fig. 2.[12] A wide variety of test environments can be applied but only provided that the fiber is

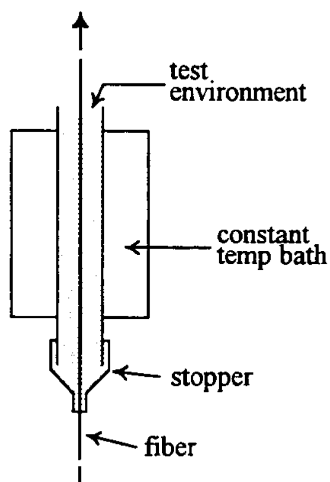

Fig. 2. Apparatus for applying liquid test environments to tensile static fatigue specimens (after Ref. 12).

weaker in that environment than in the ambient environment around the grips.

Static fatigue testing is normally accomplished by wrapping the fiber around capstans, as in Fig. 1a, and then hanging dead weights from the end of the capstans.[13] This technique suffers the same difficulties as the dynamic test, and in particular, the test environment must be more aggressive than ambient.

Despite these difficulties, tensile testing has some unique attributes. The tested length can be typically from 10 mm to 10 m or even up to 10 km using special apparatus (see below). Thus, the tested length is substantially longer than in any of the bending techniques and more nearly matches the length of fiber in many practical applications. Since, unlike bending, the stress is uniform, the tensile technique is particularly appropriate for specimens that do not have a uniform flaw distribution, such as splices, connections and fiber ends. Fiber ribbons can be tested in tension, but each fiber should experience the same tension for the results to be accurate.[3]

The precision of tensile tests is determined by the analog load cell used to measure the failure load and so may be marginal for determining strength variability of fibers with the lowest scatter. The technique is unsuitable for the strongest and thickest fibers since the polymer coating can not withstand the high loads necessary to produce failure. The technique is costly, especially per fiber, and the apparatus is bulky.

To summarize, while the tensile technique is the least convenient of the techniques discussed in this article, it is the only technique that is available for some purposes and specimen types.

3.1. Variants of Tensile Testing

Modifications of the tensile test technique have been described in the literature that either extend or improve some aspect of the technique. This usually bears some cost. Glaesemann and Walter[14] describe an apparatus (Fig. 3) based on a standard proof test machine, in which ~20 m of fiber is loaded to a certain stress (typically 2 to 3 GPa) by a pulley and load cell shown to the right of Fig. 3. If the fiber fails, its strength is recorded and the fiber is re-threaded into the machine. If the fiber does not fail, the proof test machine feeds another 20 m section of fiber. By continuously testing sequential lengths in this fashion, the strength statistics for multi-kilometer lengths can be directly determined. The results are important parameters for insertion into current reliability models (*e.g.* Hanson[15] or Griffioen[16]). Disadvantages of the technique are that the apparatus is costly, consumes large quantities of fiber and can only test in environments close to ambient. However, these inconveniences are compensated for by the unique capabilities of this test.

Björkman and Svensson[17] describe an "expander" technique in which several meters of fiber are wound around a drum and clamped to it with sheet

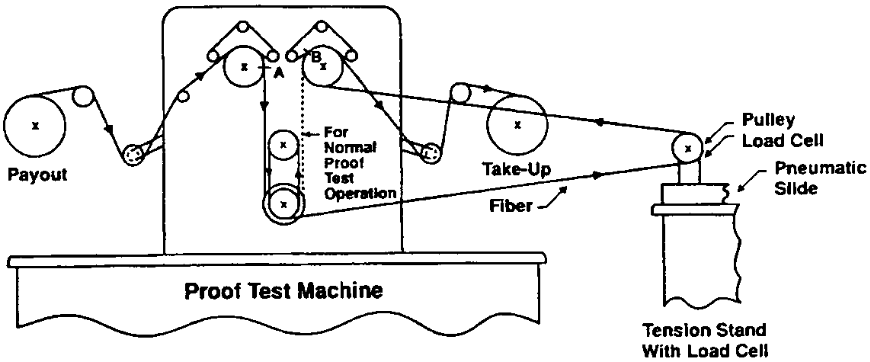

Fig. 3. Apparatus for measuring the strength distribution of long fiber lengths (after Glaesemann and Walter[14]).

