FATIGUE BEHAVIOR OF A UNIDIRECTIONAL NON-CRIMP FABRIC GLASS FIBER REINFORCED REACTIVE THERMOPLASTIC COMPOSITE

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ABSTRACT

Wind turbines are being used in regions where exposure to extremely low temperatures and high winds has become the standard operating condition, which increases the demand on the turbine blade structure. Wind turbine blades are typically manufactured from glass fiber/epoxy laminates, which tend to exhibit increased brittle failure modes with decreasing operating temperatures. In order to improve the performance of wind turbine blades under extreme operating conditions, replacing conventional glass fiber/epoxy composite materials with resin infusible glass fiber/reactive thermoplastic composite materials may provide several benefits, including improved low-temperature toughness and end-of-life recyclability. The goal of this study was to assess the fatigue performance of a resin-infused unidirectional (UD) non-crimp fabric (NCF) glass fiber/acrylic composite material at room temperature (RT) and -50°C. Tension-Tension fatigue tests were conducted on UD specimens to compare the relative performance, fatigue life, and fatigue resistance. The increase in temperature during the different stages of the RT fatigue tests was monitored using a high-definition infrared camera to provide a qualitative assessment of damage evolution.

1 Introduction

Owing to their low density, high specific strength/stiffness, and good fatigue resistance, fiber-reinforced plastic (FRP) composites have been widely used in many industries, such as aerospace, automotive, and wind energy. Since the early 2000s, wind energy has played an important role in generating electricity with a significant global increase in installation of of wind turbines [1]. In recent years, wind turbines have been frequently used in locations where they are exposed to extreme operating conditions, such as low temperatures (e.g., -50°C) and strong winds [2], which increases the demand on the blade structure. Furthermore, as wind turbines reach their designed life (typically 20 years) or undergo damage during their service life, end-of-life recyclability becomes a challenge. Glass fiber/epoxy composites are commonly used in wind turbine blade structures, which makes them more difficult to recycle. It is projected that the global decommissioned or damaged wind blade material will reach 2 million tons per year by 2050 [1], with a cumulative total of 43.4 million tons of waste [3]. Glass fiber/thermoplastic composites may be a suitable replacements for glass fiber/epoxy in wind turbine blades. In addition to enabling the recyclability of wind turbine blades, thermoplastic composites may exhibit improved damage tolerance, fracture toughness, and fatigue resistance, particularly at low temperatures, when compared with their counterparts. This is important since fatigue loading is one of the primary causes of stiffness degradation of wind turbine blades [4]. In order to improve the fatigue performance of next-generation wind turbine blades under extreme operating conditions and extend their useful life, there is a need to fundamentally understand the corresponding damage mechanism.

Cormier et al. [5] performed R=0.1 and R=-1 fatigue tests for glass-epoxy laminates ($\mp 45_{2s}$) at RT and -40°C. They found that the fatigue life was improved significantly at lower temperature for both tests, with a steeper decrease of the S-N curves. Shindo et al. [6] performed R=0.1 fatigue tests for plain weave glass-epoxy laminates at RT, 77K, and 4K. The fatigue life was increased at 77K compared to RT, followed by significant loss when further decreasing the temperature to 4K, similar results to their previous study on woven glass-epoxy laminates [7]. Pannkoke et al. [8] compared the residual stress after 10^7 cycles for 4 different material systems at 77K. They concluded that the fatigue behavior was determined by matrix and fiber-matrix bond had little influence on fatigue properties.

A review of the literature has shown that few studies have reported low temperature fatigue data for FRP composite materials, while there are even fewer for fiber-reinforced thermoplastics. In this study, tension-tension fatigue tests were performed on a vacuum-infused glass fiber/acrylic composite material at both RT and -50°C. The objective is to study the effect of temperature on fatigue performance of the material. The surface temperature was also monitored at RT using a high-resolution IR camera to track the damage evolution during the different stages of the cyclic tests.

2 Material and Experimental Details

2.1 Material description

The material investigated in this study comprised a reactive thermoplastic acrylic resin, namely Elium® 188 XO (Arkema, France), reinforced with a unidirectional non-crimp fabric. The unpolymerized acrylic resin had a post-cure dry-Tg of 123°C [9] and a low viscosity of 0.1 Pa·s at room temperature [10], which enables use with resin infusion processes, such as vacuum-assisted resin transfer molding (VARTM). The UD fabric layers consisted of silane-sized E-glass fiber rovings (StarRov® 090, Johns Manville, US) with a linear density of 1100 tex and a filament density of 2.55 g/cm^3 [9]. A light polyester (PE) stitch (29 dtex) in a tricot pattern was used to connect the aligned longitudinal fiber tows, while transversely oriented glass fiber yarns and a nonwoven polymeric veil were used on the bottom side of the fabric to maintain the integrity of the fabric during manufacturing (Figure 1). The polymeric veil also assisted with the infusion of the resin during processing.

