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THE EFFECTS OF IN-SITU TEMPERATURE AND RELATIVE HUMIDITY ON THE TENSILE RESPONSE OF FLAX VS. GLASS FRP COMPOSITES

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Abstract

The development of bio-based fibre-reinforced polymer composites (FPRs) has accelerated in recent years aiming at replacing synthetic FRPs in primary structures. Comparative case studies on biobased fibres (such as flax and hemp) indicate their potential to replace synthetic glass and carbon fibres in certain FRP structures as more sustainable and environmentally friendly alternatives. In those studies, the effects of in-situ hygrothermal conditions on the physical and mechanical performance of the natural fibre composites were generally overlooked, however, due to hygroscopicity of lignocellulosic natural fibres, flax fibre composites mechanical response is sensitive to its environmental temperature and relative humidity. To quantify and understand the effects of in-situ hygrothermal conditions on flax FRP composite, a quasi-static tensile testing campaign was conducted at various temperatures and relative humidities. Glass and flax FRP laminates were tested in cross-ply and angle-ply configurations. It was observed that the strength and stiffness of cross-ply and angle-ply FFRP laminates were significantly affected by relative humidity contrary to GFRP counterparts. All laminates exhibited strength and/or stiffness variation with temperature that can be attributed to the sensitivity of the common epoxy matrix. However, a distinct difference was observed between the flax and glass cross-ply laminates with the modulus of the flax FRP being highly affected by temperature and relative humidity while the glass FRP modulus was unaffected.

1. Introduction

In the quest for optimal performance in structural engineering, synthetic fibre-reinforced polymer composites (FRPs) have emerged as promising materials for light weight design of structures thanks to their high specific stiffness and strength. Regarding durability, synthetic FRPs do not rust or corrode or biologically decay unlike traditional materials such as steel or wood. Degradation in FRPs due to harsh environmental conditions can be mitigated by selecting a matrix system or coating designed to not degrade in the in-situ environmental conditions by preventing water diffusion through the matrix. Furthermore, the mechanical response of synthetic FRPs remains stable in most in-situ hygrothermal conditions because synthetic fibres such as glass are insensitive to moisture and have little stiffness variations with temperatures ranging from -20 to 50°C [1].

Due to recent sustainability and environmental concerns with synthetic FRPs, biobased FRPs have emerged as an alternative with the replacement of synthetic fibres such as glass by plant fibres such as flax. In addition to sustainability benefits, flax fibres have the structural advantages of being comparatively light [2] and effective at damping vibrations [3]. However in terms of durability, the cellulosic microstructure of flax fibres is hygroscopic resulting in a high moisture sorption in flax FRPs (FFRPs) [4] compared to the sorption in glass FRPs (GFRPs) [5]. This high moisture absorption and desorption induces swelling and shrinkage of the fibres, respectively, an order of magnitude larger than the swelling/shrinkage of the matrix [4]. Consequently, internal stresses are created, the fibre-matrix interface might get damaged, and the presence of water at the interface might reduce the fibre-matrix interface strength [6]. Furthermore, the stiffness and strength of single flax fibres are dependent on the moisture level in the fibres, with an increase in moisture reducing the modulus, and increasing the strength [7]. Regarding temperature (T), the mechanical properties of single flax fibres are affected with a significant reduction of modulus and strength between 20°C and 60°C [8].

Since the properties of flax fibres significantly vary at different in-situ temperatures and relative humidities due to their viscoelastic and hygroscopic nature it is pivotal to assess the mechanical response of biocomposites at different environmental conditions. As example, biobased FRP bridges and wind turbine are structural applications subjected to diurnal and seasonal variation of in-situ hygrothermal conditions.

In this study, we aim to evaluate how in-situ hygrothermal conditions impact the quasi-static tensile performance of composite laminates made from flax and glass fibres. Four FRP laminates were characterized at in-situ conditions ranging from -20 to 50C and 50% to 90% relative humidity. Cross-ply [0/90/0] and angle-ply $[+45/-45]_S$ laminates were manufactured and tested to highlight hygrothermal effects on fibres and the combination of matrix/interface, respectively. This experimental investigation helps to assess how the in-situ hygrothermal conditions affect the mechanical response of flax and glass FRP laminates.

