FATIGUE OF FLAX-EPOXY LAMINATES UNDER CONSTANT STRAIN-AMPLITUDE CYCLING

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ABSTRACT

Interest in composite reinforcement by natural fibres has been driven by concerns of sustainability and recyclability. Of all candidate natural fibres, Flax fibre reinforcement has been shown to offer favourable specific strength and stiffness characteristics that are comparable to Glass fibre reinforced composites. Recent fatigue studies on Flax-composites have offered some description of damage mechanisms involved, and data on expected life under load-controlled cyclic tests. However, natural fibre composites, and particularly those reinforced by Flax, have been convincingly shown to demonstrate rate-dependent viscous effects under tensile loading. Considering that tested material properties are sensitive to strain rate, stress-life tests may not prove an accurate strategy of examining fatigue life or mechanical properties evolution – since the strain rate in such tests is continuously varying. Our study tests several common Flax-laminates ([0], $[0/90]_{4S}$, $[\pm 45]_{4S}$, and quasi-isotropic $[0/-45/90/45]_{2S}$) under strain-controlled fatigue, and contrasts the fatigue lives with those of equivalent Glass-laminates. Strain-life plots are generated, and the trends are found to be linear in ϵ-log(N) space. Our strain-life study indicates that Flax-composites tend to have a longer fatigue lives than Glass-composites – which is a promising revelation in considering Flax-composites for fatigue-critical applications.

1 INTRODUCTION

Fibre-composites can be expected to continue being a popular class of engineering material. It follows that the sustainability and end-of-life disposal of load-bearing composites should be of pressing interest to the engineering designer. Compared to the currently dominant synthetic fibre-composites, such as those reinforced by Carbon or Glass, bio-based composites such as natural fibre reinforced composites (NFC) offer opportunities to use renewable, non-toxic constituent materials that are less-energy intensive to process [1], [2].

Adoption of NFCs in industrial-scale load-bearing applications seems to be hampered by a lack of confidence in the material performance, owing to a relative scarcity of reliable data on mechanical response (including fatigue properties) when compared to traditional engineering composites. Fibres harvested from the bast layer of the Flax plant stem (*Linum usitatissimum*) have been shown to be one of the best candidate natural fibres, since its derived composites have specific mechanical properties comparable to Glass-composites [1], [3], [4]. Consequently, Flax-composites have become a subject of aggressive research interest in the last decade or so [3], [5]. In similar vein, this study contributes to the investigation of high cycle fatigue performance of Flax-composites.

Recently published studies of Flax-epoxy fatigue are all load-controlled, where the cycling amplitude is of a constant stress range [6]–[9]. However, investigation by Poilâne et al [10] found that Flax-reinforced composites demonstrate viscous behaviour, where the tested mechanical properties are clearly sensitive to the applied strain-rate (see *Figure 1*). Increasing the applied strain-rate markedly reduces the observed modulus and strength of Flax-epoxy composite in the fibre-dominant direction. Correlation with strain rate appears to be roughly proportional on a logarithmic scale (as shown in Figure 1), i.e. the reduction in modulus or failure stress is about the same for each strain-rate increase of one order of magnitude.

Considering that the tested material properties (i) of modulus and strength are sensitive to strain rate, and (ii) demonstrate considerable inelasticity and low 'yield' strengths [11], [12], stress-life fatigue tests alone may not prove to be a reliable strategy for examining fatigue life performance of NFCs, particularly Flax-composites – since the strain rate in such tests is *continuously varying*. Our study tests several common layups of Flax-laminates (UD, crossply, quasi-isotropic) under strain-controlled (constant-strain amplitude) tension-tension fatigue, and contrasts them with the performance of similarly tested Glass-epoxy specimens.

2 MATERIALS AND MANUFACTURING

A thermoset matrix material is chosen for the fabrication of composite specimens. A hot-curing epoxy system is used, which is a combination of low-viscosity epoxy resin Araldite® LY 1564 and a cycloaliphatic polyamine hardener Aradur® 22962 (Huntsman Corporation, Advanced Materials, The Woodlands, TX, USA). The epoxy-hardener ratio is 4:1 by weight, per supplier specifications.