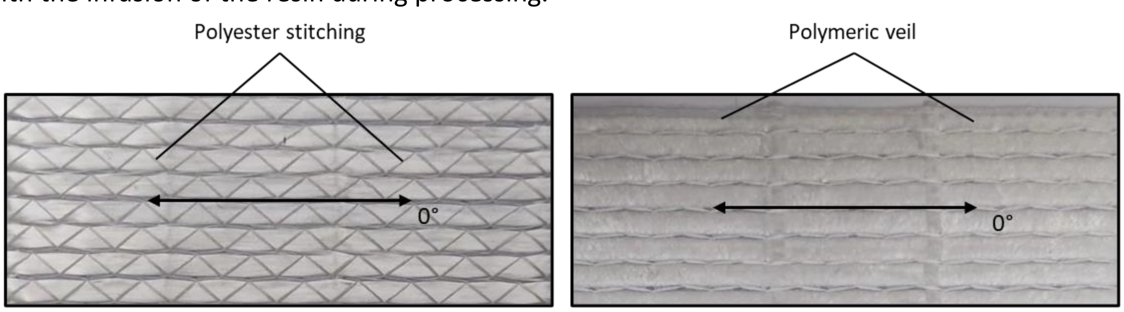


Figure 1. Photograph of UD-NCF glass fabric (a) upper surface with tricot stitching patterns, and (b) bottom surface with veil

A custom VARTM set-up was used to manufacture flat panels comprising 4 layers of the UD-NCF with a stacking sequence of $[0]_4$. The acrylic resin monomer was pre-mixed with a dibenzoyl peroxide initiator, namely Luperox® AFR40 (Arkema Inc., France) and infused into the mold at room temperature to enable in-situ polymerization of the resin. The final dimensions of the panels were 305 mm x 305 mm with a fiber volume fraction of approximately 35%. Test specimens were cut from the fabricated panels using an abrasive waterjet cutting machine. Aluminum end tabs of 50mm and 60mm in length were bonded to RT and -50 °C specimens respectively to avoid any potential issues with gripping induced failure and end tab slippage. The specimen geometry complies with ASTM D 3479 [11] (Figure 2.).

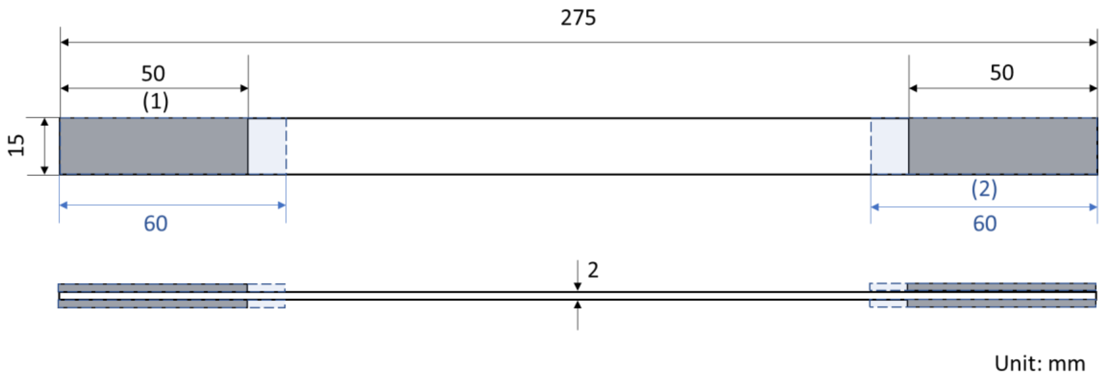


Figure 2. Photograph of specimen geometry for RT (1) and -50°C (2) tests (fibers oriented along the specimen axis).

