Tomas Bata University in Zlín
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Doctoral Thesis Summary

Prestressed Fibre Reinforced Composites: Manufacturing and Mechanical Characterisation

Předpjaté kompozity vyztužené vlákny: Výroba a mechanická charakterizace

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ABSTRAKT

Kompozity na bázi polymerů vyztužených vlákny (FRP) jsou díky svým vynikajícím mechanickým vlastnostem a nízké hmotnosti dlouhodobě využívány v řadě inženýrských aplikací. Jejich mechanická výkonnost však může být snížena zejména v důsledku problémů při zpracování, které vedou ke zvlnění vláken a vzniku vnitřních zbytkových napětí, což může vést k selhání materiálu. Z tohoto důvodu se výzkum zaměřený na minimalizaci těchto problémů, zejména zbytkových napětí vznikajících při výrobním procesu, stal mimořádně důležitým. Jedním ze slibných přístupů je předpínání vláken, tedy aplikace řízeného zatížení na výztužná vlákna před nebo během vytvrzovacího cyklu kompozitu. Tato technika si klade za cíl indukovat tlaková napětí do materiálu, čímž se kompenzují tahová zbytková napětí a snižuje se zvlnění vláken. Jedná se o nákladově efektivní způsob, jak zlepšit mechanické vlastnosti kompozitních struktur, aniž by bylo nutné zvyšovat hmotnost nebo rozměry materiálu.

Tato studie představuje systematické zkoumání vlivu elastického předpínání vláken na vlastnosti laminátů z uhlíkových vláken vyztužených polymerem (CFRP). Byly testovány dvě konfigurace jednosměrná a křížová přičemž každá byla vyrobena při šesti úrovních předpětí v rozsahu 0 až 25 MPa pomocí speciálně navržené mechanické přípravky. Lamináty byly podrobeny komplexní charakterizaci zahrnující tahové, ohybové a rázové Charpyho zkoušky; dynamickou mechanickou analýzu (DMA); a měření elektrické vodivosti za stejnosměrného (DC) i střídavého (AC) proudu. Fraktografická analýza byla provedena za účelem identifikace převládajících mechanismů porušení ve vzorcích.

Výsledky ukázaly, že elastické předpínání vláken významně zlepšilo mechanické vlastnosti CFRP kompozitů. U jednosměrných laminátů došlo při předpětí 25 MPa ke zvýšení tahového modulu o 32,8 % a pevnosti v tahu o 67,3 %, zatímco ohybová pevnost a rázová odolnost se zlepšily o 34,4 %, resp. 55,7 %. Křížové lamináty vykazovaly mírnější, ale konzistentní zlepšení mechanických vlastností, přičemž maximální nárůst pevnosti v tahu dosáhl 52,1 % a rázová houževnatost vzrostla o 79,8 %. Termická analýza odhalila zvýšený skladovací modul a vyšší teploty skelného přechodu (Tg) u obou konfigurací, což naznačuje lepší vazbu mezi vláknem a matricí. Měření elektrické vodivosti dále prokázalo, že podélná DC a AC vodivost jednosměrného laminátu se s rostoucím předpětím výrazně zlepšila (až o +1500 %). Naopak příčná vodivost mírně poklesla v důsledku sníženého kontaktu mezi svazky vláken. U křížových laminátů byla zaznamenána maximální zlepšení vodivosti při středních úrovních předpětí (5-10 MPa), po jejichž překročení vodivost klesala, pravděpodobně v důsledku redistribuce mezivrstvového napětí.

Obecně lze konstatovat, že elastické předpínání vláken účinně zlepšuje výkonnost CFRP laminátů, přičemž optimálních výsledků je dosaženo při předpětí 15–20 MPa.

ABSTRACT

Fibre-reinforced polymer composites (FRPs) have continuously been utilised for many engineering applications due to their outstanding mechanical properties and lightweight. However, a decrease in their mechanical performance, primarily due to processing challenges resulting in waviness and induced internal residual stresses, may result in failure. Therefore, research to mitigate processing challenges, particularly process-induced residual stresses in composite materials, has become increasingly vital. One promising approach involves fibre prestressing, which involves the application of a controlled load to the fibre before or throughout the curing cycle of the composite. The technique aims to induce compressive strength to the material. This counteracts the tensile residual stresses and reduces fibre waviness, thus offering a cost-effective approach to improving the mechanical properties of composite structures without necessarily increasing the mass or dimension of the material.

This study presents a systematic examination of the effect of elastic fibre prestressing on the performance of carbon fibre reinforced polymer (CFRP) laminates. A unidirectional and cross-ply laminate configuration was investigated, with each fabricated under six prestressing levels, ranging from 0 to 25 MPa, by utilising a custom-designed mechanical jig. The laminates were subjected to a comprehensive characterisation technique that includes tensile, flexural, and charpy impact testing; dynamic mechanical analysis (DMA); and electrical conductivity measurements under both direct current (DC) and alternating current (AC) regimes. Fractographic evaluation was also conducted to identify dominant failure modes across the mechanical test samples.

