Composites: Part A 67 (2014) 149–156

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Investigation of the residual tensile behavior of fiber bundles after static fatigue: Implications for the prediction of durability of composites

J. Lamon [a,*], M. R'Mili [b]

[a] LMT (CNRS/ENS), Cachan, France
[b] MATEIS (CNRS/INSA/University of Lyon), Villeurbanne, France

ARTICLE INFO

Article history:
Received 31 March 2014
Received in revised form 27 July 2014
Accepted 14 August 2014
Available online 2 September 2014

Keywords:
A. Glass fibers
B. Fatigue
C. Analytical modelling
D. Mechanical testing

ABSTRACT

Several brittle inorganic fibers (including glass, SiC- or alumina- based fibers) are sensitive to slow crack growth activated by environment (water, high temperature air, etc.) in fatigue, so that failure can occur under stresses much smaller than the fracture stress. The delayed fracture of glass fibers has been investigated in a previous paper, on multifilament tows loaded under constant deformation in water. This tow testing technique was shown to be powerful for the estimation of the intrinsic crack growth law and the determination of the statistical distribution of rupture times pertinent to filaments. The present paper focuses on the residual behavior of filaments and tows after static fatigue (under constant deformation). It is aimed at assessing this tow-based approach to slow crack growth in filaments, i.e. demonstrating validity of the model, of the values of slow crack growth constants and of the equation of residual strength. For this purpose, E-glass fiber tows that comprised 2000 single filaments were subjected to interrupted static fatigue tests under constant deformation in water in a first step, and, then to residual tensile tests in inert environment in a second step. The residual behavior of tows was predicted using the slow crack growth constants that have been extracted from the static fatigue tests, and the fast fracture statistical parameters estimated from tensile tests on as-received tows. Validity of the approach was established by comparing experimental and predicted results. Then, the equations of residual strength and residual behavior were used for the investigation of residual behavior of filaments and tows.

1. Introduction

Life of materials and structures is an important issue with economic implications. The resistance to fatigue can be measured by the time-to-failure or by the residual strength or behavior. In composites, fibers are fundamental constituents as they carry nearly all the load in polymer matrix composites as well as in ceramic matrix composites after saturation of matrix damage. In multi directionally reinforced composites, such as woven composites, fiber tows are the pertinent length scale for fracture. Furthermore, fiber bundles are interesting test specimens for the characterization of filament properties, since the filaments exhibit a variation in fracture properties. A single test on tow provides hundreds or thousands of data, when testing hundreds or thousands of single-fiber samples would require weeks to months of careful sample preparation and analysis. For these reasons, testing the bundle of filaments as a whole is an attractive goal for many researchers [1–15]. In the past, most of the work was devoted to fast fracture and the statistical distribution of strengths [1–9]. Recently, emphasis was placed on the resistance to static fatigue [10–15].

Several inorganic fibers are sensitive to subcritical crack growth activated by environment. Many papers have addressed the delayed failure of glass [16–22]. They concentrated on the investigation of slow crack growth mechanism. The issue of lifetime has received less attention. The mechanism of slow crack growth in glass is well-known. It results from reaction between a strained Si–O–Si bond and water at crack tip [16–19]. The power function $V = A\,K_I^n$ has been shown to provide a sound description of subcritical crack propagation, although the exact relationship between crack velocity V and stress intensity factor K_I is not known [19,23]. A wide scatter in n values has been reported in the literature. Values between 12 and 40 measured on single filaments have been collected in [19]. $n = 15$ was extracted from static fatigue tests on tows of E-glass using a complex model [22]. In both Refs. [20,21] it was argued that there should be a relationship between n and applied stress. Then, it was suggested that a variety of flaw sizes and shapes as well as a variation in residual stresses and inert strength, results in a similar variability in fatigue behavior [19].

* Corresponding author. Tel.: +33 147402715; fax: +33 147402785.
E-mail address: lamon@lmt.ens-cachan.fr (J. Lamon).

http://dx.doi.org/10.1016/j.compositesa.2014.08.014
1359-835X/

In a previous paper [15], it was shown that static fatigue testing of fiber tows under constant deformation is a very powerful technique for the investigation of slow crack growth in filaments activated by environment. But the first prerequisite for sound analysis is the control of deformations. During each test on tow, 2000 filaments were tested, which provided a significant database for the statistical analysis of data. Each fiber is subject to constant stress during the entire test. Load relaxation was shown to follow a power law, with n as force exponent. It was shown that the life of each fiber is commensurate with the reference fiber strength. Then, it was shown that the rank of each failing fiber could be derived from relaxation of load on bundle, so that the reference strength of each failing fiber is no longer an unknown. This is an important feature that is worth pointing out. Stress-failure time relations were established, as well as the equation of life distribution. This latter equation depends on stressed volume, time and applied stress. It can be used for lifetime predictions, as well as for establishing stress–probability–time diagrams.

