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Review

Fatigue of flax-epoxy and other plant fibre composites: Critical review and analysis

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ABSTRACT

Examining response of natural fibre composites (NFC) under cyclic loading is essential to encourage confidence in their mechanical durability. Considerable variation exists amongst reported studies in fibre architecture (UD-based, twill-fabric, short-fibre), testing parameters (frequency, stress ratio), and fibre content. There is need to conduct a holistic review of these disparate studies in order to establish the state-of-the-art. Testing parameters and physical variables (off-axis plies, moisture, 'out-of-plane' weave) are seen to influence longevity. Stress-life data of various NFCs are analysed and found to be well-modelled by linearised relationships. *Specific* stress-life (density-normalised) is proposed as a fairer measure of comparing fatigue endurance that minimises the influence of fibre content. Flax fibre offers better fatigue resistance than Hemp, but comparable performance to Sisal and Jute. Several NFC laminate configurations are found to exceed, or be similar to, Glass-laminates in fatigue endurance. Contradictory reports of stiffness evolution is found: fibre-direction elastic modulus may increase or decrease over fatigue life depending on test parameters. Limitations of available fatigue studies are identified. Existing knowledge of fatigue damage evolution is deficient or ambiguous, therefore inadequate for engineering design consideration.

1. Introduction

Fibres extracted from the bast layer of certain plant stems (flax, jute, hemp, sisal, etc.) have shown considerable potential to be sustainable, environment-friendly alternatives to traditional synthetic fibres as reinforcement in engineering composites [1–6]. These plant-based natural fibre composites (NFCs) offer good specific mechanical properties [7,8,4], good thermal and acoustic insulation [7], greater energy absorption at large strain rates [9], are low-cost, lightweight, and require less energy to manufacture [3], are CO_2-neutral [10], are easier to tool and less toxic during processing [3,10], and result in simpler, non-toxic recycling [1,11,10]. Of all plant fibres, those harvested from flax (*Linum usitatissimum* L.) have proven to be the best candidate to replace Glass fibres as reinforcing material [7,2,5,12]. Flax fibres are comparable to, or exceed, Glass in specific strength (1300 vs 1350 MPa/g-cm^{-3}) [2], specific modulus (20–70 vs 30 GPa/g-cm^{-3}) [7,2], cost per weight (0.5–1.5 vs 1.6–3.25 USD/kg) [2], cost per length of minimum fibre material required to resist 100 kN (0.05–0.65 vs 0.1–0.4 USD/m) [7], and production energy consumption (11.4 vs 50 MJ/kg) [5]. Despite a steadily expanding body of work demonstrating the potential of natural fibres, industry adoption in load-bearing engineering applications is still reluctant due to a general lack of confidence in their mechanical performance, their complex loading behaviour, and the relative immaturity of research compared to that for synthetic fibres.

It is well documented that fatigue-related mechanisms are responsible for many, if not most, failures in engineering structures where dynamic repetitive loading (vibration, rotation, wind and wave action, turbulence, pressurisation, etc) at levels much lower than ultimate strengths still result in sudden and catastrophic failure due to internal damage accumulation over a period of time [13–15]. It follows that determining the fatigue life and observing fatiguing mechanical properties (damaged response) is an essential aspect of characterising NFCs. Being given serious academic attention for engineering applications only recently, research on *fatigue behaviour* of NFCs is still limited. Only in the last decade has there been a steady rise in available fatigue test data for NFCs [16–26,4,27–33], of which only a handful of publications have studied Flax-reinforced fatigue response [4,22,27–33]. Understanding fatigue behaviour, e.g. damage mechanisms, changes in mechanical properties (stiffness, strength, irreversible deformation), and critical failure development, are essential for the efficient and predictable design of load-bearing components. This study reviews and analyses the literature on all openly-available original fatigue-related NFC studies to the best of the authors' knowledge, excluding those on hybrid composites of natural and synthetic fibres. The analysis collates