The result revealed that elastic Fibre prestressing significantly enhanced the mechanical properties of the CFRP composites. In the unidirectional laminates, tensile modulus and strength increased by 32.8% and 67.3% respectively, at 25 MPa prestress, while flexural strength and impact resistance improved up to 34.4% and 55.7%, respectively. Cross-ply laminates exhibited moderate but consistent improvements in mechanical performance, with peak tensile strength gains of 52.1% and impact toughness increases of 79.8%. Thermal analysis revealed improved storage modulus and elevated glass transition temperatures (Tg) in both configurations, indicating improved fibre-matrix interfacial bonding. Electrical conductivity testing further demonstrated that longitudinal DC and AC conductivities of the unidirectional laminate improved dramatically with increasing prestress (up to +1500%).

In contrast, transverse conductivity declined slightly due to reduced inter-bundle contact. The cross-ply laminates exhibited peak electrical improvements at moderate prestress levels (5-10 MPa), after which conductivity degraded, likely due to interlaminar stress redistribution. Generally, elastic Fibre prestressing effectively enhances CFRP performance, with 15-20 MPa yielding optimal results.

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1. INTRODUCTION

1.1 Background of the Study

In recent decades, there has been a significant increase in the demand for fibre-reinforced polymer composites (FRPs), particularly in engineering applications that necessitate a high strength-to-weight ratio [1, 2]. These composites are progressively substituting traditional metals and alloys. FRPs provide excellent fatigue and corrosion resistance, design flexibility, and good performance at high temperatures in addition to their mechanical strength and lightweight nature. Because of these characteristics, they are highly adaptable and crucial in a variety of sectors, supporting infrastructural development, technological innovation, and sustainable production [3].

Despite their many advantages, FRPs also have certain limitations. The main disadvantage is that FRPs are susceptible to shear failure in laminated composites under certain loading conditions due to their low out-of-plane properties and high in-plane strength and stiffness [4]. In addition, manufacturing and processing challenges can significantly affect their mechanical properties. The impact of manufacturing and processing challenges on the mechanical characteristics of the composite is another crucial factor to take into account [5]. For example, the material's strength and performance may be hindered by high void fraction, fibre waviness and residual stresses induced through fabrication, curing, cooling, or variations in thermal expansion throughout the manufacturing process [6–8].

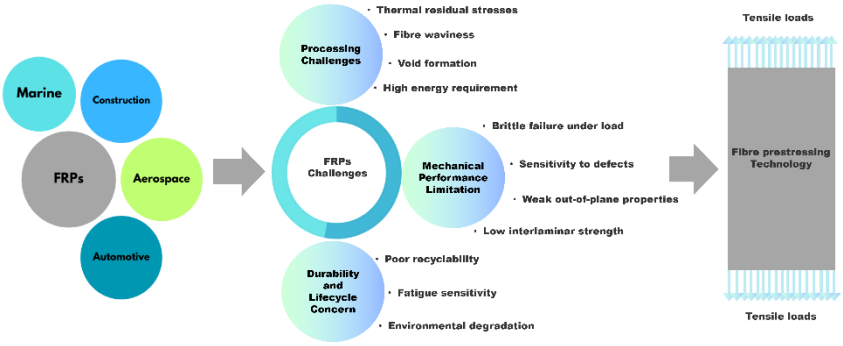

Fig. 1.1: Schematic representation of the application, challenges and fibre prestressing technology of FRP composite

One approach to reduce the effect of processing challenges, particularly residual stresses, is by mechanical fibre prestressing [9]. This technique offers a viable and low-cost alternative without necessarily increasing the mass or geometry of the

intended composite structure. It involves the application of tensile force to a reinforced fibre before or during the composite manufacturing process [10].

1.2 FRP Processing Approaches and Comparative Techniques

The process of manufacturing an FRP composite generally involves two important phases, namely, the preform phase, where fibres and polymers are arranged in a desirable configuration, such as prepreg, or in-situ combination, and also the processing phase, which involves the consolidation of the composite by utilising pressure and temperature [11]. The final properties of the composite material depend not only on the material used but also on other factors such as fibre configuration, volume fraction and specific processing technique [12]. Autoclave processing is considered the first choice, especially for advanced composite fabrication for aerospace applications [13]. This process is built on three major operating parameters, which include vacuum pressure for degassing, autoclave temperature to initiate curing and consolidate the isothermal phase, and autoclave pressure to minimise gas buildup. The application of these processing parameters results in a high-quality composite with low void content. High cost and long cycle time are the significant limitations of this technique. Other alternative processing technique includes hand layup and vacuum bagging; resin transfer moulding, vacuum-assisted resin infusion; pultrusion; compression moulding and hot pressing; out-of-autoclave technique serves different design, cost and performance requirements as explained in Table 1.1[14]

