ANALYSIS OF THE FAILURE PROBABILITY OF AN OPTICAL FIBRE UNDER TENSILE LOADING

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ABSTRACT

The present paper deals with the study of the failure probability of an optical fibre when submitted to uniaxial loading. In our case, optical fibres should be used as embedded sensors to follow the mechanical response of a composite structure. This involves investigating the mechanical behaviour of the only silica optical fibres. The influence of optical or structural parameters (multimode or monomode, type of coating…) of fibres on the mechanical behaviour are then assessed. To do so, discussions on the grip system improvement performed in order to prevent fibres from sliding during testing are required. Finally, all previous results allow predicting the failure of the fibre by the way of a distribution of failure probability, using the Weibull statistics.

KEYWORDS: Optical fibre, mechanical behaviour, fibre coating, Weibull statistics

1. INTRODUCTION

The use of optical fibre for structural composite monitoring is closely related with the smart structure concept which emerged in the early 1990s. Smart structures describe mechanical and civil engineering structures that integrate a sensing system. This sensing system may help to identify structural wear, damage or deterioration.

Due to their versatility, robustness and easiness of integration, optical fibre sensors have rapidly been recognised as an ideal sensing tool for smart structures. Compared to conventional electrical sensors, the technology of the optical fibre sensors has the following advantages:

- Immune to electromagnetic interference (sparks, railways, high voltage lines),
- Chemically inert (does not corrode),
- Long term reliability,
- Weakly intrusive thanks to its small size,
- Resistant to nuclear and ionising radiations.

Due to their small size and generally permanent integration in the structure, optical fibre sensors are considered to be a non-destructive testing tool with low invasive effect. The integration of sensing elements such as optical fibres into composite structure presents additional advantages and challenges. The embedded sensors are protected by the composite material and can be installed during production, avoiding external installation.

But the mechanical properties of optical fibres [1, 2] are still quite unknown. An optical fibre can experience delayed fracture from the interaction with water and suffer reduced transmission as a result of macro-bend, microbend, and hydrogen diffusion. Moreover, these processes are intensified under harsh conditions and some others appear such as degradation of the coatings caused by water or corrosive chemicals. The presence of surface flaws or cracks, mechanically or chemically induced, reduces the strength of silica optical fibres. These flaws act as local stress concentrators under strain, resulting in a much lower tensile strength than the theoretical value of silica glass. Furthermore, the reaction of these flaws with moisture causes delayed fracture or fatigue of the fibre. We focus on the embedment of optical fibre in a composite [3] in order to use these optical fibres as strain sensors. It seems fundamental to assess the reliability and the average lifetime of these optical fibres. Also, it is necessary that optical fibres keep the same mechanical characteristics against environment attack. When we embedment an optical fibre into the composite structure and this structure undergo a strain, the behaviour of the optical fibre is quite unknown. That is the reason why we are interesting by the mechanical properties of optical fibre before embedment itself.

An optical fibre is made of silica (SiO_2) and a polymer coating. It consists of an inner cylinder with a diameter of a few micrometers (core) surrounded by an outer cylindrical layer of smaller refractive index (cladding), as seen in Figure 1. The refractive index difference ensures total reflections at the core-cladding interface, allowing for propagation of the light along the fibre. The coating is a protective layer applied over the fibre cladding during the drawing process to protect against environmental attack. The main role of the coating is to inhibit cracks growth from the surface flaws.

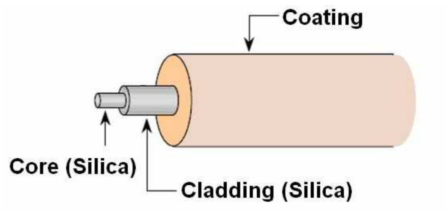

Fig. 1: A typical optical fibre, showing the component layers.

Optical fibres have usually a diameter of 125 µm. Silica (SiO_2) is a vitreous material with a Young's modulus of 72 kN/mm^2 and can withstand an elongation up to 2-8%. An elongation of 2% is by at least one order of magnitude higher than the maximal possible elongation of composite fibre. Silica fibres are therefore ideal as displacement sensors for composites structures.

