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Thermo-mechanical stress-strain behavior of carbon fiber composites using FEM under extreme temperatures

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Abstract. The stress-strain behavior of carbon fiber reinforced polymer matrix composites (CFRPs) is highly influenced by thermal expansion mismatches, particularly due to their anisotropic nature and directional mechanical properties. While prior research has explored thermal and mechanical loading separately, a critical gap remains in understanding their combined effects concerning fiber orientation and load application. This study integrates finite element modeling (FEM) with optimized coefficient of thermal expansion (CTE) selection to improve stress-strain prediction accuracy under coupled thermal-mechanical loading for various fiber orientation. Experimental tensile tests at -53°C, 82°C, and room temperature reveal that improper CTE selection significantly impacts transverse loading, causing premature matrix cracking and interfacial debonding. The proposed FEM framework captures thermally induced residual stresses, improving predictive accuracy and reinforcing the need for thermo-mechanical coupling in aerospace applications to ensure long-term material reliability.

Keywords: carbon fiber reinforced polymer; finite element analysis; meshes and discretization; modeling and simulation; stress-strain under extreme temperatures

1. Introduction

The mechanical properties of composite materials over varying temperature conditions have been extensively investigated owing to their growing utilisation in aerospace, automotive, and structural engineering. Fadlalla et al. highlighted the critical challenges and emerging research directions in composites for aircraft, as the importance of accounting for uncertainties in material properties [1]. The stress-strain behavior of carbon composites under varying temperatures and applied loads is a critically important area of material science. Understanding these behaviors can enhance the predictive capabilities of FEM and inform engineering decisions regarding the applications of such materials in various thermomechanical environments. This text synthesizes findings concerning the stress-strain response of carbon composites, including the effects of temperature, strain rate, fiber orientation, and thermal expansion considerations, particularly in the context of CTE mismatches. The most common types of Fiber Reinforced Plastics (FRP) are Glass Reinforced Plastic (GFRP), Carbon Reinforced Plastic (CFRP), Aramid Reinforced Plastic

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(AFRP), and Basalt Reinforced Plastic (BFRP). These composite materials are favoured for their lightweight, corrosion resistance, low heat conductivity, and non-magnetic properties. Conversely, the primary disadvantage of these composites is their lack of ductility compared to steel. Their behaviour under significant temperature fluctuations is a crucial consideration in its application. Thermal expansion characteristics are a crucial factor in the strength [2].

This research examines carbon fiber-reinforced polymer composites, which have high specific strength, high specific modulus, and low CTE. The CTE is crucial when composite designs encounter significant temperature differences during manufacturing and use. The CTE of a composite material is affected by its constituent materials; therefore, understanding the thermal characteristics of both the fibers and the matrix is essential for comprehending the composite's behaviour [3]. Throughout processing and service life, thermal residual stress (TRS) develops in composites because of differences in thermomechanical properties—such as CTE—between the fibers and the matrix [4, 5]. Shrinkage stress occurs when the polymer hardens during polymerization as it reaches its glass transition temperature. Thermal cooling stress is caused by the difference in CTE between the matrix ($20–100 \times 10^{-6}$/K) and the fibers, such as carbon fibers with a CTE range of -1×10^{-6}/K to 0.5×10^{-6}/K. During cooling, both the matrix and fibers contract, but the matrix's contraction is limited by its bond with the fibers. As a result, the fibers are compressed, while the matrix experiences tensile residual stresses [6]. Yang et al. investigated the novel role of yarn-level fiber hybridisation in tailoring thermomechanical properties and thermal residual stress fields in 3D orthogonal-woven flax/E-glass hybrid composites using a two-scale homogenisation approach. Finite element results revealed that under in-plane tensile loading, matrix-rich regions maintained stress levels below 1 MPa, while binder yarns exhibited stress concentrations up to 8.71 MPa under shear loading. They demonstrated that fiber hybridisation significantly enhances stiffness, thermal stability, and residual stress control from the micro- to meso-scale, offering an effective strategy for optimizing lightweight composite designs [7].