Table 1.1: Comparative summary of the FRP Processing Technique

Processing Method	Pressure Level	Void Content	Part Complexity	Cost	Typical Applications
Autoclave Processing	High (0.5-0.7 MPa)	<1%	High	High	Aerospace, military, high-end automotive
Hand Layup + Vacuum Bagging	Low (~0.1 MPa)	3-5%	Medium	Low	Marine, construction, sports
RTM	Moderate (~0.3 MPa)	1-3%	High	Moderate	Automotive, wind energy, rail
VARI	Low (vacuum only)	2-4%	High	Low-Moderate	Marine, wind turbine blades
Pultrusion	Moderate	<2%	Fixed profiles	Low	Structural beams, utility poles

Compression Moulding	High	<2%	Simple shapes	Moderate	Panels, brackets, and thermoplastic parts
Out-of-Autoclave (OOA)	Low	~1-3%	Medium	Moderate	Secondary aerospace structures

1.3 Fibre-reinforced Polymer Composite Processing Challenges

FRP composites exhibit critical challenges during processing, which can impact their performance and structural integrity. Void formation, fibre waviness and thermal residual stresses are commonly associated with processing challenges.

1.3.1 Void Formation

Voids are microscopic air pockets that are trapped in a polymer matrix during manufacturing. Their presence can disrupt the fibre-matrix interface, thereby reducing the load-bearing capacity and thermal properties of the material [15]. Voids are formed as a result of air entrapment during curing. Other factors, such as incomplete wetting of the resin, thermal outgassing or high resin viscosity, can result in void formation. Depending on their size and location, voids can be classified as microscopic, macroscopic and mesoscopic. Although their presence cannot be avoided, choosing the proper processing technique (Table 1.1) might reduce void content in the composite [16, 17].

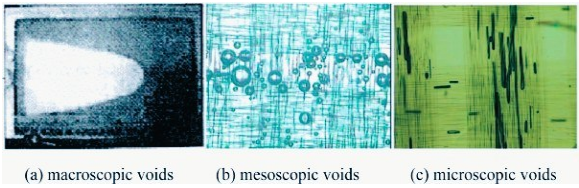

Fig. 1.2: Classification of voids

1.3.2 Fibre Waviness

Fibre waviness is the misalignment of fibre from its original or intended position [18]. This defect can be due to the force of resin flow, preform deformation or mishandling of the fibre. The manifestation of fibre waviness results in the degradation of compressive strength as a result of the introduction of geometric imperfection that may lead to early failure through fibre buckling and delamination. In FRP laminates, fibre waviness may result from in-plane shear during draping, interaction of the two parts or pressure-induced displacement during resin infusion [19]. The presence of waviness in composite structures can be predicted through simulation or modelling techniques such as Darcy's law. They can be controlled

through fibre prestressing, an automated layup system, design optimisation of the preform or by carefully controlling the resin flow [20].

1.3.2 Thermal Residual Stresses

Thermal stresses occur due to a mismatch in thermal expansion between the fibre and polymer matrix during heating and cooling phases [21]. The expansion and contraction of the composite generate internal stresses (tensile stresses in the matrix while compressive stresses are generated in the fibre). This may lead to matrix microcracking, delamination, warpage and debonding of the fibre from the matrix. This defect may compromise structural integrity, particularly in laminated composite materials where the matrix is exposed to moisture that rapidly causes failure. Minimising thermal mismatches and other forms of residual stresses is very important to improve the integrity of composite materials.

1.4 Fibre Prestressing in FRP Composites

Fibre prestressing is a mechanical technique that can be employed to improve the mechanical performance of FRP composites by reducing the effects of process-induced residual stresses, fibre waviness, and other processing challenges [22]. The technique involves the application of controlled tensile force to the fibre before or during curing. Upon curing and cooling, the prestressed fibre contracts and during stress relaxation, beneficial compressive stresses are induced into the polymer matrix [23]. The approach offers a cost-effective alternative for improving composite performance without adding mass or other functional material.

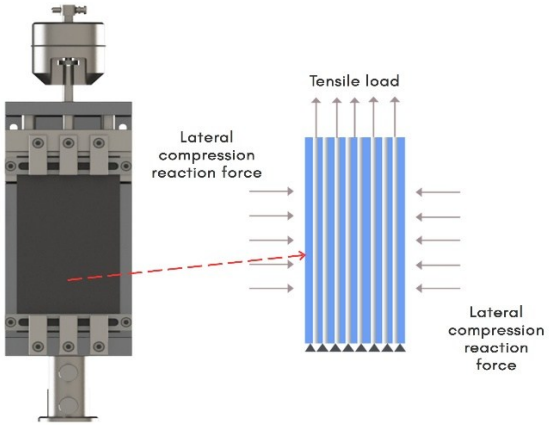

Fig. 1.3: Schematic representation of elastic fibre prestressing of a composite laminate

Implementation of fibre prestressing can be achieved through two distinct strategies: Elastic and viscoelastic prestressing (comparison between EPPMC and VPPMC is shown in Table 1.2).