Weibull probability

The most suitable and reliable law which allows describing the distribution of the probability of failure of optical fibre is the Weibull law [4]. It gives a relationship between the probability F of fibre rupture with a length L, σ_0 the Weibull scaling parameter and the applied stress σ:

$$\ln\left[\frac{1}{L}\left(\ln\frac{1}{1-F(\sigma)}\right)\right] = m\left(\ln(\sigma) - \ln(\sigma_0)\right)$$

A Weibull plot implies a ln-ln representation as expressed in the previous relation. The two parameters that characterize a Weibull distribution are the m-value and σ_0 which, respectively correspond to the curve slope and to the curve intersection with the stress axis.

The m parameter characterizes the defect size dispersion. A high m value indicates that along the fibre, dispersion of the defects size is low. A low m value reveals that the defects found at the fibre surface have varying sizes, which results in different values of the failure stress.

Assuming a group of M samples, the cumulative failure probability F for each of them is experimentally determined as follows:

$$F(\sigma_i) = \frac{i - 0,5}{M}$$

The failure stresses are listed in increasing magnitude as $\sigma_1 \leq \sigma_2 \leq \cdots \leq \sigma_I \leq \cdots \leq \sigma_M$

2. EXPERIMENTAL PROCEDURE

The strength of a glass fibre is determined by the weakest link theory [5, 6]. Subcritical crack exists on a glass fibre surface and the slow growth leads up to the breaking of the optical fibre. Several methods exist to characterize this breaking. There are the uniaxial tension and the 2 point bending mechanical test techniques. Here, we decide to use the most common one, it means the uniaxial tension test [7]. The ends of the fibre are pulled in a direction coaxial with the fibre. With this method, the fibre undergoes a uniform stress state. But gripping the fibre is a major concern. The most reliable and widely used technique is to wrap two or three turns of fibre around a capstan. The capstans can be cover with a rubber layer which smoothes any stress discontinuities. The capstan diameter should be large enough so that bending stresses are negligible. But the short specimens can not be tested with this gripping system.

Various techniques can be employed for gripping short specimens. It is possible to use a rubber faced pneumatic grips, or specimens can be glued to card tabs … But with these techniques it is necessary to have a sufficient friction with the fibre to avoid slipping fibre. For short specimens it is important that the load train and fibre be accurately aligned in order to avoid preferential failure caused by bending between fibre and grips.

For realize a mechanical test of failure, it is necessary to measure the strength. The fibre is hold by the grip at the crosshead of a tensile test machine. Then a load is applied to the fibre. The failure stress is calculated from the failure load which is measured by a load cell. The failure strain is deduced from the crosshead movement because it is very difficult to attach an extensometer at this fibre. We measure the displacement of the crosshead with an optical interferometer of Mach Zendher. Like thus we verify that the information of crosshead corresponds by displacement indicated by interferometer.

The load cell records the load at failure. The strain rate is described in terms of percent change in length per minute, relative to the gauge length. A standard method for tensile strength measurements is described in FOTP-28 [8].

None of the sub-mentioned grip methods allow preventing the fibre from sliding. The technique we used consists in combining previous different methods. The fibre is wrapped around a capstan, then fibre glued with this capstan and ends of fibre are held mechanically in the rubber. Doing so, the slide of the optical fibre is negligible.

We use a DMA Bose Electroforce 3200 device (Figure 2) with a cell load of 450 N. The lengths of our samples are fixed at 30 mm and silica is between 110 and 220 µm diameter. This test is realized at 0.02 mm/s. At least 20 specimens testing were required to be able to plot the Weibull distribution. Thanks to this method, we tested the strength of silica optical fibres.

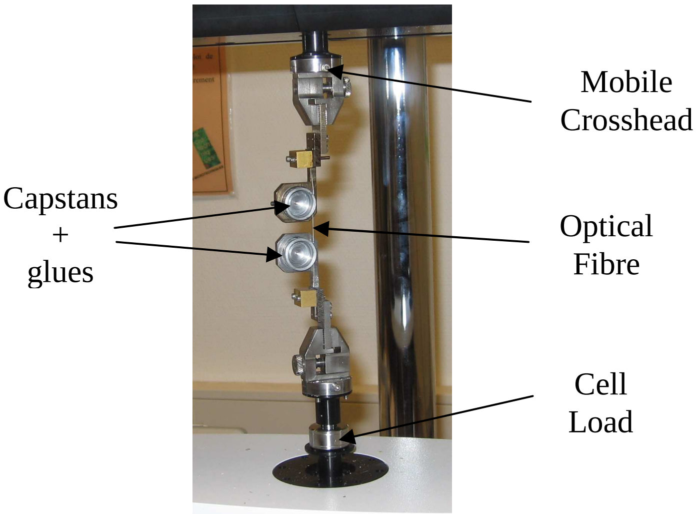

Figure 2: Testing grip technique

Experiments have been carried out on optical fibres coated with epoxyacrylate, ETFE and polyimide coatings. ETFE coating (Etylene tertafluoroethylene) is a fluocarbon-based polymer: a kind of plastic. Table 1 list depending on the tested fibre the manufacturer code, the geometry, the optical properties and the type of coating.