The stress-strain characteristics of carbon composites exhibit significant variability depending on the loading conditions. For instance, the behavior under tensile loading shows that the carbon/epoxy composites maintain relatively linear elastic characteristics before failure at ambient to moderately elevated temperatures [8]. Furthermore, Zhang and Zhou highlighted that while the composite's tensile strength remains fairly linear below 600°C, a substantial reduction in load-bearing capabilities is observed above this temperature due to oxidative effects impacting the composite's integrity [9]. This linear response can also be influenced by the strain rate applied, with Chaurasia et al. documenting a substantial strain rate sensitivity in quasi-isotropic CFRP composites, particularly under dynamic loading conditions [10].

The role of temperature is significant, as evidenced by findings indicating an increase in thermal expansion capacity among carbon composites. Lu et al. noted that differential thermal expansion due to CTE mismatches between fiber and matrix materials can create significant thermoelastic stresses within composite structures [11]. Additionally, during the curing process, thermal shrinkage disparities can induce internal stresses, potentially leading to premature failure even without external loads [12]. This internal stress can become critical during service at elevated temperatures where pre-existing thermal residual stresses exacerbate material degradation, exemplified by research documenting brittle failure modes at elevated load and temperature [13]. The effect of elevated temperatures on RC joints and retrofitted beams with FRP laminates was numerically investigated using finite element analysis and validated through regression analysis. The results confirmed that FRP retrofitting—especially with CFRP—significantly improved structural performance at high temperatures, reducing deflection and increasing principal stress resistance compared to conventional models [14].

Different loading orientations relative to fiber direction—parallel and perpendicular—also influence the stress-strain characteristics of the composite. The mechanical performance in the longitudinal direction often surpasses that of the transverse direction due to the inherent structural anisotropy of these materials [15]. Almeida et al. reported distinct behavior under compressive loading that depends on fiber alignment, highlighting the necessity for accurate modeling of internal stresses to predict failure reliably [16]. Moreover, the directionality of fibers under load must be adequately incorporated into finite element models to capture their nonlinearities, as considerations of shear strains can fundamentally modify performance predictions [17].

Finite element analysis (FEA) has become indispensable for simulating the mechanical behavior of carbon composites under various thermal and strain rate conditions. The accuracy of these simulations relies on adopting advanced material models that reflect the complex behavior of composites, including Hashin's damage models, which effectively simulate progressive material degradation under dynamic loading [18]. It is crucial to integrate detailed micromechanical models that account not only for elastic and viscoplastic behaviors but also for complexities associated with the flow of stress through heterogeneous composite materials [19]. Additionally, numerical models improve understanding of how local thermal strains influence larger-scale phenomena. Hamood et al.'s study emphasized the need for robust modeling techniques to capture the nuances in stress-strain behaviors across different structural scales [20]. A constitutive model and bidirectional thermo-mechanical coupling simulation for CF/PEEK drilling were developed and validated through experimental tests and thermal–mechanical monitoring. High model accuracy with average absolute errors below 6% was achieved, and resin melting phenomena at high spindle speeds were successfully predicted [21].

The research gap in understanding the stress-strain behavior of carbon composites under combined thermal and mechanical loads, particularly in transverse and longitudinal orientations, is characterized by several key deficiencies. Current studies predominantly focus on either thermal or mechanical loading in isolation, leading to a limited understanding of how anisotropic materials respond to simultaneous stresses. Additionally, existing finite element models often neglect the temperature dependence of mechanical properties, which is crucial for accurate predictions. There is also a lack of experimental data that explores the combined effects of these loads, hindering the validation of theoretical models. Furthermore, the interaction between thermal expansion and mechanical loading remains underexplored, particularly regarding how thermal expansion coefficients influence stress distribution and failure mechanisms. Most research has not adopted multi-scale approaches that connect micro-scale interactions between fibers and matrix to macro-scale behavior, and environmental factors affecting the stress-strain response are often overlooked. Addressing these gaps is essential for developing more accurate predictive models and improving the design and performance of composite materials in practical applications, particularly in high-performance sectors like the aerospace and automotive industries. This research focuses on integrating experimental data with advanced modeling techniques to fill these gaps and provide a comprehensive understanding of the material behavior under complex loading conditions.

