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Fatigue behaviour assessment of flax–epoxy composites

F. Bensadoun [a,*], K.A.M. Vallons [a], L.B. Lessard [b], I. Verpoest [a], A.W. Van Vuure [a]

[a] KU Leuven – Department of Materials Engineering, Kasteelpark Arenberg 44 – bus 2450, 3001 Heverlee, Belgium
[b] McGill University – Department of Mechanical Engineering, 817 Sherbrooke St. West, Montreal, Quebec H3A0C3, Canada

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ABSTRACT

The present study focuses on the characterisation and evaluation of the fatigue behaviour of flax–epoxy composites. A better understanding of this behaviour allows the prediction of long-term properties to assess the viability and long-term durability of these materials. The purpose of this work is to systematically compare the tension–tension fatigue behaviour of flax fibre composites for one random mat, six textile architectures and two laminate configurations, which are used in a wide range of applications. The fibre architecture was found to have a strong effect on the fatigue behaviour, where higher static strength and modulus combinations present the best fatigue characteristics. They have a delayed damage initiation and increased fatigue life as well as a reduced damage propagation rate combined with higher energy dissipation in the early stages of fatigue loading.

1. Introduction

The use of flax fibres in the composites industry is increasing, thanks to their advantageous characteristics such as good acoustic and thermal insulation, enhanced vibration absorption, as well as renewability. In terms of mechanical performance, flax is one of the strongest of the natural fibre family and is known to be as stiff as glass fibre. As of today, a major lack of data on flax fibre durability properties, such as fatigue behaviour, has been limiting the use of these fibres in high performance applications like wind turbine blades and sporting goods.

Liang et al. [1] have found out that non-crimp glass fibre/epoxy composites have an increased resistance to fatigue loading compared to non-crimp flax/epoxy composites which, both having a $[0,90]_{3s}$ lay-up, is due to their higher static strength (380 MPa vs ≈170 MPa). On the other hand, for the same lay-up, the glass composites have a larger reduction in fatigue life illustrated by a steeper specific *S–N* curve, in comparison to flax/epoxy, 56.2 MPa/decade vs 25.2 MPa/decade (which corresponds to a decrease of 15% of the ultimate tensile strength (UTS) per decade for both of them) as seen in Fig. 1. This demonstrates a more steady fatigue behaviour through time for the flax/epoxy composite. Silva et al. [2] have shown that for technical sisal fibres (one fibre), at fatigue stresses below 50% of the ultimate tensile strength (UTS), all fibres resist more than 10^6 cycles. Furthermore, the authors have observed a slight increase in stiffness during the early cycles. A study published in 2014 by Shahzad and Isaac [3] showed that short hemp fibre random mat composites were less fatigue sensitive than the glass fibre chopped strand mat counterpart in tension–tension fatigue, which could be related to the lower stiffness degradation at equal normalised stress levels (S/S_o). When the fibre architecture is varied, Shah et al. [4] found that increasing off-axis loading angle may improve the fatigue life at high loading rate (90% of the UTS). A steeper *S–N* curve (faster degradation) was observed for the $[\pm45]_4$ F50/polyester laminate in comparison to unidirectional composite ($[0]_4$) laminate and the $[90]_4$. Tension–tension fatigue tests results from the same author showed that the textile architectures with fibre orientations off-axis to the loading direction resulted in lower fatigue properties, which is in line with the significant drop in composite static strength in those off-axis directions.

As is the case for all property characterisations performed in these studies, the textile architecture, fibre and matrix types and fibre volume content were all found to have a strong effect on the fatigue life. It is expected that higher static properties are a sign of superior fatigue load-carrying capacities [4]. It was shown by Gassan [5] that by using higher fibre strength and modulus unidirectional (UD) natural fibre-based composites, which have a better fibre–matrix adhesion, a delayed damage initiation and reduced damage propagation is observed. Furthermore, Shah et al. [4] found that the fatigue strength degradation rates, obtained from the slope of the *S/N* curve of flax/polyester UD composites, are lower than for their glass counterparts. Throughout the lifetime of composites, they will encounter certain damage that will affect their

* Corresponding author.
E-mail address: farida.bensadoun@mtm.kuleuven.be (F. Bensadoun).

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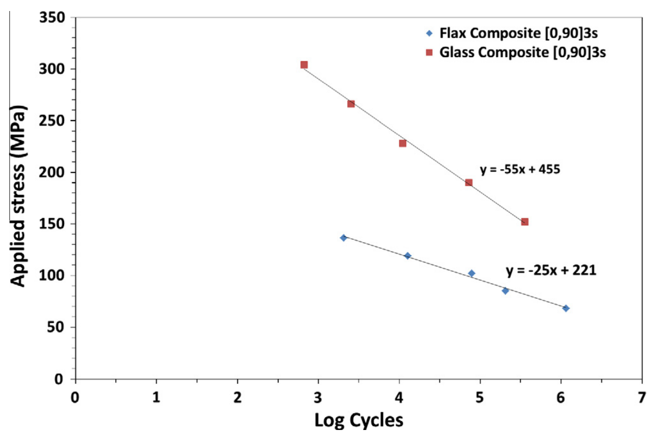

Fig. 1. *S–N* curves of $[0,90]_{3s}$ cross ply flax/epoxy and glass/epoxy composites adapted from [2]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

overall performance. Although fatigue loading does not instantly reduce the strength of the composite, it does have an effect on the stiffness. During fatigue testing, early damage causes a fast and steep decrease of the stiffness, which is followed by a stabilisation and slow degradation of the composite properties. Close to failure, heavily damaged zones develop, leading to a strong decrease in stiffness, and this finally will cause the material to break [6,7]. To monitor the damage, the cyclic hysteresis is used by many authors in order to evaluate the loss of stiffness, material energy dissipation and damage development [8,9].