2.2 Experimental set-up

All fatigue tests were conducted at either RT or -50°C on an MTS 810 test frame with a +/-50 kN capacity load cell. An integrated LN2 cooled Instron E3119-609 Environmental chamber was used for the low-temperature tests. A FLIR A8581 infrared (IR) camera with a pixel resolution of 1280 x 1024 and a temperature sensitivity of <25 mK was synchronized to the controller of the test frame and used to monitor the surface temperature of the specimen during RT fatigue tests as a means to monitor damage evolution (Figure 3).

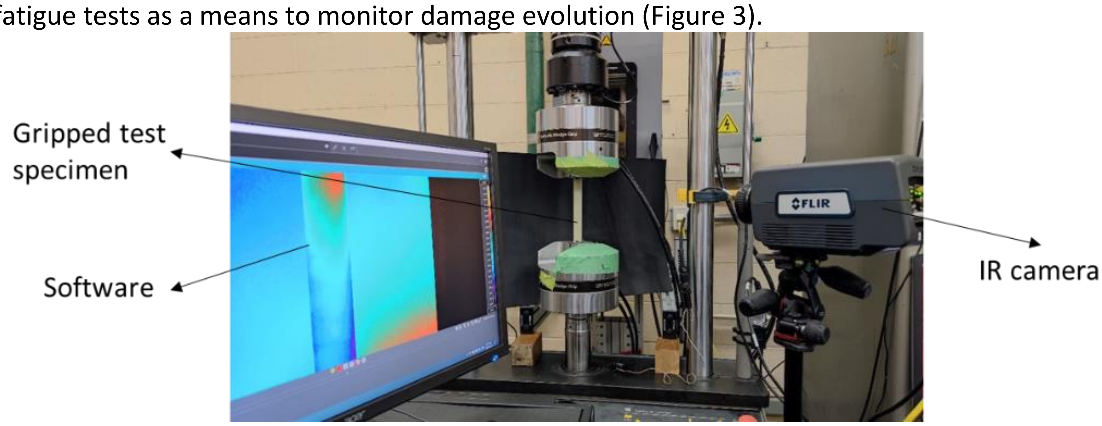


Figure 3. RT fatigue test set-up with IR camera

Tension-tension fatigue tests were conducted under load control using a sinusoidal waveform with constant amplitude, a loading frequency of 5Hz, and a stress ratio of 0.1 at different maximum applied stress levels. At least three tests were conducted at each test condition, to provide fatigue life, to monitor damage evolution, to track surface temperature change, and to study the effects of temperature on fatigue performance of UD NCF glass/acrylic composite material.

3 Experimental Results

Quasi-static tension tests were conducted at RT to determine the ultimate tensile strength (UTS) of the glass fiber/acrylic material. Table 1 provides the corresponding mechanical properties.

Table 1 Averaged material properties at RT

Stacking sequence	UTS (MPa)	E (GPa)	ε_f (%)
$[0]_4$	570.5	28.9	2.28

Fatigue tests were conducted at maximum applied stress levels of 65% and 85% of the RT-UTS for both RT and -50°C test specimens until final failure occurred. The test conditions and results are listed in Table 2. At the same applied stress level, the average fatigue life at -50°C is at least 2X higher when compared with that at RT. The scatter of the fatigue life, represented using a coefficient of variation (CV), is greater at -50°C. These observations indicate the damage evolution process is affected to some extent by temperature, but the final failure mode seems to remain unchanged, as shown in Figure 4.

Table 2 Fatigue test conditions and results

Test condition	Specimen No.	S_{max} (MPa)	N_f	Mean (CV, %)
RT, 85% UTS	1	484.9	563	739 (16.96)
Tension-Tension	2	484.9	845	
fatigue, R=0.1, 5Hz	3	484.9	809	
-50°C, 85% UTS	1’	484.9	2379	1484 (42.84)
Tension-Tension	2’	484.9	1115	
fatigue, R=0.1, 5Hz	3’	484.9	959	
RT, 65% UTS	4	370.8	5460	4124 (23.02)
Tension-Tension	5	370.8	3336	
fatigue, R=0.1, 5Hz	6	370.8	3578	
-50°C, 65% UTS	4’	370.8	8767	10656 (32.27)
Tension-Tension	5’	370.8	15483	
fatigue, R=0.1, 5Hz	6’	370.8	7720	

(a) (b) (c) (d)

Figure 4. Typical failed specimens. (a) RT- 85% UTS; (b) -50°C - 85% UTS; (c) RT- 65% UTS; (d) -50°C - 65% UTS

Specimen surface temperature data were recorded under 85% UTS and 65% UTS at RT to provide information on the different stages of damage during cyclic loading. Four temperature profiles are plotted against life fractions, the average temperature of the region of interest (ROI), and the temperatures of the point of interest where the fracture occurred (POI-1, POI-2, POI-3), as shown in Figure 5 and Figure 6. It is evident that the surface temperature and damage evolution exhibit a three-stage progression, and at lower stress levels the three stages are more distinct, which is in agreement with those described in [12] and [13]. The overall increased temperature is caused in part by the energy released during fiber breaking, formation of splitting cracks, or clusters of adjacent fiber breaks (as will be demonstrated below).

