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Failure of nano-structured optical fibers by femtosecond laser procedure as a strain safety-fuse sensor for composite material applications

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ABSTRACT

As shown in a previous paper (Delobelle et al. (2013)) if synthetic flaws are generated on the surface or in the core of optical fibers thanks to single-shot femtosecond laser procedure, the rupture strength of these modified fibers can be controlled.

In this paper, numerous new experiments have been conducted to show the potentialities of the embedded structured fibers within composite materials to act as a strain safety fuse sensor. The choice of a multimode optical fiber with polyimide coating has been validated. New Weibull's statistics on short fibers have been determined for two kinds of structuration, flaws on the surface or in the core of the silice fibers and in the failure strains range consistent with sensor applications on composite materials. Long structured fibers have been embedded within plane specimens of two components materials (glass fibers composite (16–20 plane sheets, 0°) and carbon fibers composite (4 sheets, ±45°)) and the comparison between the failure strains of these fibers with those issued from the Weibull's statistics of short fibers shows, at least for the superficial structuration, the possibility to use these structured fibers as strain fuse sensor. A very simple phenomenological model has been proposed.

1. Introduction

The use of optical fiber for structural composite monitoring is closely related with the smart structure concept which describes mechanical and civil engineering structures that integrate a sensing system. This system may help to identify structural wear, damage, deformation or deterioration.

Due to their versatility, robustness and easiness of integration, optical fiber sensors have rapidly been recognized as an ideal sensing tool for smart structures [1–7]. Moreover, due to their small size and permanent integration in the structure, optical fiber sensors are considered to be non-destructive and minimally invasive testing tool. The integration of optical fibers into composite structure also presents different advantages and challenges. As an example, compared to conventional electrical sensors, the technology with optical fiber has the following advantages: immune to electromagnetic interference, chemically inert, long term reliability, resistant to nuclear and ionizing radiations and as previously mentioned weakly intrusive. Moreover, the embedded sensors are protected by the composite material and can be installed during production, avoiding external installation.

The mechanical properties of the current optical fibers are still quite known [8–15]. However, as shown by Semjonov and Kurkjian [16] on nano-indented fibers with diamond cube corner and more recently by Delobelle et al. [17] on nano-structured fibers by single-shot femtosecond laser, if synthetic flaws are generated on the surface or in the core of the fibers the rupture strength of these modified fibers can be controlled. These flaws act as local stress concentrators under strain, resulting in a much lower tensile strength than that of the initial fiber. Thus, embedment of such structured fibers into a composite structure can be use as strain sensors, as an example to detect if locally the structure has undergoes a given strain. In that case, the sensor acts as a strain safety-fuse. Hence, the present paper deals with the study of the failure probability of nano-structured optical fibers with femtosecond laser procedure, embedded into composite materials when this latest is submitted to uniaxial tensile loading. The final objective of this study is to use the nano-structured fibers as a safety sensor to detect maximum strain level in cylindrical composite fuel vessels [5,18,19].

In two previous papers [17,20], on one hand, a detailed study of the morphology of nano-craters drilled in borosilicate glass by single shot femtosecond laser near the ablation threshold has been

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reported [20], and on the other hand the failure probability of nano-structured optical fibers thanks to femtosecond laser when submitted to uniaxial tensile loading has been presented [17]. Note that a nano-structuration procedure of optical fibers has equally been proposed [17]. In this paper, taking the strain levels within the composite structure to be detected into account, new results on nano-structured fibers with two different structuration procedures, flaws at the surface or into the core of the silica of the fibers, are presented. Then, the rupture probability of these structured fibers embedded within two different composite materials and submitted to tensile loading are studied.

2. Mechanical analysis theory

The most suitable and reliable law which describe the distribution of the probability P of failure of optical fibers is the Weibull's law [11,17,21–25]. Its common form is the two parameters Weibull's distribution given by:

$$P(\sigma) = 1 - \exp\left(-L\left(\frac{\sigma}{\sigma_o}\right)\right)^{m_o} \tag{1}$$

where L is the length of the fiber, σ is the applied stress, σ_o and m_o the two scaling parameters: the Weibull's stress and the Weibull's modulus, respectively. However, as shown by Kurkjian et al. [24] for relatively small length ($L < 1$ m) the probability $P(\sigma)$ is independent of the fiber's length. Hence, a lnln representation as expressed in Eq. (2) allows the determination of the two scaling parameters: m_o is the slope of the curve and σ_o corresponds to the intersection with the stress axis.

$$\ln\left[\ln\left(\frac{1}{1-P(\sigma)}\right)\right] = m_o[\ln\sigma - \ln\sigma_o] \tag{2}$$

Assuming a group (i) of M samples, the cumulative failure probability $P(\sigma)$ for each of them is experimentally determined as follows:

$$P(\sigma_i) = \frac{i-0.5}{M} \quad \text{with} \quad \sigma_1 \le \sigma_2 \le \cdots \le \sigma_i \le \cdots \le \sigma_M \tag{3}$$

The failure stresses are listed in increasing magnitude. Note that, at least 15–30 specimens testing are required to be able to evaluate the distribution of probability of failure.