Optical Fibre	Type of fibre	Core (µm)	Cladding (µm)	Coating (µm)	Type of coating
SMF28e	monomode	8	125	250	acrylate
SMT-A1310H	monomode	5.8	125	155	polyimide
TCG-MA100H	multimode	100	110	140	polyimide
TCG-MA200H	multimode	200	220	250	polyimide
HCP-M0125T	multimode	125	140	250	ETFE

Tab. 1: Properties listing for each testing fibre

More specifically, Fibre 1 was a standard fibre for telecommunication with acrylate coating. This fibre is monomode with 125 µm diameter of silica and a 62.5 µm thick epoxyacrylate coating.
Optical fibers are covered with protective coatings to maintain the strength of the glass fiber. However, in the mechanical breaking test, only the silica part plays a role in the failure mechanisms.

3. EXPERIMENTAL RESULTS

A fibre can be viewed as a glass cylinder, between 110 and 220 µm in diameter having an infinite length with a distribution of surface flaws. Therefore the most severe crack controls the strength of the fibre. The strength of brittle materials (optical fibre) is determined by flaws or defects in the material, and the way in which these flaws grow. The mechanical behaviour of optical fibre is described by parameter such as the strength distribution. This parameter is originally a statistical parameter, and is described by a Weibull function.
Figure 3 shows two stresses versus displacements curves obtained with two different grip systems. The curve obtained with the so-called Standard Method illustrates the sliding phenomena that may occur when no care is brought to the grip technique.

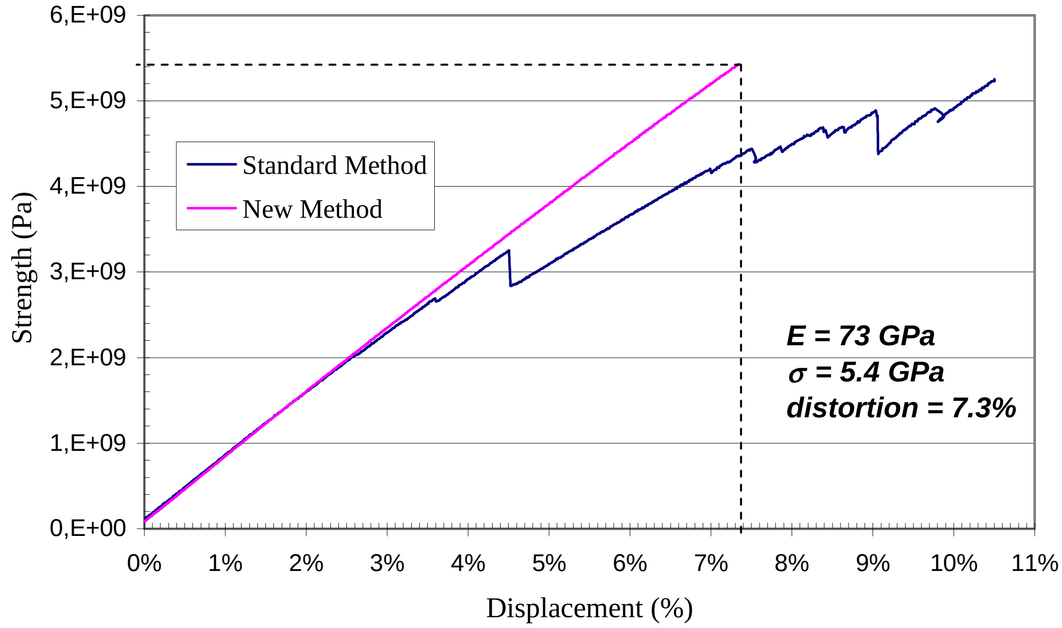

Fig. 3: Stresses versus displacements curves: effect of the grip system improvement.

The shock occurring at the sliding end decreases the strength of fibres. No slide is observed with the so-called New Method and the slope is linear which means the deformation is purely elastic. The fibre failure happens roughly. This is a characteristic of brittle materials.