2. MATERIALS AND METHODS

2.1 Composite laminates architecture/manufacturing

In this study, four types of composite laminates were manufactured by vacuum infusion. These include GFRP [0/90/0], GFRP $[(+45/-45)]_S$, FFRP $[0/90/0]_S$, FFRP $[(+45/-45)_2]_S$. The glass fibres employed are non-crimp high stiffness glass fabric with an aerial weight of 1260 g/m^2 manufactured by Kush Synthetics PVT.LTD. The flax fibres employed are quasi-unidirectional flax mat Amplitex, weighing 280 g/m^2 and manufactured by Bcomp (Switzerland). The epoxy resin system, SWANCOR 2511-1AL/BL, was used as matrix for manufacturing both GFRP and FFRP laminates. The method employed for manufacturing was vacuum assisted resin infusion (VARI) followed by autoclave post-cure at 70°C for 18 hours. The specimens were then cut into rectangular coupons of dimensions 250 × 15 mm using a waterjet cutter. Optical microscopy was utilized to qualitatively evaluate the consistency of the manufacturing quality. Differential scanning calorimetry (DSC) analysis was used to verify the completion of the epoxy curing. The fibre volume fraction was determined through density calculations at 42% and 53% for FFRP and GFRP laminates respectively.

2.2 Pre-conditioning protocol

Pre-conditioning was performed to ensure that the specimens are at equilibrium with the selected in-situ hygrothermal conditions during testing. To that end, the specimens were placed in a WK11-340/40 climate chamber at 50°C and at the desired relative humidity (RH) for at least two weeks to equilibrate the moisture content. To ensure that the specimens reach at least 90% of saturation, the moisture content was tracked by weight measurements initially at daily intervals and then 3 days intervals. Once the desired moisture content was reached the specimens were transferred to the climate chamber enclosing the tensile testing setup set to the in-situ hygrothermal testing conditions. Specimens stayed at least 30 minutes in the climate chamber to equilibrate to the testing temperature.

2.3 Quasi-static tensile testing

Tensile testing was performed on an Instron 1251 with a 100 kN loadcell and equipped with hydraulic grips and a Klimaatkast Weisstechnik climate chamber enclosing the grip area. An extensometer is attached to the specimen with rubber bands to measure the strain. A thermocouple is attached with tape to the surface of the specimen to ensure the specimen is at the desired temperature during testing. Loading is performed at a rate of 2 mm/min up to failure. The in-situ hygrothermal conditions range from -20°C to +50°C and 50% to 90% RH to simulate common and extreme outdoor conditions.

3. Results

3.1. Effects of temperature and relative humidity on the tensile response of GFRP laminates

3.1.1. Cross-ply laminate

The stiffness of GFRP cross-ply laminate was observed to be negligibly affected by the temperature and the relative humidity with an overlap of all the stress-strain curves (figure 1). The highest ultimate tensile strength (UTS) was observed at -20°C and the lowest at 50°C showing an effect of temperature on UTS despite no remarkable effect on the modulus.

