Composites Science and Technology 69 (2009) 2152–2157

Contents lists available at ScienceDirect

Composites Science and Technology

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

The effect of mechanical defects on the strength distribution of elementary flax fibres

J. Andersons *, E. Poriķe, E. Spārniņš

Institute of Polymer Mechanics, University of Latvia, Riga LV 1006, Latvia

ARTICLE INFO

Article history:
Received 12 January 2009
Received in revised form 13 April 2009
Accepted 20 May 2009
Available online 27 May 2009

Keywords:
A. Fibres
B. Defects
B. Strength
C. Probabilistic methods
Flax

ABSTRACT

Flax fibres are finding non-traditional applications as reinforcement of composite materials. The mechanical properties of fibres are affected by the natural variability in plant as well as the damage accumulated during processing, and thus have considerable variability that necessitates statistical treatment of fibre characteristics. The strength distribution of elementary flax fibres has been determined at several fibre lengths by standard tensile tests, and the amount of kink bands in the fibres evaluated by optical microscopy. Strength distribution function, based on the assumption that the presence of kink bands limits fibre strength, is derived and found to provide reasonable agreement with test results.

1. Introduction

The efficiency of fibre reinforcement in a composite material is determined primarily by the mechanical characteristics of reinforcing fibres and their adhesion to matrix. Natural fibres have been shown to possess higher scatter of the mechanical properties than the man-made ones [1–4]. While the scatter of fibre stiffness exerts limited effect on composite properties, fibre strength distribution affects both strength and toughness of a composite. Weakest-link character of fibre failure is reflected in the commonly used Weibull two-parameter distribution of fibre strength, based on the seminal work [5]

$$F(\sigma) = 1 - \exp\left[-\frac{l}{l_0}\left(\frac{\sigma}{\beta_0}\right)^{\alpha'}\right] \tag{1}$$

where l stands for fibre length, l_0 is a normalizing parameter, σ is the tensile stress at fibre failure, and α', β_0 designate Weibull shape and scale parameters, respectively. Fibre length rather than volume is typically used as the scale variable in Eq. (1) due to limited scatter of fibre diameters of inorganic fibres. Natural fibres exhibit more pronounced variability of geometrical characteristics that, to some extent, also affects their strength [3,6,7]. However, for comparability and convenience, Eq. (1) is frequently applied also to describe the strength distribution of natural fibres.

The values of the shape parameter α', characterizing the scatter of strength, range from 2 to 4.3 for elementary flax fibres of 5 to 20 mm length extracted from green and dew-retted flax [1,2,4,8,9], being consistently lower than those of glass fibres of comparable dimensions obtained by the same specimen preparation and tension test procedure (see e.g. [10]). Thus the higher strength variability is likely to be caused by factors intrinsic to flax fibre.

It has been shown that the two-parameter Weibull distribution, Eq. (1), may not comply with the experimental data of flax fibre strength variation with gauge length [1,2]. Instead, the modified Weibull distribution

$$F(\sigma) = 1 - \exp\left[-\left(\frac{l}{l_0}\right)^{\gamma}\left(\frac{\sigma}{\beta}\right)^{\alpha}\right] \tag{2}$$

with $0 \leqslant \gamma \leqslant 1$ is found to agree with elementary flax fibre strength [1]. The physical origin of the distribution Eq. (2) is thought to be related to inter-fibre variation of strength characteristics. Namely, Weibull distribution Eq. (1) follows from the assumption that the distribution of critical flaws along the fibre is a homogeneous Poisson process with intensity Λ being a power function of stress, $\Lambda \sim \sigma^{\alpha'}$, identical for all the fibres of a given batch. However, the production process of man-made fibres can introduce a different damage intensity Λ in each fibre that manifests as a larger scatter of strength among fibres than between different segments sampled along a fibre. One could expect a similar variability in damage level among agrofibers stemming from differing growth and processing histories of individual fibres. The strength of such a fibre batch does not comply with Eq. (1) but can be approximated by Eq. (2) (see e.g.

* Corresponding author.
E-mail address: janis.andersons@pmi.lv (J. Andersons).

0266-3538/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compscitech.2009.05.010

the discussion of fibre strength issues in [11,12]). It has been demonstrated by numerical modelling [13] and experimentally [10] that the distribution Eq. (2) for a fibre batch is obtained if each of the fibres possesses Weibull strength distribution Eq. (1), but the parameters of Weibull distribution for individual fibres differ. In [14] the appearance of strength distribution given by Eq. (2) is attributed to the presence of a large-scale fluctuation of the density of defects (flaws) in fibres.

Elementary flax fibres may contain cell-wall defects, i.e. local misalignments of cellulose microfibrils, originating during growth and processing of flax. Such defects are variously called dislocations, kink bands, nodes, or slip planes [15,16]. Kink bands are seen in polarized light microscopy [17] as bright zones crossing fibre and oriented roughly perpendicularly to its axis. The largest of them can also be discerned without polarizers as seen in Fig. 1. The effect of such defects on fibre strength is a subject of controversy. No correlation between the number of kink bands in a fibre and its tensile strength has been found in [18] for flax. Similarly, the relative fraction of kink bands in hemp fibres did not correlate appreciably with their strength and modulus [17]. Nevertheless, it has been argued that flax fibre strength is reduced by the presence [9] and amount [8] of kink bands. There is also experimental evidence of flax fibre failure in tension initiating within a kink band [16,18,19]. Therefore it appears reasonable to introduce a strength distribution function that accounts for the presence of kink bands in the fibre.