rubber. The drum is then expanded by pushing apart the components from which it is made. The expansion puts the fiber under uniaxial tension because the drum is sufficiently large that bending stresses are negligible. When the fiber breaks, the fracture ends are held in place by the rubber clamping so that stress is only relieved along a short length of fiber; loading continues and subsequent breaks can be recorded. The test can therefore be used to produce 30 to 60 breaks in a single specimen in a "single shot." Analysis of the results requires somewhat different, though no less convenient, techniques; for N breaks the test measures the N weakest defects in a single long specimen; the normal tensile test measures the weakest single defect in each of N separate specimens. While the expander technique can generate fracture statistics very much more quickly than the standard tensile test, it is relatively complex and expensive equipment that requires careful calibration and which is not yet commercially available. Additionally, testing is limited to ambient conditions because of the nature of the clamping system.

Svensson and Sundberg[18] describe a modification of their expander apparatus for static fatigue in which the fiber is wrapped around a cylindrical former which is expanded more at one end than the other. The fiber then experiences a range of stresses along its length. Provided the scatter in the strength of the fiber is small, then the scatter in the times to failure measured in this apparatus depends on the distribution of applied stress. By a suitable semi-empirical analysis Svensson and Sundberg[18] show that the fatigue parameter, n, can be extracted from the data. Effectively, a complete fatigue experiment over a range of stresses is performed in a single test. The convenience is countered by the limited range of applied stress accessible in a single test; the technique has the same limitations upon usable test environments as the standard expander.

3.2. Torsion

In all the test techniques discussed so far the state of stress in the fiber has been uniaxial tension; even in pure bending the stress is uniaxial but varies in magnitude from tension to compression across the section of the fiber. However, in practice a fiber might experience some twist which results in a shear component to the stress. If a fiber of length l is twisted about its axis through an angle θ, the fiber is subjected to pure shear which varies linearly from zero at the center of the fiber to a magnitude:

$$\tau = G\frac{\theta d_f}{2l}, \tag{6}$$

at the outside of the fiber, where d_f is the fiber diameter and G (= $E/2(1+\nu)$, where ν is Poisson's ratio) is the shear modulus of fiber. A long thin fiber can not be subjected to shear alone since it would experience an elastic instability; it would buckle and coil up into a helical shape. Therefore, some axial tension must be applied to suppress this behavior. The effect of torsion on strength has therefore been limited to determining the combined effects of tension and torsion. Test techniques are therefore based on the tensile test methods described above but in which the fiber has been twisted by a known amount before testing.

Brittle materials, and silica glass in particular, are relatively insensitive to shear stresses. Brittle cracks grow so as to orient themselves perpendicular to the maximum tensile stress. To a good approximation, the effect shear is therefore limited to its effect on the maximum tensile stress in the fiber surface, *i.e.* to the value of the biggest principal stress. Since the fiber surface is in a state of plane stress, the bigger of the two non-zero principal stresses is given by:

$$\sigma_1 = \frac{\sigma}{2} + \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2}, \tag{7}$$

where σ is the axial tension and τ the shear stress. Although there are few published data on the strength in combined shear and tension, the shear appears to have a comparatively small effect except at very high twist.[19]

3.3. Proof Testing

The practical strength of fiber can be assured by proof testing. This involves loading the fiber up to some stress level, σ_p; fiber that survives this test must be at least as strong as σ_p. The purpose of the test is to remove the severest defects and this can only be performed successfully if the entire fiber surface experiences the proof stress. Therefore most current proof test machines stress the fiber in uniaxial tension. The apparatus of Glaesemann and Walter[14] (Fig. 3) shows such a machine; the fiber passes over a series of pulleys; two of which (A and B in Fig. 3) grip the fiber by flexible belts which stop the fiber slipping. The proof stress is then applied to the fiber by the lower center pulley. Brownlow[20] describes an modified method in which the lower pulley is fixed and the pulleys A and B in Fig. 3 are of different radii so that the proof stress results from the differential feed rates and depends on the ratio of the pulley radii.

Bending is not normally suitable for proof testing since half of the bent fiber is under compression and large flaws in this region will escape failure. However, France[21] describes an apparatus in which the fiber passes over four sets of rollers inclined at 45° to each other. The fiber bends in four different directions as it traverses the apparatus so that its whole surface experiences substantial tension. Therefore a weak flaw that survives the compressive zone in one bend will fail in tension in another bend. However, if the fiber twists as it passes through the pulleys there is a possibility that a weak flaw could escape detection. Twisting is possible if the fiber is not paid out or taken up carefully. Also, if the polymer coating deforms plastically or visco-elastically, then the fiber can become curved during its passage over the first pulley so that there is a tendency to twist as it passes over subsequent pulleys.