Table 1.2: Comparison between EPPMC and VPPMC

Feature	EPPMC (Elastically Prestressed)	VPPMC (Viscoelastically Prestressed)
Prestressing Mechanism	Load applied after embedding fibres in an uncured matrix	Load applied to unbound fibres before moulding
Fibre Behaviour	Elastic deformation	Creep (elongation) under sustained load
Load Application Timing	During the curing process	Before the curing stage
Material State During Prestressing	Uncured polymer matrix	Unbound state (not yet in the matrix)
Complexity	Simpler (single loading/unloading cycle)	More complex (separate load steps)
Residual Stress Focus	Counteract tensile residual stresses	Counteract tensile residual stresses

1.4.1 Elastically Prestressed Polymer Matrix Composite (EPPMC)

An EPPMC or elastic fibre prestressed composite can be achieved by applying a tensile load within the elastic limit of the fibre while embedded in a resin (uncured matrix) [24]. After cooling and solidification of the matrix, the load is released while the fibre undergoes stress relaxation, thus inducing compressive stresses into the polymer matrix. The use of flatbed deadweight (Fig. 1.4) offers a cost-effective strategy for achieving elastic fibre prestressing. However, uneven fibre prestressing or premature failure of the fibre due to excessive load impacted by the deadweight might limit its efficiency. Also, filament winding provides a continuous automated solution, especially for long fibre rovings impregnated with resin [25]. Although the technology is expensive, it might be challenging to achieve a constant resin volume fraction.

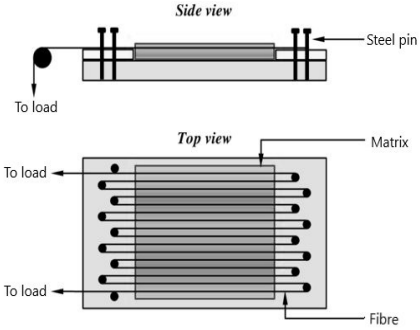

Fig. 1.4: Schematic representation of a flatbed deadweight

1.4.1 Viscoelastically Prestressed Polymer Matrix Composite (EPPMC)

VPPMCs rely on the creep and recovery behaviour of viscoelastic fibres [26]. In these materials, the fibres are first tensioned and held under a sustained load to induce creep. Afterwards, they are released and then carefully incorporated into the matrix, where they gradually recover. This recovery process induces long-term compressive stress. One significant advantage of this approach over EPPMC is that it separates the steps of prestressing and moulding, which provides greater flexibility in how fibres can be arranged. Additionally, it allows for compatibility with a broader range of materials, enhancing its adaptability.

For VPPMC to work effectively, fibres need to act like "energy banks." They must store and gradually release mechanical energy over time. Essential characteristics include the fibre's ability to exhibit enough creep when bearing a load, and to exhibit elastic recovery, while maintaining minimal permanent deformation. Annealing fibres prior to prestressing helps remove manufacturing stresses, especially in synthetic options like Nylon 6,6.

Fibre prestressing, whether it is elastic or viscoelastic, offers a compelling way to boost the mechanical strength of FRP composites and manage their residual stresses. This technique allows for cost-effective and lightweight solutions, which are perfect for cutting-edge structural applications. By continually refining our materials and processing methods, the full potential of this approach can be unlocked.

2. AIM AND METHODOLOGY OF THE WORK

The aim of this work is to study the influence of elastic fibre prestressing on the mechanical properties of carbon fibre reinforced polymer laminate. Further studies were also conducted on the influence of prestressing on the thermal and electrical performance of CFRP laminate.

A unidirectional carbon fibre prepreg, containing 38% resin and measuring 0.3 mm thick, was used to fabricate two laminate configurations: unidirectional ($[0°]_8$) and cross-ply ($[0°/90°]_{2s}$). Each laminate possesses an average thickness of 2.4 mm and has a fibre volume fraction of 62%. A custom prestressing jig was used to apply uniaxial tensile loads to the fibres both before and during curing.

Prestress levels, ranging from 0 to 25 MPa, were applied using a tensile testing machine, ensuring they stayed below the carbon fibre's tensile strength of 4100 MPa. The necessary force for each prestress level was calculated based on the laminate dimensions and fibre volume. The prepreg layers were stacked, the two ends were pre-cured to improve grip, and the prepreg was mounted into the jig. Then the laminate was prestressed, secured in a vacuum bag, and oven-cured at 140°C for 90 minutes, followed by a 24-hour controlled cooling period.