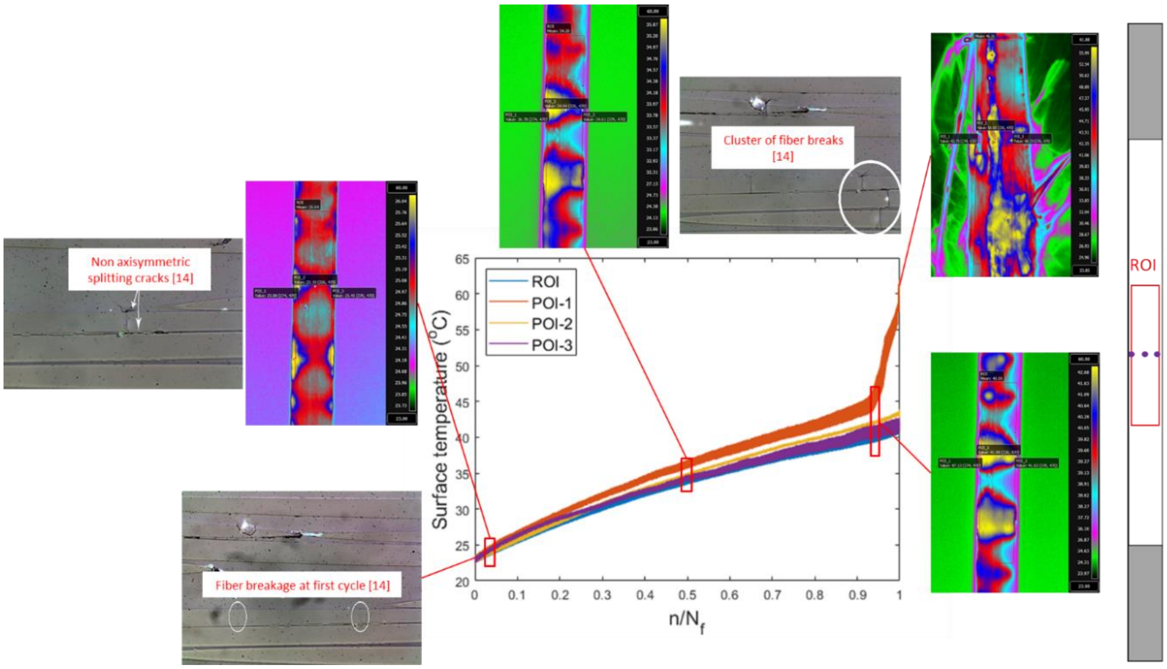


Figure 5. Surface temperature evolution for RT fatigue specimens with peak stress of 85% UTS