4. MANDREL BENDING

Mandrel or uniform bending involves wrapping the fiber around the outside of a precision diameter rod or mandrel (Fig. 4). The fiber is then subjected to uniform curvature and the maximum tensile stress on the outside of the bend is given by

$$\sigma = E\frac{d_f}{d_m + d_c}, \tag{8}$$

where E is the Young's modulus of the fiber and d_m, d_f, d_c are the diameters of the mandrel, the glass fiber (excluding the coating) and of the overall fiber (including the coating). Different stresses are achieved by using mandrels of different diameters; clearly the technique is only suitable for static fatigue testing. The ends of the fiber require careful clamp which can be achieved using an adhesive or mechanical clamp such as, for example, a heat-shrink polymer

a)

b)

c)

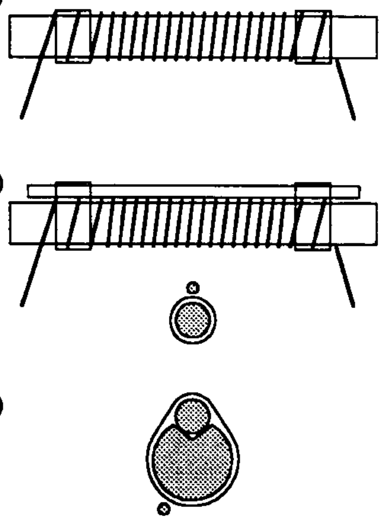

Fig. 4. Different arrangements for static fatigue by mandrel bending.

sleeve (Fig. 4a). Clamping a second rod onto the side of the fibers (Fig. 4b) effectively isolates each turn which then becomes a separate specimen so that adequate statistics can be obtained from one winding. Clamping stresses can cause premature failure but this can be avoided using double mandrels (Fig. 4c).[22]

The main advantages of mandrel bending are its compactness and ease of use. An effective tensile test length, l_e, can be defined for any technique which is the length of fiber that would have to be tested at the same stress in tension to give the same time to failure for static fatigue. Matthewson and Kurkjian[8] show that if the tensile failure time follows a Weibull distribution with shape parameter, m_t, then the mandrel data are also Weibull with the same shape parameter. In addition, they showed that the mandrel bend effective test length, l_m, for a winding of length l is given by:[8]

$$l_m = l\frac{\Im(nm_t)}{\pi}, \tag{9}$$

where n is the stress corrosion susceptibility parameter and $\Im(x)$ is the definite integral defined by

$$\Im(x) = \int_0^{\pi/2} \sin^x \xi \, d\xi = \frac{\pi^{1/2}}{2}\Gamma\left(\frac{x+1}{2}\right)\Big/\Gamma\left(\frac{x+2}{2}\right), \tag{10}$$

where $\Gamma(x)$ is the well-known gamma function. The Weibull modulus for the failure times is related to the Weibull modulus for the strength, m, by $nm_t \approx m$.[7,8] Using typical values of $n = 20$ and $m = 100$ gives an equivalent test length of ~40 mm for 1 m of fiber wound on the mandrel; only some 4% of the fiber is under substantial stress.[8] While this is short compared to the tensile test, it is substantially longer than for other bend techniques.

The principal disadvantage with mandrel bending is difficulty with adequately gripping the ends of the specimen. Premature failure at the gripped section can occur due to chemical attack by the adhesive or localized stresses at a mechanical clamp. Whatever gripping scheme is used must be stable in the test environment; any slippage can slacken the windings and reduce the applied stress. This technique is therefore not always usable in harsh environments or at high applied stresses. Uniform tension can be superimposed upon the bending stresses if the winding tension is too high or if the fiber coating swells due to absorption of certain species from the environment; such tensile stresses should be minimized since they are not measurable and so can not be compensated for.

The mandrel bend technique is not suitable for bare fiber, which would be damaged by contact with the mandrel, nor for short lengths of fiber, nor for fibers with non-uniform flaw distributions, such as a fiber splices. There is no dynamic equivalent to mandrel bending for making strength or dynamic fatigue measurements (with the exception of the crude technique described below).