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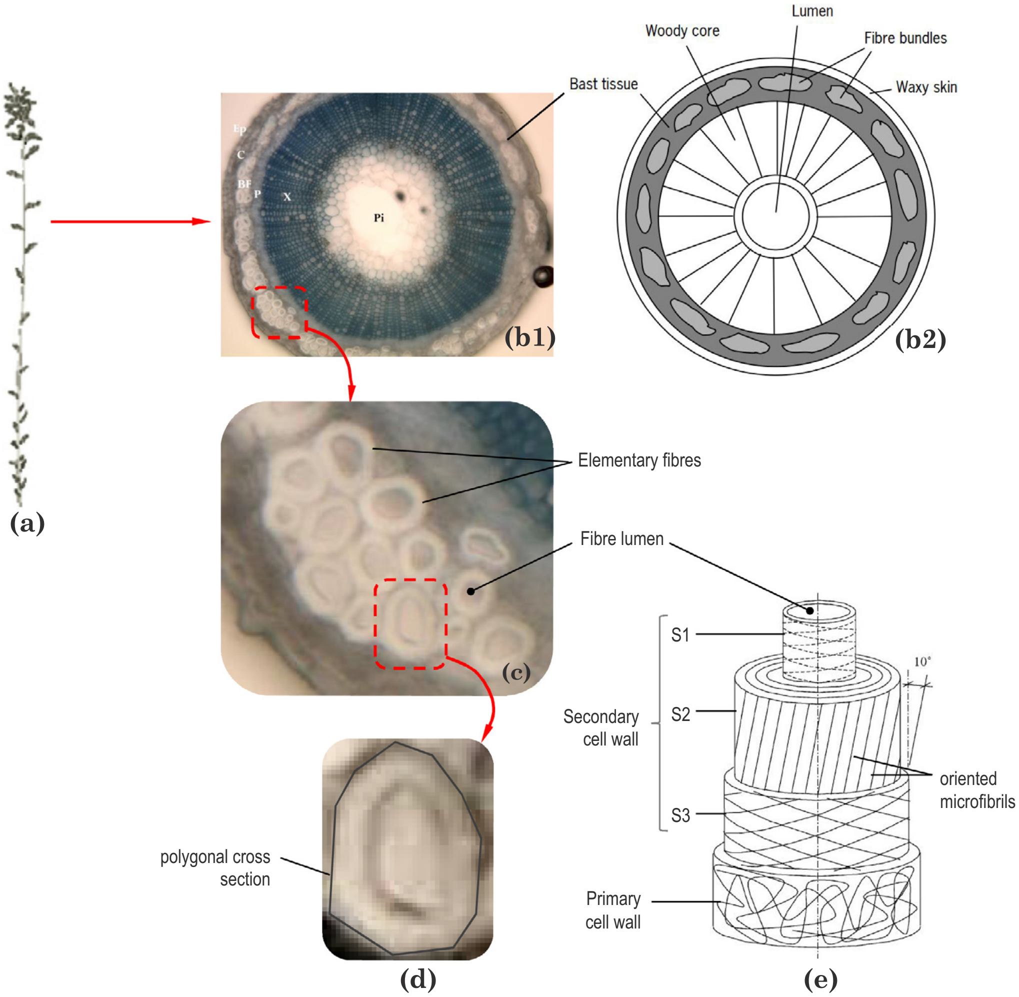

Fig. 1. Structure of Flax plant stem: (a) Flax plant, length ~90 cm; (b) Stem cross-section, dia. 1–3 mm; (c) Fibre bundle (*technical fibre*), dia. 50–200 µm; (d)-(e) Elementary fibre cross section and schematic, dia. 10–30 µm. Reproduced with permission: (a) from [38], (b1) and (c) and (d) from public domain [66], (b2) from [67], and (e) from [35]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

disparate data on NFC fatigue performance in order to investigate and, where possible, quantify trends in endurance (*S-N* curves), effects of varying testing parameters or laminate architecture, damage accumulation behaviour, and the suitability of potential damage indicators.

1.1. *On the structure and loading behaviour of natural fibres*

The hierarchic multi-layer nature of plant fibres contributes to their anisotropic, nonlinear deformation and complex damage progression behaviour under loading [34]. These fibres are complex hierarchical structures of cellulosic polymers, extracted from the outer *bast layer* of the plant stem [35,36]. The fundamental tubular unit in the bast layer is the *elementary fibre* (alternatively, *ultimate fibre* or *monofilament*) that has a polygonal cross section (dia. 10–30 μm) with a hollow central *lumen* [35] (see Fig. 1(d)). About 10–40 elementary fibres are held together by pectins [37] in bundles (dia. 50–200 µm) called *technical fibres* [35,34,37,38] (see Fig. 1(c)). The cells of elementary fibres have multiple concentric layers of *cell walls* (Fig. 1(e)) that provide necessary structural rigidity to the plant stem [39]. The *secondary cell wall* layer (5–15 µm thick) forms the bulk of the fibre structure. Cellulose is the dominant chemical component in natural fibre [40]. Cellulose chains are arranged in aggregate crystalline bundles called *microfibrils*. In the secondary cell wall, these microfibrils are highly ordered in a helical, angled orientation to the fibre axis. This orientation is approximately 10° in flax (Fig. 1(e)), 8° in jute, 6.2–11° in hemp, and 20° in sisal [41,42]. Upon axial tensile loading, these microfibrils tend to re-orient and straighten towards the loading axis, which is understood to contribute towards the stiffness variation observed in several studies [43,35,38,44]. After unloading, the microfibrils do not completely return to their original orientation, which contributes to the apparent *inelastic* nature of their deformation [35]. In both primary and secondary cell walls, microfibrils are embedded in a matrix of hemicelluloses, pectins, and possibly crosslinked lignins and some amorphous cellulose [45,46,37,47]. It is hypothesised that some of these amorphous polymer chains may also re-organise towards the loading axis under tensile straining (*strain-induced crystallisation*), thereby contributing to 'stiffening' along the fibre-direction [48]. The multi-scale structure of natural fibres have been shown to directly influence the behaviour and damage mechanisms of the composites derived from them [49].

2. Fatigue studies on NFCs

2.1. *Flax-epoxy composites*

Most available fatigue studies to date on Flax-composites are based on constant stress amplitude, tension-tension uniaxial tests. Unless otherwise stated, these fatigue studies were conducted at 5 Hz and loading ratio $R = 0.1$. Liang et al. [4] compared the fatiguing behaviour of Flax-epoxy (FE) and Glass-epoxy (GE) laminates of similar volume