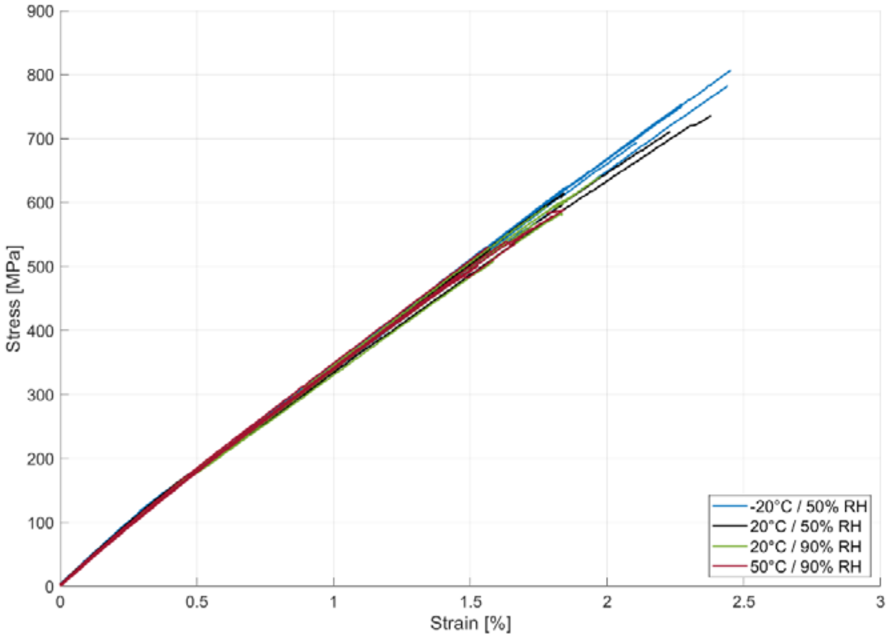

Figure 1. Stress-strain curves of the GFRP [0/90/0] laminate for 4 different in-situ hygrothermal conditions.

3.1.2. Angle-ply laminate

The stress-strain curves of the angle-ply GFRP laminate show three distinct responses governed by the in-situ temperature with a temperature increase resulting in lower modulus, lower UTS, and higher strain to failure (figure 2). The in-situ relative humidity had a negligible effect both at 20°C and 50°C.

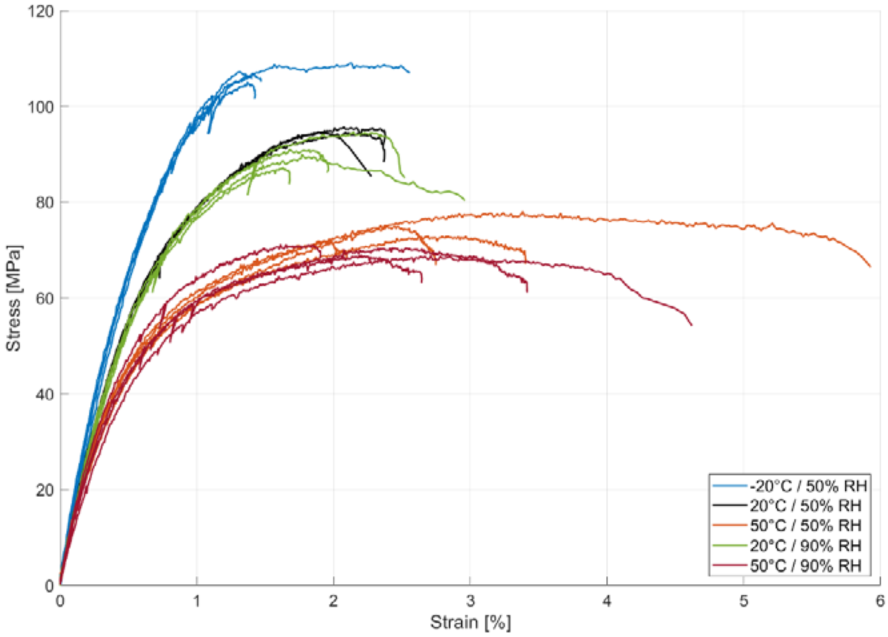

Figure 2. Stress-strain curves of the GFRP [+45/-45]$_S$ laminate for 5 different in-situ hygrothermal conditions.

3.2. Effects of temperature and relative humidity on the tensile response of FFRP laminates

3.2.1. Cross-ply laminate

The mechanical response of the cross-ply FFRP laminate was observed to be significantly dependant on the in-situ temperature and relative humidity (figure 3). The increase in temperature was observed to decrease the modulus and UTS of the laminate manifested by knock down effect on the entire stress-strain curve, observation valid at 50% and 90% RH. Interestingly, the high in-situ relative humidity of 90% caused the shape of the stress-strain curve to change compared to that at 50% relative humidity. The high relative humidity increased the UTS of the laminate.