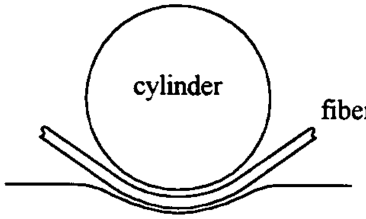

Fig. 5. Schematic of the mandrel bend strength measurement technique (after Hillig[23]).

4.1. Variants of Mandrel Bending

Hillig[23] describes a method for measuring the strength of short fiber lengths by placing them on a compliant elastic base and pushing cylinders of sequentially smaller diameter against the fiber (Fig. 5). The elastic base deforms during loading thus allowing the fiber to conform to the surface of the cylinder. Eventually, for a sufficiently small cylinder, the bending stress exceeds the strength of the fiber and failure occurs; the failure stress is then bounded by two values defined by the diameters of the two smallest cylinders used. While this technique is extremely crude, it is easy to use and is very useful if only very short lengths of fiber are available.

5. TWO-POINT BENDING

In two-point bending, a short length of fiber is bent double and held between two faceplates (Fig. 6). Usually the fiber is accurately located between the faceplates by grooves. In its dynamic form the two faceplates are brought together until failure occurs. A manually operated system was first described by Murgatroyd[24] but the technique can readily be automated using a computer controlled motorized translation stage.[25] The bending stress that the fiber experiences has a maximum magnitude of

$$\sigma = 1.198\frac{E d_f}{d - d_c} \tag{11}$$

where d is the faceplate separation, d_c is the overall coating diameter (d–d_c is the distance between the centers of the two arms of the fiber) and d_f is the diameter of the glass fiber. The fiber strength is calculated from the faceplate separation at failure. The bending stress falls away from the center of the bend and is nominally zero where the fiber contacts the faceplates.[10] This is a key attribute of the technique; the stresses are zero where the fiber is gripped so that the gripping problems encountered with the other techniques present no difficulty here. In fact, by using carefully polished faceplates it is possible to measure the strength of bare fiber with this technique.[10] Many specimens can be tested simultaneously by using faceplates with many accurately machined grooves and equipment is commercially available that can test up to 30 specimens at once.

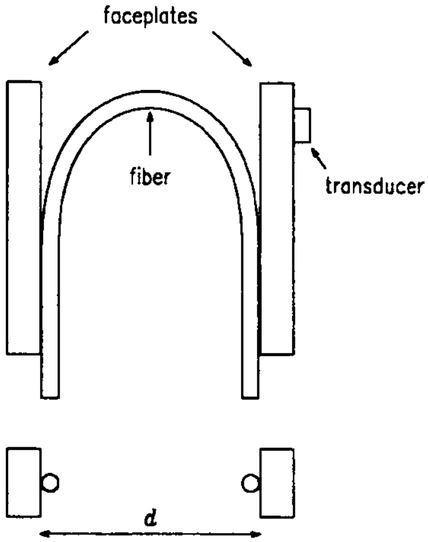

Fig. 6. Schematic (plan and section) of the two-point bend apparatus.

In its simplest implementation, the faceplates are brought together at a constant velocity. However, differentiation of Eq. (11) shows that at constant velocity, $\dot{d}$, the stress rate, $\dot{\sigma}$, is constantly varying. In such an experiment, the fatigue parameters are calculated using somewhat different equations.[26] Alternatively, by using a continuously varying step rate for the stepper motor driven faceplates it can be arranged that the fiber experiences a constant stress or strain rate.[27,28] It has been verified that the fatigue parameters are independent of whether faceplate velocity, strain rate or stress rate are held constant.[29] However, for direct comparison between the results of two-point bending and other techniques, the measurements should be made at a constant stress or strain rate.

The two point bending technique is particularly useful for static fatigue experiments. In this case the fibers can be inserted into precision bore glass tubes[30,8] or between accurately parallel plates; in either case 30 or more fibers can be tested simultaneously. The test fixtures are compact, simple and, if glass tubes are used, inexpensive.