Mechanical tests included tensile testing (ISO 527-5), flexural testing (ISO 14125), and Charpy impact testing (ISO 179-2), all using Zwick Roell machines. DMA was conducted in 3-point bending mode from 25°C to 200°C to examine viscoelastic properties. Electrical conductivity, both DC and AC, was measured under controlled thermal conditions using a Keithley electrometer and a Hioki LCR meter, respectively. To ensure stable electrical contact, conductive silver paste and copper electrodes were utilised. A TGA/DTA analysis of a glass-fibre epoxy reference laminate was also conducted to verify the matrix's thermal stability.

Overall, these procedures provided a systematic and controlled approach to evaluating the effects of fibre prestressing on CFRP laminate performance.

3. RESULTS AND DISCUSSION

This tensile analysis explored how elastic fibre prestressing affects both unidirectional and cross-ply CFRP laminates at six different prestress levels, ranging from 0 to 25 MPa.

In unidirectional laminates, it was observed that the tensile strength increased significantly, rising from 942.3 MPa in the control samples to 1576.9 MPa at 25 MPa prestress. This represents a remarkable 67% improvement. The tensile modulus also showed an increase, going from 100.6 GPa to 133.6 GPa, indicating a 33% enhancement. Such improvements were nearly linear up to a prestress of 15 MPa (Fig. 3.1), beyond which the gains tended to plateau. While strain-to-failure remained relatively consistent across all samples, higher prestress levels slightly enhanced ductility and delayed failure, suggesting improved toughness and increased energy absorption.

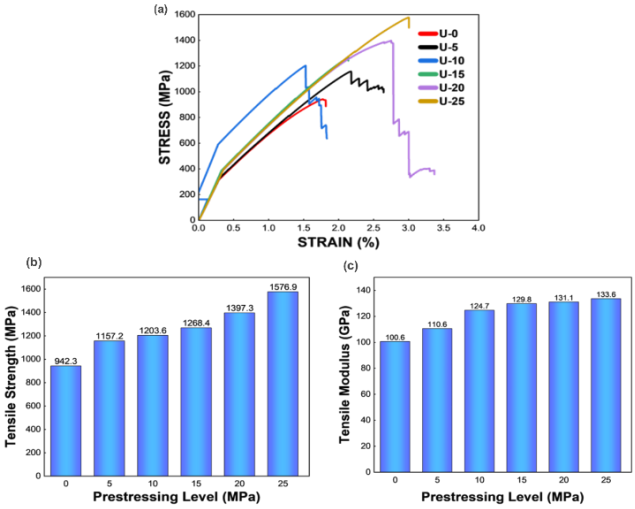

Fig. 3.1: Representative tensile properties of prestressed unidirectional CFRP laminates (a) stress-strain curve, (b) effect of prestressing level on tensile strength, (c) effect of tensile modulus on prestressing level

Fractographic analysis revealed that as prestress increased, the failure mode shifted from a brittle, abrupt fracture (U-0) to a more fibrous, diffuse failure (U-25). There was evidence of crack deflection, fibre bridging, and enhanced fibre-matrix bonding. These mechanisms indicate better stress distribution and interfacial adhesion due to the influence of prestressing.

For cross-ply laminates, the improvements were generally more modest. Tensile strength increased from 606.4 MPa to 922.4 MPa, which represents a 52% increase, and the modulus rose from 51.8 GPa to 68.7 GPa (Fig. 3.2). However, the trend was less linear than for unidirectional laminates because only half the fibres, those in the 0° plies, aligned with the load direction.

Fracture surfaces showed more complex and layered failures, mainly due to ply interactions. Delamination and interfacial shear were dominant at lower prestress levels. Higher prestress helped reduce ply separation and promoted fibre fragmentation, but at 25 MPa, slight delamination appeared again, likely as a result of overstressing during cure and localised residual stresses.

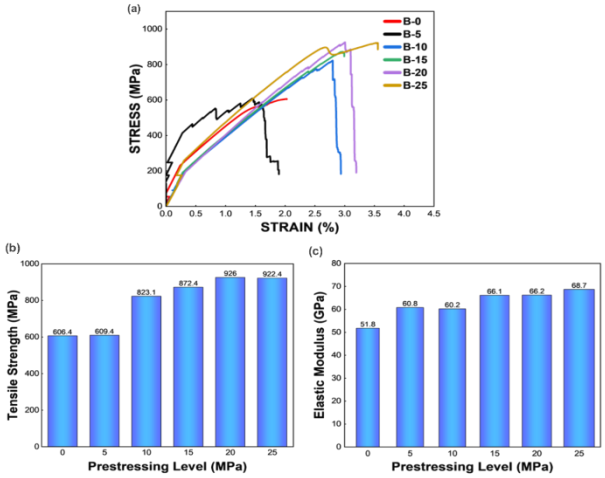

Fig. 3.2: Representative tensile properties of prestressed Cross-ply CFRP laminates (a) stress-strain curve, (b) effect of prestressing level on tensile strength, (c) effect of tensile modulus on prestressing level

Overall, prestressing enhanced tensile performance by improving fibre alignment, stress transfer, and internal residual stress distribution. The most effective gains were observed in the 10-20 MPa range, after which performance improvements diminished, likely due to stress saturation or internal damage. Unidirectional laminates showed greater improvements due to uniform stress distribution, while cross-ply laminates, despite lower gains, offer better multidirectional load handling for real-world applications.