3.2.2. Angle ply laminate

The angle-ply FFRP laminate exhibit three distinct yield plateau for the three in-situ temperatures (figure 4). The modulus was reduced by the increase in temperature and the increase in relative humidity. Remarkably high strains to failure were reached by the FFRP angle-ply laminate in particular at 50°C where the displacement limit of the tensile testing machine of 16% strain was reached by some specimens without failure. The flax fibre angle was measured on the post-mortem specimens of the angle-ply FFRP laminate (figure 5). At -20°C an angle of 45° was measured, corresponding to the flax fibre angle on the pristine specimens. At 20°C and 50°C the fibres show a permanent rotation of the fibres towards the loading direction.

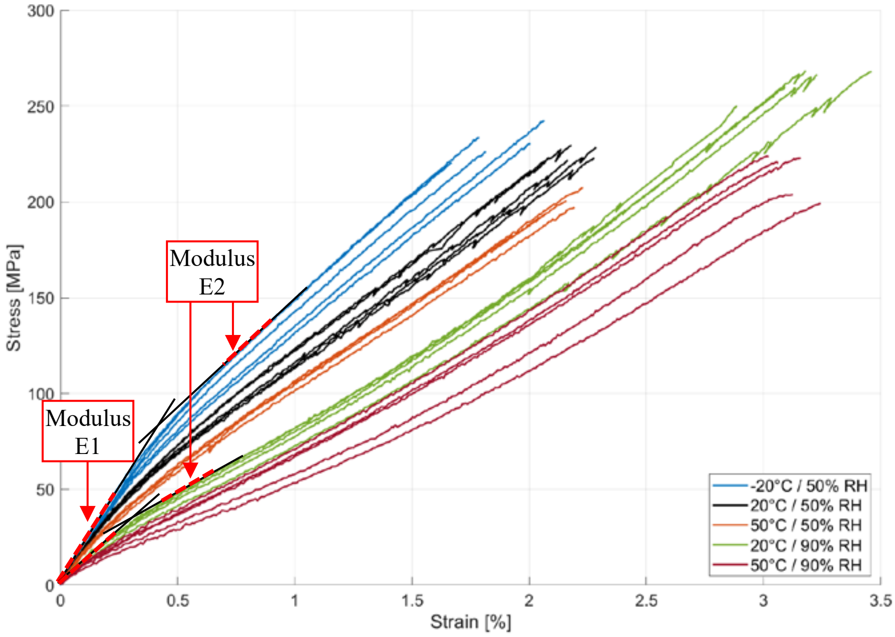

Figure 3. Stress-strain curves of the FFRP $[0/90/0]_S$ laminate for 5 different in-situ hygrothermal conditions.