2. Material and methods

2.1 Experimental methods

CFRP composites will be fabricated in two distinct fiber orientations: 0 degrees (parallel to the

(a) Room temperature (b) Low temperature (c) High temperature

Figure. 1 Test set-up for room, low and high temperature

loading direction) and 90 degrees (perpendicular to the loading direction). Each specimen will be cut to standardized dimensions as specified by ASTM D3039, ensuring uniformity and consistency across all tests. The preparation process will include careful attention to the surface finish and thickness of the specimens to minimize variability in the results. Prior to testing, the specimens will be conditioned in the temperature-controlled chamber to stabilize at the target temperatures, allowing for accurate assessment of their mechanical properties under the specified thermal conditions.

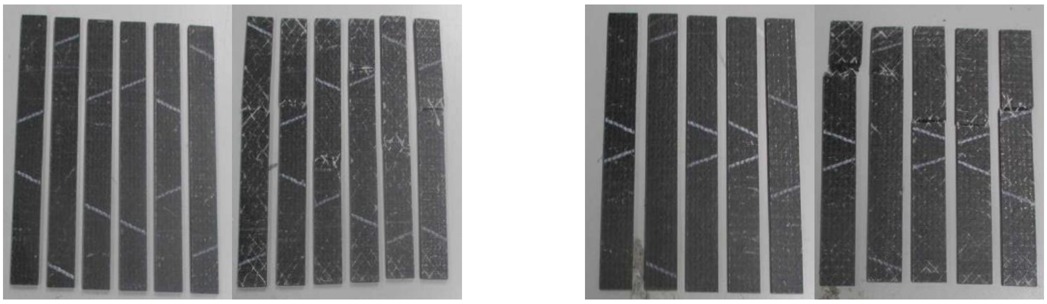
The experimental setup for investigating the stress-strain behavior of carbon composites under combined thermal and mechanical loads involves the use of a Universal Testing Machine (UTM) integrated with a temperature-controlled chamber. This setup is designed to simulate room temperature, both low temperatures (e.g., -53°C) and high temperatures (e.g., 82°C) in accordance with ASTM D3039 standards for tensile testing. The UTM will be equipped with appropriate grips to securely hold the composite specimens during testing, ensuring that the applied loads are accurately transmitted to the material without introducing additional stresses. The temperature-controlled chamber will allow for precise regulation of the testing environment, enabling the specimens to reach the desired temperatures before mechanical loading is applied. This capability is essential for understanding how temperature variations influence the mechanical properties of the composites, particularly in terms of their stress-strain behavior.

During the tensile testing process, the UTM will apply a controlled load to the specimens at a constant rate, while simultaneously monitoring the resulting strain through integrated extensometers or strain gauges. Data acquisition systems will record the load and displacement in real-time, enabling the generation of stress-strain curves for each specimen orientation and temperature condition. The tests will be conducted in a systematic manner, alternating between the two fiber orientations and temperature settings to facilitate direct comparisons of the stress-strain behavior. This comprehensive approach will provide valuable insights into the mechanical performance of carbon composites under combined thermal and mechanical loads, highlighting the differences in behavior between the 0-degree and 90-degree fiber orientations and contributing to a deeper understanding of their material properties in practical applications. The setup of the experimental test is shown in Fig. 1.

After conducting both experimental tensile tests, a detailed post-test analysis of the specimens was performed to examine the fracture characteristics, deformation patterns, and failure mechanisms under different temperature conditions. The observations were categorized based on fiber orientation (0° and 90°) and temperature effects (room, high, and low temperatures). Fig. 2, 3 visually

(a) Low temperature (b) High temperature

Figure 2. Specimens with 0° fiber orientation due to low and high temperature before (left) and after (right) test



(a) Low temperature (b) High temperature

Figure 3. Specimens with 90° fiber orientation due to low and high temperature before (left) and after (right) test

represent the fracture characteristics observed in the 0° and 90° fiber orientation specimens, respectively. These figures illustrate the variations in failure mechanisms across different temperature conditions.