Figure 3.3 shows the flexural behaviour of the unidirectional laminates of CFRP. As the level of fibre prestressing increases, the flexural behaviour of CFRP laminates improves quite noticeably. For unidirectional laminates, applying prestress in the range of 5 MPa to 25 MPa results in higher stiffness and strength. This improvement is evident in the steeper stress-strain slopes, higher peak loads, and more gradual drops post-peak. Remarkably, the flexural strength increases from 1010.5 MPa in the control group (U-0) to a maximum of 1373.2 MPa at U-20, demonstrating a 36% improvement. Simultaneously, the flexural modulus jumps from 103.6 GPa to 136.8 GPa at U-25, indicating approximately a 32% increase. Moreover, the failure mode transitions from brittle, abrupt fractures in U-0 to more progressive failures with fibre bridging and matrix cracking observed in U-20 and U-25. This suggests enhanced energy absorption as well as improved damage tolerance.

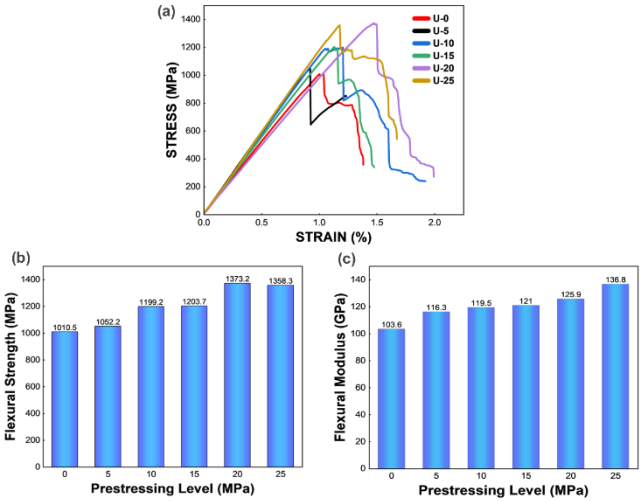

Fig. 3.3: Representative flexural properties of prestressed unidirectional CFRP laminates (a) stress-strain curve, (b) effect of prestressing level on flexural strength, (c) effect of flexural modulus on prestressing level

In the case of cross-ply laminates, the flexural strength sees an increase from 716.3 MPa (B-0) to 884.8 MPa (B-25) (Fig. 3.4), which is about a 24% enhancement. Additionally, the modulus rises from 66.7 GPa to 107.8 GPa at B-20, reflecting a substantial gain of 62%. However, at B-25, the modulus drops sharply, suggesting that excessive prestress might introduce stress imbalances or result in interfacial degradation.

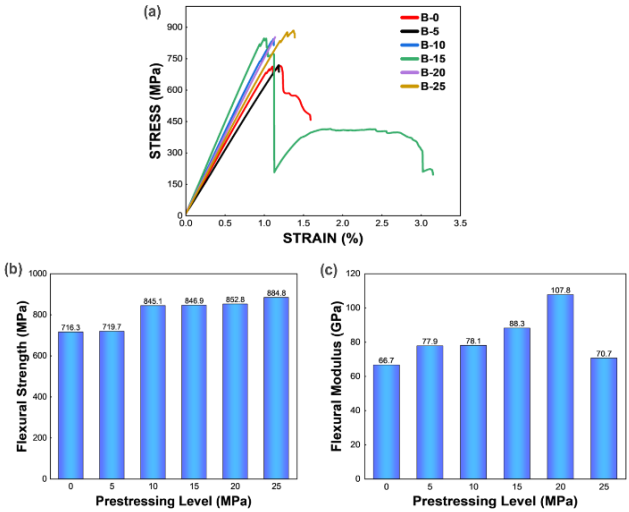

Fig. 3.4: Representative flexural properties of prestressed cross-ply CFRP laminates (a) stress-strain curve, (b) effect of prestressing level on flexural strength, (c) effect of flexural modulus on prestressing level

Cross-ply specimens generally fail with more delamination and ply separation, although increasing prestress reduces these defects up to B-20, after which localised interply issues reappear. Meanwhile, fractographic observations show that unidirectional laminates transition from top-surface crushing and brittle splits in U-0 to cohesive fractures with dense multi-site cracking and fibre bridging at higher prestress levels, especially in U-20 and U-25.

For cross-ply samples, initial tendencies for large-scale delamination give way to tighter ply stacking and reduced fibre pull-out with prestressing, notably at B-15 and B-20. Nevertheless, at B-25, renewed signs of ply separation indicate potential overstressing.