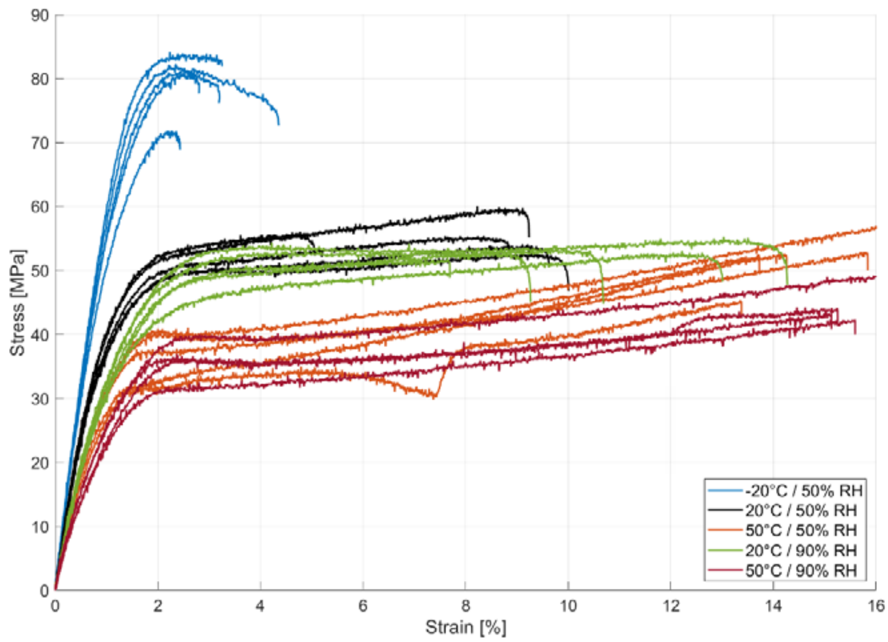

Figure 4. Stress-strain curves of the FFRP $[(+45/-45)_2]_S$ laminate for 5 different in-situ hygrothermal conditions. Beyond 6% strain the deformation was calculated based on the actuator displacement.

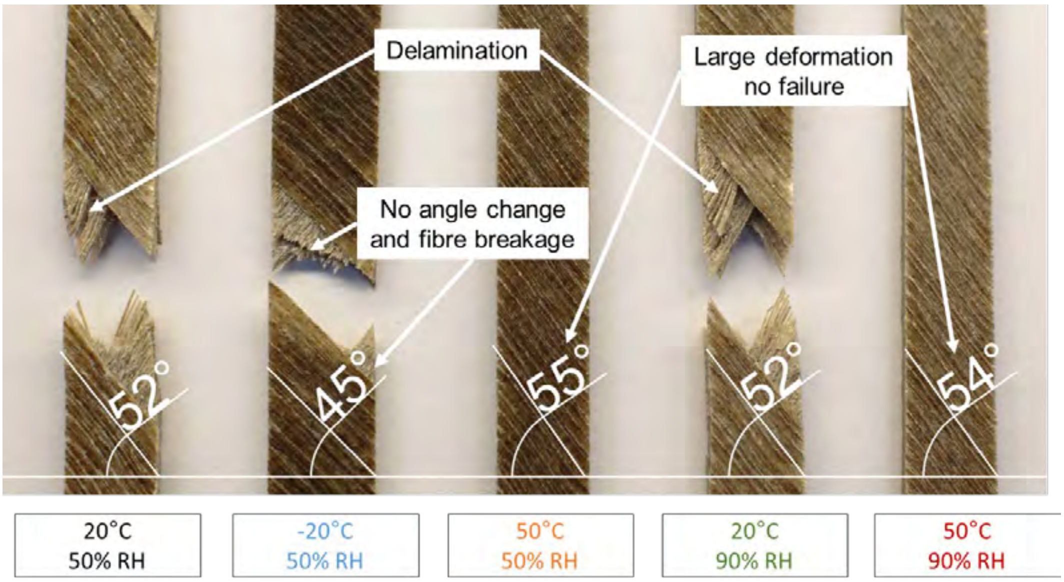

Figure 5. Pictures of post-mortem specimens and visual measure of fibre angle. Observation of different failure mechanisms (or no failure) for different in-situ temperatures.

4. Discussion

The characterisation of the four laminates at -20, 20, and 50°C showed a general trend of lower mechanical performance at higher temperatures (figure 6). While the GFRP and FFRP angle-ply laminates have a similar temperature effect on their modulus, likely due to the common temperature sensitive epoxy matrix system, the GFRP and FFRP cross-ply laminates have a distinct modulus sensitivity to temperature visible by comparing figure 2 with overlapping stress-strain curves and figure 4 with 3 distinct stress-strain curves. This observation suggests that the glass reinforcement is not sensitive to the in-situ temperature but the flax reinforcement is.