2.2 Computational analysis

CFRPs exhibit unique stress-strain characteristics under varying thermal conditions. [22] Conducted tests on various fiber reinforced polymer composites, revealing that tensile properties can change significantly at elevated temperatures (250 °C and 450 °C), highlighting the influence of thermal conditions on material performance. Such studies illustrate how different strain rates further complicate the mechanical response, emphasizing the necessity for integrated FEM approaches that can simulate varying conditions accurately. Eskandar et al. emphasizes computational optimization of laminate configurations for mechanical performance [23].

The significance of implementing FEM arises from its capacity to model the thermal expansion behaviors of CFRPs under complex load conditions. [24] Performed mesoscale finite element analyses which detailed the thermal displacement and thermal stress distributions within unidirectional carbon/epoxy composites. This research underpins the thermal strain analysis under various loading scenarios, presenting vital insights into the material's behavior and validating FEM methodologies for accurately predicting the stress-strain relationship in CFRPs subjected to extreme temperatures.

Zhang et al. emphasis on precise stress-strain characterization through FEM in both works highlights their complementary roles in advancing composite material research one through improved experimental design for mechanical testing [25]. Gopalan et al. employ finite element modeling techniques to predict stress-strain responses in composite materials; however, this paper emphasizes bio-based reinforcements and static structural analysis rather than extreme temperature effects [26]. Vini et al. give insights into strengthening mechanisms via particle reinforcement and strain-induced microstructure refinement providing foundational knowledge relevant for thermo-mechanical behavior studies in composite materials [27]. Moreover, advancements in strain measurement technologies, as reviewed by Zhou et al. [28], underscore the critical need for in-situ monitoring in high-performance applications of FRP composites. These methods facilitate the real-time assessment of structural deformations, thereby evaluating the reliability of FEM models in predicting mechanical behavior under extreme thermo-mechanical conditions.

It is also essential to consider the effects of thermal cycling, which can lead to fatigue cracking in CFRPs, as noted by Gao et al. [29]. The investigation into fatigue under thermal cycling highlights the complexity when using FEM to simulate the performance of materials that undergo repeated heating and cooling cycles. Such analysis is crucial when designing components that must withstand harsh operational environments, as they provide insight into potential failure modes that need to be mitigated through design and material selection. Additionally, the interaction between curing processes and residual stresses is a pivotal aspect that can lead to significant property reductions in composite materials. This was illustrated by Luo et al., who examined how the curing process generates temperature gradients leading to residual stresses. Understanding these effects is essential for accurate FEM modeling, as incorrect assumptions about the stress states within the composite can lead to poor predictability of performance. FEM utilizes an integrated experimental, finite element, and theoretical methodology to examine the impact of diverse parameters on specimen performance [30].

The thermo-mechanical stress–strain behavior of carbon fiber composites is a key focus in material analysis due to their extensive use in aerospace and other high-temperature environments. In finite element modeling, thermo-mechanical analysis accounts for the coupled effects of temperature variation and mechanical deformation, enabling accurate prediction of composite performance and failure under combined loading. The Coefficient of Thermal Expansion (α(T)) is fundamental for converting temperature changes into thermal strains and stresses arising from restricted expansion. For anisotropic composite shells, each ply's directional CTE (α_1–α_2) is defined in its local coordinate system and transformed into the global frame according to ply orientation (θ). Using Classical Lamination Theory, the solver integrates these transformed values through the laminate thickness to compute in-plane thermal forces and bending moments due to temperature gradients. This approach enables accurate prediction of thermal stresses, distortion, and residual strains resulting from mismatched thermal expansion between fiber and matrix or between adjacent plies.

The relationship between temperature change and thermal strain is defined by the coefficient of thermal expansion (CTE). The CTE is expressed as Eq. (1)

$$\alpha = \frac{1}{L_0}\frac{dL}{dT} = \frac{d\varepsilon}{dT} \tag{1}$$

where α is the linear coefficient of thermal expansion $[1/℃]$, L_0 is the original length $[mm]$, L is the instantaneous length at temperature T, and $\varepsilon = \Delta L/L_0$ is the linear thermal strain [31]. In practice, experimental and numerical data are discrete rather than continuous, so Eq. (1) is

