



Chapter 7

Effect of Loading Frequency on Fatigue Behavior of Additively Manufactured Short Fiber Thermoplastics via Infrared Thermography

Pharindra Pathak, Kaniz Fatema Bristy, Vipin Kumar, and Suhasini Gururaja

Abstract This study investigates the fatigue behavior of additively manufactured compression-molded short fiber thermoplastics (AM-SFTs), focusing on the effects of loading frequency. Utilizing passive infrared thermography (IRT), the mean temperature changes due to ‘self-heating’ under cyclic loading applied at varying frequencies were monitored. Previous research demonstrated that IRT could efficiently assess fatigue limits, significantly reducing fatigue characterization time. While traditional methods required up to two weeks and 18 specimens to establish the S-N curve for 20% short carbon fiber-reinforced Acrylonitrile Butadiene Styrene (C/ABS) AM panels, IRT achieved comparable results with just three specimens in a five-hour time frame using a staircase cyclic loading profile [1]. This study builds upon that foundation, investigating the effect of loading frequency on the fatigue behavior of AM-SFTs. In spite of higher loading frequencies generating increased heat due to viscoelastic dissipation and internal friction, which can soften the matrix, the fatigue life of the specimens increased. This heat accumulation, particularly originating at the fiber ends, accelerates inherent progressive damage mechanisms only after crossing the fatigue limit in AM-SFTs. Additionally, microstructure - fiber length distribution, fiber orientation distribution, and porosity distributions - play a significant role in determining the structural performance of AM-SFTs. Micro-computed tomography characterization of AM-SFTs provided information about the composite microstructure. Fatigue testing of AM-SFTs and baseline ABS were performed at varying loading frequencies of 5 Hz and 20 Hz using a servo-hydraulic machine to delineate the role of fibers on the self-heating phenomenon. Additionally, dynamic mechanical analysis (DMA) testing was conducted on AM-SFTs and baseline ABS to assess the effect of fibers on viscoelastic behavior.

Keywords AM-SFTs · IRT · Fatigue · Frequency · Damage

Introduction

Short fiber-reinforced thermoplastic composites (SFTs) have garnered significant attention for structural applications due to their lightweight nature, cost-effectiveness, and ease of manufacturing. Their superior fatigue resistance makes them particularly valuable in the automotive and aerospace industries. Despite its advantages, the fatigue behavior of SFTs is complex and significantly affected by factors such as fiber orientation, porosity, stress ratio, and loading frequency [2]. Under cyclic loading, SFTs typically exhibit continuous softening, characterized by a gradual reduction in stiffness and load-bearing capacity. This behavior is primarily attributed to the initiation and progression of damage within the matrix, as well as at fiber ends and the fiber-matrix interface [3]. Due to the viscoelastic nature of thermoplastics and their relatively low melting temperatures, loading frequency significantly influences fatigue performance, primarily through heat buildup and time-dependent deformation [4]. The fatigue resistance of SFTs is also governed by factors such as fiber reinforcement, orientation, and distribution, which are inherently linked to the effective material response of the SFT [5]. Due to the complexity and the numerous parameters affecting the mechanical behavior of SFTs, fatigue behavior has primarily been studied

Pharindra Pathak · Kaniz Fatema Bristy · Suhasini Gururaja
Department of Aerospace Engineering, Auburn University, Auburn, AL 36849
e-mail: pzp0057@auburn.edu; kzb0153@auburn.edu; szg0130@auburn.edu

Vipin Kumar
Manufacturing Science Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830
e-mail: kumarvi@ornl.gov

through experimental methods. Traditional fatigue assessment methods, such as the stress-life (S-N) approach, require extensive experimental testing, rendering them both time- and resource-intensive. This highlights the necessity for dependable, efficient methods to predict fatigue life and comprehend damage mechanisms in SFTs.

Infrared thermography (IRT) has emerged as a promising non-destructive evaluation (NDE) tool for real-time monitoring of damage evolution, leveraging heat dissipation during cyclic loading [1, 6, 7, 8]. By correlating dissipated hysteretic energy with surface temperature changes, IRT enables rapid fatigue characterization. Under constant amplitude fatigue (CAF), the surface temperature evolution typically exhibits three distinct phases: an initial rapid temperature rise (Phase I), followed by a stabilized mean temperature indicating steady-state damage (Phase II), and finally, an unsustainable rapid temperature increase (Phase III) that precedes failure. Notably, the stabilized Phase II temperature (ΔT_{stab}) increases with the applied cyclic stress amplitude, and plotting ΔT_{stab} against the stress amplitude yields a bilinear curve that defines the fatigue limit. Furthermore, by employing a staircase-loading protocol where blocks of increasing CAF amplitudes are applied to a single specimen, the fatigue limit of a material system can be determined with minimal specimen usage. Previous studies have demonstrated that the IRT method can accurately capture the fatigue limit for 20 wt.%C/ABS SFTs manufactured via an additive manufacturing compression molding (AM-CM) process, achieving a 100-fold increase in testing speed while requiring only one-sixth the number of specimens compared to traditional approaches [1]. This efficiency of the IRT method instills confidence in its potential for the study of SFTs, particularly those processed via advanced techniques like AM-CM.