Therefore, elastic fibre prestressing effectively enhances the flexural strength, stiffness, and damage tolerance in both types of laminates. Unidirectional laminates show more predictable improvements at all levels of prestress, while cross-ply laminates benefit most up to about 20 MPa. Prestressing beyond this threshold risks introducing internal stress concentrations that may compromise modulus or interfacial integrity, particularly in multidirectional layups.

Charpy impact testing demonstrated that prestressing the fibres markedly boosts the energy absorption (Fig. 3.5) and impact resistance (Fig. 3.6) of both unidirectional and cross-ply CFRP laminates.

For unidirectional laminates, energy absorption jumped by 40.4% from U-0 to U-20, reaching its peak at U-20 and then levelling off at U-25. Impact strength climbed from 76.3 kJ/m² to a maximum of 118.8 kJ/m² at U-15, a considerable increase of 68.2%, but it dropped slightly at higher prestress levels due to possible matrix embrittlement or internal stress concentrations.

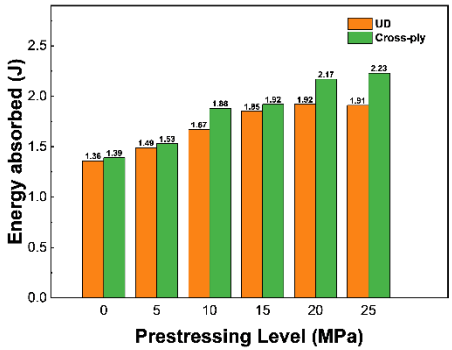

Fig. 3.5: Representative absorbed energy of the prestressed and non-prestressed unidirectional and cross-ply CFRP laminates

Fractography showed a shift from a brittle and planar fracture in U-0 to more dispersed and energy-absorbing damage modes in U-15 and U-20, characterised by fibre breakage, matrix smearing, and interfacial friction. At U-25, the fracture appeared slightly more brittle again, hinting at overstressing effects.

Cross-ply laminates showed even more considerable and steady improvements. The absorbed energy rose by 60.4% from B-0 to B-25, while impact strength peaked at 129.0 kJ/m² at B-20, roughly an 80% increase from the baseline. Unlike the unidirectional setup, the cross-ply laminates did not show early saturation. This is attributed to enhanced energy dissipation through mechanisms like delamination control, interlaminar shear, and matrix cracking, all enabled by the [0°/90°] layup. Damage evolution pointed towards layered delamination in B-0 transitioning to complex, controlled cracking and fibre-matrix disruption at B-20. B-25 displayed a slight drop in toughness, indicating localised internal stress beyond the optimal prestress range.

Hence, the research further confirms that elastic fibre prestressing enhances impact resistance, with cross-ply laminates benefiting the most due to multidirectional energy dissipation and enhanced structural tolerance at higher prestress levels.

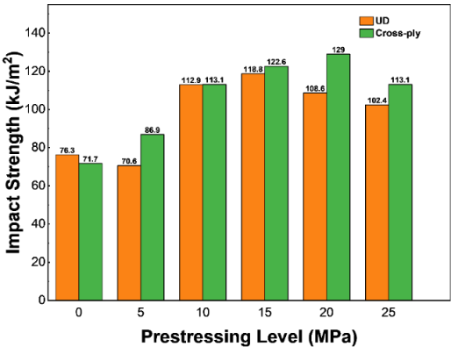

Fig. 3.6: Representative impact strength of the prestressed and non-prestressed unidirectional and cross-ply CFRP laminates

Likewise, the dynamic Mechanical Analysis (DMA) was used to evaluate the viscoelastic and thermomechanical performance of prestressed unidirectional and cross-ply CFRP laminates across a temperature range of 25°C to 200°C. Four key properties were assessed: storage modulus (E′), loss modulus (E″), damping factor (tan δ), and complex modulus (E*).

Results showed that fibre prestressing significantly enhanced stiffness, thermal stability, and energy dissipation (Fig. 3.7 and Fig. 3.8). For unidirectional laminates, prestressing increased the storage modulus from 16.5 GPa (U-0) to 17.5 GPa (U-25), reflecting better fibre alignment and fibre-matrix interaction.