A wide range of fiber diameters can be accommodated in two-point bending and strength measurements have been successfully made by the author on 10 μm diameter ceramic whiskers and 1000 μm diameter high strength silica fiber.[31] The force required to break the fiber in bending is substantially lower than is required in tension (their ratio is $\varepsilon_f/8$ for a cylindrical fiber with a failure strain ε_f, *i.e.* the force is typically more than 100 times lower) so that the largest fibers can be broken. A broad range of fiber strengths can be determined ranging from the highest ~14 GPa for silica fiber in liquid nitrogen[32] down to reasonably low strength. Since the fiber must be loaded into the apparatus under some stress, the lowest measurable strength is determined by the size of the apparatus. While arbitrarily weak fiber can be tested with arbitrarily large apparatus, it is more convenient to use a complimentary technique such as four-point bending (see below) for the weakest specimens. However, for equipment with a maximum faceplate separation of 50 to 100 mm, the minimum measurable strength is ~500 MPa for 125 μm diameter silica fibers.

The effective tested length in two-point bending is short since the fiber is only under significant stress at the outside of the tip of the bend. Matthewson *et al.*[10] showed that if the strength in tension follows a Weibull distribution with shape parameter m, then the strength in two-point bending follows a Weibull distribution with shape parameter $m - 1$ and that the effective tensile test length, l_2, (the length of fiber tested in tension that gives the same strength as the same fiber tested in two-point bending) is, to a good approximation, given by:[10]

$$l_2 = \left\{ \frac{d_f}{\pi \varepsilon_f l_0^{1/m}} \Im(m) \Im\left(\frac{m-1}{2}\right) \frac{\Gamma^m(1+1/m)}{\Gamma^{m-1}(1+1/(m-1))} \right\}^{\frac{m}{m-1}}, \qquad (12)$$

where ε_f is the strain to failure of a tensile specimen of length l_0. Given typical values of $\varepsilon_f = 5\%$, $l_0 = 1$ m and $m = 100$ for a high strength silica fiber, l_2 is about 20 μm but for weaker fiber ($\varepsilon_f = 0.5\%$, $m = 5$) the length is ~1 mm. For static fatigue the equivalent expression is:[8]

$$l_2 = \frac{d_f}{\pi \varepsilon_f l_0^{1/m}} \Im(nm_t) \Im\left(\frac{m_t - 1}{2}\right), \qquad (13)$$

where m_t is the Weibull modulus of the failure times measured in tension. Given that $nm_t \approx m$,[7,8] the previous numbers and $n = 20$ again gives l_2 is about 20 μm for high strength silica and 1 mm for weak material.

The short test length in two-point bending means that it can not be used to determine the practical strength of relatively long lengths of fiber since occasional extrinsic weak defects usually control long-length strength. Additionally, since the stress field along the fiber is non-uniform it is not a suitable technique for measuring the strength of specimens with a non-uniform flaw distribution, such as splices.

Despite these drawbacks, two-point bending is the most convenient test technique; equipment is comparatively inexpensive for both capital and operating costs. The simplicity of the gripping system and its compactness makes the technique useful for the broadest range of test environments, ranging from liquid nitrogen to hot gases and liquids. The faceplate separation can readily be determined accurately so the technique has high precision. Some systematic error can result from poor faceplate alignment or deformation of the polymer buffer coating. However, random errors are small leading to excellent reproducibility.

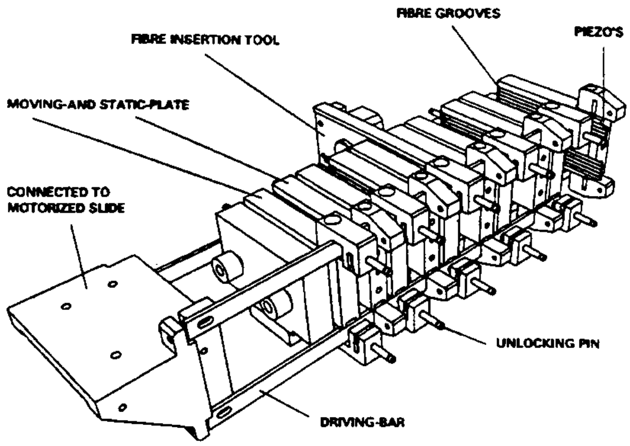

Fig. 7. Schematic of the apparatus for testing several groups of fibers sequentially (after Griffioen[33]).

5.1. Variants of Two-Point Bending

Griffioen[33] describes apparatus in which several groups of fibers can be loaded simultaneously in two-point bending (Fig. 7). Initially, one group is loaded to failure, after which the faceplates for that group are disengaged and the next group are loaded at a different loading rate and so on. In this way many fibers can be tested at several strain rates in a single experiment. This is particularly convenient for experiments which require long equilibration times before testing, such as testing in vacuum. The price of this convenience is the complexity of the apparatus.