In this study, the fatigue behavior of 20 wt.% C/ABS AM-SFTs was investigated. By leveraging IRT, a rapid and efficient method for predicting fatigue limit is established. The influence of loading frequency and fiber orientation on the fatigue limit of 20 wt.% C/ABS AM-SFTs have been investigated in the current study.

Materials and Methods

Materials and Characterization

This study investigated two material systems: pure ABS and ABS reinforced with 20 wt.% chopped C-fibers. These materials were manufactured at Oakridge National Laboratory using a two-step process. For the composite material, chopped carbon fibers were first mixed with ABS pellets and then extruded using a KUKA robotic arm operating at 1200 rpm, with a nozzle speed of 280 mm/s, and a 9.88 mm gap between the substrate and the nozzle outlet [9]. This process created an AM preform, which underwent compression molding at a pressure of 500 kN for 5 minutes. The final product results from the combination of the AM process promoting high fiber alignment and the CM process, which reduces porosity, ultimately enhancing the composite's mechanical performance [9].

The AM-CM process, a key aspect of this study, creates a unique microstructure. The chopped fibers tend to align along the bead (deposition) direction, resulting in directionally dependent properties. This unique microstructure provides a novel platform to assess the effect of material orientation on mechanical properties and fatigue behavior and to compare these results with the pure ABS matrix. Specimens were machined at different angles relative to the bead direction (0° , 30° , 45° , 60° , and 90°) using abrasive waterjet machining following ASTM D638 Type I specimen dimensions as seen in Fig. 1(a).

To further investigate the microstructure, a specimen along bead direction (0°) was subjected to high-resolution 3D X-ray imaging using a Zeiss Xradia 620 Versa system at Auburn University. For optimal image resolution during μ -CT acquisition, each specimen was mounted on a rotary stage perpendicular to the X-ray source. μ -CT data were collected at a power setting of 140 kV and 21 W using a 4 \times scintillator objective lens with 2 \times 2 binning, resulting in a voxel size of approximately $0.6 \mu\text{m} \times 0.6 \mu\text{m} \times 0.6 \mu\text{m}$. An air filter was used to enhance image clarity. After acquiring X-ray projection images, a 3D reconstruction was performed using the system's image processing unit, generating 997 images stacked in the out-of-plane direction. Noise reduction and intensity-based thresholding were applied to determine the fiber, which is seen as red in color (Fig. 1(b)), pores, and matrix constituents. Optimized AM-CM processing yield up to 80% fiber alignment in the deposition direction, within the 0° – 30° range, with a typical fiber aspect ratio of 5–7 and an average fiber diameter of $8 \mu\text{m}$ as shown in Fig. 1(c).

Quasi-Static Tensile Testing

Quasi-static tensile tests were conducted on pure ABS and composite specimens with varying fiber orientations using a 100 kN servo-hydraulic MTS machine at a displacement rate of 2 mm/s. For each specimen type, three replicates were tested to ensure statistical reliability. The measured mechanical properties of ultimate tensile strength (σ_{UTS}) and failure strain (ϵ_f) are summarized in Table 1.