For Flax fibre reinforcement, a unidirectional (UD) fabric is chosen as it can be hand-cut to desired fibre-orientations, thereby allowing the highest flexibility in manufacturing composite specimens of desired layups. The reinforcing Flax material used is a commercially available dry UD fabric FlaxPly® (Lineo NV, Belgium) of area-weight 150 g/m^2 per supplier specifications. Based on measurements at our laboratory, the average density of the Flax fabric is 1.473 g/cm^3. The FlaxPly® architecture consists of twisted fibre bundles predominantly in 0° direction, held together by a periodic 90° cross-weave. The ratio of 0°-90° fibres is 40:3, i.e. for every 40 strands in the 0°-direction there are 3 across, within a unit-squared area of fabric. Microstructure observations of the eventual Flax-composite cross-section indicate that the fibre bundles measure 150-300 µm in diameter, consisting of individual 'elementary' Flax fibres of diameter 10-30 µm.

For Glass reinforcement in this study, commercially available E-Glass (14-oz ×12" Model 1115 supplied by Composites Canada, Mississauga, ON, Canada) was used. Individual Glass fibres are closely bundled and held together in a loose 'fabric' by an overlaid coarse mesh of the same Glass fibres. Micrographs indicate that the Glass fibres are cylindrical with circular cross-sections of diameter 14-18 µm – the same order of magnitude as that of elementary Flax fibres.

Composite plates were manufactured in our laboratory by hand-layup followed by heated-platen compression at a holding pressure of 5 bars (0.5 MPa). 16 layers of Flax and 12 layers of Glass are used to manufacture the respective Flax-epoxy (FE) and Glass-epoxy (GE) composites. The manufacturing setup diagram is shown in *Figure 2*. cure cycle follows the recommendation of the epoxy resin supplier: 120°C for 15 minutes, followed by 150°C for 2 hours. The optimal manufacturing pressure of 5 bars was determined by trial-and-error, such that the resulting plates had a ~50-50% fibre-matrix ratio. For FE specimens, image analysis of SEM micrographs indicates a fibre volume fraction of 49.6% ±2.3, and porosity of 3.3% ±3.0. Similar measurement for GE specimens indicates 49.6% ±3.6 fibre volume fraction and 0.12% ±0.04 porosity. Cross-section micrographs of the manufactured composites (Figure 3) show very good matrix impregnation.

3 EXPERIMENTAL METHODS

As noted earlier, four FE laminates are studied for fatigue performance: unidirectional $[0]_{16}$, crossplies $[0/90]_{4S}$ and $[\pm45]_{4S}$, and quasi-isotropic $[0/-45/90/45]_{2S}$. The crossply FE are compared with equivalent stacking-sequence GE laminates that are also tested for fatigue: $[0/90]_{3S}$ and $[\pm45]_{3S}$. All composite specimens were cut from the manufactured plates using a fine-cutting 0.35 mm diamond-edged saw, followed by grinding to produce a flat edge finish. Rectangular 250×25 mm specimens were cut from the manufactured plates (3-4 mm thick). Laboratory trials indicated that specimens fitted with tapered aluminium tabs often fractured near the grips during fatigue testing, while those with rectangular Flax-epoxy tabs (quasi-isotropic layup) always fractured in the middle gauge section. Specimen and tab dimensions (see Figure 4) are within the guidelines of fatigue testing standard ASTM D3479.

All tests were carried out at room temperature and pressure in a servo-hydraulic MTS 322 (Eden Prairie, MN, USA) test. In order to determine the relative failure strains of each composite chosen for fatigue study, displacement-controlled tests were conducted at 2 mm/min for baseline monotonic mechanical properties. For fatigue testing, loading for constant-amplitude strain was controlled via feedback from a 0.5-in (12.7 mm) gauge uniaxial extensometer. Tensile-tensile-strain tests were conducted at a frequency of 5 Hz, and strain ratio $R_\epsilon = \epsilon_{min}/\epsilon_{max} = 0.1$. Specimens were cycled until failure or up to a maximum of 2 million cycles.