Table 1. Material properties of CFRP

Parameter	Room Temperature (20°C)
Elastic Modulus (Longitudinal), E1, [MPa]	26059.31
Elastic Modulus (Transverse), E2 [MPa]	2251.27
Poisson Ratio, v12	0.30
Shear Modulus, G12 [MPa]	10022.81
Shear Modulus, G13 [MPa]	10022.81
Shear Modulus, G23 [MPa]	865.87

approximated as Eq. (2).

$$\alpha = \frac{\varepsilon(T_2) - \varepsilon(T_1)}{T_2 - T_1} \tag{2}$$

where $\varepsilon(T_1)$ and $\varepsilon(T_2)$ are the total measured strains at temperatures T_1 and T_2, respectively. Eq. (2) represents the slope of the strain–temperature curve and forms the basis for determining α from experimental or FEM results. Thermal expansion in fiber-reinforced composites is anisotropic, and distinct coefficients are established along the main axes of the material, as shown in Eq. (3).

$$\alpha_{11} = \frac{d\varepsilon_{11}}{dT}, \alpha_{22} = \frac{d\varepsilon_{22}}{dT} \tag{3}$$

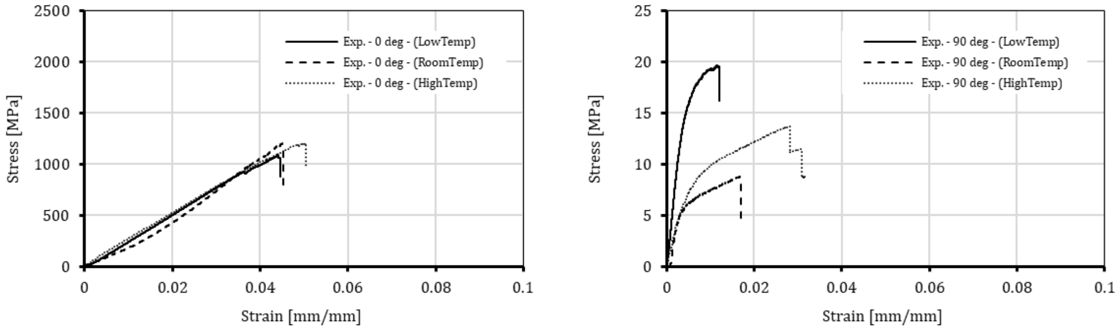
where α_{11} is the longitudinal (fiber-direction) CTE, and α_{22} is the transverse CTE.

FEM was conducted using ABAQUS to simulate the experimental tensile tests and assess the thermo-mechanical behavior of CFRP specimens at three distinct temperatures: low (-53 °C), ambient (20 °C), and elevated (82 °C). The specimens' geometry was modeled based on the experimental dimensions: the overall length for the 0° orientation was 253 mm, with a gage length of 137.41 mm, and a width of 11.12 mm; the overall length for the 90° orientation was 177.80 mm, with a gage length of 96.01 mm, and a width of 24.09 mm. Shell elements were used in the development of all models. Temperature-dependent elastic constants, yield strength, plastic strain curves, and coefficients of thermal expansion were all directly derived from the experimental data, defining the material properties as orthotropic (Table 1, 2). Through performing it, the simulation was guaranteed to take into consideration both progressive plasticity and thermal effects at various temperatures. Then, boundary conditions followed the experimental test setup: one end of the specimen was fully constrained. In contrast, the opposite end was subjected to a displacement-controlled uniaxial load applied until fracture. The model was thermally conditioned before loading by keeping the specimens at the desired temperature for 120 seconds. Temperature-dependent strain fields were activated in the material model to implement thermo-mechanical behavior.