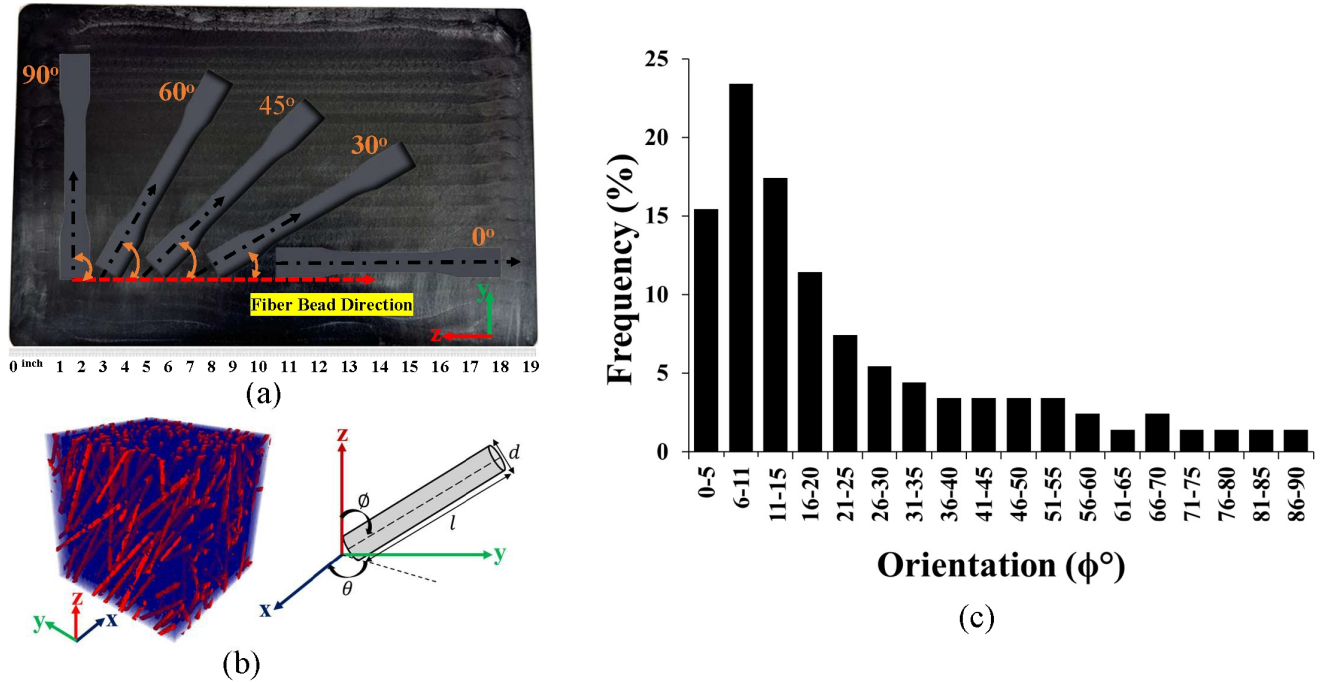


Fig. 1 (a) Schematic of AM-CM composite panel with fiber bead direction and different oriented specimens; (b) Visualization of fibers from μ -CT, and semi-axes and orientation conventions for a geometric representation of fiber. The aspect ratio is given by l/d , and (c) Distribution of fiber parameters obtained from μ -CT scan of orientation ϕ .

Table 1 Ultimate tensile strength and failure strain for various specimens.

Specimen	Ultimate Tensile Strength, σ_{UTS} [MPa]	Failure Strain, ε_f [%]
Pure ABS	54.000 ± 1.810	1.320 ± 0.050
0° fiber orientation	87.320 ± 1.240	0.730 ± 0.003
30° fiber orientation	61.720 ± 0.770	0.910 ± 0.001
45° fiber orientation	44.600 ± 0.190	0.935 ± 0.005
60° fiber orientation	43.320 ± 1.490	0.877 ± 0.002
90° fiber orientation	42.420 ± 1.180	1.055 ± 0.004

The results indicate a strong dependence of σ_{UTS} and ε_f on fiber orientation. Specimens with fibers aligned at 0° exhibited the highest σ_{UTS} and the lowest ε_f , as expected. At 0°, the fibers carry most of the applied load efficiently making the material stiffer but brittle, resulting in restriction in matrix deformation. As the fiber orientation deviates from 0°, σ_{UTS} decreases while ε_f increases, indicating that transverse fiber orientations (e.g., 90°) provide minimal load-bearing capacity and are more matrix-dominated. Interestingly, for fiber orientations 45° to 90°, σ_{UTS} was found to be lower than pure ABS matrix. These changes in behavior for different orientations are primarily due to the load transfer efficiency between the fibers and the polymer matrix, which depends on fiber alignment relative to the loading direction.

Fatigue Testing

To evaluate the fatigue behavior under cyclic loading, interrupted fatigue tests were performed using the same 100 kN MTS machine Fig. 2(a). The tests were carried out at two frequencies: 5 Hz and 20 Hz under a constant stress ratio ($R = 0.1$). Each specimen was initially loaded at a stress level corresponding to 30% of its σ_{UTS} , and the stress was incrementally increased by 5% until failure. Between each stress increment, the specimen was cycled for 7500 cycles, with a rest period provided to allow the specimen to return to ambient temperature Fig. 2(b). This protocol enabled the specimen to experience a range of stress levels and capture various damage modes.