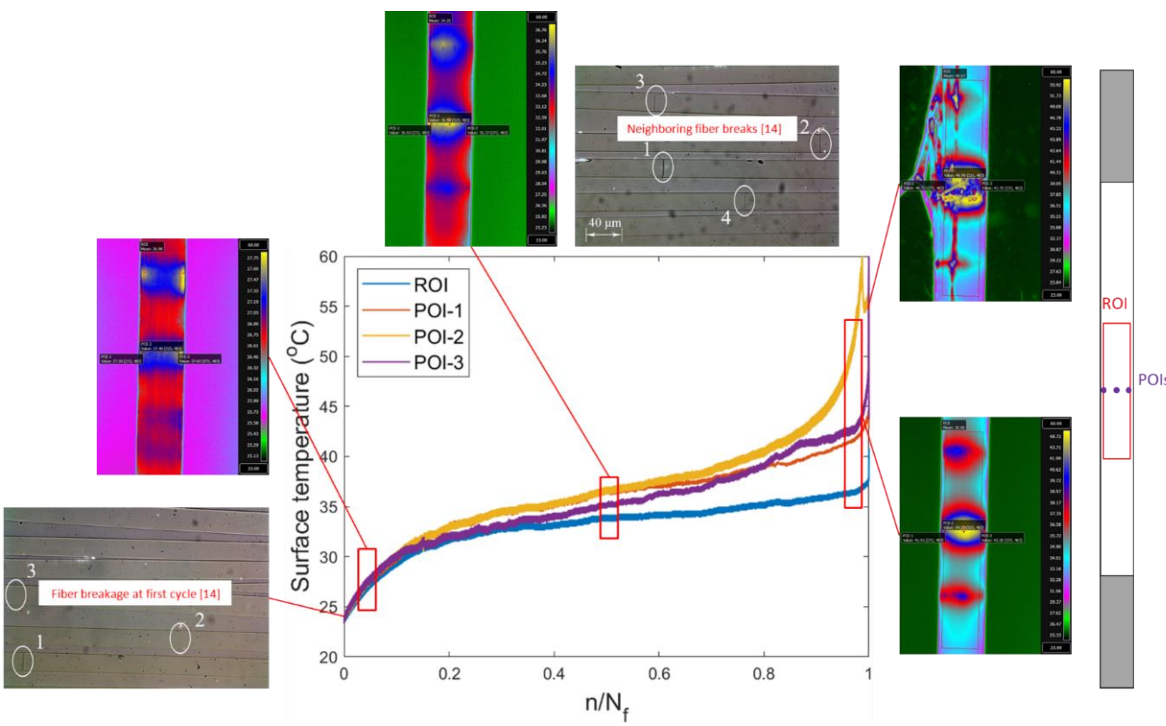
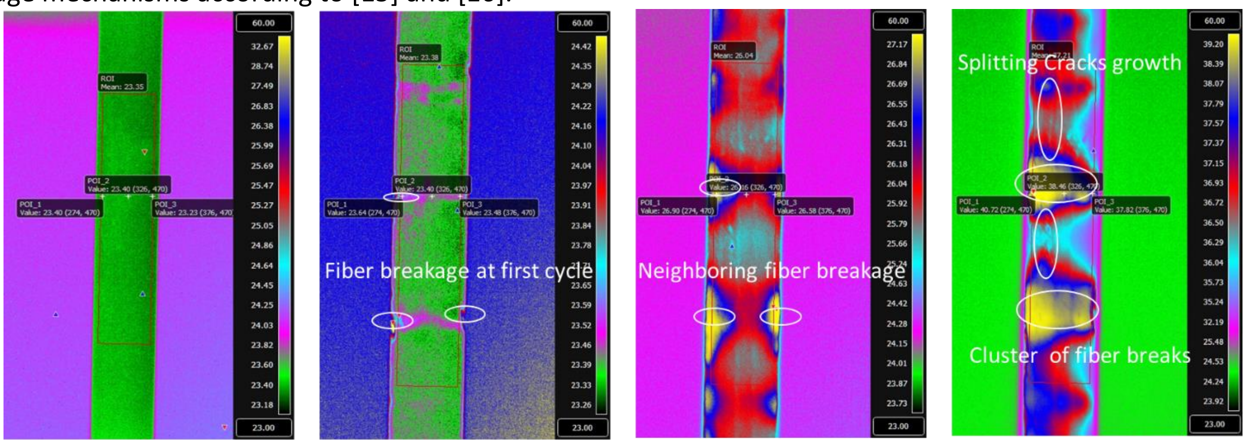


Figure 6. Surface temperature evolution for RT fatigue specimens with peak stress of 65% UTS

The specimen surface temperature maps captured by IR camera correlate well with the optical microscopic observations reported by Castro et al. [14] using 6 layers of a UD glass/epoxy composites under tension-tension cyclic loadings. As shown in Figure 7 and Figure 8, the fatigue damage initiated during the first cycle when localized fiber breakage occurred at several locations at maximum stresses lower than the UTS of the composite material.