Sinclair[34] describes a bending method in which the fiber is twisted into a loop (Fig. 8a); the ends of the fiber are pulled until the fiber breaks by bending in the loop. Sinclair showed that the breaking stress is inversely proportional to the width of the loop, D. Substantial torsion must be applied to strong fiber to avoid the loop untwisting. Eitel and Oberlies[35] tie the fiber into a knot (Fig. 8b) which restrains the loop from unwinding. The stress distribution is then approximately

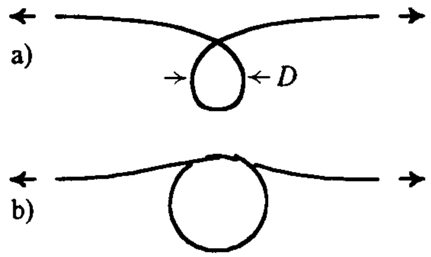

Fig. 8. Schematic of (a) the fiber loop and (b) the fiber knot tests.

uniform bending. These two techniques are crude and not particularly accurate, but they are very simple and require little in the way of apparatus except for a ruler in front of which to perform the experiment.

Two-point bending can be used to make optical bending loss measurements.[36] Standard techniques involve wrapping fiber around mandrels of various diameters which is labor intensive. In contrast, two-point bending can be automated allowing large quantities of data to be taken with little operator intervention. The technique is highly accurate enabling loss to be determined for very small curvature changes. As a result, certain interference effects have been observed that are not resolvable using mandrel bending.[37]

6. FOUR-POINT-BENDING

Fig. 9 is a schematic of the four-point bend apparatus for strength measurement in which the specimen is supported by two outer pins and then pushed in bending by the two inner loading pins. The technique has been widely used to measure the strength of glasses and ceramics by determining the force applied to the loading pins that produces failure. The technique has recently been successfully applied to testing optical fibers.[38,39] For this application the high specimen compliance means that the applied force is small while the specimen deflection is large; the pin movement, *d*, required to produce failure is therefore used to determine the failure stress:

$$\sigma = E\gamma\frac{3dd_f}{8a^2} \tag{14}$$

where d_f is the fiber diameter and a is the pin spacing. The factor γ is a factor of order unity which corrects for the finite deflection (*i.e.* d/a not small) leading to nonlinear bending. Fig. 10 shows γ as a function of d/a. While γ depends to some extent on friction between the fiber and pins, the effect is usually small.

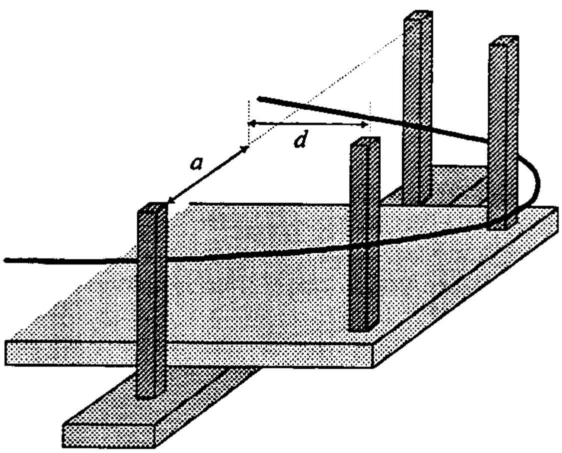

Fig. 9. Schematic of the four-point bend apparatus.

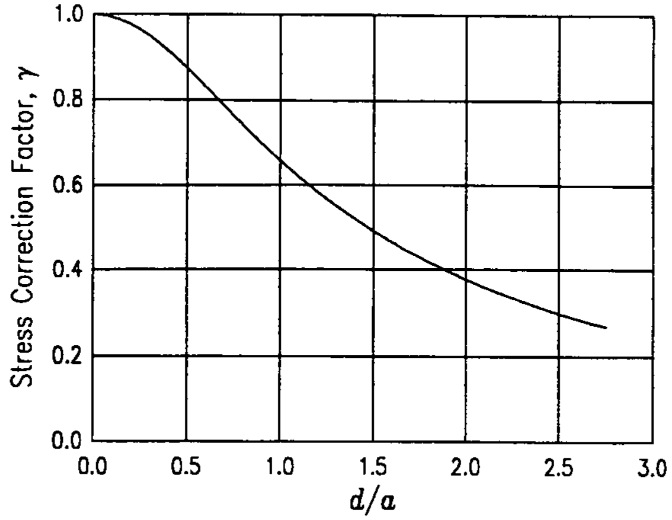

Fig. 10. Correction factor for nonlinear four-point bending, γ, as a function of the normalized pin displacement, d/a.