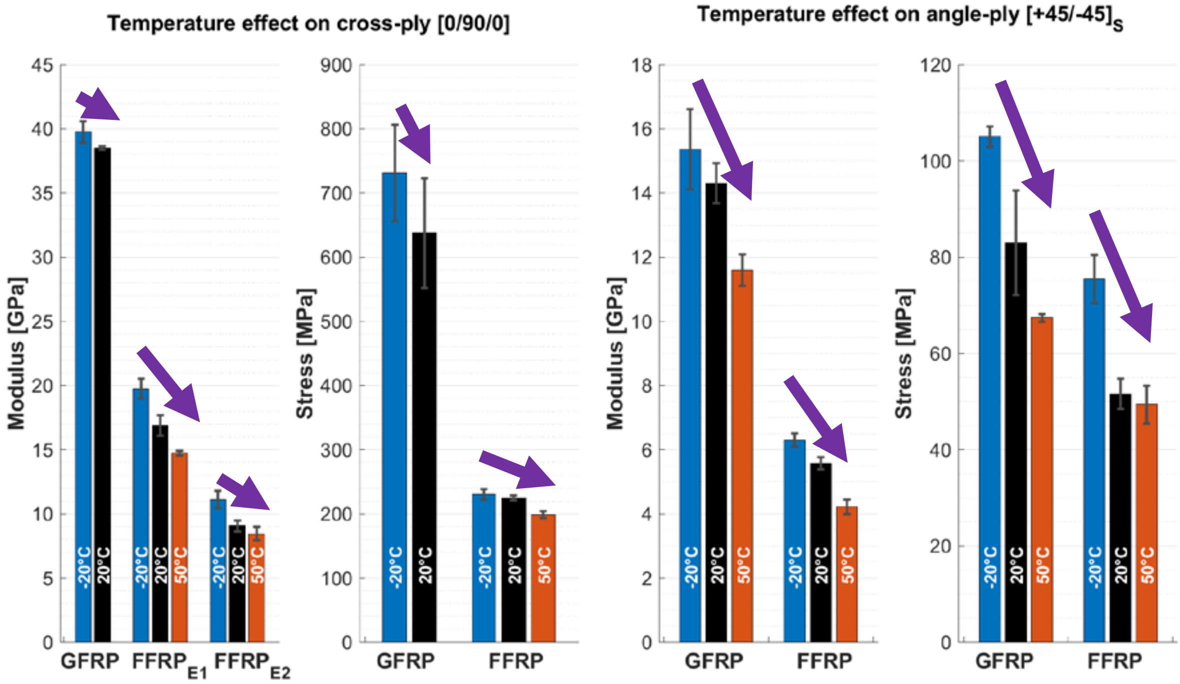

Figure 6. Tests at 50% RH. Decrease of stiffness and strength with increase of temperature. For cross-ply FFRP the E1 modulus is measured from 0 to 0.2% strain (before the knee) and the E2 modulus from 0.7 to 0.9% strain (after the knee) as indicated in figure 3. For the other laminates, the modulus is measured from 0 to 0.2% strain. The stress is measured at tensile failure.