The crack propagation diagrams $V(K_I/K_{IC})$ were found to consist of two distinct curves characterized by ($n \approx 30$, $V^* \approx 10^{-6}$ m/s) and ($n \approx 12$, $V^* \approx 10^{-9}$ m/s). This unusual diagram results from the presence of two families of fibers: a family of weak fibers with short life, and a family of strong fibers with long life. The family of weak fibers was present only under small deformations. The family of strong fibers was found to dominate under larger deformations ($\varepsilon > 0.8\%$, $\sigma > 600$ MPa).

The purpose of the present paper is to assess this approach to lifetime governed by slow crack growth and to validate the concept of residual strength introduced in [24]. For this purpose, E-glass fiber tows that had been subjected to interrupted static fatigue tests in water were tested in monotonous traction to determine the residual behavior. The slow crack growth constants that had been extracted from the static fatigue tests were used to calculate the residual strength of filaments in the tow. The tow behavior that was predicted was compared to the experimental one for assessment of the approach. In a second step, the equations were used for the prediction and investigation of residual behavior.

2. Static fatigue and residual tensile tests

2.1. Experimental procedure

The experimental procedure of static fatigue was detailed in a previous paper [15]. Only the main steps of the experimental tests are presented here. The tests were carried out on bundles of E-glass fibers with approximately 2000 filaments with 14 ± 2 μm diameter each. The precise number of filaments in tows was derived from the initial slope of the stress–strain curve (Tables 1 and 2). The preparation of test specimens was detailed in a previous paper [5]. Main fiber characteristics are given in Table 1.

Tensile tests under monotonous loading (displacement rate = 2 μm/s) [5,9,25] were performed in inert environment on as-prepared tows for the determination of reference behavior, and on tows that had been subjected to static fatigue for the determination of residual behavior. Lubricant oil was used to avoid friction between the fibers.

The static fatigue tests were carried out in water under constant deformation [15]. During all the tests, deformations were measured using a contact extensometer (with a ± 2.5 mm elongation displacement transducer) that was clamped to the specimen using two 4-mm-long thermoretractable rings. The rings were located close to the grips in order to avoid possible bending introduced by the extensometer. The inner distance between the rings defined the gauge length (≈63 mm). During the static fatigue tests, the strain was monitored directly by the extensometer. Specimens were first impregnated with water and then loaded at 5 μm/s displacement rate to the test deformation. Then the strain was kept constant. Results of the static fatigue tests were reported in [15].

2.2. Determination of filament strength data

The parameters of statistical distributions of filament strengths were estimated by adjustment of equation of tensile behavior to experimental force–strain curve. The force–strain equation is given by the bundle model of parallel and independent fibers [1,7,26]:

$$F(\varepsilon) = NS_f E_f \varepsilon[1 - P(\varepsilon)] \tag{1}$$

where N is the initial number of intact filaments in tow, S_f is the average filament cross sectional area, E_f is the filament Young's modulus. $P(\varepsilon)$ is the failure probability at deformation ε. The Weibull equation is a satisfactory approximation of filament tensile strength distribution [8]:

$$P(\varepsilon) = 1 - \exp\left(-\frac{v}{v_0}\left(\frac{\varepsilon}{\varepsilon_0}\right)^m\right) \tag{2}$$

$$P(\sigma) = 1 - \exp\left(-\frac{v}{v_0}\left(\frac{\sigma}{\sigma_0}\right)^m\right) \tag{3}$$

where σ is the stress corresponding to ε; m, ε_0, and $\sigma_0 = E_f\,\varepsilon_0$ are the statistical parameters.

Fig. 1 shows an example of fitting of force–strain curve by Eq. (2). It is worth pointing out that there is an excellent agreement between experiment and theory. It can be noticed that the force decrease beyond maximum compares fairly well with that obtained experimentally. It cannot be concluded that it is steeper, as it is obtained when groups of filaments fail [7].

3. Strength degradation in fatigue

The subcritical crack growth model is based on the simple power form of crack velocity versus stress intensity factor, which is usually employed to describe the slow propagation of cracks caused by environment under load in ceramics and glass materials [15]:

$$V = \frac{da}{dt} = V^*\left(\frac{K_I}{K_{IC}}\right)^n \tag{4}$$

where V is crack velocity, a is crack length, t is time, K_I is the stress intensity factor, K_{IC} is the critical stress intensity factor, V^* and n are constants depending respectively on environment and material.

When crack propagates from initial flaw size a_i to length a_R, the stress intensity factor increases from K_{Ii} to K_{IR}. The associated propagation time period t_R for a single filament under constant stress σ is:

Table 1
Main characteristics of glass fibers and initial numbers of filaments N_0 in tows tested in static fatigue.

Fatigue test	N_0	E_f (GPa)	r_f (μm)	l_0 (mm)	K_{IC} (MPa$\sqrt{}$m)	Y	n	V^* (10^{-9}m/s)	m	V_0 (m^3)	σ_0 (MPa)
#4	1824	72	7	63	0.75	1.12	11.2 11.9	2.1	4.8	1	8.0
#6	1823	72	7	65	0.75	1.12	10.5	1.7	4.8	1	8.0