Considering both orientations, a mesh convergence study was carried out in order to ensure numerical accuracy. For the 0° specimen, element counts ranged from 102 to 762, while for the 90° specimen, 78 to 264 elements were tested. According to the results, the maximum stress and strain error stabilized below 3% for both orientations at the final mesh sizes as element density increased. Meshes of 762 elements (0° orientation) and 264 elements (90° orientation) were

Table 2. Coefficient of Thermal Expansion parameter of CFRP

Parameter	Temperature (Ref.: 20°C)	
	Low Temperature (-53°C)	High Temperature (82°C)
Coef. of Thermal Expansion (Longitudinal), α11	1.354E-06	3.670E-06
Coef. of Thermal Expansion (Transverse), α22	6.494E-06	7.913E-06



(a) Fiber 0° (b) Fiber 90°

Figure. 4 Experiment test result fiber orientation at different temperatures

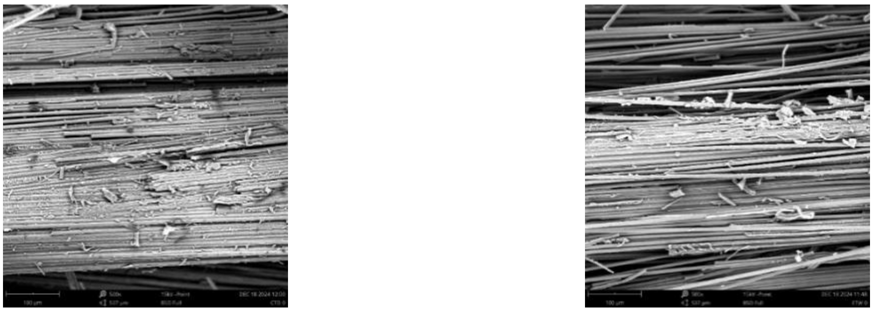
chosen for further simulations based on this analysis, which offered a compromise between predicted accuracy and computational efficiency. Fracture behavior was simulated using a displacement-to-failure evolution approach, with a stress triaxiality factor of 0.33 applied following Hillerborg's method (1976). This enhanced the ability of the FEM model to capture brittle fracture modes at cryogenic conditions as well as matrix softening at elevated temperatures. Overall, the developed FEM framework reproduced the experimental stress–strain responses with high fidelity, validating its use for predicting the thermo-mechanical performance of CFRPs under extreme environments.

3. Results and discussion

The investigation of CFRPs under extreme thermal conditions, as shown in Fig. 4, integrates experimental tensile testing and FEM to assess temperature-dependent mechanical performance. Scanning Electron Microscopy (SEM) identified interfacial debonding and crack propagation, emphasizing thermal expansion mismatches. FEM validation enhances predictive accuracy, improving material design for aerospace and cryogenic applications.

This study provides a comprehensive evaluation of CFRP thermo-mechanical behavior, emphasizing fiber-dominated (0°) and matrix-dominated (90°) failure mechanisms under varying temperatures. Stiffness remains stable in 0° loading, while temperature-sensitive failure mechanisms dominate in 90° orientation. The SEM analysis, as shown in Fig. 5, reveals that 82°C induces matrix softening, leading to fiber pull-out and interfacial debonding, whereas -53°C causes matrix embrittlement, crack initiation, and rapid propagation, highlighting the critical role of thermal expansion mismatches in aerospace and automotive composite applications.

The 90°-oriented composites exhibit strong dependence on matrix behavior under transverse stress. At low temperatures (−53 °C), the matrix becomes brittle and unable to accommodate



(a) Fiber 0° at -53°C (b) Fiber 0° at 82°C

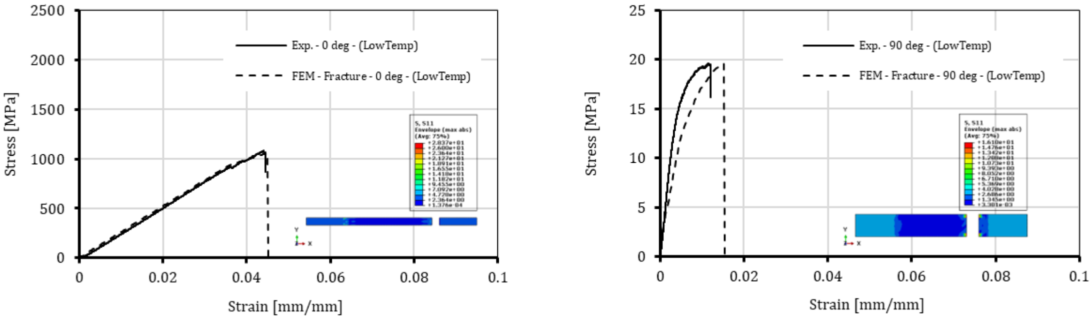
(c) Fiber 90° at -53°C (d) Fiber 90° at 82°C