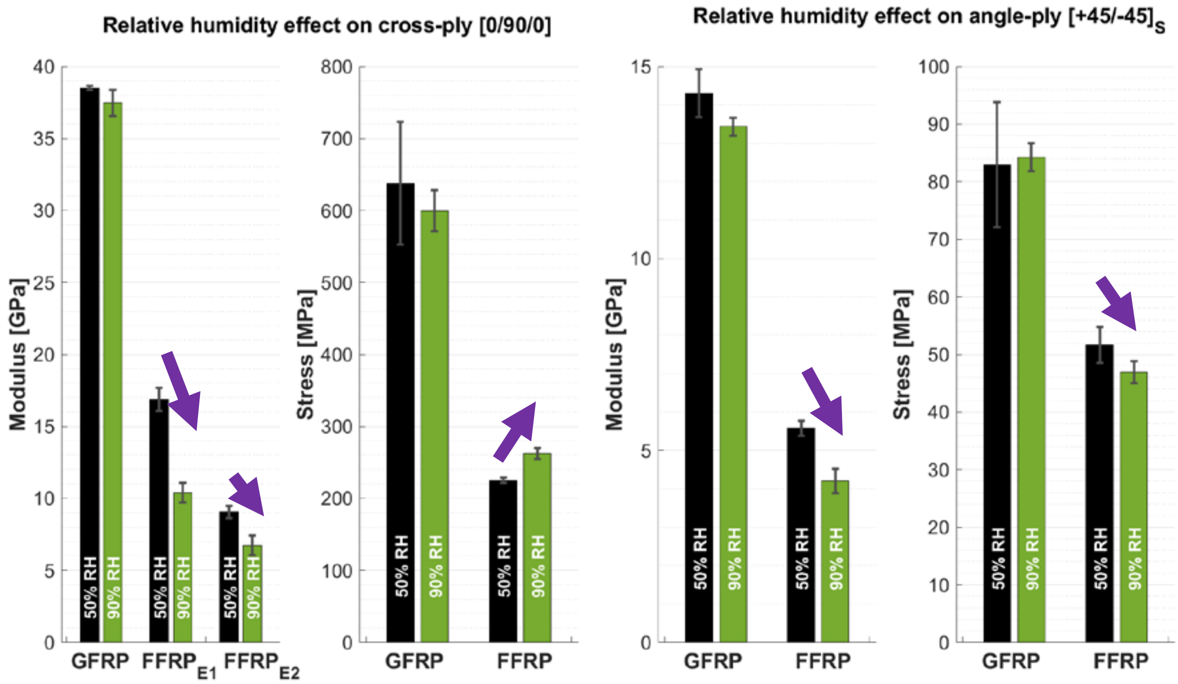

Figure 7. Tests at 20°C. Sensitivity of FFRPs stiffness and strength to relative humidity and insensitivity of GFRPs. For cross-ply FFRP the E1 modulus is measured from 0 to 0.2% strain (before the knee) and the E2 modulus from 0.45 to 0.65% strain (after the knee) as indicated in figure 3. For the other laminates, the modulus is measured from 0 to 0.2% strain. The stress is measured at tensile failure.

The characterisation of the four laminates at 50% and 90% RH showed that the effect of in-situ relative humidity is not significant on GFRP laminates (within standard deviation) but significant on FFRP laminates highlighting flax sensitivity to moisture and its consequences on the mechanical response of the composite (figure 7). Surprisingly, the shape of the cross-ply FFRP laminate stress-strain curve at 90% RH matches that of single flax fibres found in literature [9].

With the combination of in-situ temperature and relative humidity effects (50°C and 90% RH) the results of the FFRP laminates suggest a possible superposition of effects allowing modelling of hygrothermal effects by independent temperature and humidity knock-down factors. For example in figure 3, a factor could be applied on the 20°C/50% RH curve to obtain the same slope as the 50°C/50% RH curve. Then, the same factor could be applied on the 20°C/90% RH curve to obtain the slope of the 50°C/90% RH curve.

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On the plastic region of the angle-ply FFRP laminate, a surprisingly high strain to failure was reached especially at 50°C with some specimens reaching more than 16% strain (figure 4). This large deformation cannot be solely explained by the fibre deformation as single flax fibre reach failure before 4% strain, even at 50°C [8]. However, a rotation of the flax fibres from the initial 45° to 55° (scissoring) was measured on the surface of the post-mortem specimens (figure 5). By trigonometry, this fibre rotation results in a longitudinal strain of 15.8% explaining the 16% strain reached. How such a large deformation can occur is not clear yet as the maximum strain reached by the equivalent GFRP angle-ply laminate is below 6%. The large rotation in the FFRP angle-ply laminate may be allowed by a weak flax fibre-matrix allowing for a relative displacement without failure which is exacerbated by elevated temperatures increasing matrix plasticity. The microstructure of the FFRP laminate may also contribute to allowing large fibre rotation because of larger spacing between fibres tows in FFRP than in GFRP, resulting in matrix rich areas susceptible to scissoring (figure 8). Also, low spacing between glass fibre tows in the fabric can also limit the scissoring effect.