During fatigue, a gradual build-up of residual strain in the samples is often noticed, especially in samples with none or only a limited amount of fibres in the testing direction [1,10–12]. In tensile–tensile fatigue cases, if the strain at minimum applied stress in each cycle is plotted versus the number of cycles, a steep increase is seen in the initial stages of the test, indicating a build-up of permanent or residual strain. After this, the increase of this strain becomes more moderate. The build-up of such residual strain during fatigue has been explained by the development of damage in the material, e.g. in [11,12]. El Sawi et al. [12] have shown that there is a correlation between the residual strain increase and the matrix crack density in flax fibre reinforced epoxy manufactured with UD and ±45 cross ply laminates. Such permanent deformation has also been linked to creep phenomena occurring under the influence of a continuous tensile load for UD and [0,90] cross ply laminates and this factor is even more pronounced in off-axis loading cases such as ±45 lay-ups [10].

If fatigue testing is stopped before final failure has occurred, the residual quasi-static properties can be measured and compared to the pre-fatigue behaviour. Vallons et al. [11] have done this for cross-ply carbon–epoxy composites. They found no influence of the fatigue loading on the post-fatigue quasi-static behaviour when the loading was applied in the fibre direction. In the bias direction, however, small decreases in strength and stiffness were found and a significant decrease in failure strain. In another study on a carbon ±45 biaxial non-crimp fabric composite, fatigue stress levels that caused no discernible damage in bias direction samples were found to have no effect on the post-fatigue tensile strength [13]. Yuanjian and Isaac [14] have looked at the influence of fatigue loading on the quasi-static modulus of randomly oriented hemp and stitch bonded biaxial ±45° glass fibre composites at different stages of the fatigue process. For transverse tested samples, they found a steady decrease in modulus for the glass fibre composite, but no decrease was noted for the hemp fibre composite up to final failure.

Paper contribution

In the present study, the investigation of the damage development will be performed through the assessment of modulus degradation and the cyclic creep phenomena, but also by observation of the hysteresis loops. The residual properties are later on evaluated and correlated to the observed modulus degradation and cyclic creep. Furthermore, the originality of this work is that it seeks to understand not only the fatigue behaviour of flax composites but also how the architecture such as woven, unidirectional and random orientation affects the properties.

The aim of this study is to investigate *S–N* diagrams constructed from fatigue data at stress ratios of $R = 0.1$ (tension–tension) at various stress levels for nine different flax textile architectures combined with an epoxy matrix. The composites were manufactured via the resin transfer moulding process. The samples were then cut and mechanically tested in tensile direction to obtain the required ultimate tensile strength value, needed for the determining the stress levels during the fatigue testing. Strain monitoring was used during fatigue testing in order to assess the stiffness degradation rates as well as the hysteresis loops. These data were also used to investigate the energy dissipation capability and the gradual build-up of the permanent strain of each material. The post-fatigue properties are also evaluated in order to assess the degradation rate of the composite through time. This investigation is crucial in order to understand the damage state, the post fatigue properties and fatigue life. This information will help to assess the durability of these types of composite materials, since these properties have a great influence on the service life, product safety and liability.

2. Experimental

2.1. Materials

The flax fibre reinforced composites were made by combining a thermoset epoxy matrix with nine flax textile configurations. For the cross-linking, the matrix *Epikote 828LVEL* (viscosity $\eta \approx 10–12$ Pa s at 25 °C) is mixed with the hardener *Dytek DCH-99* at a 15.2 phr ratio. The 2 mm thick laminates are composed of several layers of fabrics in order to obtain a fibre volume fraction (V_f) of ≈40%, except for the random mat composite which has a $V_f \approx 30\%$.

The different textiles used as well as the matrix are described in Table 1. All twill fabrics have a 2 × 2 structure. For the Quasi-UD and UD laminate a unidirectional configuration and a symmetric cross-ply lay-up was used $[0,90]_{xs}$ where s means the laminate is symmetric and *x* is the number of times the layers are repeated. All composites were manufactured with the number of layers needed to get a fibre volume fraction (V_f) of 40%. The density of the fibres is 1.45 g/cm^3 [15]. The unidirectional fibres (UD) were water-treated as presented by the patent [16]. The areal density used in the calculation was provided by the manufacturer and these values were verified in-house by measuring the weight of several 30 × 30 cm textile pieces and calculating the average weight per unit area. The values found were equivalent to the data provided by the textile suppliers. These 9 textile architectures were chosen because of their wide use in the industry for different applications. The choice was based on actual applications that are today made with glass or carbon fibres. For example, the random mat is widely used in automotive industry for low cost parts like bumpers and car door interior panels. The cross-ply laminates, UD and Quasi-UD (also called non-crimped fabrics) are also widely used in sporting goods, in the wind energy and aeronautics industries.