For unstructured short fibers the Weibull's probabilities are appreciably linear and thus Eq. (1) is written as:

$$P(\sigma) = 1 - \exp\left(-\left(\frac{\sigma}{\sigma_{max}}\right)\right)^{m_{max}} \tag{4}$$

The two scaling parameters are σ_{max} and m_{max}.

However, as shown in a previous paper [17] the Weibull's probabilities of fracture of structured fibers are clearly bilinear and Eq. (4) is rewritten as:

$$P(\sigma) = 1 - \sum_{i=1}^{2}\alpha_i \exp - \left(\frac{\sigma}{\sigma_{oi}}\right)^{m_{oi}} \quad \text{with} \quad \sum_{i=1}^{2}\alpha_i = 1 \tag{5}$$

Thus, five parameters have to be identified, the two Weibull's exponents m_{o1}, m_{o2} associated to the two scaling stresses σ_{o1}, σ_{o2} and a ponderation parameter $\alpha_2 = (1-\alpha_1)$. To describe the evolutions of the Weibull's parameters of Eq. (5) as a function of the optical (NA, E_p, E_{po}, λ) and of the superficial nano-structuration parameters (dx, dy, dz, n_ℓ) a model has previously been proposed [17]. Hence:

$$\sigma_{oi} = \sigma_{max}\left[\frac{\beta}{1+\delta_i\sqrt{\frac{E_p}{E_{po}}-1}\left(\mathrm{Ln}\frac{E_p}{E_{po}}\right)^q} + \frac{1-\beta}{1+\gamma\left(\mathrm{Ln}\frac{E_p}{E_{po}}\right)^r}\right] \quad \text{with} \quad \delta_i = A_i I(dx, dy, n_\ell)\frac{2\alpha^2\pi\lambda}{M^2 NA^2 dz} \tag{6a}$$

$$m_{oi} = m_{max}\left[1 - 4\left(1-\left(\frac{m_{min}}{m_{max}}\right)^{1/P_i}\right)\frac{\sigma_{oi}}{\sigma_{max}}\left(1-\frac{\sigma_{oi}}{\sigma_{max}}\right)\right]^{P_i} \quad \text{and} \quad \alpha_2 = 0.45(\alpha_1 = 0.55), \quad i = 1, 2 \tag{6b}$$

In these equations E_p and E_{po} are the pulse energy of the laser beam and the ablation threshold energy of the silica fibers, respectively. σ_{max} and m_{max} are the two Weibull's parameters of the unstructured fibers (Eq. (4)). The other experimental parameters (NA, λ, dx, dy, dz and n_ℓ) will further be defined in Sections 3.3.2 and 3.3.3. β, γ, r, q, m_{min}, A_i and P_i are different coefficients of the model and $I(dx, dy, n_\ell)$ a function of the geometrical parameters of the structuration (as a example, see Fig. 4).

Eqs. (4), (5), (6a) and (6b) will be validated, quantified and then simplified in Section 4.

3. Experimental set-ups and nano-structuration procedures

3.1. Mechanical set-up

3.1.1. Tensile tests on short fibers

To evaluate the distribution of the probability of failure of unstructured and structured optical fibers, tensile tests on relatively short specimens have been carried out. A dynamic mechanical analysis (DMA) Bose-Electroforce 3200 device with a load cell of 450 N has been used. However, gripping the fibers is a major concern, particularly to prevent the sliding of the fibers. For unstructured fibers which present the maximum rupture force F_{max} (50–200 N), the fibers are wrapped around two capstans covered with rubber layer, then glued on these capstans and the ends of the fibers are held mechanically in the rubber. With this method the slide of the fibers is negligible. For structured fibers, as further shown, the rupture forces are lower than 25 N, the samples have been glued and tightened between two card tabs to avoid slipping. The useful length of the specimens is fixed at 30 mm and the tests have been realized at 0.02 mm/s at room temperature. Note that for these short samples the load train and fiber must be accurately aligned in order to avoid preferential failure caused by bending between fiber and grips. With the first method applied to virgin fibers, only the results where the failures occur in the useful length have been considered (about 70% of the fibers). However, with the last procedure applied to structured fibers about 90% of the failures occur in the beam impacted zone, in the middle of the useful length. For the different virgin tested fibers (Table 1) the stress–strain curve slopes are consistent with a 73 ± 8 GPa Young's modulus in agreement with the known value of silica. The fiber elongations range is 6–8%.

3.1.2. Pull-out tests on short fibers

Pull-out tests on different types of fibers have been performed with the DMA Electroforce device to evaluate the strength transfer, via the fiber's coating, between the composite and the optical fiber. The fibers are embedded over a length L_c = 20 mm within a M10 resin which is used in carbon fiber composite materials (Hexcel Composite). The polymerization of the resin is obtained thanks to an aging of 90 min at 150 °C. The free extremity of the tested fiber is wrapped around a capstan covered with a rubber layer. Then a tensile test is performed to evaluate the de-bounding force F_d. If $\emptyset_{coat}$ and $\emptyset_{clad}$ are the coating and the cladding diameters respectively, the shear de-bounding stress σ_d and the tensile stress σ_T when the de-bounding occurs can simply be calculated by: