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Combined and isolated effects of humidity and temperature on monotonic and fatigue response of flax fibre/epoxy composites

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ABSTRACT

FRP structures are subjected to a combination of environmental and mechanical loads that act in an interactive way, determining service life. This study investigates the isolated and combined effects of in-situ temperature and relative humidity on monotonic and tension-tension fatigue response of two flax/epoxy laminates ([0/90/0]_S and [+45/-45]_{2S}), benchmarked against equivalent GFRP laminates. Particular emphasis was given to stiffness evolution, strain accumulation, and hysteretic behaviour particularly energy dissipation. Increasing temperature consistently reduced stiffness, strength, and fatigue life for both flax FRP laminates, leading to downward shifts and tilts of the S-N curves. The effect of moisture alone was laminate-dependent: elevated moisture content reduced stiffness, strength and fatigue life in the shear-dominated [+45/-45]_{2S} laminate, whereas the [0/90/0]_S laminate showed increased fatigue life attributed to enhanced ductility and increased laminate strength. Combined elevated temperature and moisture content lead to reduced monotonic stiffness and strength whilst their effects on fatigue life were cumulative. The largest effect was observed for the [+45/-45]_{2S} laminate, where fatigue life decreased by approximately three orders of magnitude. Across all hygrothermal conditions, energy dissipation was found to be an indicator of fatigue life with higher hysteretic energy dissipation per cycle correlated with reduced fatigue life. When assessed relative to baseline S-N behaviour, flax FRPs exhibit a proportional sensitivity to combined temperature and humidity comparable to GFRPs, indicating that flax composites are not disproportionately penalised under hot-wet fatigue loading.

1. Introduction

Engineering structures operating in outdoor environments are simultaneously exposed to mechanical and environmental loadings, including fluctuations in temperature and moisture. These factors may interact and generate coupled damage mechanisms that collectively govern material degradation and service life. For emerging materials, particularly bio-based composites, it is therefore essential to characterise their mechanical response under controlled hygrothermal laboratory conditions representative of in-service environments, to ensure reliable and durable structural design.

Natural fibre-reinforced polymer composites (NFRP) have gained growing attention as sustainable alternatives to synthetic FRP composites reinforced with glass (GFRPs). Their environmental and structural credentials, including biodegradability, low density, competitive specific mechanical properties, low embodied energy, clean manufacturing,

and environmentally favourable end of life scenarios, make them an attractive alternative to glass FRPs for structural applications in transportation, construction, and renewable energy sectors. However, unlike inorganic chemically inert glass fibres which are largely insensitive to environmental conditions, flax fibres exhibit pronounced sensitivity to environmental temperature and moisture. This hygrothermal sensitivity may limit their reliable structural use and remains one of the main perceived obstacles to broader adoption of NFRPs in demanding service environments. The pronounced hygrothermal sensitivity of flax fibre reinforced polymers (FFRPs) originates from both the chemical composition and the hierarchical microstructure of the reinforcing flax fibres. Flax fibres are composed primarily of natural polymeric constituents, namely cellulose, hemicellulose, and lignin, with smaller amounts of pectin (mainly in the middle lamellae), and surface waxes. Hydroxyl groups within hemicellulose and amorphous cellulose, together with carboxy groups within pectin, form hydrogen-bonded networks with

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water [1]. Moreover, flax fibres exhibit a complex hierarchical microstructure. Elementary fibres are bound together by pectin to form technical fibres, while the cell walls within each elementary fibre consist of concentric primary and secondary layers within which distinct cellulose microfibril orientations. In addition, the central lumen of the fibre, being hollow, can absorb and transport moisture, further amplifying moisture sorption and swelling. This hierarchical and anisotropic microstructure of flax fibres further contribute to their sensitivity to environmental temperature and relative humidity [2–5].

Moisture absorption plasticises flax fibres and alters their stiffness and strength. It also causes fibre swelling, which, within a composite, leads to a mismatch with the typically lower extent of matrix swelling, thereby generating internal stresses and promoting microdamage at the fibre–matrix interface. These effects ultimately degrade fibre/matrix interfacial adhesion and compromise overall composite integrity [6,7]. Moisture absorption plasticises flax fibres and alters their stiffness and strength. Temperature variations further influence the mechanical response of flax fibres through alterations of molecular mobility within the amorphous regions of cellulose and hemicellulose, leading to reversible softening and a reduction in fibre stiffness and strength in moderate elevated temperatures [7]. Conversely, at subzero temperatures, restricted molecular mobility and freezing of bound water can induce local microcracking and alteration of the fibre properties [7,8].

The fibre and matrix properties as well as fibre–matrix interface are therefore influenced by both moisture and temperature. These hygrothermal effects act simultaneously within the same regions of the material and become particularly critical under cyclic loading, where they accelerate damage initiation and propagation induced by repeated application of stress and strain [9,10].

Consequently, understanding and precisely assessing the effects of environmental temperature and relative humidity on the monotonic and fatigue behaviour of flax fibre-reinforced composites is essential for the reliable design and optimisation of structural components intended for outdoor applications. Such knowledge enables the development of predictive models that describe environmental degradation mechanisms, allowing engineers to adapt material selection, structural design, and protective strategies to ensure long-term performance and durability under real service conditions.

While the fatigue response of natural fibre composites exhibits pronounced sensitivity to moisture, whose extent depends on the type of matrix used [9], in synthetic FRPs where glass or carbon fibres are negligibly affected by moisture, the observed fatigue degradation primarily arises from changes in the polymer matrix and fibre–matrix interface. The extent of this degradation depends strongly on the exposure conditions and the laminate lay-up architecture. For angle-ply and cross-ply glass FRPs exposed to controlled relative humidity (RH), Malpot et al. [11] investigated three relative humidities, RH0 (dry-as-moulded), RH50 and RH100 that were conditioned in a climatic chamber until mass stabilisation and tested in fatigue inside a climate chamber. Under those conditions, fatigue life was found to shorten with increasing RH only in the low-cycle regime ($N \lesssim 10^4$). At higher cycle regime, the S–N curves for RH 0–100% essentially converged, indicating a negligible influence of humidity on fatigue performance for lower stress levels. By contrast, water immersion produces larger, stress-dependent reduction in fatigue performance. For quasi-isotropic E-glass/epoxy tested in water after long moisture absorption in immersion, fatigue strength dropped $\sim 20\%$ at 10^3 cycles and $\sim 8\%$ at 10^6 cycles versus dry controls. The quasi-static tensile modulus of this laminate was negligibly affected by water immersion and the authors hypothesized that the reduction in fatigue properties was related to the reduction in adhesion between the fibres and the matrix [12]. Isolated and combined effects of moisture and temperature have recently been reported for Mode I fatigue delamination in CFRP, where combination of moisture uptake and elevated temperature increased crack growth rates and reduced the fatigue threshold due to matrix plasticisation and interfacial degradation [13].

In-situ temperature alone can exert a strong influence on fatigue performance of synthetic composites, even for CFRP/GFRP where fibres themselves are comparatively (to natural fibres) insensitive to temperature variations. Because the viscoelastic behaviour of polymeric matrix is highly temperature-dependent, increasing temperature reduces the matrix modulus and strength, which lowers the laminate stiffness and monotonic tensile strength resulting in larger displacements, faster damage accumulation, and shorter fatigue life. In addition, mismatch between fibre and matrix coefficients of thermal expansion further intensifies local stress concentrations and damage initiation. The extent of this effect becomes more pronounced in lay-ups that are more matrix and interface dominated ($90^\circ > \text{cross-ply} > 0^\circ$). Consequently, higher temperatures lead to shorter fatigue lives, demonstrated by a reduction in the number of cycles to failure at a given stress level [14].

Testing of angle-ply CFRP laminates under combined in-situ temperature and humidity conditions also exhibited a downwards shift of the S–N curve with increasing temperatures and moisture levels reflecting a systematic reduction in fatigue life due to accelerated crack initiation and propagation under hygrothermal exposure. Numerical analysis performed in the same study demonstrated that fatigue properties of the angle-ply laminate were significantly more sensitive to temperature than moisture [15].

For flax fibre-reinforced polymer composites (FFRPs), humidity is regarded as a major concern for fatigue performance due to the inherent hygroscopicity of natural fibres. Immersion studies have shown that long-term water uptake can markedly reduce tensile strength (e.g., a 27% reduction after 26 days at 70°C) and significantly shorten fatigue life at high stress amplitude levels [16]. However, extrapolated S–N curves suggest that, at low-stress levels corresponding to long-life (high cycle) regimes, fatigue performance may remain largely unaffected [16]. By contrast, more application-relevant humidity conditioning involving exposure to high relative humidity ($\sim 85\%$ RH) produces only modest effects: stiffness is reduced, but tensile strength remains stable or slightly increase, and differences in fatigue life relative to dry conditions are typically within experimental scatter [9,17,18]. Temperature, however, exerts a stronger influence, with elevated testing temperatures (e.g., 60°C compared with 23°C) tilting the S–N curve such that short-life fatigue performance (high cycle fatigue regime) remains comparable, whereas fatigue strength in the high-cycle fatigue regime is reduced. This behaviour highlights the critical role of in-situ thermal effects in governing the fatigue durability of flax composites [9].

Despite increasing interest in the fatigue behaviour of flax FRPs under hygrothermal exposure, most existing studies have focused either on unidirectional laminates or on isolated moisture or temperature effects, leaving limited understanding of how laminate architecture and combined environmental conditions influence fatigue performance and damage evolution. From an industrial perspective, this knowledge gap is critical because durability under coupled environmental and cyclic mechanical loading remains a key requirement for the wider adoption of flax FRP composites. In practical applications flax FRPs must retain sufficient stiffness, strength, and fatigue resistance despite variations in temperature and humidity during service. To address these gaps, the present study investigates the monotonic and fatigue response of two flax FRP laminate configurations, $[0/90/0]_S$ and $[+45/-45]_{2S}$, conditioned and tested under controlled various relative humidities and temperatures. Damage development under different hygrothermal conditions is analysed through visual inspection, optical microscopy, and X-ray micro-computed tomography (micro-CT), while cyclic stress-strain measurements are used to evaluate hysteretic energy dissipation and its relationship with fatigue life. Finally, to contextualise the sensitivity of flax FRP performance to in-situ hygrothermal conditions, glass FRP laminates are also included as reference benchmarks representing conventional synthetic FRP composite counterparts. In this way, the study aims not only to clarify the governing hygrothermal fatigue mechanisms, but also to generate knowledge that supports material selection and design for safe operation under service hygrothermal conditions.

2. Materials and methods

2.1. Laminates manufacturing and specifications

Two flax FRP laminates were selected with the lay-ups [0/90/0]_s, to promote longitudinal and transverse fibre loading, and [+45/-45]_{2s}, to promote in-plane shear deformations primarily governed by matrix and fibre/matrix interfacial properties. For the longitudinal fibre loading, a fully unidirectional laminate was initially considered, but preliminary tests showed systematic longitudinal splitting, which prevented controlled and reproducible fatigue failure. The [0/90/0]_s lay-up was therefore selected as a stable alternative, because the introduction of two 90° plies suppressed splitting while retaining a majority of 0° plies, such that the response remained primarily governed by the load-aligned fibres. Correspondingly, benchmark GFRP laminates were prepared with the lay-ups [0/90/0] and [+45/-45]_s, representing the same laminate configurations but with half the number of plies. This adjustment was done because the glass fabric available was approximately twice as thick as the flax fabric, and using half the number of plies allowed the GFRP and FRP specimens to have approximately the same overall thickness. All laminates, summarized in Table 1, were manufactured using quasi-UD non-crimp preforms Bcomp Amplitex 280 g/m² flax and Kush Synthetics high stiffness 1260 g/m² glass reinforcement. Upon request, Bcomp did not disclose details of any fibre treatment or sizing applied to the flax fibres. No additional pretreatments were considered or applied to the fibres by the authors prior to composite manufacturing. This was considered acceptable because raw flax/epoxy systems, including untreated Bcomp Amplitex, have been reported to develop effective fibre–matrix adhesion, with interfacial shear strengths of the same order as moderately sized glass/epoxy systems [19–21]. The laminates were infused with the Swancor 2511-1AL/BL epoxy resin system. Regarding specimen geometry, a rectangular shape was initially chosen. However, preliminary tensile tests on the [0/90/0]_s laminates showed premature failure at the edges of the grips. Therefore, specimens with this lay-up were subsequently cut with a narrower central section and wider grip regions, following the geometry proposed in a previous study [22].

The FRP laminates were manufactured using the vacuum-assisted resin infusion (VARI) process. Both storage of the preforms and vacuum infusion were done in laboratory conditions (19–22 °C and 30%–60% RH) without fibre pre-drying to improve durability with variations of hygrothermal conditions [23]. After infusion, the plates were left to cure at laboratory conditions for at least of 24 h, followed by post-curing in an autoclave at 70 °C and 7 bars for 18 h. The glass transition temperature, T_g , of the cured composites was measured with differential scanning calorimetry (DSC) and was found to be above 70 °C for all

laminates with an average of 79 °C and a standard deviation of 3 °C. Therefore, all mechanical tests in the present study, including those at the maximum of 50 °C, were conducted below T_g .

2.2. Pre-conditioning protocol of composite laminates

To evaluate the effects of in-situ hygrothermal conditions, the specimens were pre-conditioned prior to monotonic and fatigue testing. First, the specimens were equilibrated to the target relative humidity in a Weiss WK111 climate chamber. The climate chamber temperature was set to 50 °C to accelerate moisture diffusion, while the relative humidity was set to one of the selected in-situ values: 30%, 50%, or 90%. Although multi-temperature sorption data for flax-epoxy composites are limited, studies on aramid-, glass- and carbon-fibre epoxy laminates consistently show that the equilibrium moisture content is governed principally by relative humidity, with temperature exerting only a secondary influence within the range relevant for structural applications [24–26]. In these systems, increasing temperature primarily accelerates diffusion rather than altering the maximum moisture content. Given the similar epoxy matrix in both flax and glass laminates, the same assumption was adopted here. For flax-fibre composites, the available literature indicates that temperature can also affect moisture uptake because of the hygroscopic nature of the fibres and the temperature dependence of water transport in the cellulosic constituents challenging this assumption. However, this evidence has been obtained under water-immersion ageing conditions, whereas the present study considers equilibration under controlled relative humidity [27,28]. The evolution of specimen weight was monitored relative to the specimen initial weight. Specimens were kept in the Weiss WK 111 climate chamber for a minimum of 12 days to ensure moisture absorption corresponding to at least 90% of the estimated equilibrium moisture content. Additionally, it was verified that the rate of weight change was below 0.1% per day before transferring the specimens to the tensile testing setup. The moisture sorption curves obtained during pre-conditioning are provided in Fig. 1 of the supplementary data. The limited mass change observed at 50% RH, compared with the mass decrease at 30% RH and the mass increase at 90% RH, is consistent with the manufacturing and storage conditions in the laboratory, where the relative humidity was 50% ± 10%. Thus, conditioning at 50% RH produced little net change, whereas conditioning at 30% RH led to desorption and conditioning at 90% RH led to sorption. Once the specimens reached the desired moisture equilibrium conditions, they were transferred to the tensile testing setup equipped with a climate chamber, which has been pre-equilibrated to the target testing relative humidity and temperature. For tests conducted at –20 °C, the relative humidity could not be actively controlled due to the freezing of absorbed water within the specimens and moisture sublimation in the chamber environment. Hence, in this study, the condition denoted as –20 °C/50% RH refers to specimens that were pre-equilibrated to 50% RH at 50 °C and subsequently cooled to –20 °C. A thermal probe was installed on the surface of the specimen to be tested and another one near the specimen to measure air temperature in addition to the climate chamber sensor. Before starting each tensile test, it was ensured that both the air and specimen surface temperatures were within 1 °C of the desired test temperature, –20 °C, +20 °C, and +50 °C.

2.3. Low and high speed monotonic tensile testing under controlled hygrothermal conditions

Monotonic tensile tests were performed with an Instron 1251 hydraulic tensile testing machine equipped with a 100 kN load cell and hydraulic clamps. A Klimastast Weisstechnik climate chamber was installed around the tensile testing setup enclosing the specimen and clamps maintaining the target environmental conditions. An extensometer was attached on the specimen with rubber bands to measure the strain. A picture of the setup is provided in Fig. 2 of the supplementary

Table 1
List of laminates used in the experimental campaign.

Lay-up	Fibre type	Fabric model	Matrix	Laminate thickness [mm]	Fibre volume fraction [%]
[0/90/0] _s	Flax	Bcomp Amplitex 280	Epoxy resin system SWANCOR2511-1AL/BL	2.9 ± 0.1	36 ± 2
[0/90/0]	Glass	Kush Synthetics High stiffness 1260		2.9 ± 0.1	52 ± 1
[+45/-45] _{2s}	Flax	Bcomp Amplitex 280		3.9 ± 0.1	41 ± 1
[+45/-45] _s	Glass	Kush Synthetics High stiffness 1260		3.6 ± 0.1	55 ± 2

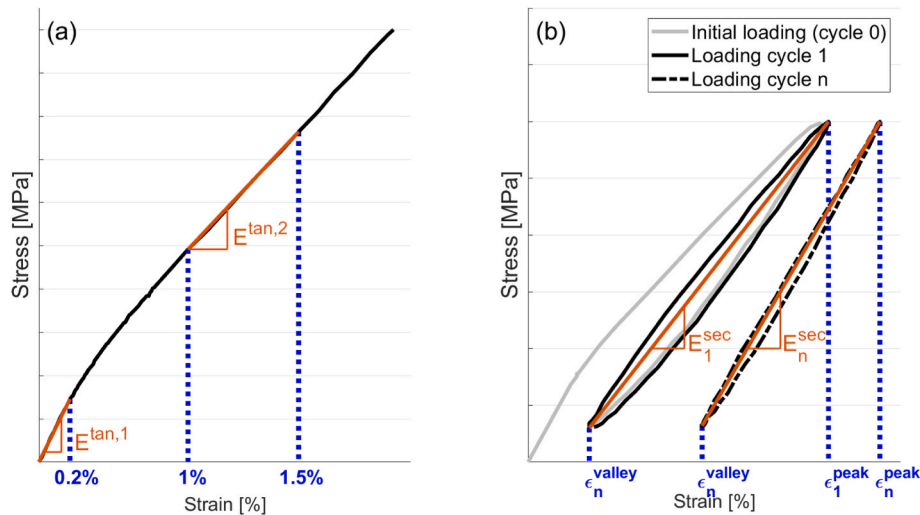


Fig. 1. Illustration of the tangent modulus determined from monotonic tests (left), and the secant modulus with corresponding peak and valley strains obtained from fatigue tests (right).

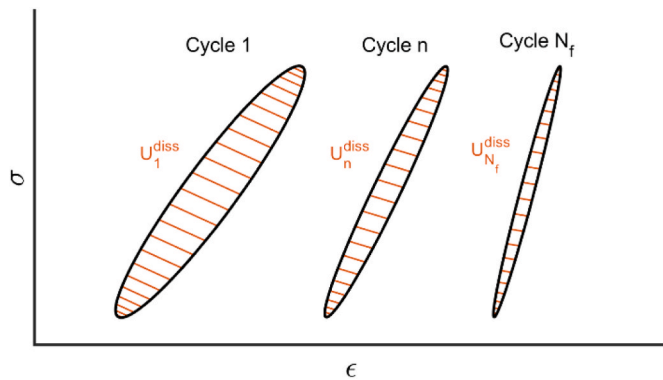


Fig. 2. Schematic of fatigue hysteresis with definition of dissipated energy and maximum stored elastic energy.

data. The same configuration was used for fatigue testing. Testing was initially performed in displacement control at a conventional quasi-static displacement rate of 2 mm/min with 5 repetitions per hygro-thermal conditions. As the tested laminates exhibited sensitivity to strain rate due to their viscoelastic behaviour, and since the monotonic tests were intended to serve as reference for the fatigue tests, a second set of monotonic tests was performed using identical test settings, with the sole exception that the strain rate was adjusted to match that of the fatigue tests. In the fatigue tests, the load and displacement signals followed approximately sinusoidal waveforms. Therefore, the instantaneous actuator displacement rate varied continuously during each cycle and became zero at the reversal points. To define a representative loading rate for comparison with monotonic tests, an equivalent mean absolute actuator displacement rate was calculated by replacing the sinusoidal fatigue cycle with a triangular waveform having the same peak and valley levels and the same frequency. This equivalent triangular waveform provides a constant loading and unloading slope over each half-cycle, corresponding to the average absolute displacement rate experienced during cyclic loading. Based on the 5 Hz fatigue tests conducted at the reference condition (20 °C/50% RH) on FRP laminates, the average actuator displacement rates measured during cyclic loading were approximately 480, 900, and 1320 mm/min for the [0/90/0]_s laminate at maximum stress levels of about 80, 160, and 240 MPa, respectively, and approximately 600, 900, and 1380 mm/min for the [+45/-45]_{2s} laminate at 35, 45, and 55 MPa, respectively. On this basis,

additional monotonic tests were performed at nominal displacement rates of 300, 600, and 1200 mm/min to represent the low, intermediate, and high loading-rate regime experienced during fatigue testing. In certain conditions, the ultimate strain during monotonic testing exceeded the operational range of the extensometer. Hence, for strains above 6%, the deformation was determined from the actuator displacement.

2.4. Tension-tension fatigue testing under controlled hygrothermal conditions

Tension-tension fatigue testing was performed using the same Instron 1251 hydraulic tensile testing machine enclosed with a Klimaatkast Weisstechnik climate chamber used for monotonic testing. An extensometer was installed on the specimen as for monotonic testing. A temperature probe was attached to the specimen surface to monitor temperature evolution, but it was established during the testing campaign that this probe systematically underestimated the actual surface temperature. This discrepancy was identified through measurements performed with a portable thermal camera. For high stress levels fatigue, the most critical case for self-heating, additional thermal camera measurements were conducted in the 20 °C/50% RH environment. These measurements indicated that the maximum temperature rise relative to the chamber environment did not exceed 9 °C. The fatigue tests were performed under force-controlled conditions. The maximum stress levels were selected and adjusted for each testing condition to span a fatigue lifetime between 10^3 and 10^6 cycles. For each test, the minimum stress level was determined from the maximum stress using a stress ratio $R = 0.1$. A constant loading frequency of 5 Hz was applied in all fatigue tests. During fatigue testing, stress and strain signals were acquired at a sampling rate of 250 Hz, corresponding to 50 data points per loading cycle. Continuous recording was performed over the first 1'000 cycles to capture the rapid evolution in stiffness and strain accumulation occurring during the early phase of fatigue. Beyond this point, data acquisition was reduced to one recorded cycle every 1'000 cycles to limit data volume during long-term fatigue tests.

2.5. Data processing of monotonic and fatigue data

2.5.1. Calculation of stiffness and strain

To characterise the stiffness properties from the monotonic tests, the initial tangent modulus, $E^{\tan,1}$, was determined from the slope of the stress-strain curve between the origin and 0.2% strain, as illustrated in Fig. 1a. Because of the bilinear mechanical behaviour exhibited by the

[0/90/0]_S flax FRP laminate, a secondary tangent modulus, $E_n^{\text{tan},2}$, was additionally calculated over the strain interval from 1% to 1.5%.

In the fatigue tests, stiffness was defined as the secant modulus, E_n^{sec} , as illustrated on Fig. 1b, where the subscript n denotes the cycle number. The secant modulus was employed instead of the tangent modulus because, under cyclic loading, the instantaneous tangent stiffness continuously varies during both the loading and unloading phases of each cycle. In contrast, the secant modulus provides a representative average stiffness over the complete load–unload cycle. Strain during fatigue was characterised at the minimum and maximum points of the hysteresis loop, denoted as $\epsilon_n^{\text{valley}}$ and ϵ_n^{peak} , respectively. The accumulated strain during fatigue (ratcheting), ϵ_n^{acc} , was defined as the difference between the peak strain at cycle n and the peak strain in the first cycle as expressed in equation (1):

$$\epsilon_n^{\text{acc}} = \epsilon_n^{\text{peak}} - \epsilon_1^{\text{peak}} \quad (1)$$

2.5.2. Energy dissipation during fatigue cycles

The energy dissipation during fatigue cycles was evaluated from the stress-strain hysteresis loops recorded throughout cyclic loading. The area enclosed by each hysteresis loop, denoted U_n^{diss} , represents the energy dissipated mechanically per cycle n (Fig. 2). This dissipated energy was calculated numerically by integrating the stress-strain curve over one complete loading-unloading cycle, using linear interpolation in-between measurement points.

$$U_n^{\text{diss}} = \oint \sigma d\epsilon \quad (2)$$

The dissipated energy corresponds to the portion of mechanical work that is not recovered elastically after each loading cycle. It includes both viscoelastic losses which manifest as heat generated by internal friction, and irreversible energy contributions associated with microdamage such as plastic deformation, interfacial debonding, or matrix microcracking. Although damping ratios are not presented in the present paper, U_n^{diss} remains physically related to the concept of damping in a specific cycle, n , which expresses the fraction of mechanical energy lost per cycle relative to the energy stored elastically. This relationship can be expressed as:

$$\eta_n \propto \frac{U_n^{\text{diss}}}{U_n^{\text{el,max}}} \quad (3)$$

where η_n represents the effective damping for cycle n , U_n^{diss} denotes the dissipated energy, and $U_n^{\text{el,max}}$ is the maximum elastic strain energy stored during that cycle.

2.6. Microscopy for post-mortem damage analysis

Post-mortem optical microscopy after fatigue testing was conducted to examine fatigue-induced damage in both cross-ply [0/90/0]_S and angle-ply [+45/-45]_{2S} FFRP specimens. Specimens were selected at comparable stress levels to represent three conditions: the reference state (+20 °C/50% RH), the most brittle case (−20 °C/50% RH), and the most ductile case (+50 °C/90% RH). After fatigue testing, sections of 15 × 15 mm were cut and oriented as such to allow observations both parallel and perpendicular to the loading direction. Specimens were imaged with a Keyence VHX-7100 digital microscope.

Micro-CT was used to assess internal damage in fatigue-tested specimens. Specimens were cut into 5 × 50 mm strips to minimise beam attenuation and improve resolution. Scans were acquired using a TESCAN CoreTOM system with a voxel size of 3 μm, tube voltage of 80 kV, a power of 15 W. In total, approximately 4000 radiographic projections were collected per specimen each with an exposure time of 130 ms, without frame averaging. The acquired projections were reconstructed to tomographic slices using the TESCAN Reconstruction Suite

software and were processed in Avizo 3D v2025 software to generate 3D visualisations of the damage. These visualisations were used to qualitatively assess and compare the spatial distribution of cracks under the different hygrothermal conditions.

3. Results and discussions

3.1. Monotonic tensile experiments

Monotonic tensile tests were first conducted to establish the baseline behaviour of the flax fibre reinforced laminates under different hygrothermal conditions, with glass fibre reinforced laminates tested as benchmarks. These tests provide a reference for interpreting the fatigue results and highlight the combined influence of temperature, relative humidity, and strain rate on the mechanical performance of the composites. The monotonic test results confirm that the mechanical response of flax FRP composites is strongly dependent on in-situ environmental temperature, relative humidity levels, and strain rates as demonstrated in Fig. 3a–d. Both investigated laminates, [0/90/0]_S and [+45/-45]_{2S}, exhibited variations in stiffness (E_1 and E_2), strength, and strain to failure (see Table 3).

3.1.1. Temperature effects on flax FRP laminates

An increase in temperature resulted in a systematic reduction in stiffness and strength for both flax FRP laminates. This effect was particularly pronounced for the [+45/-45]_{2S} laminate, where increasing the temperature from −20 °C to 50 °C led to a reduction of approximately 32% in ultimate tensile strength and 36% in longitudinal modulus E_1 . The [0/90/0]_S laminate exhibited a more moderate sensitivity to temperature in terms of stiffness and strength with 24% and 14% reduction respectively. Temperature had a markedly different influence on ductility depending on laminate architecture. For the [+45/-45]_{2S} laminate, the ultimate strain increased substantially with temperature, rising from about 3% at −20 °C to 9% at 20 °C and reaching approximately 15% at 50 °C. This behaviour is attributed to the shear-dominated response of the angle-ply laminate, in which increasing temperature makes the epoxy matrix more compliant and facilitates in-plane shear deformation, fibre scissoring, and reorientation. For the [0/90/0]_S laminate, the ultimate strain also increased slightly with temperature, rising from approximately 1.9% at −20 °C to about 2.2% at 20 °C and 2.1% at 50 °C, thus remaining within a narrow strain interval over the investigated temperature range. In this fibre-dominated laminate, the tensile response remains governed mainly by the 0° plies, so matrix softening has only a limited effect on the overall strain to failure.

3.1.2. Moisture effects on flax FRP laminates

Relative humidity had a significant influence on the tensile response of flax FRPs, primarily through increased ductility and reduced stiffness. For both laminate configurations, the ultimate strain increased with increasing humidity. When relative humidity increased from 30% to 90%, the ultimate strain rose from 1.7% to 3.2% for the [0/90/0]_S laminate and from 4.4% to 11.0% for the [+45/-45]_{2S} laminate. Concomitantly, the longitudinal modulus E_1 decreased with increasing humidity, dropping from 17.5 GPa to 11.3 GPa for the [0/90/0]_S laminate and from 5.3 GPa to 4.3 GPa for the [+45/-45]_{2S} laminate. For the [0/90/0]_S laminate, although E_1 was reduced by 35%, the tangent modulus E_2 showed a slightly smaller decrease of 28% from 9.9 GPa to 7.1 GPa. This difference in modulus reduction could be explained by microfibril and yarn reorientation mechanisms occurring at higher strain levels, within the region E_2 . As shown in our previous work [22], such mechanisms can increase the stiffness of flax FRP laminates. Their contribution may therefore provide a modest stiffness increase at higher strain levels, where E_2 is defined, thereby slightly compensating for moisture-induced softening. This interpretation is consistent with the stress–strain curve shape at 90% RH, where an inflection point becomes visible (Fig. 3c). Such behaviour closely resembles the tensile response

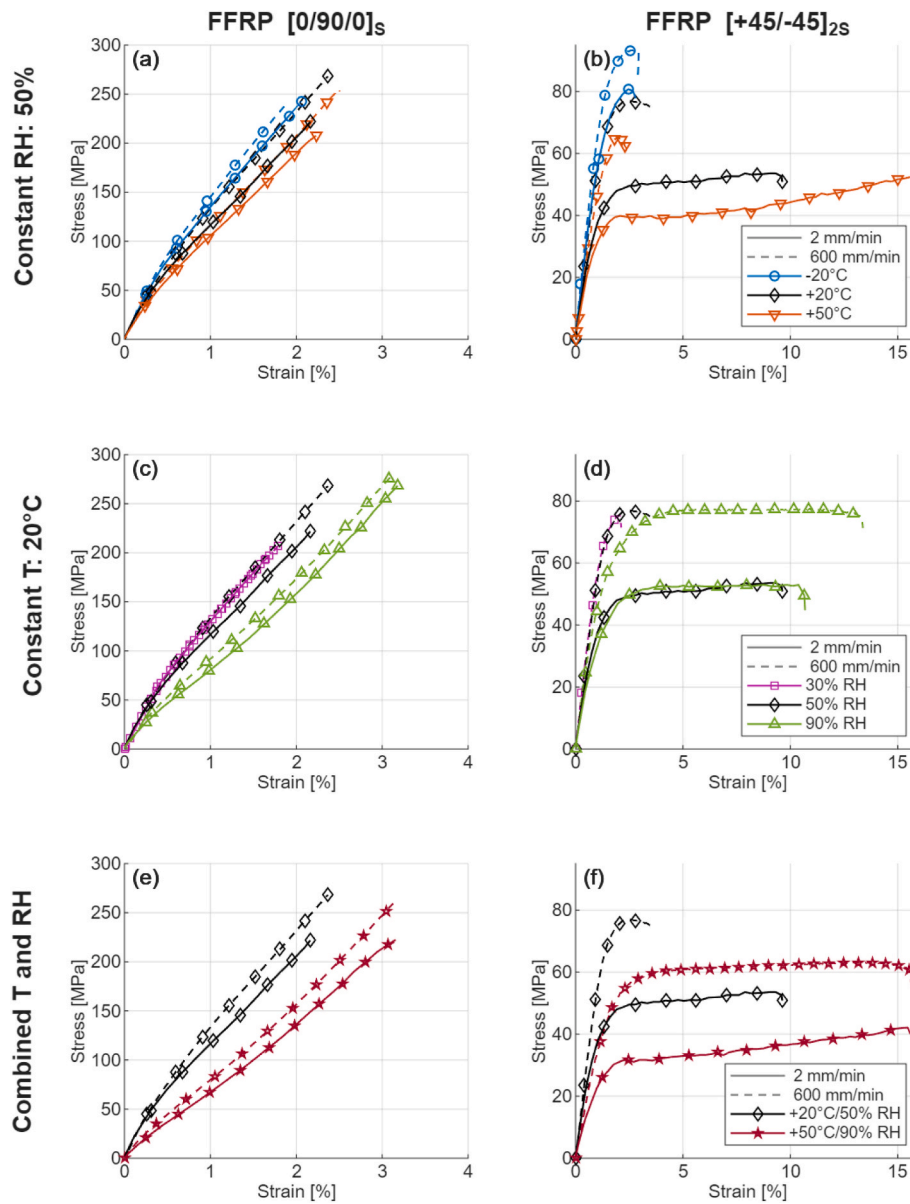


Fig. 3. Stress–strain response of flax fibre composites under monotonic tension at different hygrothermal conditions and loading rates. The solid lines correspond to monotonic loading displacement rate of 2 mm/min equivalent to an extensometer-based strain rate of 0.017 ± 0.001 %s⁻¹. The dashed lines represent displacement rate of 600 mm/min equivalent to an extensometer-based strain rate of 5.3 ± 0.4 %s⁻¹.

reported for individual flax fibres, where an initial linear region is followed by a nonlinear regime attributed to microfibril reorientation and viscoelastic effects [29].

Regarding strength, moisture effects were laminate dependent. For the [+45/-45]_{2S} laminate, the ultimate tensile strength remained broadly similar across the investigated humidity levels, varying from about 57 MPa at 30% RH to 53 MPa at 90% RH. Given the experimental scatter (± 2 MPa), this change does not indicate a clear reduction in monotonic tensile strength nor provide strong evidence of matrix–interface degradation. Nevertheless, the modest downward trend observed at high RH may be related to some reduction in load-transfer efficiency in this shear-dominated laminate. This interpretation is consistent with previous studies showing that moisture uptake in flax fibre composites can promote fibre swelling and fibre–matrix debonding, thereby reducing interfacial shear strength and load-transfer efficiency [6,30]. Although microscopy evidence for the isolated humidity effect is not available in the present study, the combined effect of increased temperature and humidity shown in Section 3.3.2 and Fig. 14 indicates

increased interfacial debonding under the severe hot–wet fatigue condition.

Conversely, for the [0/90/0]_S laminate, the ultimate tensile strength increased with humidity, rising from 195 MPa at 30% RH to 263 MPa at 90% RH. Although interface weakening would typically be expected to reduce strength, moisture uptake has been reported to increase strain to failure and, in some cases, the tensile strength of elementary flax fibres [7]. This behaviour is generally attributed to plasticisation of the non-cellulosic amorphous constituents of the fibre cell wall, which facilitates shearing of microfibril during tensile loading resulting in partial realignment and reduction of internal stress concentrations delaying failure [3,7,29]. In addition, moisture-induced plasticisation of the matrix may promote stress redistribution within the laminate, delaying catastrophic failure compared with the more brittle response observed at low humidity.

3.1.3. Combined effects of temperature and moisture on flax FRPs

For the [0/90/0]_S laminate, increasing temperature resulted in a

reduction of the stress-strain slope (E_1 and E_2) and of ultimate strength (Fig. 3a), whereas high humidity seems to have a knock-down effect on the modulus whilst increasing ultimate strength and strain to failure (Fig. 3c). Under combined conditions of 50 °C and 90% RH (Fig. 3e), temperature and moisture effects appeared to superimpose, leading to a reduction in modulus that was greater than that observed under either temperature or humidity alone. This superposition was less evident for ultimate tensile strength. Relative to the reference condition (20 °C/50% RH), the ultimate tensile strength decreased by 5% under 50 °C/90% RH. This combined reduction should be compared with the isolated effects, for which elevated temperature at 50 °C/50% RH reduced the ultimate tensile strength by 12%, whereas high humidity at 20 °C/90% RH increased it by 17%. Based on a simple additive estimate, these isolated effects would therefore predict a combined strength change of 5% increase, while a decrease of 5% is measured. For comparison, the corresponding [0/90/0] GFRP laminate exhibited a larger reduction of 19% under the same combined condition. The lesser reduction in the flax [0/90/0]_S laminate could be attributed to the humidity-induced increase in strength partly offsetting the detrimental effect of elevated temperature. Thus, while the stiffness response was broadly consistent with an additive hygrothermal effect, the strength response under the combined condition was not accurately captured by a simple additive superposition of the isolated temperature and moisture effects for the [0/90/0]_S FRP laminate. However, this interpretation should be treated with caution, as additional tests would be required to establish stronger statistical significance. Nevertheless, together with the simultaneous increase in strength and decrease in modulus observed at higher relative humidity, this indicates that stiffness and ultimate strength were not governed by identical sensitivities to temperature and moisture. These observations point to a combination of sub- T_g temperature-induced softening of the epoxy matrix and moisture-induced plasticisation, together with temperature- and moisture-dependent changes in the flax fibres. Since the measured T_g of the cured composite system remained above 70 °C, the behaviour observed at 50 °C is not attributed to the epoxy crossing its glass transition, but to a progressive reduction in matrix stiffness and an increase in viscoelastic compliance as the temperature approaches T_g . For the [+45/-45]_{2S} laminate combined hygrothermal effects on stiffness and strength were also observed. The increase in stress after an initial plateau observed at 50 °C (Fig. 3b), attributed to shear-driven fibre reorientation and scissoring mechanisms, was also present under combined high temperature and high humidity conditions (Fig. 3f).

To model the combined hygrothermal response, the variations induced by temperature and relative humidity were analysed relative to a reference condition and interpreted as additive contributions. A simple

phenomenological model based on linear superposition of the isolated effects was therefore proposed. The predicted tangent modulus $E_{T,RH,prediction}^{tan}$ is defined as:

$$E_{T,RH,prediction}^{tan} = E_{ref}^{tan} + \Delta E_T^{tan} + \Delta E_{RH}^{tan} \quad (4)$$

where:

- E_{ref}^{tan} is the tangent modulus at the reference condition (20 °C/50% RH),
- ΔE_T^{tan} is the variation in modulus due to the isolated effect of temperature (20 °C to 50 °C),
- ΔE_{RH}^{tan} is the variation in modulus due to the isolated effect of relative humidity (50% RH to 90% RH).

The prediction of the modulus based on this linear superposition shows close agreement with the experimentally measured values at 50 °C and 90% RH for both FRP laminates, as shown in Table 2a. The deviations between $E_{T,RH,prediction}^{tan}$ and $E_{T,RH,measured}^{tan}$ are 0.3 GPa for [0/90/0]_S E_1 , 0.2 GPa for [0/90/0]_S E_2 , and 0.0 GPa for [+45/-45]_{2S} E_1 . These results suggest that additivity is appropriate as a first-order description of the combined stiffness response. This principle of effect superposition was also applied to predict the ultimate strain and ultimate tensile strength (UTS), (Table 2b and c). For the ultimate strain, the prediction remains within the experimental scatter (standard deviation). For UTS the superposition approach systematically overestimates the measured values, suggesting that non-linear synergistic interactions between temperature and moisture occur, leading to a more pronounced strength degradation than expected from the sum of isolated effects, likely reflecting enhanced fibre-matrix interface weakening under combined hygrothermal exposure. However, the trends observed here should be interpreted with caution, as they are based on a limited number of data points and the differences remain modest relative to the experimental scatter.

3.1.4. Strain rate effects on flax FRP laminates

An increase in strain rate led to higher stiffness and strength for all flax FRP laminates, with the magnitude of the effect depending on laminate architecture and environmental condition. For the [0/90/0]_S laminate, increasing the displacement rate from 2 mm/min to 300–1200 mm/min resulted in a moderate increase in tensile modulus and ultimate strength under all environmental conditions. For example, at 20 °C and 50% RH, the modulus E_1 increased by 8% when the rate was raised from 2 mm/min to 600 mm/min, accompanied by a 19% increase

Table 2

Prediction of combined temperature and humidity effect on modulus, ultimate strain, and ultimate stress based on isolated effects and assumption of additive effects.

(a)		Modulus					
		E_{ref}^{tan}	ΔE_T^{tan}	ΔE_{RH}^{tan}	$E_{T,RH,prediction}^{tan}$	$E_{T,RH,measured}^{tan}$	
[0/90/0] _S	(E_1)	17.1	−2.6	−5.8	8.7 ± 1.7	8.4 ± 1.3	[GPa]
	(E_2)	8.8	−0.7	−1.7	6.4 ± 0.4	6.2 ± 0.6	[GPa]
[+45/-45] _{2S}	(E_1)	5.1	−1.0	−0.8	3.3 ± 0.6	3.3 ± 0.4	[GPa]

(b)		Ultimate strain					
		ϵ_{ref}^{peak}	$\Delta \epsilon_T^{peak}$	$\Delta \epsilon_{RH}^{peak}$	$\epsilon_{RH,T,prediction}^{peak}$	$\epsilon_{RH,T,measured}^{peak}$	
[0/90/0] _S		2.2	−0.1	1.0	3.1 ± 0.2	3.1 ± 0.1	[%]
[+45/-45] _{2S}		8.6	7.6	2.4	18.6 ± 3.5	14.9 ± 1.4	[%]

(c)		Ultimate strength					
		UTS_{ref}	ΔUTS_T	ΔUTS_{RH}	$UTS_{RH,T,prediction}$	$UTS_{RH,T,measured}$	
[0/90/0] _S		225	−26	38	237 ± 11	214 ± 11	[MPa]
[+45/-45] _{2S}		55	−1	−2	52 ± 4	43 ± 4	[MPa]

in ultimate tensile strength. The strain to failure was largely unaffected by strain rate across the investigated environments.

For the $[+45/-45]_{2S}$ laminate, the strain rate sensitivity was substantially higher. At 20 °C and 50% RH, increasing the displacement rate from 2 mm/min to 600 mm/min raised E_1 by 12% and the ultimate tensile strength by 40%. For this laminate, the strain to failure was approximately halved at higher strain rates under 20 °C/50% RH, 50 °C/50% RH, and 20 °C/30% RH, whereas only marginal variations were observed under the remaining environmental conditions. The pronounced strain rate sensitivity of the $[+45/-45]_{2S}$ laminate is attributed to its shear-dominated architecture, in which the mechanical response is largely governed by the epoxy matrix and its intrinsic viscoelastic rate dependence.

3.1.5. Glass FRP behaviour

Glass FRP laminates were tested as benchmarks under standard conditions and under combined high temperature and high humidity (Table 4). Like flax FRPs, the $[+45/-45]_{2S}$ glass FRP laminate exhibited reductions in both stiffness and ultimate tensile strength at 50 °C and 90% RH (Fig. 4b). However, in contrast to flax FRPs, these changes were found in a previous study to be primarily induced by temperature with relative humidity having a negligible effect on ultimate stress, ultimate strain, and modulus [17]. For the $[0/90/0]_S$ glass FRP laminate (Fig. 4a), the ultimate tensile strength reduced by approximately 34% under combined conditions, whereas the modulus remained essentially unchanged. This behaviour reflects the dominant role of glass fibres, which are largely insensitive to temperature and humidity, while the reduced strength was attributed to a degradation of load transfer efficiency governed by the polymer matrix at elevated temperature. Consistent with the behaviour observed in the other laminate, previous work [17] demonstrated that humidity alone (up to 90% RH) has a negligible influence on the mechanical properties.

Regarding strain rate effects, glass FRP laminates exhibited a sensitivity as high as that observed for flax FRPs. For instance, increasing the strain rate led to an increase in E_1 at 20 °C/50% RH of approximately 43% for the $[0/90/0]$ laminate and 35% for the $[+45/-45]_S$ laminate. The strength also increased with the strain rate, by 25% for the $[0/90/0]$ laminate and 15% for the $[+45/-45]_S$ laminate, highlighting the importance of strain rate on the mechanical behaviour even for laminates reinforced with glass fibre reinforcement aligned with the load.

3.2. Tension-tension fatigue experiments

3.2.1. Effects of temperature on S–N curves of FFRP laminates

Having established the strong influence of hygrothermal conditions on the monotonic response, we examine the effects under tension-tension fatigue. The S–N curves obtained for the $[0/90/0]_S$ laminate at –20 °C and +20 °C are nearly superimposed, indicating that in this temperature range the effect of temperature on fatigue life is minimal (Fig. 5a). This observation is consistent with the monotonic tensile results shown in Table 3 and Fig. 3a, where the modulus, ultimate tensile strength, and ultimate strain remain relatively similar between –20 °C and +20 °C. This behaviour may arise from competing mechanisms: the higher stiffness measured at –20 °C under monotonic loading reduces cyclic strain amplitudes, which would tend to delay damage accumulation and extend fatigue life, while the simultaneous reduction in ductility and the more brittle monotonic response at low temperature limits the amount of deformation that can be sustained before failure, thereby counteracting this benefit. As a result, the combined effect of temperature-induced changes in stiffness and strength observed in monotonic tests leads to a negligible net influence on fatigue life within this temperature interval. For similar low stress levels, the S–N curve at +50 °C converges with that at +20 °C (~70 MPa, 10^7 cycles), while displaying a less steep overall slope. This reduced slope, resulting in fatigue life decrease at high stresses, implies that elevated temperature facilitates additional or accelerated damage mechanisms. This trend

correlates with the monotonic tensile behaviour at 50 °C (Table 3 and Fig. 5a), where a reduction of 2.6 GPa in modulus (E_1) and 26 MPa in strength is observed. The lowering of stiffness increases cyclic strain energy for a given stress level, while the reduced tensile strength decreases the margin to failure, jointly promoting earlier fatigue damage accumulation. Because the test temperature of 50 °C remained below the epoxy glass transition temperature ($T_g = 79^\circ\text{C}$), the matrix did not enter a rubbery state. Nevertheless, approaching the glass-transition range is expected to reduce the storage modulus, with moisture potentially amplifying this effect by lowering the epoxy T_g [31]. In addition, elevated temperature can induce thermal-expansion mismatch stresses between fibre and matrix, promoting interfacial microcracking and debonding and thereby reducing interface quality and load-transfer efficiency [15,32].

For the $[+45/-45]_{2S}$ laminate in Fig. 5b, a stronger temperature dependence is observed compared to the $[0/90/0]_S$ laminate. Between –20 °C and +20 °C, the S–N curve at –20 °C shows a steeper slope but converges with that at +20 °C around 10^6 cycles, indicating a stress-dependent temperature effect. This behaviour can be related to the monotonic tensile results presented in Fig. 3b, where testing at high strain rates shows an increase in ultimate tensile strength of approximately 10% at –20 °C, relative to +20 °C. The longer fatigue life at –20 °C at higher stress levels can therefore be rationalised by the higher monotonic strength and increased initial stiffness, which reduce cyclic shear strains in the off-axis plies and delay damage initiation under fatigue loading. This increased strength and stiffness at –20 °C are more plausibly attributed to the temperature dependence of the epoxy matrix in this shear-dominated laminate. Because the $[+45/-45]_{2S}$ response is governed largely by in-plane shear, cooling further below the epoxy glass-transition range restricts segmental mobility within the polymer network and increases matrix rigidity [31,33]. Previous studies on matrix-dominated off-axis or shear loading of epoxy composites have shown corresponding increases in shear modulus and shear strength at low temperature [34,35]. In the specific case of $\pm 45^\circ$ off-axis carbon/epoxy laminates, reduced matrix microcracking is observed at low temperature [34]. Taken together, these findings suggest lower cyclic shear strains and slower early damage accumulation at –20 °C. The longer fatigue life at –20 °C is therefore interpreted primarily as a consequence of matrix-controlled stiffening and delayed damage initiation.

When the temperature is further increased from +20 °C to +50 °C, the entire S–N curve shifts downward without a significant change in slope, suggesting that the dominant damage mechanisms remain similar but occur more rapidly. This downward shift is consistent with the pronounced reductions in modulus and strength observed in monotonic tests at 50 °C (Table 3), together with the substantial increase in ultimate strain. While the increased ductility reflects enhanced matrix plasticisation and fibre reorientation under monotonic loading, the associated loss of stiffness and strength leads to higher cyclic strains and lower load-bearing capacity in fatigue, resulting in a systematic reduction in fatigue life across all stress levels.

3.2.2. Effects of relative humidity on S–N curves of FFRP laminates

Fig. 5c–d shows the influence of relative humidity on the fatigue behaviour of the two laminate configurations. For the $[0/90/0]_S$ laminate, the S–N curves corresponding to 30%, 50%, and 90% RH are essentially parallel on a log-linear fit as indicated by the similar a coefficient of –29.1, –29.0, and –28.1 respectively. A systematic upward shift in fatigue life with increasing relative humidity is observed, corresponding to approximately one order of magnitude improvement in lifetime between 30% RH and 90% RH for a given stress level. This systematic increase in fatigue life reflects the monotonic properties, where both the ultimate tensile strength and ultimate strain increase markedly with increasing humidity for this fibre-dominated laminate. Although moisture may induce fibre-matrix interface weakening in the $[0/90/0]_S$ laminate, the tensile response remains governed primarily by

Table 3

Monotonic tensile properties of flax FRP laminates under different hygrothermal conditions and strain rates (including 2, 300, 600, and 1200 mm/min).

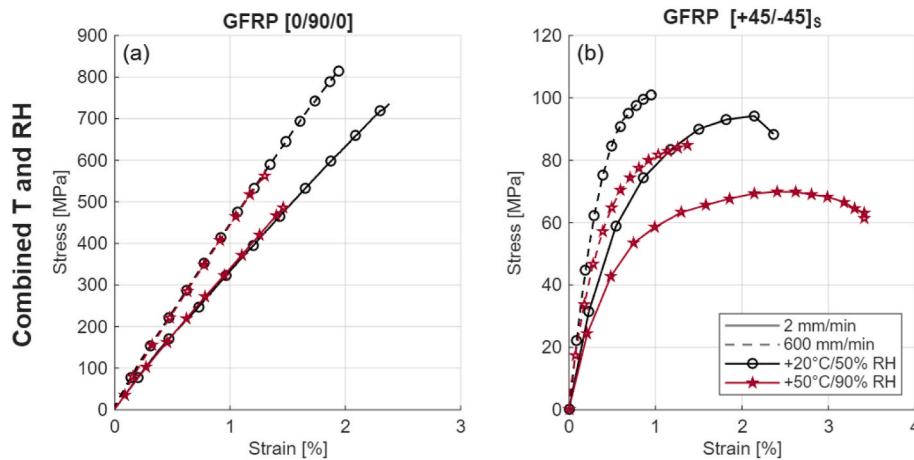
Flax FRP [0/90/0] _S							
T [°C]	RH [%]	Actuator rate [mm/min]	Extensometer rate [%/s]	Ultimate tensile strength [MPa]	Ultimate strain [%]	Tensile modulus E ₁ [GPa]	Tensile modulus E ₂ [GPa]
−20	50	2	0.017 ± 0.000	231 ± 8	1.9 ± 0.2	19.1 ± 1.3	10.6 ± 0.4
		300	2.9	232	1.8	20.0	11.1
		600	5.7	238	1.9	19.4	10.9
		1200	11.0	245	1.8	19.4	11.6
20	50	2	0.016 ± 0.002	225 ± 4	2.2 ± 0.1	17.1 ± 1.2	8.8 ± 0.2
		300	2.5	264	2.4	18.4	9.5
		600	5.3	268	2.4	18.3	9.9
		1200	10.4	257	2.4	17.1	9.7
50	50	2	0.017 ± 0.001	199 ± 6	2.1 ± 0.1	14.5 ± 1.1	8.1 ± 0.1
		300	2.4	248	2.6	15.5	8.5
		600	4.7	255	2.5	16.1	9.0
		1200	9.6	257	2.5	17.3	9.4
20	30	2	0.016 ± 0.000	195 ± 8	1.7 ± 0.1	17.5 ± 0.6	9.9 ± 0.02
		300	2.6	207	1.7	17.7	10.2
		600	5.4	209	1.8	17.2	9.9
		1200	11.0	208	1.7	17.7	10.4
20	90	2	0.018 ± 0.001	263 ± 8	3.2 ± 0.2	11.3 ± 0.6	7.1 ± 0.3
		300	2.3	277	2.9	14.6	8.1
		600	5.1	280	3.1	13.3	7.8
		1200	10.1	287	3.0	13.9	8.3
50	90	2	0.017 ± 0.000	214 ± 11	3.1 ± 0.1	8.4 ± 1.3	6.2 ± 0.6
		300	2.5	276	3.3	10.7	7.5
		600	5.6	259	3.1	10.7	7.3
		1200	10.3	272	3.3	11.4	7.5
Flax FRP [+45/−45] _{2S}							
T [°C]	RH [%]	Actuator rate [mm/min]	Extensometer rate [%/s]	Ultimate tensile strength [MPa]	Ultimate strain [%]	Tensile modulus E ₁ [GPa]	
−20	50	2	0.017 ± 0.001	80 ± 5	3.2 ± 0.7	6.4 ± 0.3	
		300	3.0	94	3.5	7.7	
		600	5.7	93	2.9	7.5	
		1200	10.5	95	2.8	7.6	
20	50	2	0.017 ± 0.001	55 ± 3	8.6 ± 2.0	5.1 ± 0.4	
		300	2.8	70	4.3	5.4	
		600	5.4	77	3.5	5.7	
		1200	10.5	81	2.7	6.2	
50	50	2	0.017 ± 0.002	54 ± 2	15.2 ± 1.1	4.1 ± 0.2	
		300	2.5	64	7.5	5.5	
		600	4.3	65	2.4	5.5	
		1200	9.6	67	3.9	5.9	
20	30	2	0.015 ± 0.000	57 ± 2	4.4 ± 0.4	5.3 ± 0.1	
		300	2.8	71	4.3	5.9	
		600	5.1	75	2.1	6.5	
		1200	9.7	79	1.9	6.4	
20	90	2	0.017 ± 0.001	53 ± 1	11.0 ± 2.7	4.3 ± 0.4	
		300	2.9	75	11.9	5.9	
		600	5.3	78	13.4	5.7	
		1200	10.9	87	10.1	6.0	
50	90	2	0.017 ± 0.001	43 ± 4	14.9 ± 1.4	3.3 ± 0.4	
		300	2.6	61	16.9	5.1	
		600	5.8	63	15.7	3.8	
		1200	11.8	64	24.7	3.7	

Table 4

Monotonic tensile properties of glass FRP laminates under different hygrothermal conditions and strain rates (including 2, 300, 600, and 1200 mm/min).

Glass FRP [0/90/0]						
T [°C]	RH [%]	Actuator rate [mm/min]	Extensometer rate [%/s]	Ultimate tensile strength [MPa]	Ultimate strain [%]	Tensile modulus E ₁ [GPa]
20	50	2	0.014 ± 0.001	651 ± 84	2.0 ± 0.3	38.3 ± 0.6
		300	1.7	778	1.9	50.7
		600	3.4	814	1.9	49.2
		1200	6.0	848	2.0	48.9
50	90	2	0.015 ± 0.001	529 ± 40	1.6 ± 0.1	37.2 ± 0.5
		300	1.8	566	1.3	48.9
		600	3.4	568	1.3	48.3
		1200	7.0	571	1.4	47.1

Glass FRP [+45/-45] _s						
T [°C]	RH [%]	Actuator rate [mm/min]	Extensometer rate [%/s]	Ultimate tensile strength [MPa]	Ultimate strain [%]	Tensile modulus E ₁ [GPa]
20	50	2	0.019 ± 0.003	88.1 ± 12.8	2.0 ± 0.7	13.5 ± 0.3
		300	2.2	97	1.0	22.8
		600	3.8	101	1.0	23.0
		1200	8.9	99	1.2	24.6
50	90	2	0.014 ± 0.004	69.7 ± 1.3	2.8 ± 1.0	12.1 ± 1.5
		300	2.3	88	1.5	19.6
		600	4.3	85	1.4	18.3
		1200	9.0	85	1.4	18.1

**Fig. 4.** Stress–strain response of glass fibre composites tested under monotonic tension at different hygrothermal conditions and loading rates. The displacement rate of 2 mm/min corresponds is equivalent to extensometer-based strain rate of $0.017 \pm 0.001 \text{ \% s}^{-1}$ and 600 mm/min is equivalent to an extensometer-based strain rate of $5.3 \pm 0.4 \text{ \% s}^{-1}$.

the continuous 0° flax yarns. Under these conditions, the detrimental effect of interface degradation is likely to have only a limited influence on the global composite strength.

By contrast, the [+45/-45]_{2S} laminate exhibits the opposite trend. In this configuration, load transfer is governed more strongly by matrix and interface shear mechanisms, so the same moisture-induced interface weakening contributes directly to the reduction in performance. The curves for 50% RH and 90% RH have similar slopes with an α coefficient of -5.1 and -5.0 respectively, but the one at 90% RH is shifted downward, indicating a reduction in fatigue life for all stress levels measures under higher moisture exposure. This downward shift is consistent with the monotonic tensile results presented in Table 3, where increasing humidity leads to a reduction in stiffness without a compensating increase in strength for this shear-dominated laminate. This reduction can be attributed to moisture-induced weakening of the fibre-matrix interface, which plays a dominant role in shear-loaded laminates such as this one.

The S–N curve for 30% RH presents a slightly different slope but still overlaps broadly with the 50% RH curve. This behaviour is coherent

with the monotonic response at low humidity (Fig. 3d), where two stress-strain curves for those conditions broadly overlap. Additional data would be required to assess the statistical significance of the difference. The observed changes in slope may also reflect the effect of humidity on the fibre-matrix interface with a drier interface in this case increasing friction.

Overall, a higher relative humidity is not inherently detrimental to fatigue life. Its effect depends strongly on the laminate architecture and the dominant damage mechanisms. In fibre-dominated configurations such as [0/90/0]_S, moderate moisture uptake can enhance the composite fatigue resistance by improving fibre strength and ductility as it is observed from the monotonic tests in Fig. 3c. In contrast, for shear-dominated laminates like [+45/-45]_{2S} increased humidity primarily weakens the fibre-matrix interface and reduces the laminate stiffness without improving its strength, promoting earlier debonding and reduced fatigue life, as evidenced by the post-mortem microscopic observations presented in section 3.3.

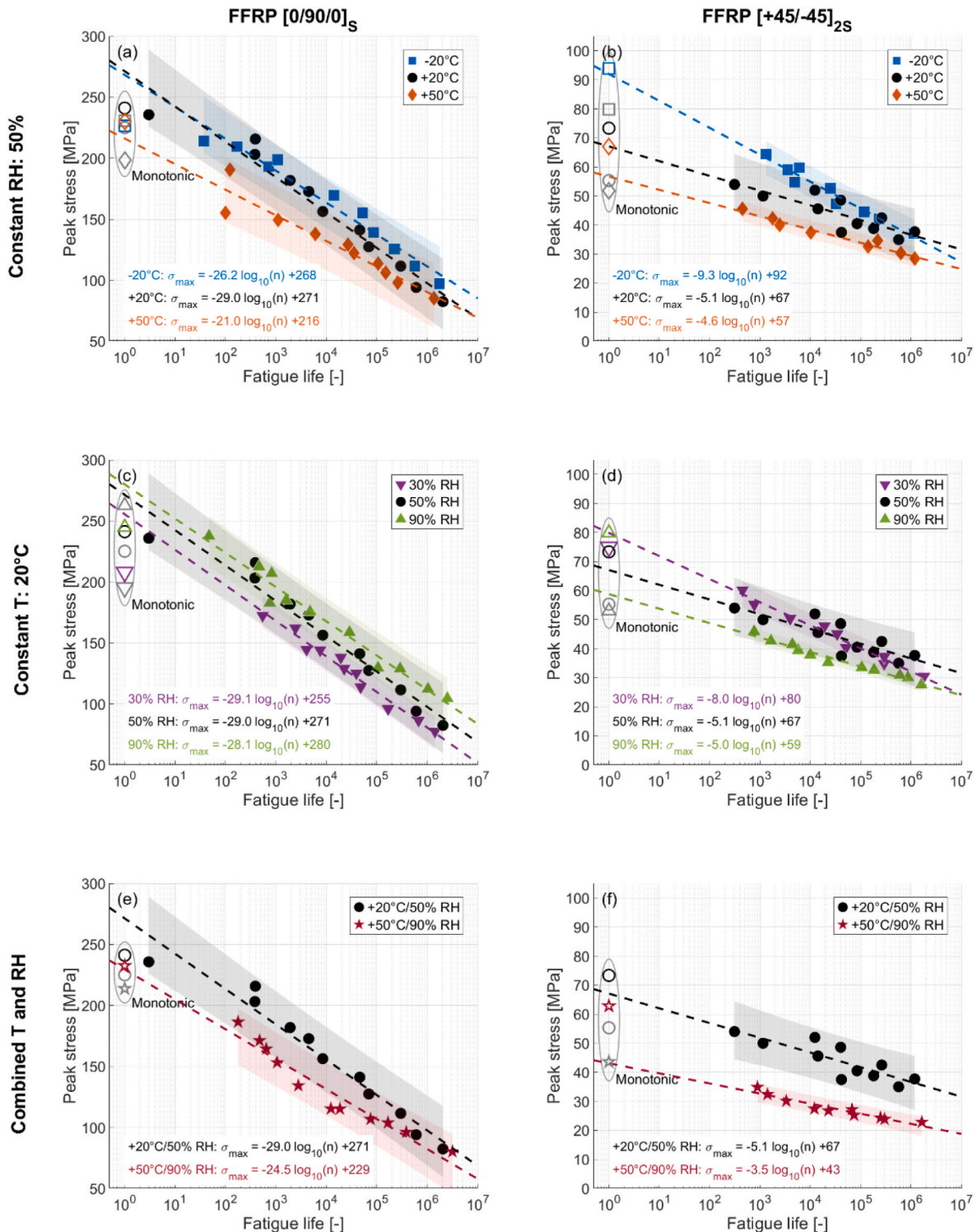


Fig. 5. S–N curves of flax fibre reinforced laminates under different hygrothermal conditions, demonstrating the temperature effects at fixed RH of 50% (a–b), the relative humidity effect for a fixed T of 20 °C (c–d), and the combined high temperature and humidity conditions (50 °C, 90%RH) (e–f). Dashed lines represent the log-linear fits to the fatigue data, expressed as $\sigma_{\max} = a \log_{10}(n) + b$, and the shaded bands indicate the corresponding 95% confidence intervals. The monotonic tests shown in grey were performed at a loading rate of 2 mm/min, whereas those shown in colour were conducted at 600 mm/min. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2.3. Combined effects of temperature and relative humidity on S–N curves of FFRP laminates

Fig. 5e presents the combined effects of temperature and relative humidity on the fatigue life of the two laminate configurations. For the [0/90/0]_s laminate, the condition at 50 °C and 90% RH exhibits an S–N

trend like that observed at 50 °C and 50% RH. Both curves converge towards the reference standard condition (20 °C, 50% RH) in the high-cycle regime around 10^6 – 10^7 cycles, while at higher stress levels, fatigue life is reduced under the elevated temperature conditions. However, at 50 °C, the reduction in life at high stress becomes less pronounced at

90% RH compared to 50% RH, suggesting that increased humidity partly mitigates the negative influence of temperature. This partial mitigation directly reflects the monotonic tensile behaviour of the [0/90/0]_S laminate, where high humidity was shown to increase tensile strength and failure strain despite a reduction in modulus (Fig. 3c).

For the combined effects of temperature and humidity on the [+45/-45]_S laminate (Fig. 5f), the isolated effects of temperature and humidity are first considered from the log-linear S-N fits, expressed as $\sigma_{max} = a \log_{10}(n) + b$. At the reference condition of 20 °C/50% RH, the fitted coefficients are $a = -5.1$ MPa and $b = 67$ MPa. Increasing the temperature alone to 50 °C/50% RH gives $a = -4.6$ MPa and $b = 57$ MPa, corresponding to an approximately 10 MPa downward displacement relative to the reference condition. Increasing the relative humidity alone to 20 °C/90% RH gives $a = -5.0$ MPa and $b = 59$ MPa, corresponding to an approximately 8 MPa downward displacement. The similar slope coefficients obtained for these two isolated conditions indicate that temperature and humidity mainly act as vertical stress shifts in the log-linear representation, with only limited changes in the S-N curve slope.

The combined condition of 50 °C/90% RH is then assessed against these isolated effects. Under this condition, the fitted coefficients are $a = -3.5$ MPa and $b = 43$ MPa. Although the slope is somewhat less steep than those obtained under the reference and isolated conditions, the effective downward displacement over the measured fatigue-life range remains close to 18 MPa. This value corresponds closely to the addition of the two isolated reductions relative to the reference condition, namely approximately 10 MPa from the temperature increase alone and 8 MPa from the humidity increase alone. Thus, the combined hygrothermal effect can be interpreted as an approximately additive vertical stress reduction on the log-linear S-N plot. This additivity is consistent with the monotonic stiffness model defined in Eq. (4) and discussed in Section 3.1.3. The combined reduction in stiffness increases cyclic shear strains, while interface weakening induced by moisture further accelerates damage initiation, jointly leading to a proportional reduction in fatigue strength. Although further testing across a broader range of isolated and combined temperature-humidity levels is required to rigorously validate this behaviour, such an additive response, if confirmed, could significantly simplify fatigue life prediction in hygrothermal environments.

For the [0/90/0]_S laminate, because the slope of the S-N curve varies

between conditions (Fig. 5a–c, and e), the environmental effects are compared here at specific fatigue lives. In this case, a single vertical shift cannot fully describe the environmental effect over the whole log-life range, because differences in the slope coefficient a cause the stress reduction to depend on the number of cycles n . This fixed-life analysis suggests that the combined effect of temperature and relative humidity may deviate from a strictly additive response, although the observed differences remain within the expected fatigue scatter. Relative to the reference condition (20 °C, 50% RH), the isolated temperature effect (50 °C, 50% RH) reduced the fatigue strength by 31 MPa at 10^3 cycles and 15 MPa at 10^5 cycles, whereas the isolated humidity effect (20 °C, 90% RH) increased it by 11 MPa and 13 MPa, respectively. Under a linear superposition assumption, the combined condition (50 °C, 90% RH) would therefore be expected to reduce the fatigue strength by 20 MPa at 10^3 cycles and 2 MPa at 10^5 cycles. Experimentally, the fitted S-N curve gave larger reductions of 29 MPa and 20 MPa. However, these deviations remained within the expected scatter, so the combined hot-wet response remains broadly consistent with an additive approximation.

3.2.4. Effects of combined high temperature and humidity on S-N curves of GFRP laminates

Fig. 6a–b shows the S-N curves of the [0/90/0] and [+45/-45]_S GFRP laminates tested under standard conditions (20 °C, 50 % RH) and under combined elevated temperature and humidity (50 °C, 90 % RH). In both laminates, a clear reduction in fatigue life is observed under hygrothermal conditions, evidenced by a downward shift of the S-N curves. This systematic degradation is consistent with the monotonic tensile results presented in Fig. 4, where elevated temperature leads to a reduction in ultimate tensile strength, while relative humidity alone has a negligible influence on the mechanical response of GFRP.

For the [0/90/0] laminate (Fig. 6a), the fatigue response under hygrothermal exposure is characterised by an almost parallel downward shift of 110 MPa. In the log-linear representation, this means an approximately constant logarithmic coefficient a for the different hygrothermal conditions. This behaviour can be explained by the monotonic tensile response shown in Fig. 4a, where a pronounced reduction in UTS is observed at 50 °C and 90% RH, while the modulus remains essentially unchanged. The preservation of the S-N curve slope

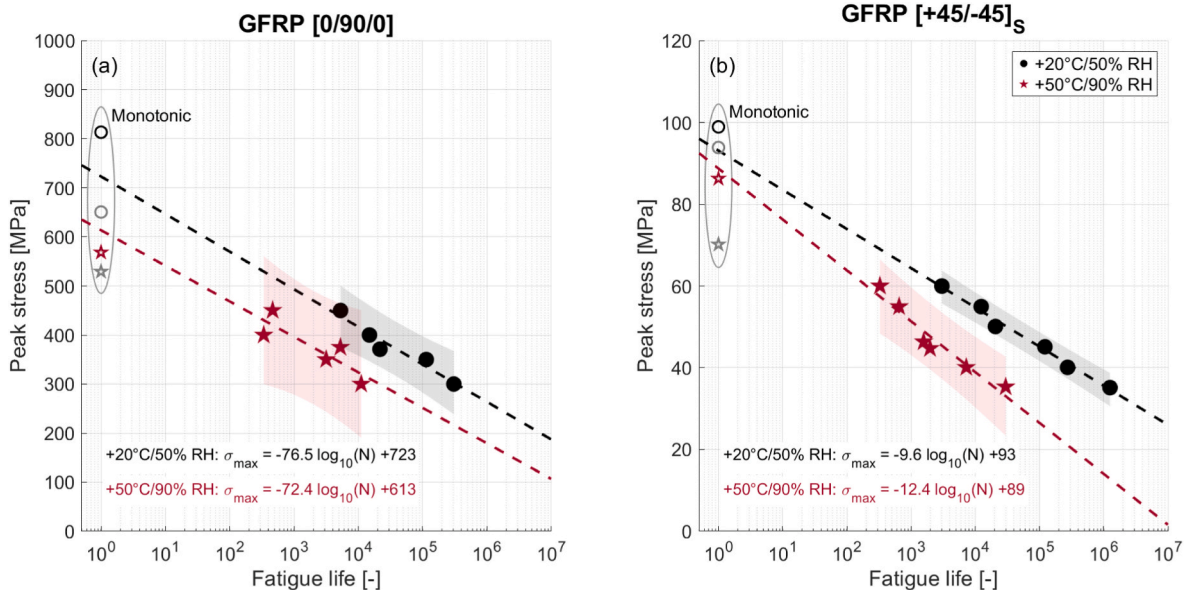


Fig. 6. S-N curve of glass fibre reinforced laminate under standard and combined hot-wet conditions. Dashed lines represent the log-linear fits to the fatigue data, expressed as $\sigma_{max} = a \log_{10}(n) + b$, and the shaded bands indicate the corresponding 95% confidence intervals. The monotonic tests shown in grey were performed at a loading rate of 2 mm/min, whereas those shown in colour were conducted at 600 mm/min. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

suggests that the rate of fatigue damage accumulation is not strongly altered by the environment. Instead, failure occurs earlier because the reduced monotonic strength lowers the maximum sustainable stress level, effectively reducing the allowable fatigue envelope without changing the underlying fatigue damage mechanisms. When normalized with respect to the UTS, this downward shift is of equivalent magnitude to that observed for the FFRP [0/90/0]_S laminate (Fig. 5e) relative to its own UTS, highlighting that GFRP is also significantly affected by hygrothermal conditions, even though the contribution of humidity alone remains comparatively limited [17].

In the [+45/-45]_S laminate (Fig. 6b), the downward shift of the S-N curve is less strictly parallel, likely reflecting the limited number of data points and the inherent scatter, particularly in the low-cycle fatigue regime. Nevertheless, for fatigue lives between 10^3 and 10^5 cycles, a consistent reduction in stress level of approximately 18 MPa is observed at a given fatigue life. This reduction is consistent with the reduction in

the monotonic ultimate tensile strength for the off-axis GFRP laminate (Table 3).

This stress reduction of 18 MPa closely matches that reported for the equivalent [+45/-45]_{2S} FFRP laminate under identical environmental conditions. Although this similarity may partly reflect experimental scatter, it suggests that the off-axis GFRP and FFRP laminates are affected in a comparable manner by hygrothermal exposure. This is mechanically consistent, as the fatigue behaviour of such laminates is largely matrix-dominated, and both systems share the same epoxy matrix, although differences in fibre-matrix interfacial characteristics between GFRP and FFRP may influence stress transfer and damage development.

3.2.5. Evolution of secant stiffness

During fatigue loading, the two FFRP laminates exhibit contrasting trends in stiffness evolution. The [+45/-45]_{2S} laminate shows a gradual

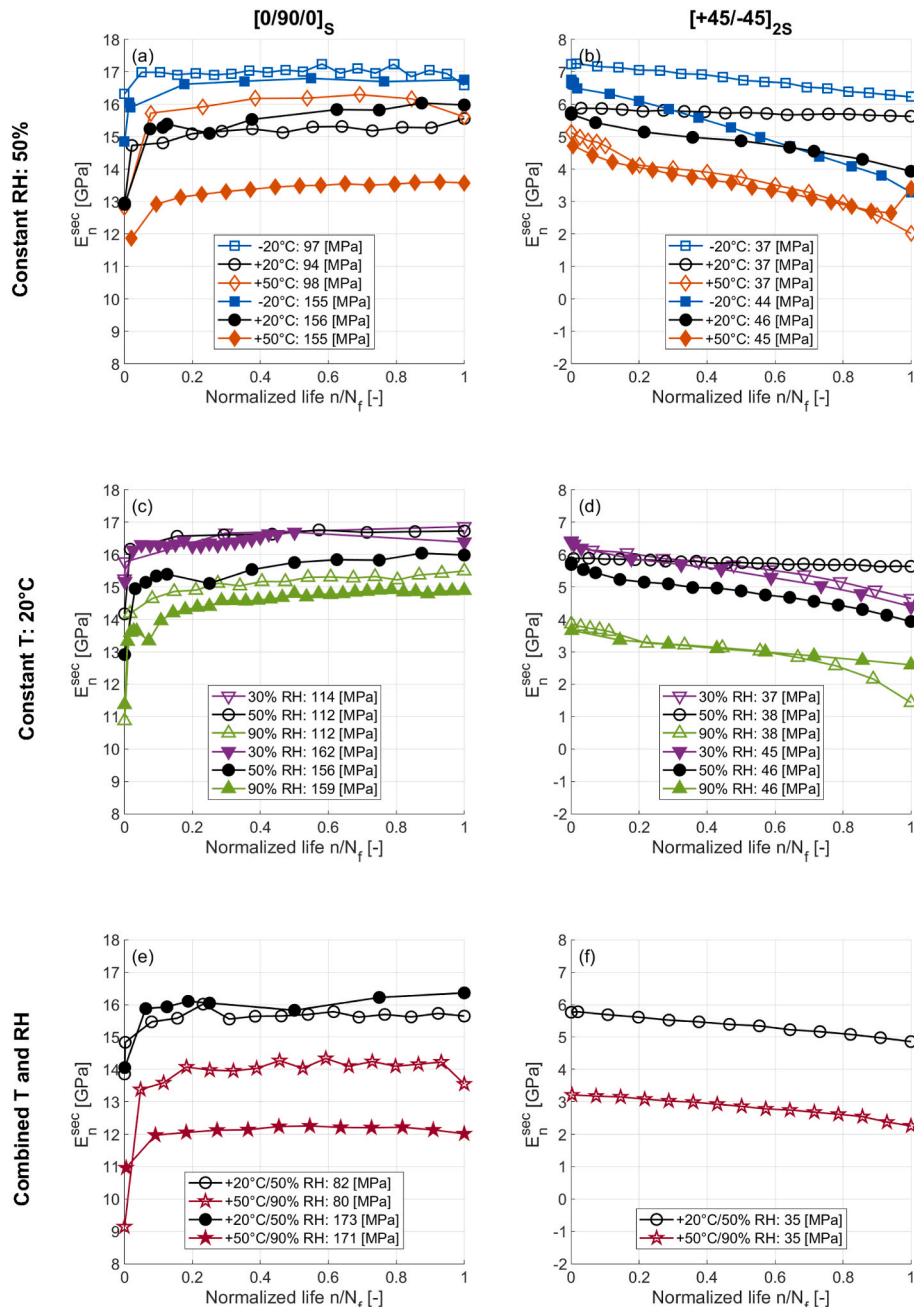


Fig. 7. Stiffness evolution over fatigue life of FFRPs.

decrease in stiffness over time, consistent with the accumulation of damage in the matrix and fibre-matrix interface (Fig. 7b–d, and f). The initial secant stiffness measured at the first fatigue cycle (E_1^{sec}) is, for most environmental conditions, in good agreement with the tangent modulus $E^{\text{tan},1}$ obtained from monotonic tests performed at comparable high strain rates, with differences typically within ± 0.5 GPa. This agreement confirms that, for this shear-dominated laminate, the initial fatigue stiffness is representative of the intrinsic elastic response measured under monotonic loading. As fatigue progresses, E_n^{sec} decreases due to matrix cracking, interfacial debonding, and shear-driven damage accumulation.

However, for the two conditions at 90% RH (20 °C/90% RH and 50 °C/90% RH) where moisture induces weakening of the fibre-matrix, the tangent modulus $E^{\text{tan},1}$ is consistently higher than the corresponding initial secant stiffness E_1^{sec} . In monotonic tests, this weakened interface may not be fully activated during the single loading event, whereas in fatigue tests damage may already be present at the end of the first stabilised cycle (cycle 0, as defined in Fig. 1b), resulting in a lower apparent stiffness.

In contrast, the [0/90/0]_S laminate exhibits an increase in stiffness as fatigue cycles progress (Fig. 7a–c, and e). The stiffness measured during fatigue, expressed here as the secant modulus E_1^{sec} , is defined from the stabilised hysteresis loop after cycle 0 (see Fig. 2b) and therefore reflects a response that already includes initial viscoelastic effects and early micro-damage. For this fibre-dominated laminate, E_1^{sec} is systematically lower than the modulus $E^{\text{tan},1}$ obtained from monotonic tests for all investigated hygrothermal conditions. This discrepancy can be rationalised by considering the way stiffness is defined in monotonic testing. The monotonic modulus reported in Table 3 corresponds to the initial tangent modulus $E^{\text{tan},1}$, which is extracted at very small strains in the initial linear portion of the stress–strain curve (Fig. 2a). As loading proceeds, the stress–strain response transitions to a second regime characterised by a reduced slope $E^{\text{tan},2}$ associated large strain accumulation and fibre realignment typical of flax-based composites. In contrast, the fatigue secant modulus E_n^{sec} is evaluated when the material response has already moved beyond the initial small-strain regime and incorporates the effects of cycle 0.

As fatigue proceeds, a progressive increase in E^{sec} is observed. This stiffening effect has been widely reported for flax FRP composites and is commonly attributed to microfibril reorientation and possible crystallisation within flax fibres under repeated loading, leading to fibre stiffening [16,29,36,37]. For flax preforms composed of twisted yarns, the progressive untwisting and subsequent alignment of elementary fibres may further contribute to the observed increase in stiffness during fatigue [38].

Fig. 7a–f further compares the evolution of the secant stiffness in fatigue under different hygrothermal conditions and stress levels. For each condition, two stress levels were selected so that the influence of load level could be examined within a given condition, while also enabling direct comparison between tests conducted at the same stress level but under different temperatures and humidities.

Regarding the hygrothermal influence, an overall decrease, sometimes negligible, in fatigue stiffness is observed with increasing temperature and/or increasing relative humidity. This trend holds for both laminate configurations (see Fig. 7e–f) and reflects the softening of the epoxy matrix and flax fibres at elevated temperature or moisture content. The effect of applied stress is also consistent with higher stress levels consistently leading to lower measured stiffness, suggesting that the extent of internal damage and microcracking increases with loading amplitude.

In summary, the evolution of stiffness in fatigue is dependent on laminate architecture and environmental conditions. The [0/90/0]_S laminate exhibits a characteristic stiffening mechanism linked to fibre realignment, whereas the [+45/-45]_S laminate shows the more conventional stiffness degradation associated with matrix dominated

fatigue damage. In the angle-ply configuration, damage development was characterised by matrix-dominated shear degradation. Direct observations from optical microscopy and micro-CT in Section 3.3.2 showed matrix cracking at –20 °C and fibre-matrix interface debonding at 50 °C/90% RH. These observations support the interpretation that the fatigue response of the angle-ply laminate is governed by environmentally dependent matrix and interfacial damage mechanisms.

3.2.6. Evolution of strain accumulation

The [0/90/0]_S laminate exhibits a two-stage evolution of strain accumulation. An initial rapid increase in strain accumulation occurs during the early phase of fatigue life, followed by a long plateau extending up to failure or near-failure (Fig. 8a–c, and e). This behaviour suggests that after an initial microstructural arrangement the laminate enters a stable deformation regime. In most cases, the rapid terminal acceleration in strain accumulation, which corresponds to the onset of macroscopic damage and specimen rupture, was not fully captured due to the recording interval of one cycle every 1000 cycles.

By contrast, the [+45/-45]_{2S} laminate exhibits a rapid increase in strain during the initiation phase, followed by a period of slower accumulation that progressively accelerates over the fatigue life, with a sharp increase approaching failure (Fig. 8b–d, and f). This behaviour is typical of shear-dominated laminates, where cyclic loading promotes gradual degradation of the matrix and the fibre-matrix interface [39–41]. The increasing rate of strain accumulation observed in this configuration reflects the progressive development of interfacial debonding and matrix cracking, resulting in a decrease in effective cross-section and leading to macroscopic failure.

Regarding hygrothermal effect at identical stress levels, increasing temperature and/or relative humidity leads to higher overall strain accumulation. This can be attributed not only to the softening of the polymer matrix, but also to the environmental sensitivity of flax fibres themselves. At elevated temperature, flax fibres exhibit reduced stiffness due to their polymeric (lignocellulosic) constituents. Similarly, moisture absorption plasticises the flax fibres, increases fibre ductility, promoting larger deformations. Higher deformation in each cycle, as a result of stiffness reduction, accelerates damage accumulation which reduces fatigue life.

3.2.7. Effects of in-situ T and RH on hysteretic behaviour of FFRPs and its influence on fatigue life

The evolution of hysteretic energy dissipation during cyclic loading can provide a means of linking the mechanical response of the material to its damage evolution. Fig. 9a–f presents the evolution of the energy dissipated per loading cycle n (U_n^{diss}) as a function of the normalized fatigue life. Conceptually, this dissipated energy encompasses both viscoelastic losses, often manifested as heat due to internal friction, and irreversible damage processes such as plastic deformation, fibre-matrix debonding, matrix microcracking, and interply shearing for the [+45/-45]_{2S} laminate. Hence, the analysis of U_n^{diss} offers a means to assess and compare the rate of damage accumulation under different hygrothermal conditions, while acknowledging that the partitioning between irreversible damage and viscoelastic dissipation may itself be dependent on temperature, humidity, and applied stress. Higher energy dissipation is interpreted either as increased viscoelasticity, greater internal friction, or enhanced damage accumulation, all of which can accelerate degradation and shorten fatigue life.

The stress levels shown in Fig. 9a–e were deliberately selected to represent distinct regions of the corresponding S–N curves. One stress level lies in the high-cycle fatigue regime, while the second lies in the low-cycle regime. The selection of distinct stress levels allows assessment of whether parallel shifts or changes in the slope of the S–N response can be explained by corresponding similarities or differences in hysteretic energy dissipation. For each regime, stress levels were chosen to be as close as possible across the different hygrothermal conditions,

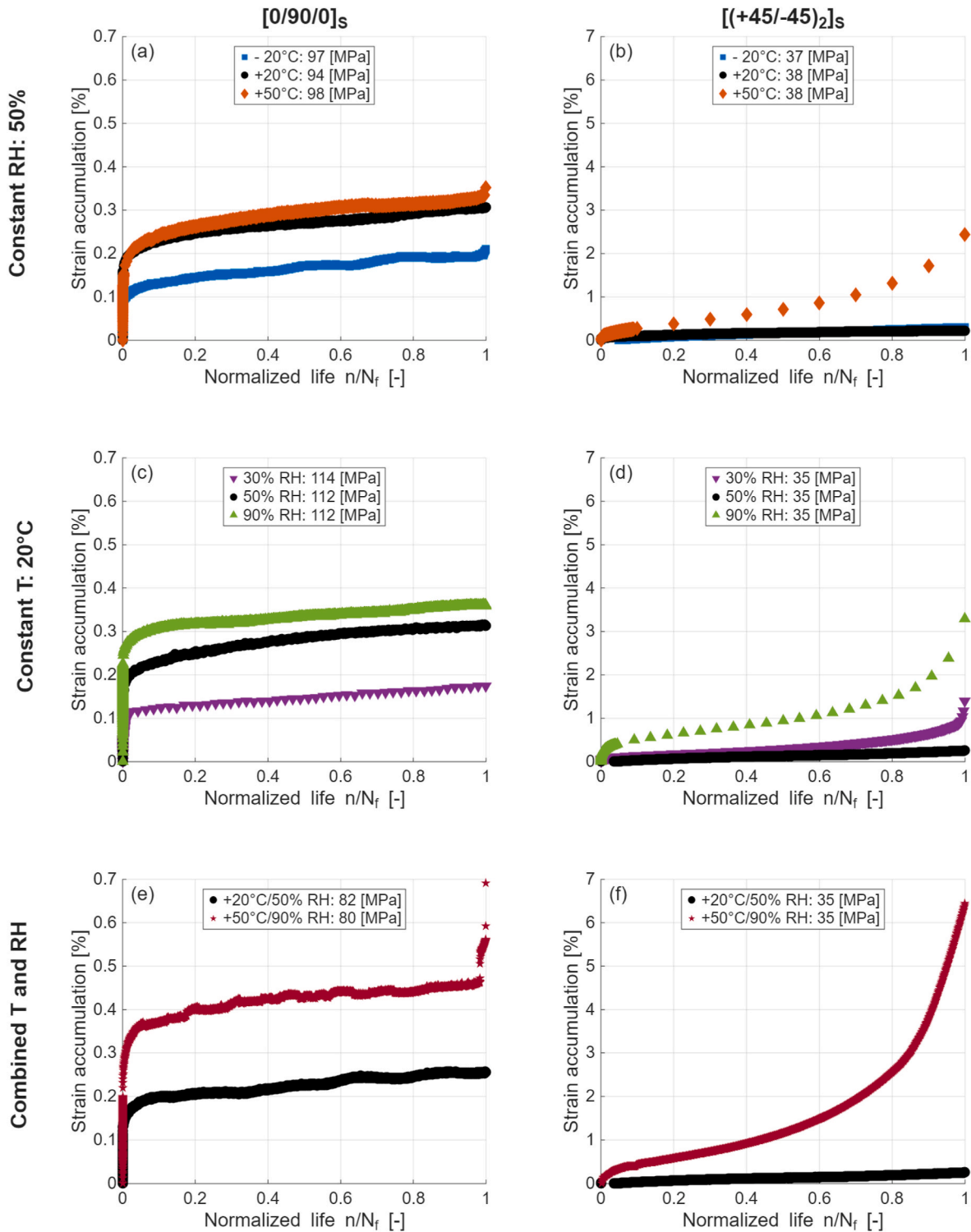


Fig. 8. Strain accumulation during fatigue life of FFRPs.

ensuring that differences in hysteretic energy dissipation can be attributed primarily to environmental effects rather than stress magnitude.

To illustrate this principle, we compare the evolution of U_n^{diss} for tests conducted on the [0/90/0]_s laminate under standard (20 °C/50% RH) and severe (50 °C/90% RH) hygrothermal conditions (see Fig. 9e). At low stress levels (80–82 MPa), the energy dissipation curves nearly overlap, indicating similar energy losses per cycle and suggesting comparable levels of microstructural damage accumulation. Consistently, the corresponding S–N curves in Fig. 5e converge in this low-stress

regime, showing almost identical fatigue lives under both environmental conditions. In contrast, at higher stress levels (171–173 MPa), the U_n^{diss} values for the 50 °C/90% RH condition are more than twice those measured at 20 °C/50% RH. This substantial increase in energy dissipation reflects intensified viscoelastic and damage mechanisms under combined heat and moisture exposure. Accordingly, the S–N curves in Fig. 5e diverges markedly at these higher stresses, with the high-temperature and high-humidity conditions exhibiting an order of magnitude shorter fatigue life.

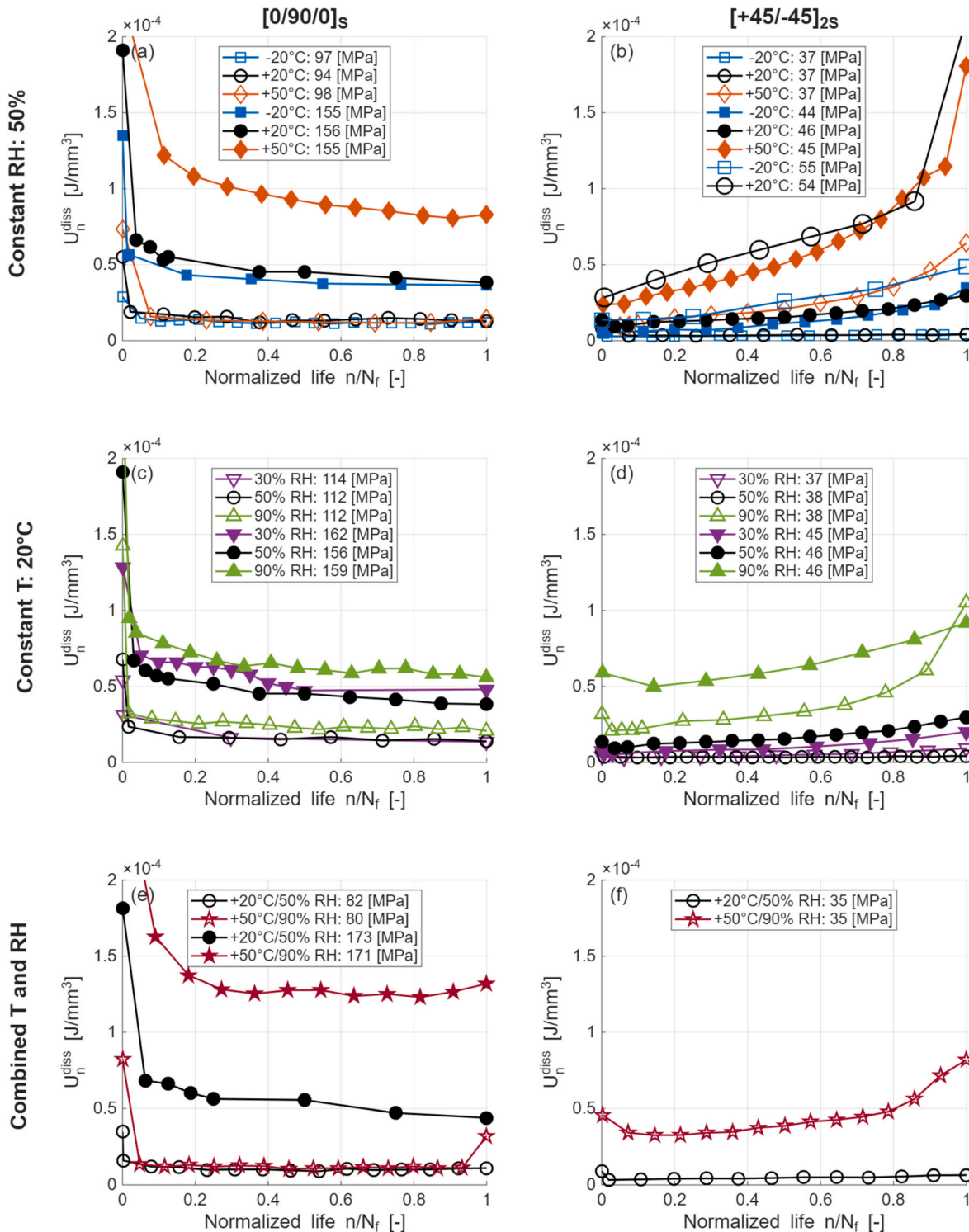


Fig. 9. Comparison of energy dissipation per fatigue loading cycle under different hygrothermal conditions and stress levels highlighting the variation in damage accumulation rates.

The relationship illustrated in this specific case is representative of the overall behaviour observed across all tested conditions for both laminates. Fig. 10a–f summarises this relationship by presenting the average energy dissipated per cycle as a function of the applied maximum stress for each hygrothermal condition. Across nearly all configurations, a trend emerges: at a given stress level, conditions associated with higher energy dissipation per cycle systematically correspond to shorter fatigue lives in the associated S–N curves shown in

Fig. 5a–f. Conversely, when the dissipated energy levels are comparable, the resulting fatigue lives are also closely aligned.

This correlation holds for all cases investigated except for [0/90/0]_s laminate subjected to varying relative humidity (Fig. 10c). In this configuration, increasing RH leads to higher energy dissipation while simultaneously resulting in longer fatigue lives. This apparent deviation can be rationalised by the monotonic tensile results (Table 3), which show increased stress and strain to failure at elevated humidity for this

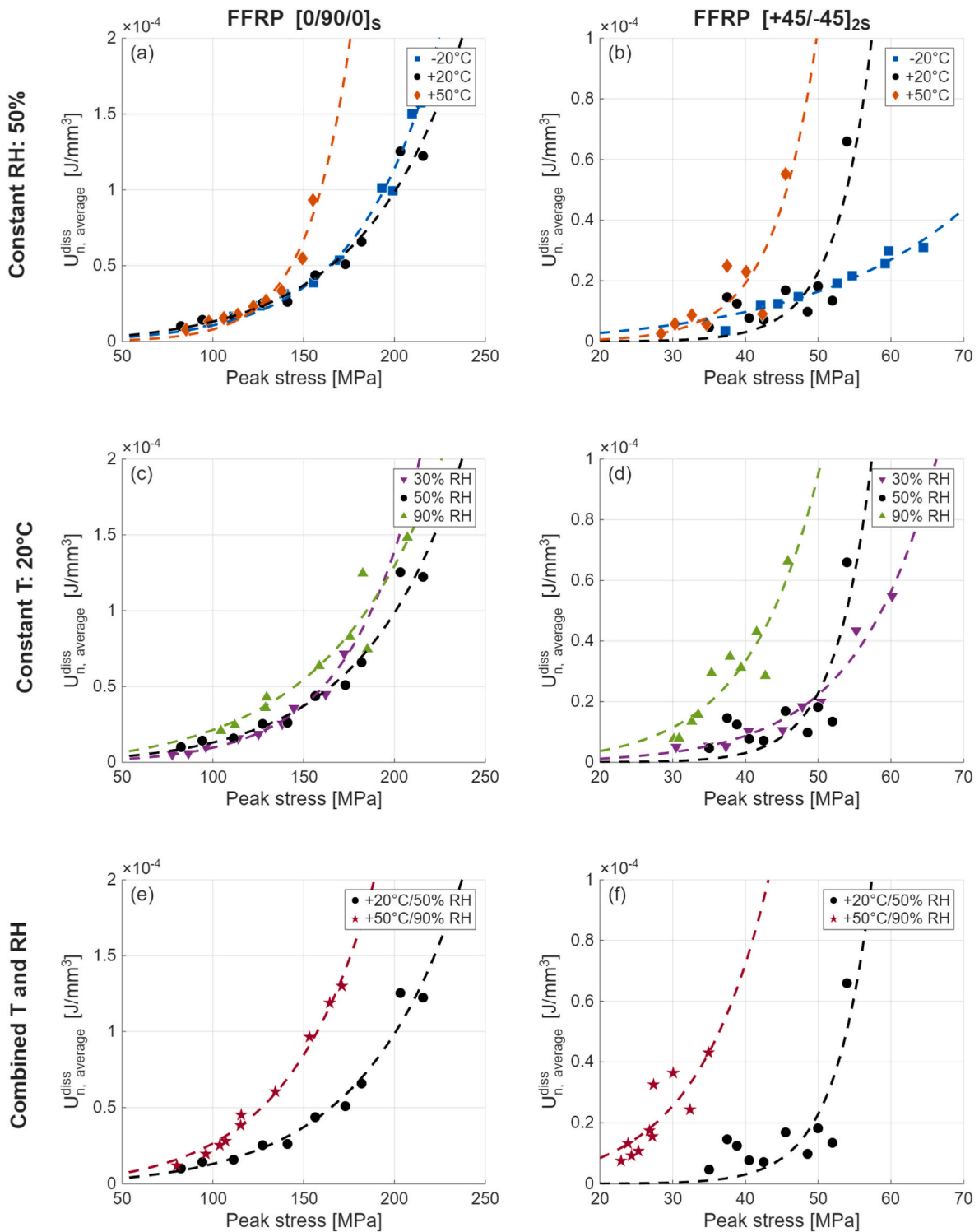


Fig. 10. Average hysteretic energy dissipated per cycle as a function of applied maximum stress for the different hygrothermal conditions, highlighting the link between hysteretic energy dissipation and fatigue life for the tested laminates.

laminates. The enhanced deformation capacity under these conditions allows the material to dissipate more energy prior to failure without a reduction in fatigue life. Overall, these results indicate that hysteretic energy dissipation provides a robust indicator of fatigue damage evolution across different hygrothermal conditions, provided it is interpreted in conjunction with the corresponding monotonic strength and deformation capacity of the laminate.

3.3. Analysis of damage morphology

Post-mortem analyses of the samples after fatigue fracture were performed using optical microscopy to examine the dominant damage features under different hygrothermal conditions. In parallel, micro-computed tomography (micro-CT) was conducted. The analysis focuses on the two extreme environmental cases of $-20^{\circ}\text{C}/50\% \text{ RH}$ (representing a brittle condition) and $50^{\circ}\text{C}/90\% \text{ RH}$ (representing a

ductile, softened condition).

3.3.1. $[0/90/0]_S$ FFRP laminate

Fig. 11a–b shows optical microscopy images of cross-sections taken perpendicular to the loading direction. A clear distinction in damage morphology is observed between the two environmental conditions. At $-20^\circ\text{C}/50\%\text{RH}$ (Fig. 11a), matrix cracks can be observed within the 90° plies. These cracks are largely confined to the matrix-rich regions and remain relatively disconnected, consistent with a brittle matrix response and strong fibre-matrix interface at low temperature. In contrast, as shown in Fig. 11b, at $50^\circ\text{C}/90\%\text{RH}$, the damage morphology changes significantly with cracks predominantly contained within the yarns or between the yarn and surrounding matrix. This suggests that the higher temperature and moisture content lead to weakening of fibre/matrix interface within the yarns or between yarn and matrix due to possible mismatch between fibre and matrix hygroscopic expansion coefficients and moisture penetration at the interface.

Micro-CT scans confirm these observations. Additional representative micro-CT slices are provided in Supplementary Fig. 3. At $-20^\circ\text{C}/50\%\text{RH}$ (Fig. 12a), few cracks are visible in the 3D visualisations due to the small width of matrix cracks and resolution limitations. At $50^\circ\text{C}/90\%\text{RH}$ (Fig. 12c), in addition to the intra-yarn cracking observed with optical microscopy cracks are also visible along the loading direction inside and at the edge of the yarns reinforcing the conclusion that at this hygrothermal conditions fibre-matrix debonding is the dominant failure mechanism. The spherical voids visible in Fig. 12c are attributed to air bubble introduced during manufacturing.

3.3.2. $[+45/-45]_{2S}$ FFRP laminate

Examination of the fracture morphologies at the macroscale provides evidence of the loading-rate dependent deformation mechanisms in angle ply $[+45/-45]_{2S}$ laminate subjected to uniaxial tension. The

comparison of post-fracture fibre orientations with the initial 45° fibre angle reveals a pronounced scissoring effect, i.e., fibre rotation and matrix shear under certain strain rate and hygrothermal conditions.

During monotonic tensile test with deformation rate of 2 mm/min, $[+45/-45]_{2S}$ laminate specimens displayed larger fibre rotation before failure than at 600 mm/min, accompanied by extensive delamination and shear-dominated fracture (Fig. 13a, b, d, and f), except for the cold, $-20^\circ\text{C}/50\%\text{RH}$ and dry, $20^\circ\text{C}/30\%\text{RH}$, conditions (Fig. 13c and e). Specimens tested at 600 mm/min showed limited fibre reorientation from the initial 45° and a higher occurrence of fibre breakage. In all hygrothermal conditions, the fracture surfaces observed after fatigue failure closely resembled those of the 600 mm/min monotonic tests, rather than the 5 mm/min case. This correspondence reinforces the importance of accounting for loading rate sensitivity when comparing monotonic and fatigue behaviours in flax FRP composites with off-axis fibre orientations that are prone to scissoring deformation mechanisms. This loading rate sensitivity is especially critical in non-dry and non-cold conditions where the laminate exhibit a ductile behaviour suggesting that distinct damage mechanisms are activated depending on temperature and relative humidity.

The damage feature in optical microscopy images in Fig. 14a and b indicate differences in damage morphology under the investigated hygrothermal conditions. Specifically, at $-20^\circ\text{C}/50\%\text{RH}$, the damage is characterised by cracks propagating predominantly through the matrix, spanning from yarn to yarn and oriented roughly perpendicular to the loading direction. These matrix-dominated cracks occur primarily in the resin-rich regions separating adjacent yarns, with little evidence of fibre-matrix debonding, consistent with a comparatively brittle matrix response at low temperature and limited interfacial damage.

Under $50^\circ\text{C}/90\%\text{RH}$, the damage morphology changes markedly. Cracks tend to follow the contours of the yarns, connecting adjacent yarns at their closest points, while very little damage is observed in the

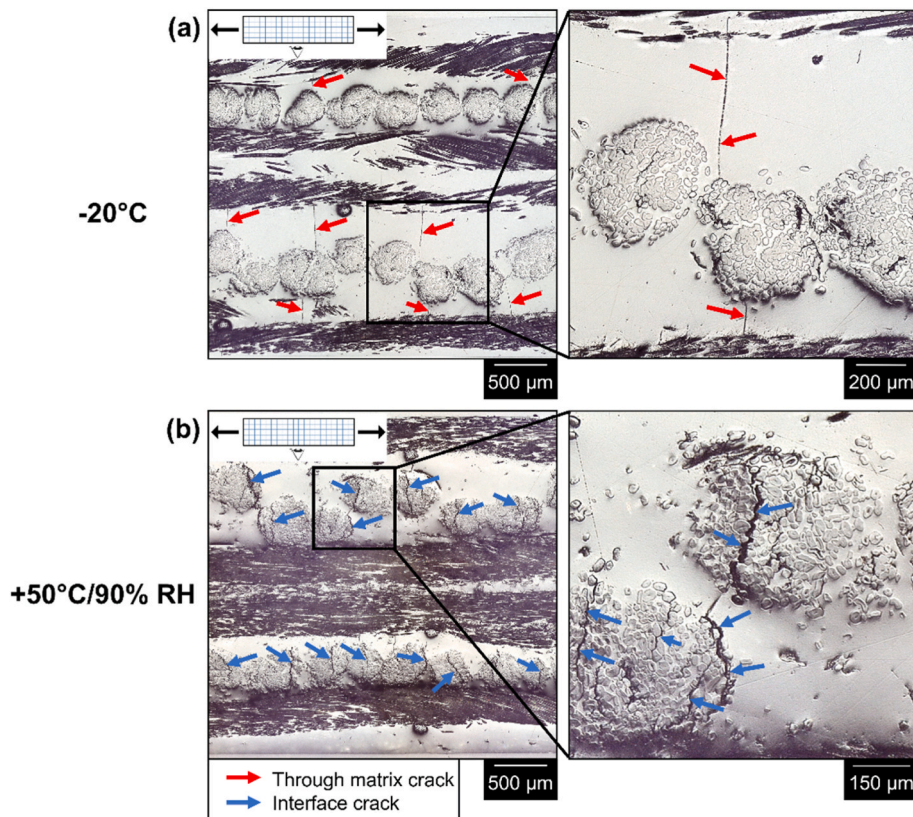


Fig. 11. Optical microscopy $[0/90/0]_S$ FFRP laminate after fatigue test, comparison of hygrothermal conditions. The coloured arrows identify damage morphology, distinguishing through-matrix cracks and fibre-matrix or fibre-fibre interface debonding.

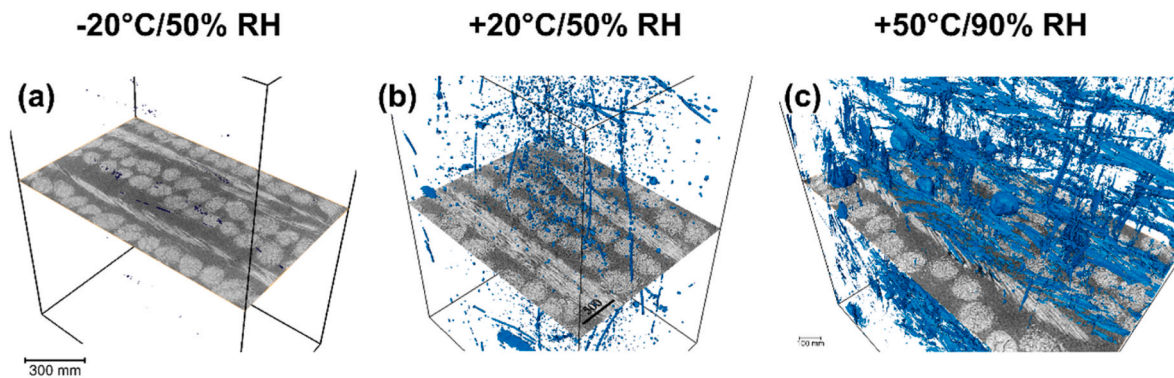


Fig. 12. Micro-CT [0/90/0]_S FFRP laminate after fatigue test. The 3D reconstruction of voids in blue shows changes in the cracking, volume, density, and pattern with temperature and relative humidity conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

epoxy-rich regions. This morphology suggests that moisture and heat promote interfacial degradation, allowing cracks to propagate preferentially along the fibre-matrix boundary rather than through the matrix itself. In the [+45/-45]_{2S} laminate, whose mechanical response is largely governed by in-plane shear and stress transfer between yarns and matrix, an interfacial weakening is expected to reduce load-transfer efficiency and provides a microstructural explanation for the reduction in monotonic tensile strength observed with increasing humidity.

The 3D micro-CT images in Fig. 15a–c further illustrate this change in failure mode. At $-20^{\circ}\text{C}/50\%\text{RH}$ (Fig. 15a), the crack network is sparse and barely visible because the crack widths are likely smaller than the voxel size of $3\text{ }\mu\text{m}$ used in the micro-CT acquisition, highlighting the resolution limitations of the technique. The spherical voids detected are attributed to entrapped air bubbles introduced during specimen manufacturing, whose spatial distribution is variability in the fabrication process. At $50^{\circ}\text{C}/90\%\text{RH}$ (Fig. 15c), a network of cracks develops around the yarns, forming interconnected planes oriented approximately 45° to the loading direction. This behaviour confirms that under warm and humid conditions, fatigue damage is dominated by interfacial and shear-related mechanisms, which is consistent with the slight reduction in monotonic tensile strength, the earlier stiffness loss, and the reduced fatigue life observed for this laminate.

3.3.3. Discussion on damage morphology

The post-mortem observations demonstrate a clear shift in dominant damage mechanisms with changing hygrothermal conditions. At low temperature (-20°C), the response is predominantly brittle, with damage localised in the matrix and relatively limited interfacial failure. At high temperature and humidity ($50^{\circ}\text{C}/90\%\text{RH}$), the damage becomes more diffuse and interfacial, characterised by debonding and intra-yarn cracking.

These observations directly affect the interpretation of hysteretic energy dissipation as a fatigue indicator. Distinct damage mechanisms are associated with different strain energy criteria for initiation and propagation, which are modified by temperature and humidity through their influence on matrix and interfacial behaviour. As a result, while hysteretic energy reflects the extent of damage activity, an energy-based fatigue model calibrated under one hygrothermal condition inherently reflects the corresponding damage energy. Its direct application to other hygrothermal environments, where damage modes and associated energy thresholds differ, may therefore be inappropriate.

4. Implications for structural design

The experimental results obtained in this study highlight the significant influence of moisture and temperature on the fatigue behaviour of FFRP composites. Understanding how these environmental factors affect stiffness, strain accumulation, and damage evolution is therefore critical

to the informed design of FFRP structures intended for real-world applications. The following discussion outlines the main implications for structural design and environmental suitability.

4.1. Moisture sorption: beneficial or detrimental?

The results demonstrated that relative humidity could have a dual influence on fatigue behaviour, depending on the laminate architecture and the dominant damage mechanism. For the fibre-dominated [0/90/0]_S laminates, an increase in relative humidity led to improved fatigue life, while in the matrix and interface dominated [+45/-45]_{2S} laminates, moisture exposure reduced it. These observations suggest that moderate moisture uptake can have a beneficial effect in flax FRPs, particularly when load transfer is governed by the fibres. This can be explained by the absorbed moisture slightly plasticising the flax fibres, reducing stress concentration delaying microcrack initiation.

From a design perspective, these findings challenge the common notion that all forms of moisture exposure are detrimental to natural fibre composites. However, the present results should not be interpreted as evidence that prolonged moisture exposure is beneficial in a general sense. The specimens were conditioned for a minimum of 12 days at 50°C only until a near-equilibrium moisture state was reached and were then tested under the same controlled relative humidity environment. The improved performance observed here is therefore attributed primarily to the short-term moisture-conditioned state reached under controlled relative humidity rather than long-term chemical ageing. Immersion in water and prolonged hot-wet exposure are reported in the literature to cause degradation in monotonic and fatigue properties through more severe mechanisms such as interfacial deterioration, leaching, and hydrolysis that may outweigh beneficial effects observed here [16,42,43].

The results also suggest that surface coatings or hydrophobic barriers should be considered carefully in structural applications. Unprotected surfaces could allow uncontrolled sorption leading to local swelling and interface degradation. Conversely, the presence of a coating can delay and limit moisture uptake. However, the criticality of this effect is strongly dependent on laminate architecture, as the influence of moisture differs between fibre-dominated and matrix-dominated laminate configurations.

4.2. Environmental temperature detrimental or beneficial?

In the present study, the measured T_g of all composites was above 70°C , whereas the highest test temperature was 50°C . Thus, all tests were conducted below T_g , and the deterioration observed at 50°C cannot be attributed to a transition of the epoxy matrix into the rubbery state. Despite being sub- T_g , the elevated temperature of 50°C had a

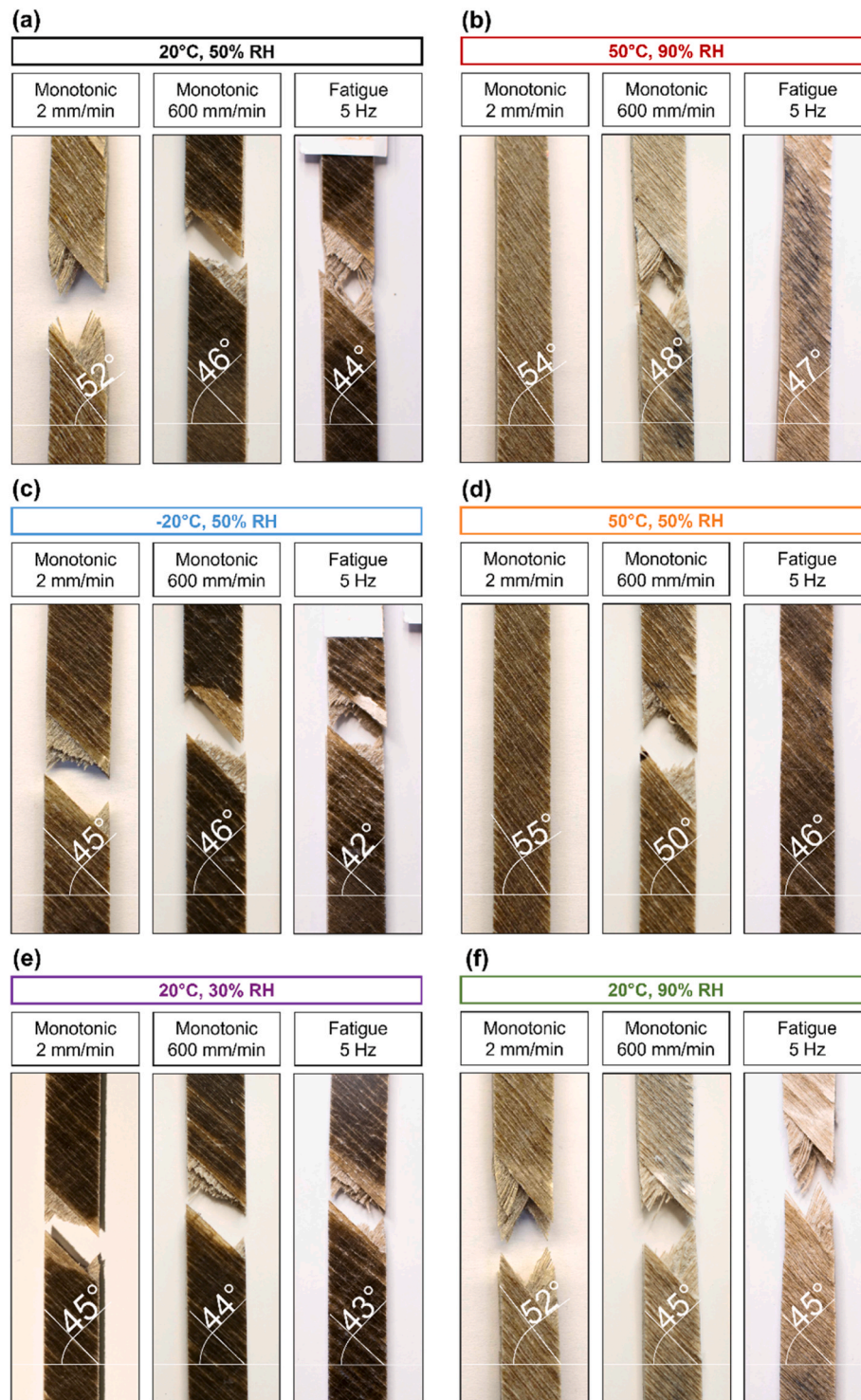


Fig. 13. A comparison of post-fracture scissoring effects in $[+45/-45]_{2S}$ flax laminates tested at different hygrothermal conditions for monotonic uniaxial tensile test with loading rates of 2 mm/min, 600 mm/min, and after fatigue tests.

clearly detrimental effect on fatigue performance of FFRPs, particularly at high stress levels for the $[0/90/0]_S$ laminate and at all stress level for $[+45/-45]_{2S}$ laminate with an order of magnitude reduction in fatigue life. In contrast, the low-temperature condition (-20°C) generally improved fatigue resistance, albeit with a more brittle damage morphology.

For structural applications, this indicates that FFRPs maintain reliable fatigue performance within temperature ranges (-20°C to $+20^\circ\text{C}$). However, even below T_g , elevated temperatures approaching or

exceeding 50°C , which may occur in direct sunlight or enclosed components, can lead to a notable reduction in fatigue life, stiffness, and strength. Therefore, FFRP structures should be designed with safety factors accounting for in-service temperatures. When higher operating temperatures are unavoidable, designers should anticipate accelerated fatigue degradation and apply suitable safety factors.

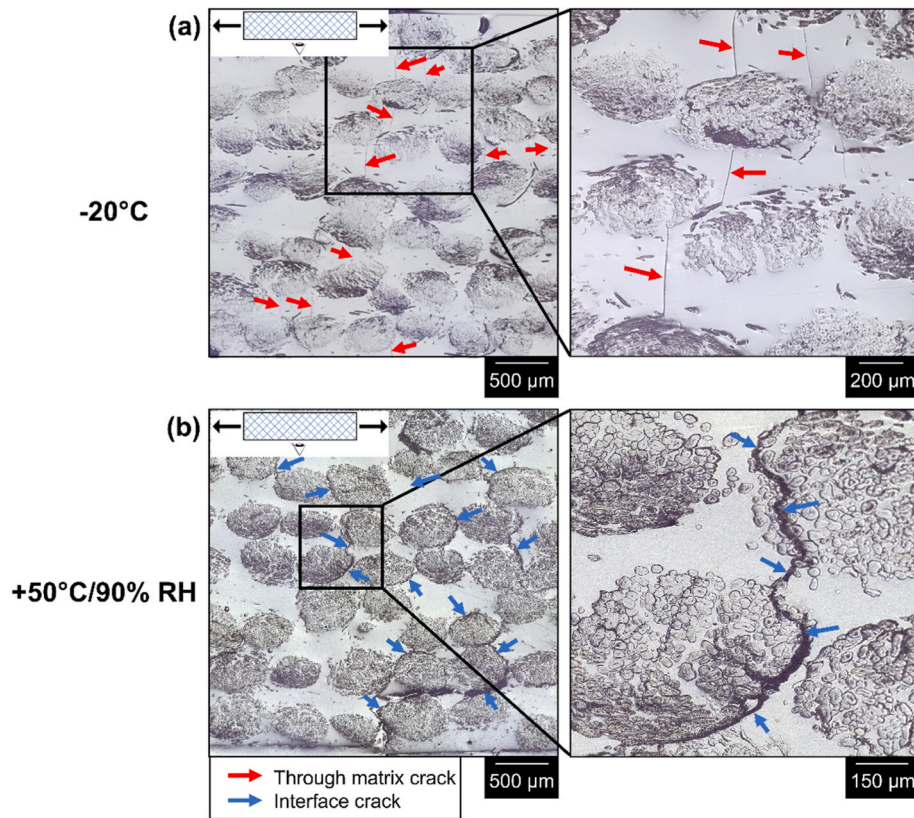


Fig. 14. Optical microscopy $[+45/-45]_{2S}$ FFRP laminate after fatigue test, comparison of hygrothermal conditions. The coloured arrows identify damage morphology, distinguishing through-matrix cracks and fibre-matrix or fibre-fibre interface debonding.

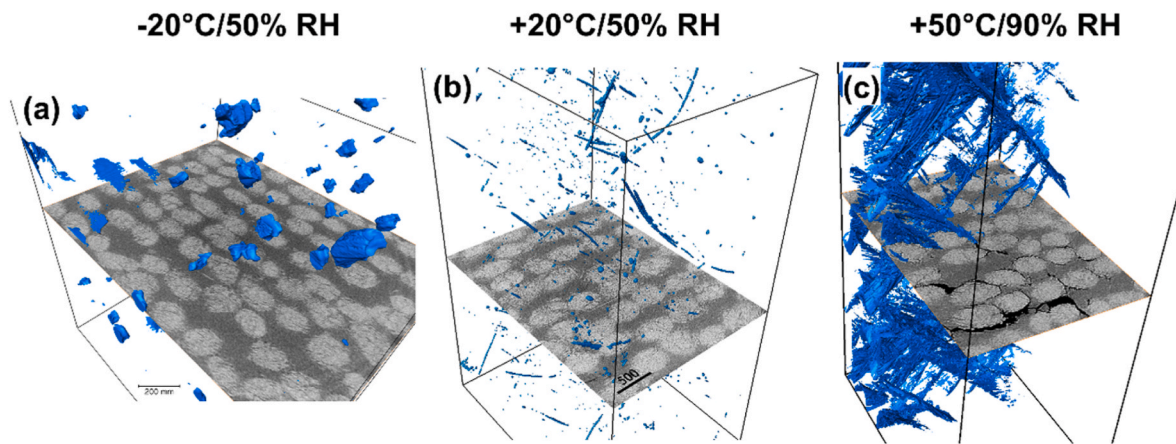


Fig. 15. Micro-CT slices of $[+45/-45]_{2S}$ FFRP laminate after fatigue test. The 3D reconstruction of voids in blue shows changes in the cracking pattern with temperature and relative humidity conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.3. Competitiveness of FFRP against GFRP with respect to environmental sensitivity

With respect to moisture sensitivity, GFRP exhibits a clear advantage over FFRP. Results from the authors' previous work show that GFRP laminates display negligible changes in strength and stiffness with changes in humidity conditions [17]. This behaviour is expected, as glass fibres themselves are essentially insensitive to moisture uptake, and moisture-related effects are largely confined to limited plasticisation of the polymer matrix and fibre/matrix interface weakening. In contrast, FFRP exhibits a pronounced moisture sensitivity due to the hygroscopic nature of flax fibres and the moisture sensitive fibre-matrix interface. As

demonstrated in the present study, this sensitivity can be either beneficial or detrimental depending on laminate architecture and dominant damage mechanisms. Consequently, moisture represents a key design variable for FFRP, whereas it is of secondary importance for GFRP in airborne humidity environments.

While glass fibres remain mechanically stable over the investigated temperature range, GFRP is nevertheless strongly affected by elevated temperature (50 $^{\circ}\text{C}$) temperature through the polymer matrix. Elevated temperatures, tested here in combination with high relative humidity, reduce the laminate strength, and ultimately reduce fatigue life of both the angle-ply and cross-ply laminate as evidenced by the S-N curves in Fig. 6a–b.

In this respect, the fatigue degradation observed for FFRP at 50 °C and 90% RH is not fundamentally different from that of GFRP. When compared to their respective S–N curves obtained under standard conditions (20 °C/50% RH), both material systems exhibit a downward shift of similar magnitude under elevated temperature and humidity, as evidenced by the comparison between Fig. 6a–b and Fig. 5e–f. This indicates that the relative reduction in fatigue life induced by severe hygrothermal exposure is comparable for FFRP and GFRP when each is assessed against its own baseline fatigue performance, and that FFRP is therefore not disproportionately penalised by elevated temperature and humidity.

From an industrial design perspective, these results show that flax FRP fatigue design must account for laminate architecture and service environment, as laminates with different fibre orientations respond differently to hygrothermal exposure. Hot-wet conditions should therefore be treated as a critical design case, particularly for off-axis loading, for which fatigue performance is more sensitive to matrix softening and fibre–matrix interface degradation.

5. Conclusion

This study investigated the fatigue behaviour of flax fibre-reinforced polymer (FRP) composites under six distinct hygrothermal conditions, designed to assess the isolated and combined effects of temperature and relative humidity (RH), with the aim of generating relevant knowledge for the engineering use of flax composites in variable service environments.

Key findings from the study are summarized below:

- **Monotonic tensile properties of FFRPs exhibited a clear sensitivity to hygrothermal conditions.** For the [+45/−45]_{2S} laminates increasing temperature and relative humidity, whether applied individually or in combination, led to reductions in strength and stiffness, accompanied by a pronounced increase in ultimate strain. For the [0/90/0]_S laminates, temperature similarly reduced stiffness and strength, with only limited changes in ultimate strain. Increasing humidity, while leading to a reduction in modulus and an increase in ultimate strain, was found to increase ultimate strength.
- **Strain-rate effects were found to significantly influence monotonic behaviour,** particularly in the [+45/−45]_{2S} laminate. Higher strain rates, representative of fatigue loading conditions, resulted in increased UTS and stiffness compared to quasi-static testing. This highlights the importance of matching strain rates between monotonic and fatigue tests to ensure comparable material viscoelastic response and possibly consistent activation of damage mechanisms. For example, at high strain rates, material will respond in a more brittle manner.
- **Temperature and relative humidity significantly influence fatigue performance of FFRPs, with humidity acting in a laminate-dependent manner.** For both laminates, increasing temperature consistently reduced fatigue life. Relative humidity had an architecture-specific effect: in the [+45/−45]_{2S} laminate, increasing RH reduced fatigue life whereas the [0/90/0]_S laminate showed limited sensitivity to humidity alone and, at 20 °C, even improved fatigue life at high RH. The effect of elevated temperature and humidity at 50 °C/90% RH, on fatigue life were largely cumulative when expressed as vertical stress offsets of the log-linear S–N curves, leading to greater reductions in both laminated. Most critically, the fatigue life of the [+45/−45]_{2S} laminate was reduced by approximately three orders of magnitude for a given stress level. This pronounced reduction under combined high temperature and humidity was attributed to a shift in the dominant damage mechanisms. Matrix plasticisation and sub- T_g temperature-induced softening, together with weakening of the fibre–matrix interface, reduced the effective composite stiffness and accelerated crack propagation, leading to premature failure.

- **Compared with GFRP, FFRP exhibits greater sensitivity to moisture but a similar proportional sensitivity to combined temperature and humidity in fatigue when assessed relative to each material's baseline S–N response.** While both cross-ply and angle-ply GFRP laminates have negligible humidity-induced degradation due to the moisture-insensitive nature of glass fibres and limited moisture absorption, their fatigue performance is also strongly reduced at elevated temperatures. When referenced to the respective fatigue behaviour under standard conditions, the downward shift of the S–N curves for flax FRP at high temperature and humidity is of comparable magnitude to that observed for GFRP, indicating that flax FRP is not disproportionately penalised by hygrothermal conditions under fatigue loading.
- **Energy dissipation was found to be an indicator of fatigue life.** For a given stress level but varying hygrothermal conditions the highest energy dissipation per cycle was consistently found to correlate with the shortest fatigue life for both laminates.
- **Hygrothermal conditions were found to affect the dominant damage mechanisms within both FFRP laminates.** At subzero temperatures (−20 °C/50% RH) matrix cracking was found to be the dominant damage mechanism while at high temperature (50 °C) and moisture (90% RH) the dominant damage mechanism shifted to fibre–matrix interface debonding and intra-yarn cracking.

Overall, the results show that the fatigue applicability of flax FRP composites must be assessed under temperature and humidity conditions representative of service. Environmental sensitivity was found to depend strongly on laminate architecture. The identification of hot–wet conditions as a critical case, together with comparison against GFRP, provides a practical basis for material selection.

CRediT authorship contribution statement

Valentin Perruchoud: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexandros Prapavesis:** Writing – review & editing, Visualization. **René Alderliesten:** Writing – review & editing, Supervision, Methodology. **Yasmine Mosleh:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.compositesb.2026.113841>.

Data availability

Data will be made available on request.

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