Figure. 5 SEM analysis for different fiber directions and temperature

shear, leading to fiber–matrix debonding, cracking, and delamination. Conversely, at elevated temperatures (82 °C), matrix softening promotes fiber slippage and separation, reducing load transfer and interlaminar strength. Unlike 0° laminates dominated by fiber strength, the 90° configuration relies heavily on matrix integrity, making it sensitive to thermal effects. Enhancing performance across wide temperature ranges requires matrix toughening, improved fiber–matrix adhesion, and hybrid reinforcement to limit brittleness or softening. Temperature-resistant resin systems and optimized fiber architectures are thus essential for ensuring mechanical stability and durability in aerospace, cryogenic, and high-temperature composite applications.

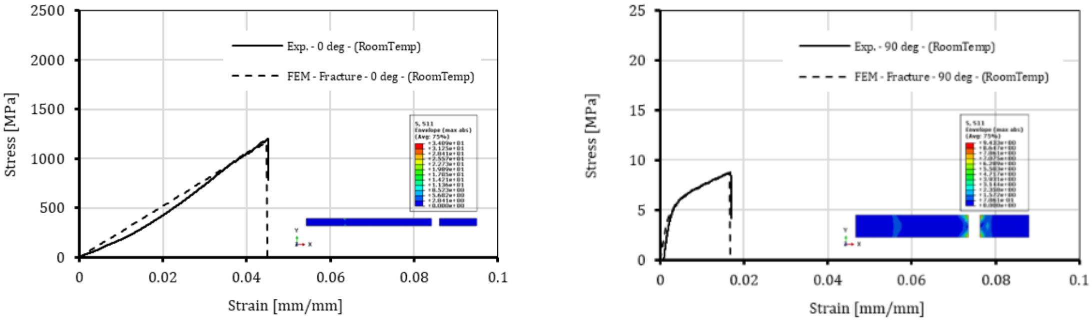
The FEM predictions with room temperature input for the stress-strain behaviour of CFRPs under tensile loading parallel to the fiber direction demonstrate a strong correlation with experimental results across all tested temperature conditions and shown by Fig. 6. At room temperature, the FEM model effectively reproduces the linear elastic stiffness and provides close estimates of tensile strength and fracture response. Minor deviations in the nonlinear region indicate incomplete representation of matrix yielding, damage progression, and interface debonding. The sharp post-peak stress decline reflects brittle fiber failure, suggesting that incorporating advanced progressive damage and energy dissipation models could improve the accuracy of nonlinear behavior predictions.

At −53 °C, the FEM model shows strong consistency with experimental results, particularly in the elastic region, where similar slopes confirm accurate stiffness representation. The close match in peak stress and failure strain demonstrates the model’s capability to reproduce ultimate strength and brittle fracture under cryogenic conditions. The sharp post-peak stress drop is also well captured, reflecting correct implementation of fracture mechanics. However, microscale mechanisms such as matrix cracking, interfacial debonding, and thermally induced stresses are only partially



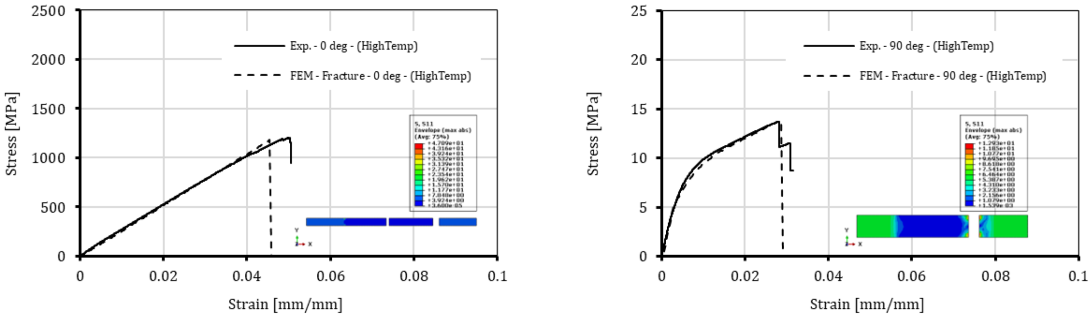
(a) Fiber 0° at low temp.