The previous curve slope is consistent with a 73 GPa Young modulus, in accordance with the known theoretical value for silica. The fibre elongation is then 7.5 %.

The figure 4 shows fibre the failure probability distribution for the only SMF28e fibre. Such a plot allows predicting the failure of 70 % of optical fibres for an applied stress of 5.4 GPa. The trend for this distribution is quite the same for other fibres except for the magnitude and the slope; this is illustrated in next plot.

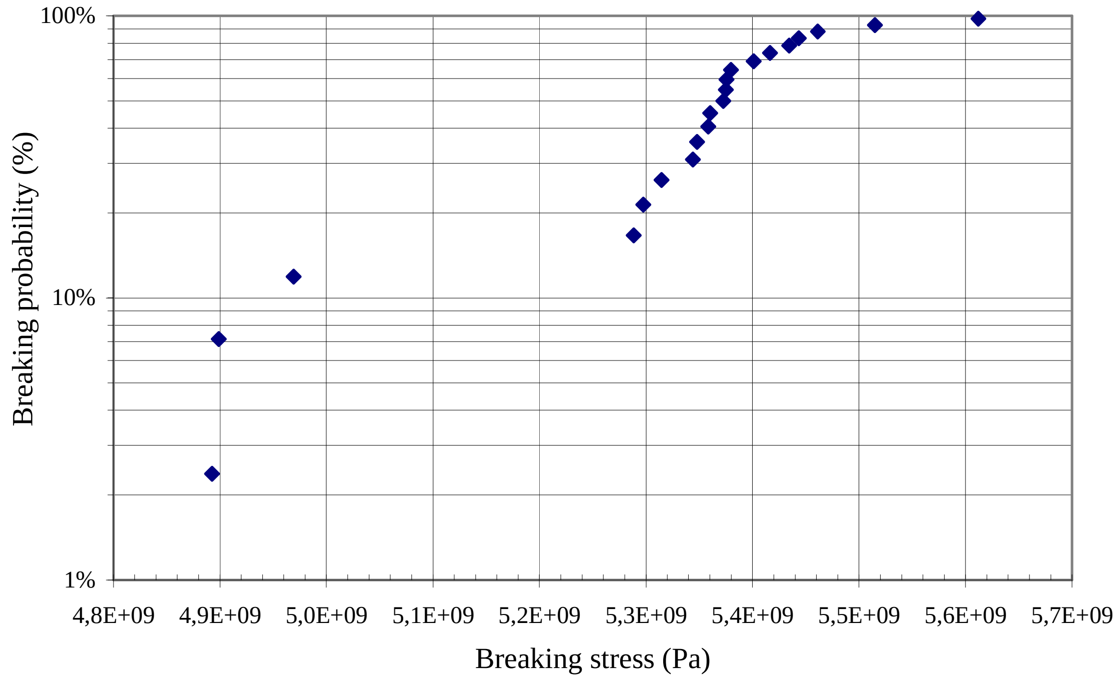

Fig. 4: Breaking probability of the optical fibre SMF28e (125 µm in diameter)

The Weibull distribution of strength is shown in figure 5 for five submentioned optical fibres.