Notably, in one of the original derivations of the weakest link strength distribution presented in [5], the number of defects per unit volume was treated as a continuous variable when obtaining an analogue of Eq. (1). As opposed to such a continuum approach to the effect of defects, a weakest-link strength distribution has also been derived assuming that a discrete, finite number of defects is present in a body [20]. Distribution functions combining the features of weakest link and random defect models have been proposed and applied to describe fibre strength scatter [21,22]. Approximation of flax fibre strength data by defect-based distribution functions has also proved successful [22–24].

In this study, we derive a strength distribution function explicitly accounting for the presence of defects in fibres and evaluate its applicability to elementary flax fibre strength data at different gauge lengths.

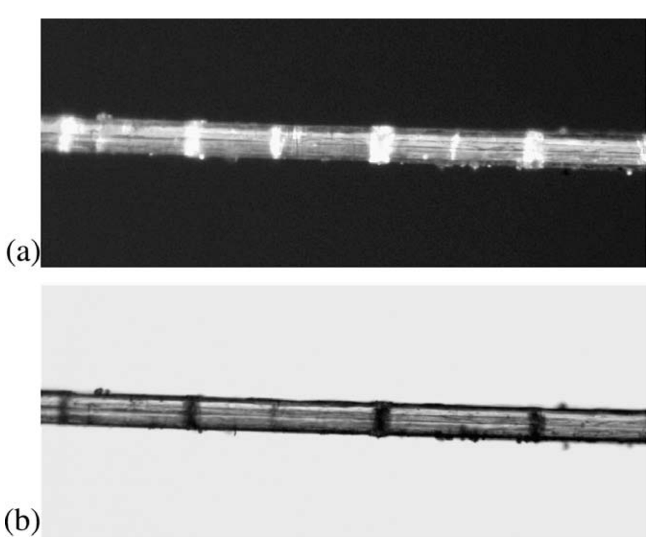

Fig. 1. Kink bands in an elementary flax fibre as revealed by optical microscopy in transmitted polarized (a) and non-polarized (b) light in the same fibre fragment. (fibre diameter is ca. 23 μm).

2. Experimental

Two types of elementary flax fibres are considered. The fibres produced by FinFlax Oy (Finland) are designated by A and those produced by Ekotex (Poland) by B in the following. The details of experimental procedure and strength test results have been presented in [1] for fibres A and in [23] for fibres B. For completeness and convenience, we briefly recapitulate them below.

The test procedure of ASTM D 3379-75 standard was followed. Single fibres were manually separated from fibre bundles. Fibre ends were glued onto a paper frame. Three gauge length specimens were prepared with free fibre length of 5, 10 or 20 mm respectively. Tension tests were carried out on an electromechanical tensile machine equipped with mechanical grips. During mounting the specimens were handled only by the paper frame. Upon clamping of the ends of the paper frame by grips of the test machine, both sides of the frame were carefully cut in the middle. The tests were displacement-controlled with the loading rate of 0.5 mm/min for fibres A, and loading rate of 10%/min for fibres B.

Fibre diameter was evaluated from observations under optical microscope or micrographs as the average of five apparent diameter measurements taken at different locations along the fibre. The mean values and standard deviations of the fibre diameters at each gauge length are presented in Table 1. The mean diameter appears not to depend, within scatter, on gauge length, being slightly but consistently smaller for fibres A. The empirical fibre strength distributions for fibres A and B are presented in Fig. 2. The fracture probabilities have been evaluated via the median rank of the measured strength values using the following approximation:

$$P = \frac{i - 0.3}{n + 0.4} \tag{3}$$

where i is the ith number in ascendingly ordered strength data of the sample and n is the sample size (i.e. the number of tests performed on fibres of given type and gauge length).

Micrographs of fibre B revealing the presence of kink bands are shown in Fig. 1. Virtually all the kink bands extended over the whole fibre width, varying only in their extent along the fibre axis. Such kink bands, spanning fibre width, were counted in a number of fibres of $l = 5$ mm gauge length by means of optical microscopy. Olympus BX51 microscope with crossed polarizers was used. The spacing, s, of kink bands in each fibre was evaluated as $s = l/k$, where k is the number of kink bands in the fibre. The spacing distributions are shown in Fig. 3 for fibres A and Fig. 4 for fibres B. The empirical probabilities for spacings were evaluated by Eq. (3).

3. Defect-governed fibre strength distribution

3.1. Limited number of defects

Consider a fibre containing a random number, k, of defects with distribution mass function p_k. The distribution of defect strength (i.e. the stress at which fibre would break at a given defect) is designated by $F_d(\sigma)$, while the strength distribution of defect-free fibre is $F_{nd}(\sigma)$. Then the survival probability of the fibre is given by the product of corresponding probability for defect-free fibre, $1 - F_{nd}(\sigma)$, and that for survival of all the defects. The latter is

Table 1
Mean value (and standard deviation) of diameter, in microns, of elementary fibres at different gauge lengths.

Fibre/gauge length	5 mm	10 mm	20 mm
A	14.4 (3.2)	16.4 (3.5)	15.8 (3.7)
B	20.6 (5.0)	17.3 (3.7)	16.9 (2.4)