4 RESULTS AND DISCUSSION

4.1 Monotonic tests

To compare the considered laminates, typical tensile loading response plots are shown altogether in Figure 5. All FE laminates that contain a 0° ply along the loading axis fail at similar strains (~1.6-1.7%), suggesting that axial deformation and failure is fibre-dominant in [0], [0/90], and quasi-isotropic specimens. The strongest of the six is GE [0/90] at 376 MPa and 1.97% failure strain, with the closest comparable FE layup being [0]. The GE [0/90] response is mostly linear, initially at a modulus of 27 GPa then relatively constant at ~20 GPa. In comparison, FE [0] response is nonlinear. Though the FE [0] is initially stiffer at 31 GPa, its tangential modulus of eventually degrades to become comparable to that of GE [0/90]. The GE angled-crossply laminate [±45] has an initial modulus and failure strength of 15 GPa and 89 MPa, respectively. To this, the closest comparable FE layups are the quasi-isotropic (in terms of tangential modulus, at least up to ~0.5% strain), and FE [±45] (in terms of failure strength and high-strain behaviour).

4.2 Fatigue tests

From Figure 5, it can be seen that the halfway-to-failure strain for most of the considered laminates is in the range of ~1.0-1.2%. So, values from this range were chosen to be the highest peak-strain level (highest ϵ_{max}) tested for all laminates. For FE laminates, at least 5 replicate tests are conducted for each strain level, while a minimum of 3 per strain level are tested for GE. The FE plots are given in Figure 6. The GE plots are given in Figure 7, where the equivalent FE-laminate plots are also reproduced for comparison. In addition to test data, all plots show the median trends and the estimated upper/lower 95% confidence bounds (hyperbolic), following procedures outlined in ASTM D3479. For convenience, all plots are presented with the same axis ranges.

The fatigue life trends are modelled by a linearised ϵ-N relation, per ASTM D3479:

$$\log N_f = A + B\varepsilon_{\max} \tag{1}$$

where N_f is the number of cycles to failure, ϵ_{max} is the peak strain, A and B are material-specific parameters determined by fitting test data. The identified parameters and their 95% confidence intervals ($ci_{0.95}$) for all tested composites are given in Table 1.

From Figure 7, the tested FE generally appear to have longer strain-fatigue lives than GE of the same stacking sequence. This observation is true at *all* tested strain levels for [0/90]. Also, the FE trend slope (B = -376.76) is nearly identical to that of GE (B = -369.35), i.e. the FE log-lives exceed those of GE by a consistent relative proportion (see Figure 7(a)). For [±45], the longer survival of FE is true only for strain levels ≥0.8%. Below this, between 0.8-0.6% strain levels, extrapolating the median trends would suggest that both FE and GE [±45] have statistically similar fatigue lives (1-3×10^6 cycles).

A natural high-cycle fatigue limit cannot be identified for any of the FE specimens, as all composite log-lives consistently follow a linearly increasing trend with decreasing strain levels, eventually exceeding the maximum limit of 2 million cycles at a low enough strain level. As such, the high-cycle fatigue limit for each laminate is considered to be the lowest tested strain level at which a specimen survives 2 million cycles.

To aid an overall inspection, all strain-life medians are plotted superimposed in Figure 8. It can be seen that the FE composites wherein response is fibre-dominant ([0], [0/90], and quasi-isotropic) produce plots that are closely placed and have similar slopes, while the FE [±45] plot is located further apart, demonstrating its considerably longer survival.

5 CONCLUSION

Thus far, from this study on fatigue lives, it can be inferred that:

- on account of their longer strain-based fatigue lives, the longevity of FE composites are comparable to, or exceed, GE composites of equivalent stacking sequence
- on account of their linear ϵ-log(N_f), Flax-composites lend themselves to reliable fatigue failure prediction, and are therefore suitable for engineering components.

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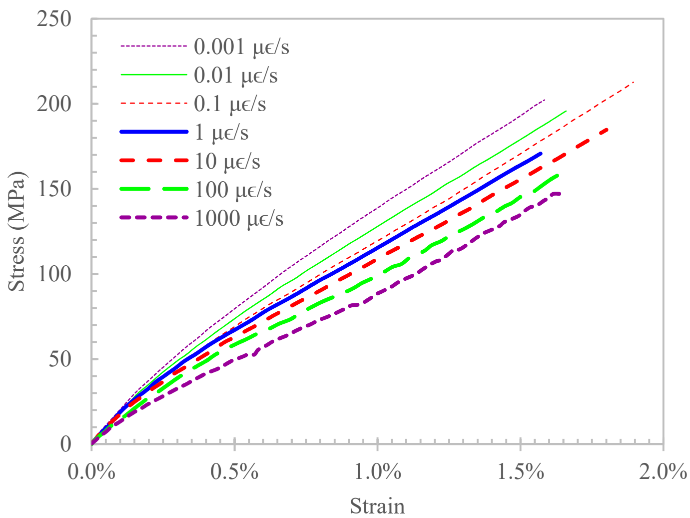

Figure 1. Non-balanced woven-Flax/epoxy composite response in fibre-dominant direction at different applied strain rates (units of microstrain per second, με/s) ; adapted from [10]

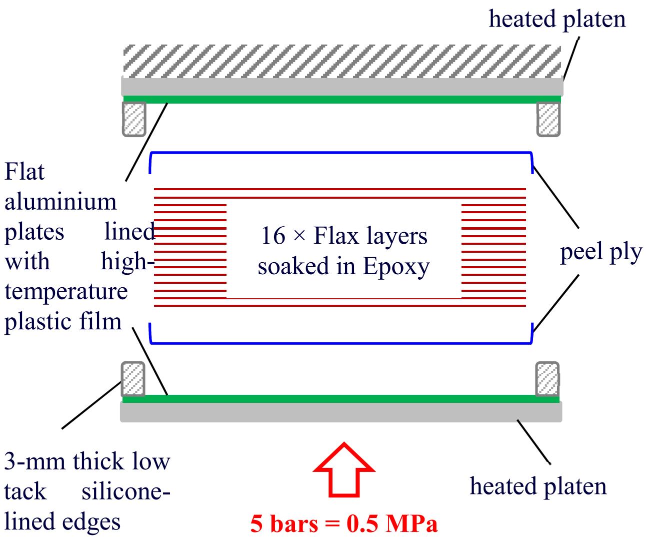

Figure 2. Manufacturing setup for composite plate; Flax-epoxy shown as example

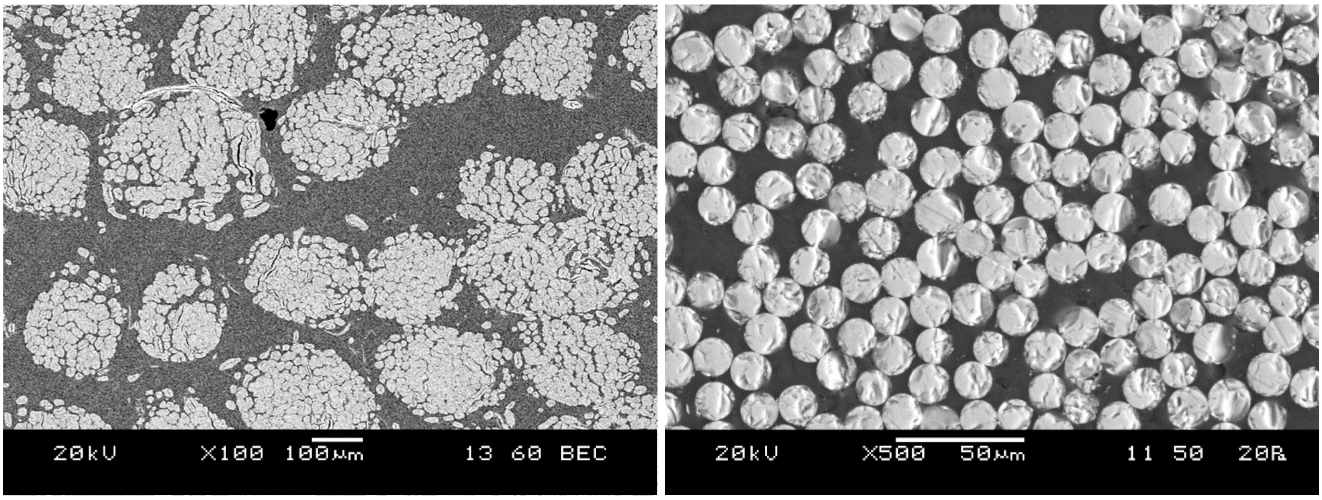

Figure 3. UD cross-sections of (left) Flax-epoxy specimen showing fibre bundles at ×100, and (right) Glass-epoxy specimen showing E-Glass fibres at ×500. Note that the magnification is different for each.

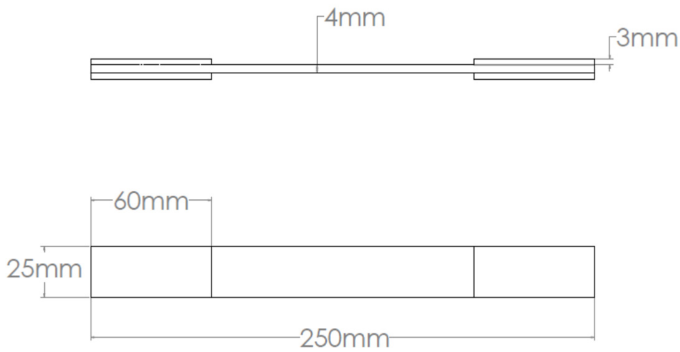

Figure 4. Test specimen geometry

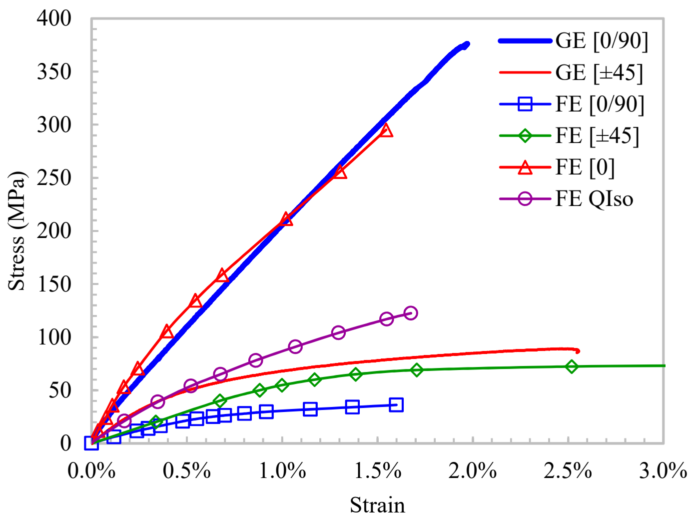

Figure 5. Typical monotonic tensile response of Flax-epoxy (FE) and Glass-epoxy (GE) laminates chosen for fatigue study. For clarity, only one curve per composite, and only up to 3% strain, is shown.

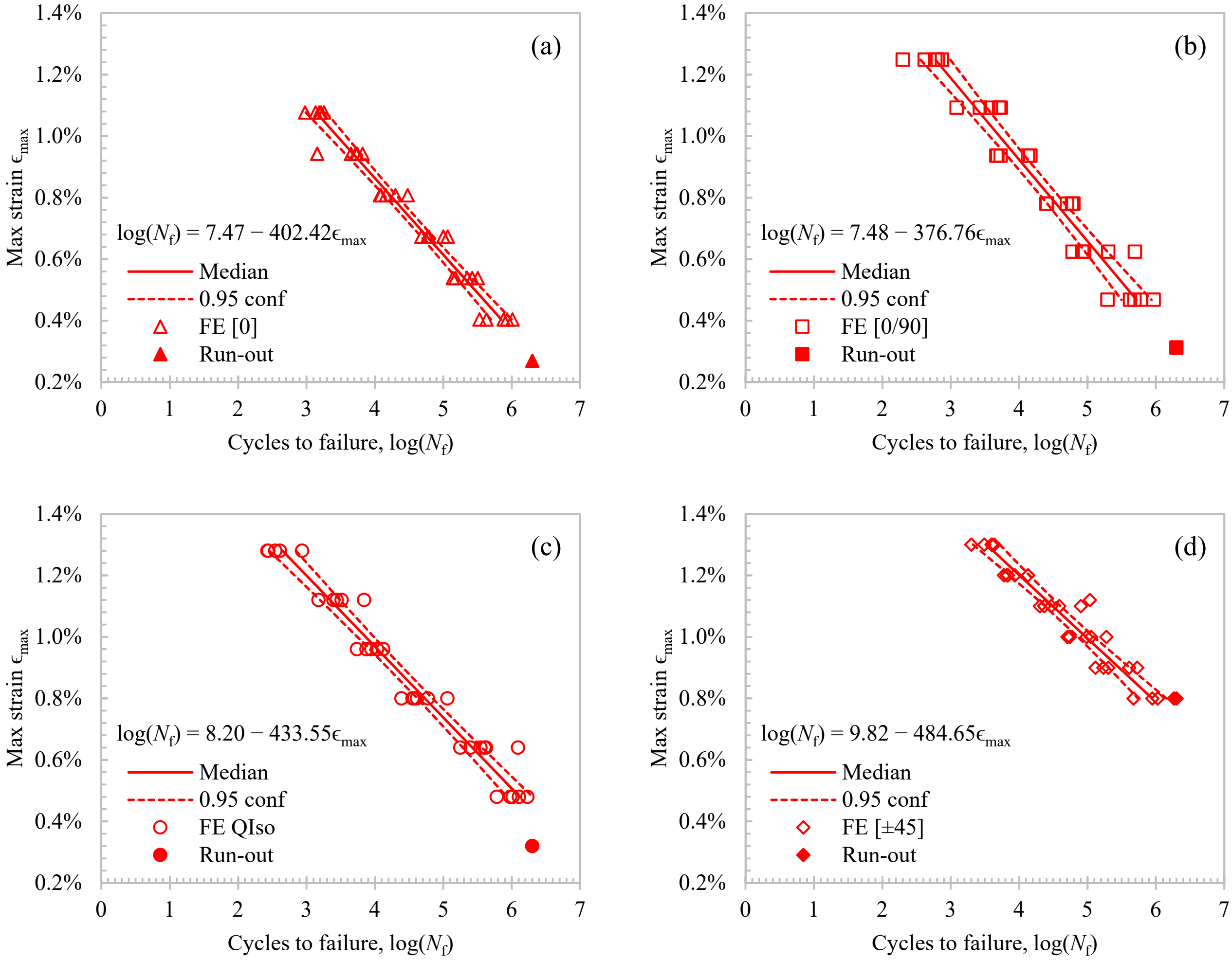

Figure 6. Strain-life plots for Flax-epoxy (FE) laminates showing test data, median trend, and 95% confidence bounds; *Run-out* = did not fail by 2E6 cycles

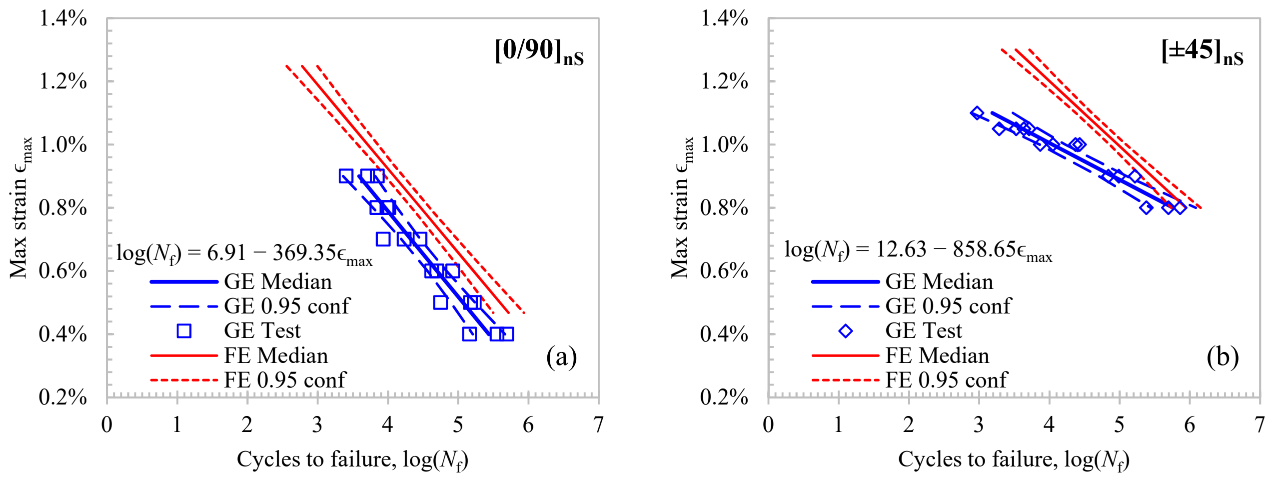

Figure 7. Strain-life plots for Glass-epoxy (GE) laminates compared with equivalent Flax-epoxy (FE), showing GE test data, median trends and 95% confidence bounds for both GE & FE

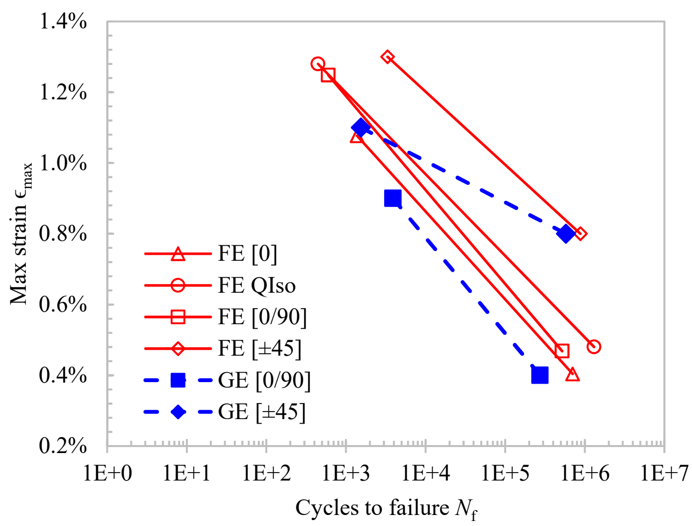

Figure 8. Strain-life medians for all FE and GE laminates tested

Laminate	$\boldsymbol{A} \pm \mathbf{ci}_{0.95}$	$\boldsymbol{B} \pm \mathbf{ci}_{0.95}$
FE $[0]_{16}$	7.472 ± 0.226	-402.42 ± 29.18
FE Quasi-isotropic $[0/-45/90/45]_{2S}$	7.480 ± 0.329	-376.76 ± 36.67
FE $[0/90]_{4S}$	8.198 ± 0.289	-433.65 ± 31.71
FE $[\pm 45]_{4S}$	9.822 ± 0.572	-484.65 ± 53.27
GE $[0/90]_{3S}$	6.914 ± 0.401	-369.35 ± 59.63
GE $[\pm 45]_{3S}$	12.632 ± 1.294	-858.65 ± 134.04

Table 1. Identified parameters of linearized strain-life relationship