Surface temperature evolution due to cyclic loading-induced self-heating was monitored using a Telops infrared camera Fig. 2(a). The camera recorded the surface temperature increment (Fig.3(a)) and generated temperature profiles at every 7500-cycle interval Fig. 3(c). The 7500-cycle step size was based on constant amplitude fatigue tests, demonstrating that

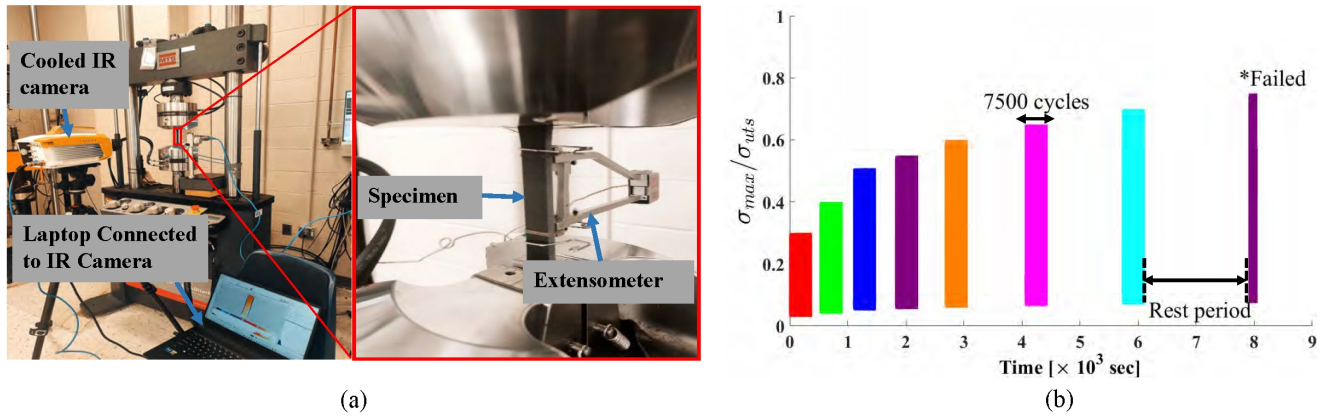


Fig. 2 (a) Experimental setup for in situ surface temperature measurements, featuring a cooled IR camera connected to a laptop with Reveal IR software, integrated with a UTM system and a 5 cm gage length extensometer, and (b) Staircase loading applied to a specimen to determine fatigue limit rapidly: early increments of 10% σ_{UTS} followed by 5% σ_{UTS} increments to σ_{max} were used to determine fatigue limit. The stress ratio $R = 0.1$ was maintained throughout the test. The rest period between load steps ensured the specimen cooled to room temperature.

the specimen's temperature stabilized after approximately 6000 cycles, even at higher stress levels. Initially, as the specimen experienced cyclic loading, the temperature increased rapidly (Phase I) due to the viscoelastic response of the ABS matrix and friction at the fiber-matrix interface, particularly at the fiber ends where stress concentrations occur. This rapid increase was followed by a plateau (Phase II), representing a saturation of damage accumulation. At higher stress levels, the energy input exceeded the bonding strength at the fiber-matrix interface, leading to matrix cracking, increased displacement, and fiber-matrix debonding. These phenomena culminated in a final rapid temperature spike (Phase III) immediately preceding failure.

Fast Fourier transform (FFT) analysis of the temperature data as explained in [6] for composite specimens tested at 20 Hz revealed that inelastic or irreversible damage initiates at stress levels above 60% of σ_{UTS} , with failure occurring near 75% of σ_{UTS} Fig. 3(b). The temperature profiles clearly indicate that higher stress levels result in more significant temperature increments beyond the fatigue onset point.