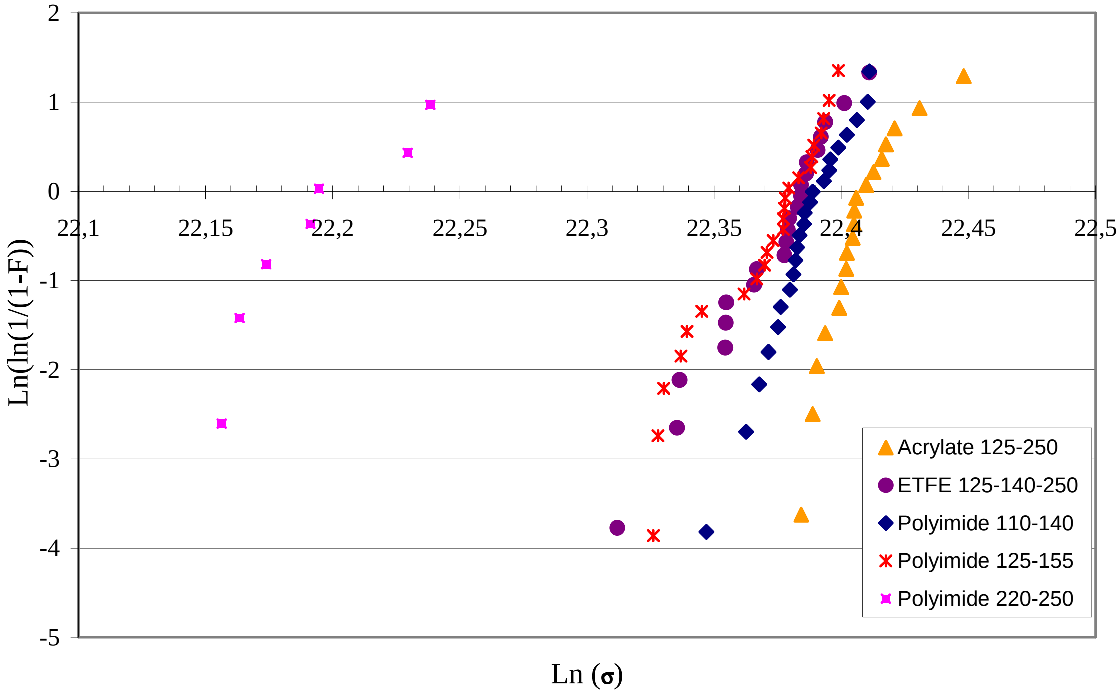

Fig. 5: Weibull distribution of the probability of failure for various types of optical fibres.

The Weibull modulus *m* is measured from the scattering in strength. Results are listed in Table 3. Weibull modulus is obtained from the slope represent on Weibull distribution and values of breaking stress are measured at 66% as show on figure 4. A fibre with a very broad distribution of strength reveals an out of control process and may have a Weibull slope less than 20. Alternately, a very tight distribution of breaking strengths will typically have a Weibull slope greater than 50.

Optical fibre	Type of Coating	Breaking stress for a 66% failure probability (GPa)	Weibull modulus *m*
SMF28e	Acrylate	5.4	73.89
SMT-A1310H	Polyimide	5.2	52.62
TCG-MA100H	Polyimide	5.3	79.84
TCG-MA200H	Polyimide	4.4	35.36
HCP-M0125T	ETFE	5.25	52.07

Tab. 3: Breaking stress for a 66% failure probability and Weibull modulus for five different optical fibers

Except for TCG-MA200H fibre, the breaking stress for 66% failure probability and the Weibull modulus are greater than 5 GPa and 50 respectively. Those results confirm the trend for which the breaking stress is lightly greater for an acrylate coating [9, 10]. As the only silica is involved in the failure mechanism, a monomode fibre has the same properties than a multimode fibre.

During tests a bad bonding strength between the silica and ETFE polymer is generally observed. When a fibre with this kind of coating is embedded into the composite structure, there is a bad strength transfer between the composite and the optical fibre. The way the strength is transmitted to the fibre is unknown.
For fibre 4 (TCG-MA200H) with a polyimide coating and a 220 µm diameter of silica, the stress level is lower. For the same specimen length, the bulk is probably bigger and probability of crack occurrence is then more important. A greater diameter involves an increase of bending stress at the grip level what probably initiate a surface flaw.

One of the most interesting results of this study deals with the identical response that is observed independently of the coating thickness. This is of prime interest in order to ensure a less intrusive influence of the embedded optical fibre.

The calculated *m* modulus is higher than the perfect silica modulus ($m = 30$). Various interpretations are proposed for this value [11, 12]. For instance, after surface observation, it has been suggested that the variation of mechanical strength is coming from diameter shift. For constant diameter, the strength of fibre will be identical. The varied breaking strength of silica fibre can be attributed to the distribution in flaw severity along the fibre length. Micro cracks can be inherent to the glass itself or a result of a manufacturing process of the fibre.

4. CONCLUSIONS

In this paper, attention is paid on the mechanical characterisation of optical fibres. The aim is to build sensors able to predict the coming failure of the structure in which the fibre is embedded. The reliability of such a sensing system should be first studied. This has been done using the Weibull law which gives the distribution of the failure strength.
Moreover, this study allows predicting a coating independent strength magnitude failure. The maximal strength is near 5.4 GPa whatever the coating is, for a given silica diameter.
It is worth to notice that the failure elongation of optical fibres are 7.5 % that is suitable in case of a composite structure (failure strain of carbon fibre is no more than 3%). Moreover, it is convenient to use optical fibres with a small diameter in order to reduce intrusion effects.
Some additional experiments are now going to be carried out in order to quantify the effect of the embedment of the fibre on a composite structure.

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