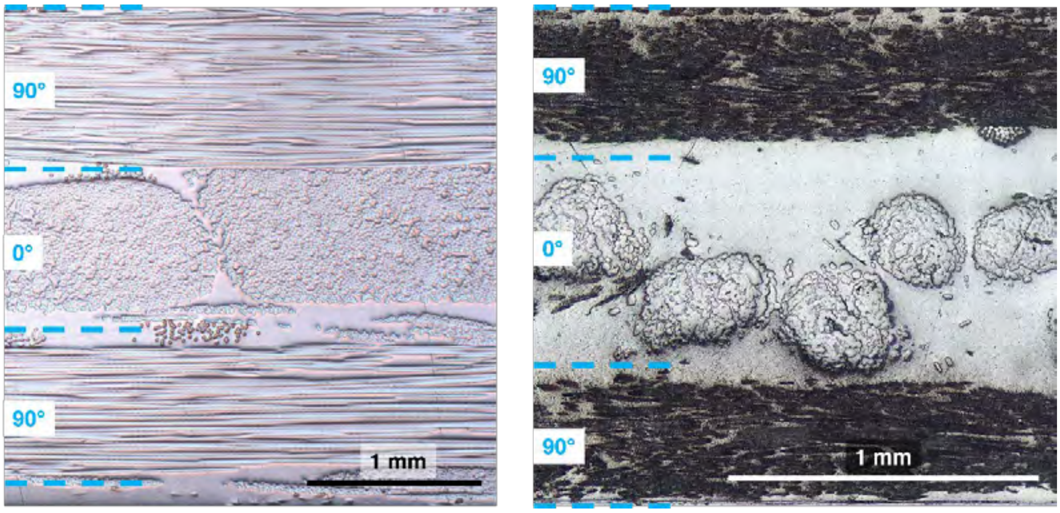

Figure 8. SEM images depicting microstructure of GFRP laminate (left) and FFRP laminate (right) demonstrating smaller spacing between glass tows compared to flax yarns. The delimitations of the plies and fibre angle relative to the observer are indicated.

4. Conclusions

In this study, we investigated the effects of in-situ temperature and relative humidity variations on the quasi-static tensile response of flax and glass FRP composites. Cross-ply and angle-ply laminates were manufactured, equilibrated to five different hygrothermal conditions with temperature and relative humidity ranging from -20 to 50°C and 50% to 90% RH, respectively and subsequently tested under controlled hygrothermal conditions. Below are the key findings:

- At higher in-situ temperatures, a general decrease in mechanical performance is noted across all laminates, with FFRP laminates displaying a more pronounced sensitivity, likely attributed to the cellulosic nature of the flax reinforcement.
- While the in-situ relative humidity had limited effects on the GFRP laminates, a significant effect of in-situ condition was observed on stiffness, strength, and strain to failure of FFRP laminates. Additionally, a change of the stress-strain curve shape was noted for the FFRP cross-ply laminate
- The in-situ temperature and relative humidity have distinct effects on the FFRP laminates. The results suggest that those effects can be modelled separately and superposed.
- For angle-ply laminates, the matrix sensitivity to in-situ environment has a large influence on the mechanical response of the composite while the hygrothermal sensitivity of the cross-ply laminates is predominantly dependant on fibre properties.
- Exceptionally large strains to failure, exacerbated at high temperatures, were measured with the FFRP angle-ply laminate and were accompanied by a fibre rotation. This large deformation is possibly attributed to scissoring in matrix rich region of the FFRP microstructure.

As a general conclusion, the results presented in this study show that the mechanical performance of FFRP laminates is sensitive to in-situ temperature and moisture conditions, and this to a significantly larger extent than in GFRP laminates. It is therefore pivotal for the safe and reliable use of biocomposites in structural applications to understand and account for in-situ hygrothermal effects.

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