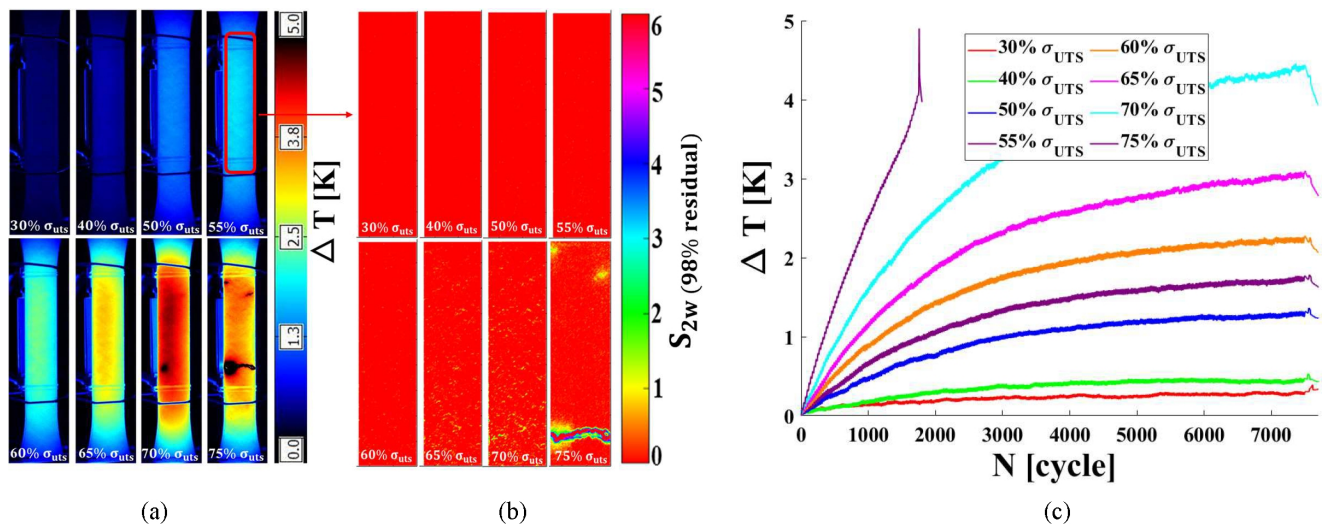


Fig. 3 (a) Stabilized full-field surface temperature profile of a 20 wt.% C/ABS specimen at 20 Hz load frequency with increasing load steps indicated in each sub-figure, (b) Evolution of irreversible damage within gage section using second harmonics approach, and (c) Evolution of maximum surface temperature of the specimen under staircase loading. The specimen was allowed to cool to room temperature after each load step.

Results and Discussion

Comparison of Pure ABS with C/ABS

In this study, the temperature rise observed in pure ABS and C/ABS composites under cyclic loading was compared to understand the contributions of fiber-matrix interactions versus the behavior of the pure matrix. For pure ABS, a significant temperature increase was observed under cyclic loading at both 5 Hz and 20 Hz. Since ABS is a viscoelastic polymer, DMA and differential scanning calorimetry (DSC) were performed to confirm a glass transition temperature of approximately 105 °C. At room temperature (25 °C), the primary source of energy dissipation in pure ABS during fatigue loading arises from internal molecular friction, mechanical damage, and creep effects rather than thermal degradation. At higher frequencies (20 Hz), the molecular chains are forced to respond to the applied load more rapidly, leading to higher levels of internal friction. As a result, energy dissipation increases at 20 Hz, which manifests as a higher temperature rise in pure ABS (see Fig. 4(a)-(b)).