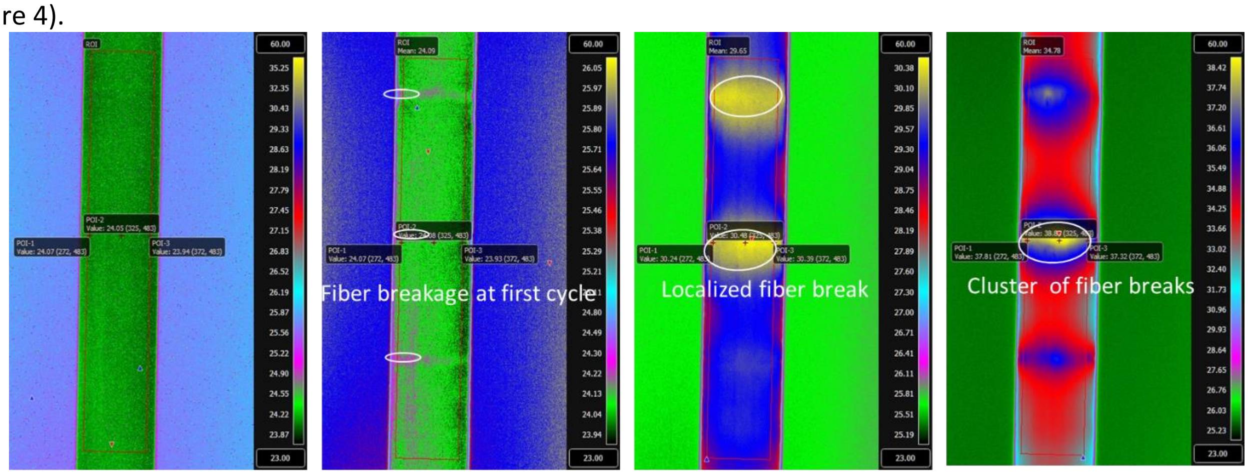
At peak cyclic stress of 85% UTS, splitting cracks were observed to initiate near the localized fiber breaks and grow along the loading direction with increasing number of cycles, and may be due to high local shear stresses and load redistribution. The splitting crack tips and neighboring fibers close to the fiber break are both affected by the stress redistribution, which can lead to further failure in the weak segments when their local strength was exceeded. According to [13], the splitting cracks tend to kink out into the matrix and propagate towards the neighboring fibers, increasing the local stress and the possibility of breakage in neighboring fibers. In this study, the cluster of fiber breaks was also captured and propagated near the location of new breaks in the neighboring fibers, one of the main damage mechanisms according to [15] and [16].



Undamaged First cycle 0.1 N_f 0.7 N_f

Figure 7. Damage evolution for RT fatigue tests under a peak stress of 85% UTS

However, at peak cyclic stress of 65% UTS, the surface temperature was found to be more uniformly distributed compared with that of the 85% UTS samples, suggesting more localized damage, which can be demonstrated from the failed specimen in Figure 4. Additionally, no obvious splitting cracks were observed during the tests possibly because the threshold needed to drive crack propagation was not reached due to the lower stress values. Thus, the stress redistribution only affected the neighboring fibers close to the fiber break, decreasing the possibility of new fiber breaks, as can be seen in Figure 8. This can also explain why few fiber breaks occurred at lower stress levels (Figure 4).



Undamaged First cycle 0.1 N_f 0.7 N_f

Figure 8. Damage evolution for RT fatigue tests under a peak stress of 65% UTS

Figure 4 also shows the difference in damage distribution between RT and -50°C fatigue samples. At -50°C, failure started at multiple individual locations, and there is less interaction between damaged regions. The damage evolution process is thus slowed down, and more regions exhibit damage, indicating more material bears the load and more efficient use of material, leading to longer fatigue life and damage tolerance.

4 Conclusions

The tension-tension fatigue performance of a unidirectional non-crimp fabric (UD-NCF) glass fiber/reactive thermoplastic composite material loaded along the fiber direction was investigated at both room temperature (RT) and -50°C. Results demonstrate that an approximately twofold increase in fatigue life can be expected at -50°C, possibly due to the increased mechanical properties of the matrix and fiber/matrix interface, and the reduced possibility of interaction between damage regions.

Damage evolution and the specimen surface temperature were tracked using an infrared (IR) camera for the RT fatigue tests. Three different stages for the temperature profile were observed, corresponding to three different damage stages, while the evolution of different damage mechanisms was also captured. The results indicate that IR thermography is a useful non-destructive tool for assessing the development of damage and predicting the damage stages of the studied material.

It was also demonstrated that the damage growth and distribution were affected by temperature. At RT, more interactions between damaged regions were observed. However, at -50°C, the failure started in multiple regions and tended to propagate locally. More regions bear the load, so more fiber breaks were observed.

Therefore, within the stress range studied herein, the effect of low temperature is beneficial for the fatigue life of UD-NCF glass/acrylic composites. However, further investigation is still needed to track stiffness degradation and damage stages for the fatigue tests performed at -50°C.

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