Nelson *et al.*[38] describe a simple technique for making *in situ* measurements of μ so that frictional effects can be accounted for.

The main advantage of four-point bending is that the fiber can be loaded into the pins under zero stress so that arbitrarily weak specimens can be tested. However, the applied stress is limited since strong fibers can be pushed through the support pins without failing. In these respects, the technique compliments two-point bending; using both techniques the strength of fiber has been found through the entire strength range of interest with both techniques giving the same results in the region of overlap.[31,40]

The attributes of four-point bending are very similar to those of two-point bending; indeed the dynamic apparatus have much of the hardware and control software in common. Four-point bending is very convenient to use; by mounting the support and loading pins at one end, the fiber can easily be immersed in a wide range of test environments. Also, many fibers can be tested simultaneously. The technique has been successfully used to break not only weakened silica,[31,40] but also heavy metal fluoride[41,42] and crystalline sapphire fibers.[43,44] The effective test length is typically of the order of 1 mm[39] and is comparable to two-point bending (Eq. 12 gives $l_2 = 0.9$ mm for a weak fiber with $\varepsilon_f = 0.5\%$ and $m = 5$).

6.1. Variants of Four Point Bending

Griffioen[45] describes a version of four-point bending in which the support and load pins are mounted on two meshed gears (Fig. 11). The fiber is bent by

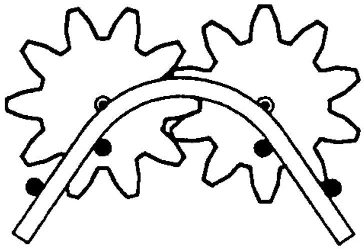

Fig. 11. Alternative method of loading fiber in four-point bending (after Griffioen[45]).

rotating the two gears. By careful choice of the positions at which the pins are mounted, it can be arranged that the length of fiber in the center section is almost constant as the fiber is loaded, and that the bending stress is almost uniform between the loading pins. This technique neatly avoids the necessity of correcting for nonlinear bending. However, the pin placement depends on the fiber diameter so that several fixtures would be needed for testing fibers of different diameters.

Three-point bending is a similar technique to four-point bending except that the two inner loading pins are replaced by one central pin. The advantage of this technique is the simpler apparatus that is easier to align. However, the stress distribution is non-uniform and has a maximum at the central loading pin. At this position the contact stresses between the pin and the fiber are superimposed on the bending stresses so that the exact stress in this position is not well know. Pukh *et al.*[46] describe a three-point bend apparatus for testing strong fiber constructed from three sharp edges with the outer supports separated by 1.1 mm when testing ~100 μm diameter fiber. They find results that are apparently consistent with other techniques. However, measurements made using this apparatus on bare fiber, either drawn and not coated[47] or stripped in hot sulfuric acid,[48] give low results with unusually large scatter. Although Baikova *et al.*[47] attribute this to atmospheric effects, what is more likely is that the supports are damaging the fiber surface. The technique is therefore not trustworthy for bare fiber and may not be usable for some coated fibers since the high contact stresses generated by having the supports so close together could penetrate the coating and damage the fiber.

7. NON-LINEAR ELASTICITY

Tensile testing imposes a force on the fiber and so measures the failure stress, while bending imposes a deflection on the fiber and so determines the failure strain. In order to compare results of the two techniques it is often necessary to convert strain to stress or *vice versa* via the elastic modulus, E. The elastic modulus of fused silica is dependent on strain, usually represented by a power series relation.

$$E = E_0\left(1 + \alpha\varepsilon + \beta\varepsilon^2\right) \tag{15}$$

where E_0 is the elastic modulus at zero strain (72 GPa). Direct measurements of stress and strain give estimates of $\alpha = 3$ but are not accurate enough to give meaningful values of β.[49,50] More sensitive acoustic measurements have been made in the range of 0 to 6% tensile strain by Krause *et al.*,[51] from whose data it can be deduced that $\alpha = 3.2$ and $\beta = 8.48$. The modulus increases with strain because α is positive, but somewhere above 6% strain the modulus must decrease again since, at the ultimate strength of silica, the tangent modulus ($d\sigma/d\varepsilon$) is zero. Eq. (15) therefore becomes invalid at high strain since β is positive. Therefore there is always some uncertainty in comparing the strengths of high strength silica (>6% strain to failure) measured in tension and bending.