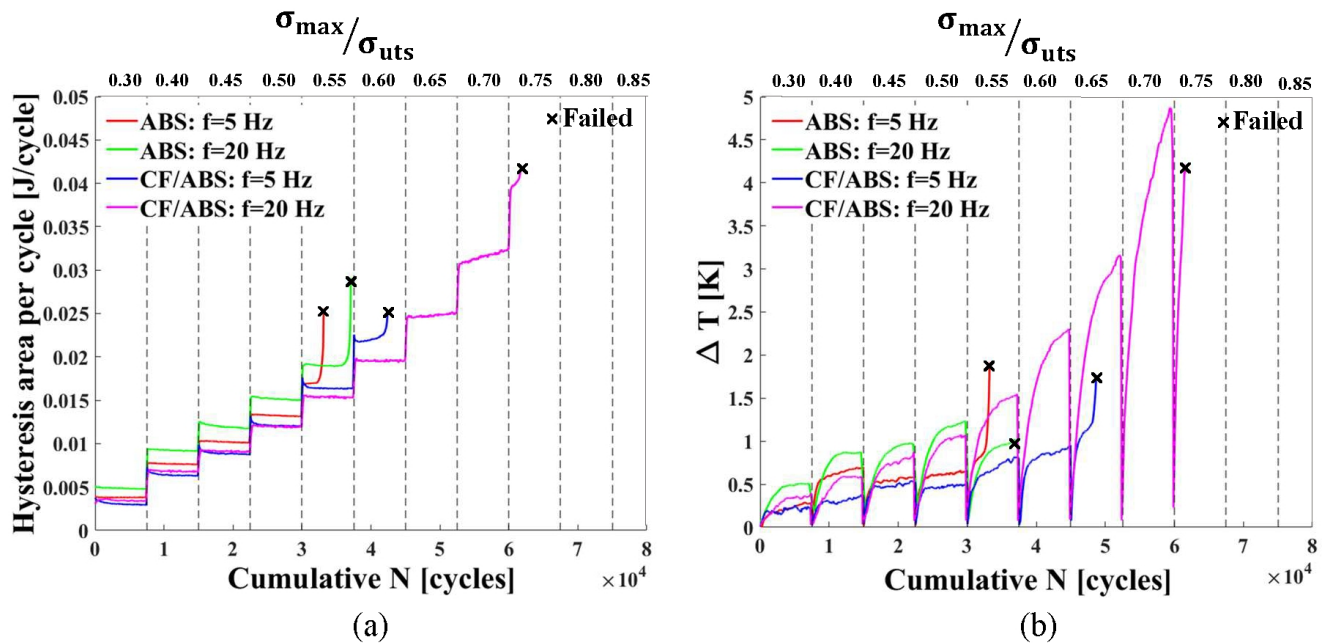


Fig. 4 Comparison of pure ABS and C/ABS composite for two different frequencies of 5 Hz and 20 Hz: (a) hysteresis energy loss per cycle, and (b) typical surface temperature evolution with cycle.

For the C/ABS composite, the fiber-matrix interaction played a significant role in temperature rise, especially at higher frequencies. At 5 Hz, the loading time was long enough for the polymer matrix to deform more significantly, with the carbon fibers restricting the mobility of the polymer chains. This resulted in increased internal friction and greater energy dissipation within the matrix, which contributed to a higher temperature rise. Furthermore, frictional interactions at the fiber-matrix interface added to the energy dissipation, especially at the fiber ends and the unsized fiber caps, which acted as stress concentrators. These micro-slip effects at the interface contributed to localized heating in the composite, resulting in a more pronounced temperature increase than pure ABS once the fatigue onset happened. This suggests that, at low frequencies, the composite's matrix behavior is still crucial in determining energy dissipation, with the fibers acting to restrict the matrix's deformation and enhance internal friction.

At higher frequencies (20 Hz), the fibers in the composite carried a greater portion of the load, reducing the strain on the polymer matrix. As a result, the energy dissipation from polymer chain movement was lower (see Fig. 4(a)), and the temperature rise was less influenced by the polymer matrix's viscoelastic behavior. However, the friction at the fiber-matrix interface became more pronounced due to localized micro-slip and fiber-matrix interactions, leading to additional heat generation. The thermal conductivity of the composite also helped in distributing heat more efficiently at lower stress levels, allowing for better overall heat distribution. Yet, at higher stress levels, fiber-matrix interfaces became active sites for micro-damage, which contributed to localized heating that exceeded the temperature rise observed in pure ABS.

On comparing both pure ABS and C/ABS, in pure ABS, the dominant mechanism of energy dissipation is molecular friction within the polymer matrix. At higher frequencies, the chains cannot fully rearrange and respond, causing more friction and, consequently, more heat. For composites, at lower stress levels, carbon fibers enhance the thermal conductivity of the composite, meaning heat generated from friction and energy dissipation can spread more quickly within the material, allowing for better heat distribution. However, at higher stress levels, fiber ends and fiber-matrix interfaces become active sites for micro-damage and frictional interactions, contributing to localized heating. This results in a temperature increase that can exceed that of pure ABS, as fatigue damage accumulates over cycles (see Fig. 4(b)).

Effect of Loading Frequency on the Fatigue Limit

The influence of loading frequency on the fatigue behavior of the C/ABS composite was investigated by subjecting specimens to interrupted fatigue tests at 5 Hz and 20 Hz. In pure ABS, displacement remained almost constant at both frequencies; however, the hysteresis loss was more significant at 20 Hz, leading to a higher temperature increase (see Fig. 4(a)). In contrast, the C/ABS composite exhibited markedly different displacement behavior. At lower stress levels, the composite experienced higher displacement at 5 Hz due to the longer cycle duration, which allowed the ABS matrix more time to relax. At 20 Hz, the shorter cycle time restricted matrix relaxation, reducing displacement (see Fig. 5(a)).