(d) Fiber 90° at low temp.



(b) Fiber 0° at room temp.

(e) Fiber 90° at room temp.



(c) Fiber 0° at high temp.

(f) Fiber 90° at high temp.

Figure. 6 Comparison of FEM and experiment result at various fiber and temperature

represented, indicating the need for temperature-dependent parameters for matrix toughness and interfacial bonding. At 82 °C, the FEM model maintains good agreement in the elastic region but diverges before failure, mainly due to unmodeled matrix softening and fiber–matrix interactions. The simulated fracture appears more abrupt than the experimental one, suggesting limited capture of progressive damage and plastic deformation, emphasizing the necessity for improved temperature-sensitive modeling of creep, plasticity, and crack growth behavior.

The comparison between FEM predictions and experimental results for CFRPs under perpendicular loading (90° orientation) highlights key trends and discrepancies across different temperatures, also shown by Fig. 6. At −53 °C, the FEM model effectively reproduces the linear elastic response but deviates in the nonlinear range before fracture, underestimating stress near failure. This indicates that low-temperature effects such as matrix embrittlement, cracking, and fiber–matrix interfacial stress are not fully captured. The experimental strain-to-failure is slightly higher, showing that real materials experience more gradual damage accumulation, while the FEM predicts a sharper, brittle failure. Both experimental and simulated stress drops confirm a brittle fracture mechanism typical of cryogenic conditions. At room temperature, the FEM model accurately represents stiffness and ultimate strength, but underpredicts nonlinear behavior and strain-to-failure, suggesting incomplete modeling of matrix yielding, shear failure, and interfacial debonding. The sharper simulated fracture compared to experiment implies a more idealized damage assumption. At 82 °C, the FEM maintains good stiffness and peak stress prediction; however, discrepancies arise post-peak as experimental results show gradual softening, while the FEM produces a brittle response. This difference stems from insufficient modeling of matrix softening, ductility, and fiber–matrix weakening at elevated temperatures. Incorporating temperature-dependent plasticity, cohesive zone interactions, and progressive failure mechanisms would enhance FEM accuracy for predicting thermo-mechanical behavior and failure evolution of CFRP composites across extreme temperature conditions.

5. Conclusions

This study offers a significant advancement in the computational design of CFRPs by bridging experimental insight and FEM-based simulation to understand temperature-induced failure mechanisms, paving the way for more robust and reliable composite structures in extreme environments.

- The research effectively combines finite element modeling with experimental results to validate thermo-mechanical behavior, showcasing a reliable pathway for multiphysics integration in composite design under varied temperature conditions.
- The validated FEM framework enables engineers to select temperature-resistant resin systems and optimize laminate stacking sequences for specific service environments.
- The study’s emphasis on temperature-dependent failure mechanisms, such us brittle fracture at low temperatures and matrix creep at high temperatures and provides actionable insight for developing more accurate, condition-specific constitutive models in advanced composite simulations.
- By identifying FEM limitations in predicting post-peak behavior and viscoelastic effects, the research contributes to the refinement of nonlinear deformation and damage accumulation models crucial for high-fidelity simulations.
- Accurate FEM outcomes are shown to be highly sensitive to thermal property definitions, especially the coefficient of thermal expansion, fiber orientation, reinforcing the importance of precision in material calibration for thermal-mechanical coupling.
- The inability to capture post-peak softening, viscoelasticity, and creep at high temperatures reveals a significant gap in current simulation capabilities, urging the integration of advanced polymer matrix models.
- The study exemplifies a successful iterative loop between simulation and validation, supporting the Advances in Computational Design vision for synergistic, data-informed modeling to guide material innovation and structural optimization.
- By predicting stiffness retention and failure modes at cryogenic and elevated temperatures,

the results can support establishing inspection intervals and service-life predictions in aerospace and automotive components.

- The FEM methodology can be embedded into multiphysics design tools to reduce the need for excessive physical prototyping, thus saving cost and development time.

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