Griffioen[50] measured the elastic modulus non-linearity, α, for compressive as well as tensile stresses and found that α is positive throughout. This means that the elastic modulus is an asymmetric function of strain so that the stress distribution across a bent fiber is also asymmetric about the center of the fiber. This causes a shift in the position of the neutral axis which reduces the maximum tensile strain. This effect can be accounted for by modifying Eq. (15) for two-point bending:

$$E = E_0\left\{1 + \left(\frac{3}{4}\alpha - \frac{1}{8}\right)\varepsilon\right\}. \tag{16}$$

(A similar analysis by Suhir[52] produced an erroneous result since in his calculations he considered the tangent rather than the secant modulus.) Griffioen[50] uses this result to evaluate the effect of the nonlinearity on the measurement of the fatigue parameters using various techniques. While Griffioen ignored the second order term proportional to β in Eq. (15), it is not significant in this context since it is symmetric in strain.

8. TECHNIQUE SELECTION

The choice of test technique for a given fiber is obviously the most convenient technique that provides the required results. The bending techniques are generally more convenient to use than tensile testing; they are compact, have relatively low costs (both capital and operating) and often many specimens can be tested simultaneously. Bending usually requires only small quantities of fiber and is usable with a broad range of test environments. Bending is therefore the technique of choice for all circumstances except where the drawbacks are important. The short test length means that tensile testing must be used for obtaining long-length strength statistics; while the non-uniform stress field obtained in bending is not usually useful for specimens with non-uniform flaw distributions. Therefore, such specimens (fiber splices, for example) are best tested in tension.

The various test techniques are the subject of several standard test procedures published by both national and international bodies. The reader is referred to the article by Yuce and Kapron[53] for information current at the time of writing.

9. SUMMARY

Table I summarizes the main attributes of the principal test techniques; tension, mandrel bending and two- and four-point bending. The two-and four-point bending techniques compliment each other in their accessible strength ranges; however, in other respects they are very similar and so have been combined. Note that the parameters listed for all the techniques are values readily accessible with standard equipment. Specially made equipment can often extend the capabilities. The reader should consult the text for more detailed descriptions of the capabilities of each technique.

Table I. Summary of the main attributes of the various test techniques.

	Tension	**Mandrel**	**2/4-Point Bending**
Principle use	Assess processing quality.	Coating and environmental effects. Static only.	Coating and environmental effects
Other uses	Low failure probability in bending	Optical bending loss measurements	Optical bending loss measurements
Gripping	Capstans, glue tabs, pneumatic grips	Full stress at grips	Zero stress at grips
Types of fiber:	Tested section weaker than gripped section	Coated fiber only	Most types
Bare	Center stripped section; only if weaker than coated section	No	Yes
Fiber ends	Yes	No	No
Splices	Yes	No	No
Ribbon	Yes	No	Yes
Test environments	Only those with test section weaker than gripped section. Inconvenient.	Any that the gripping system can withstand. Convenient.	Almost any. Convenient.
Fiber diameter	Up 200 μm for strong fiber	10 to 1000 μm	(2) 10 to 1000 μm (4) 0.1 to 10 mm

	Tension	**Mandrel**	**2/4-Point Bending**
Tested length	~1 m	Few mm per m	Strong: ~20 μm Weak: ~1 mm
Specimen Length	~1 m	1 m	30 mm
Loading rate range	Up to 1 GPa/s	Static only	Up to 1 GPa/s
Failure time range	Seconds to months	Minutes to years	Seconds to years
Strength range	Up to 10% strain	Up to 3% strain	(2) 1 to 20% strain (4) Up to 2% strain
Precision	Analog, good	Good	Relative: high Absolute: good
Number of specimens	1	Few (single) ~100 (double)	30+ per stress
Convenience	Poor	Good	Good
Cost: system	High	Moderate to low	Moderate to low
per fiber	Very high	Low	Low
Commercial availability	Yes	No	Yes
Break detection	Load	Acoustic	Acoustic

10. ACKNOWLEDGEMENTS

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