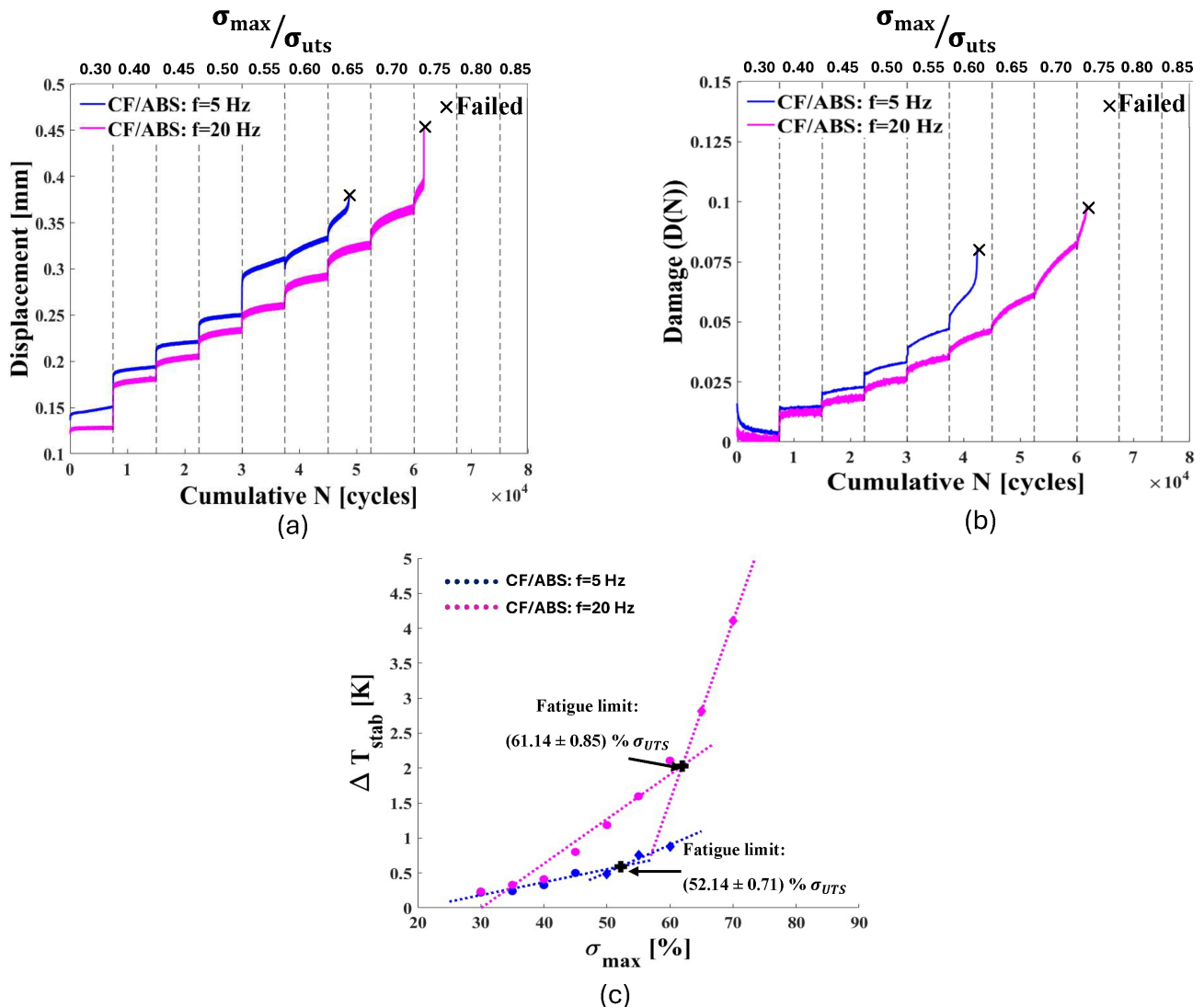


Fig. 5 Comparison of C/ABS composite for two different frequencies of 5 Hz and 20 Hz: (a) displacement for given stress level for given cycles, (b) damage progression, and (c) fatigue limit estimation of given specimens.

As stress levels increased, the displacement at 5 Hz became significantly higher than at 20 Hz. The slower loading cycles at 5 Hz promoted more extensive creep and energy dissipation, leading to higher hysteresis loss and more pronounced damage progression as seen in Fig. 5(b). In contrast, at 20 Hz, the reduced time for thermal buildup resulted in lower displacement and delayed onset of damage. Using a bilinear approach based on the stabilized temperature data, the fatigue limit of the composite was determined to be 52% of its ultimate tensile strength (σ_{UTS}) at 5 Hz and 61% σ_{UTS} at 20 Hz (Fig. 5(c)). These results indicate that the C/ABS composite can withstand more of its σ_{UTS} at increased loading frequencies, likely due to reduced damage accumulation.

Effect of Fiber Orientation on the Fatigue Limit

Fiber orientation relative to the loading direction significantly influences the fatigue performance of the C/ABS composite. All these different fiber-oriented specimens undergo interrupted fatigue loading at 20 Hz frequency with a stress ratio of 0.1. In fatigue tests, 0° specimens experienced longer fatigue lives despite exhibiting higher temperature spikes (see Fig. 6(a)-(b)). The increased temperatures result from concentrated self-heating at the fiber ends, which are stress concentrators. As the orientation of the fiber deviated from 0° with specimens oriented at 30° , 45° , 60° , and 90° , the mechanical response became more dominated by the matrix. Specimens with orientations of 45° , 60° , and 90° not only demonstrated lower σ_{UTS} (comparable to or lower than pure ABS) but also showed earlier failure in fatigue testing (see Table 2).

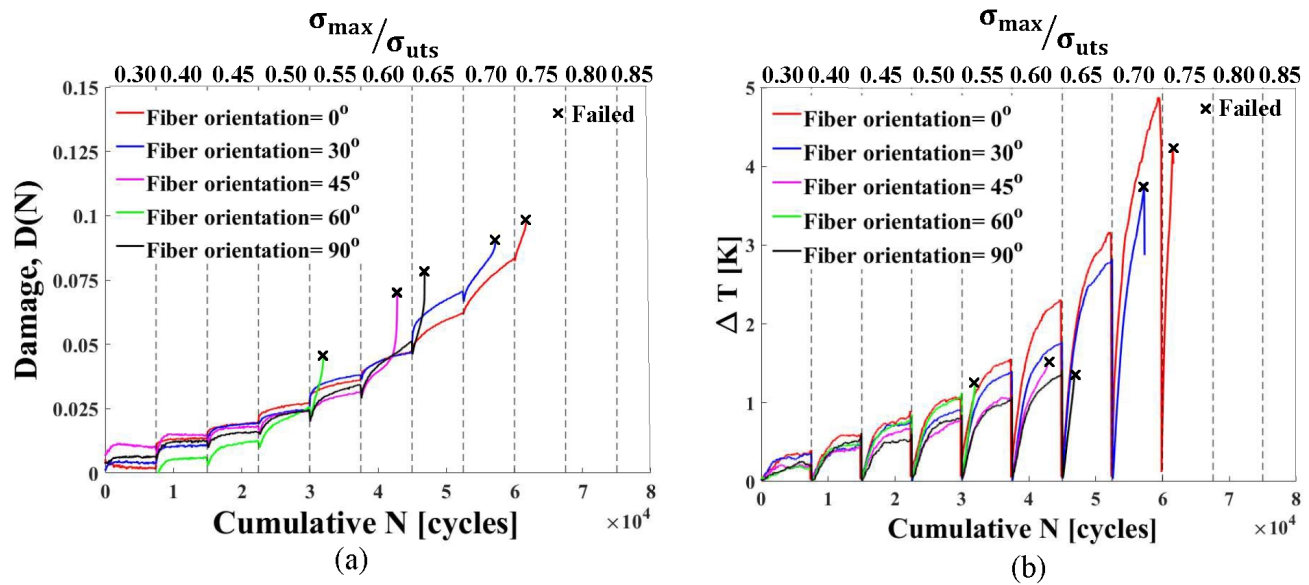


Fig. 6 Comparison of different fiber-oriented C/ABS composite at 20 Hz: (a) damage progression, and (b) typical surface temperature evolution with cycle.

Table 2 Fatigue limit for different configurations.

Specimen	Fatigue limit, [% of σ_{UTS}]
Pure ABS	51.850 ± 0.740
0° fiber orientation	61.950 ± 0.850
30° fiber orientation	56.040 ± 1.080
45° fiber orientation	50.820 ± 0.710
60° fiber orientation	36.180 ± 0.250
90° fiber orientation	38.810 ± 0.780

The damage evolution during cyclic loading was strongly dependent on fiber orientation. The 0° specimens, with fibers oriented along the load direction, exhibited the slowest damage accumulation due to efficient load transfer and effective crack bridging. In contrast, off-axis specimens (e.g., 90°) experienced rapid damage progression, as fibers could not efficiently share the load, leading to increased matrix cracking and fiber-matrix debonding. Temperature profiles further supported

these findings: while 0° specimens displayed the highest temperature rise due to more extensive energy dissipation, this did not compromise their superior fatigue performance. As expected, the lower temperature rise observed in the 90° specimens was linked to a decreased fatigue limit.

Conclusions and Future Work

The study demonstrates that loading frequency significantly influences the fatigue behavior of the C/ABS composite. Increasing the loading frequency enhances the fatigue limit, primarily due to reduced creep effects and diminished hysteresis energy loss per cycle. While the composite exhibits a lower temperature rise than pure ABS at low-stress levels, at higher stress levels, the composite shows a pronounced temperature increase up to an additional 5 K attributed to fiber–matrix interactions and localized heating.

Furthermore, fiber orientation relative to the bead direction strongly affects the mechanical properties. Specimens with off-axis orientations (45°, 60°, and 90°) behave more like the pure ABS matrix, exhibiting lower ultimate tensile strength and higher failure strain, whereas 0° oriented specimens benefit from efficient load transfer and superior fatigue resistance.

Future work will investigate the effect of stress ratio on fatigue behavior and develop an empirical model for fatigue damage accumulation based on the experimental data.

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