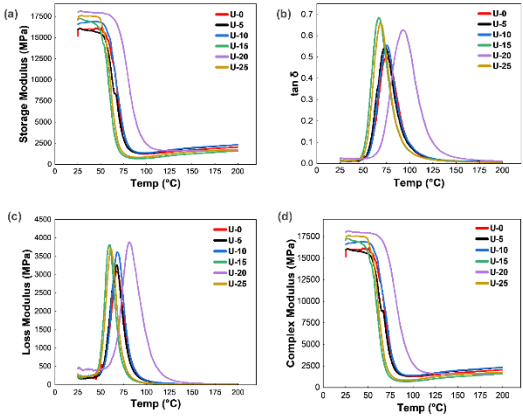

Fig. 3.7: Prestressed and non-prestressed unidirectional CFRP laminate (a) Storage modulus, (b) tan ∂ (c) loss modulus, (d) complex modulus over a temperature range 25℃ - 200℃

Prestressed samples maintained higher stiffness up to higher temperatures, indicating a delayed glass transition. Tan δ peaks shifted from 97°C to 117°C, confirming an increase in glass transition temperature (Tg) due to improved molecular limitation. Although damping capacity (tan δ height) slightly decreased at high prestress levels, this reflected a more elastic, less dissipative structure with enhanced energy transfer efficiency. The loss modulus E″ also increased, peaking near 115°C for U-25, indicating improved energy dissipation at elevated temperatures. Complex modulus (E*) followed the trend of E′, with prestressed laminates showing enhanced dynamic stiffness up to ~130°C.

These findings are consistent with prior tensile, flexural, and impact test results, confirming that fibre prestressing enhances mechanical integrity across both static and dynamic loading conditions. Cross-ply laminates showed even more significant gains. Storage modulus increased by ~58% (B-0: 9.2 GPa to B-25: 14.5 GPa), and Tg shifted from 94°C to 122°C, a 28°C increase. Tan δ and E″ peaks also shifted and rose, indicating improved damping and internal energy dissipation. The cross-ply configuration benefited from additional interlaminar synergy, with 90° plies helping distribute residual stresses more effectively and reduce brittleness. Even at high prestress levels, damping performance remained relatively stable, unlike in unidirectional laminates. The improved thermomechanical properties align closely with the superior impact strength and stiffness observed in previous tests, making cross-ply laminates ideal for multidirectional, high-performance structural applications.

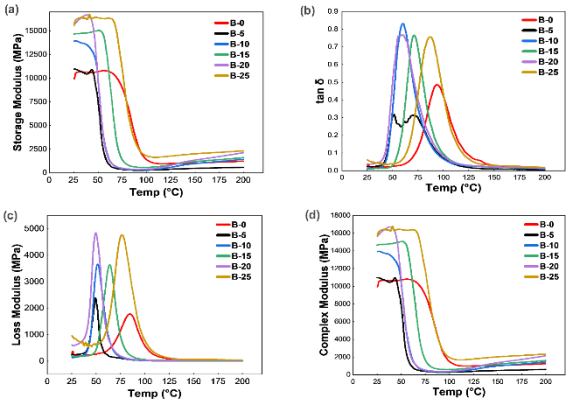

Fig. 3.8: Prestressed and non-prestressed cross-ply CFRP laminate (a) Storage modulus, (b) tan ∂ (c) loss modulus, (d) complex modulus over a temperature range 0°C - 200°C

Overall, fibre prestressing enhances thermal resistance, dynamic stiffness, and energy absorption in both laminate types. The optimal prestress range of 10-20 MPa

offers the best balance between stiffness, toughness, and damping, particularly in demanding environments such as aerospace and automotive structures.

The study on electrical conductivity examined how prestressing the elastic fibres affects both DC and AC conductivity of CFRP laminates along both the longitudinal and transverse directions. Initially, a reference composite made of glass fibre and epoxy was evaluated to ensure matrix thermal stability. This composite displayed minimal changes in conductivity and no significant degradation even at temperatures up to 200°C, thus confirming that any observed variations in CFRP conductivity are due to fibre alignment or interfacial effects, rather than matrix instability.

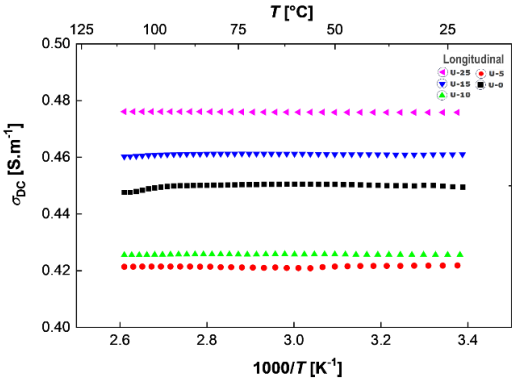

Fig. 3.9: Temperature-dependent DC conductivity of the unidirectional CFRP laminates at various prestress levels (0-25 MPa) along the longitudinal direction

In the longitudinal direction, unidirectional CFRP laminates showed a notable increase in DC conductivity with rising prestress levels. The control laminate, U-0, maintained a steady but moderate conductivity of around 7.5 S/m, while U-25 demonstrated an increase of over 1500%, indicating enhanced fibre alignment, reduced voids, and more efficient conductive pathways. AC conductivity followed a similar pattern: remaining low and stable up to U-10, then sharply rising and reaching its peak at U-20 (120 S/m), where thermally activated processes became apparent. The spike at U-20 suggests a certain prestress threshold that encourages dynamic fibre realignment and microstructural reorganisation, which facilitates charge transport.

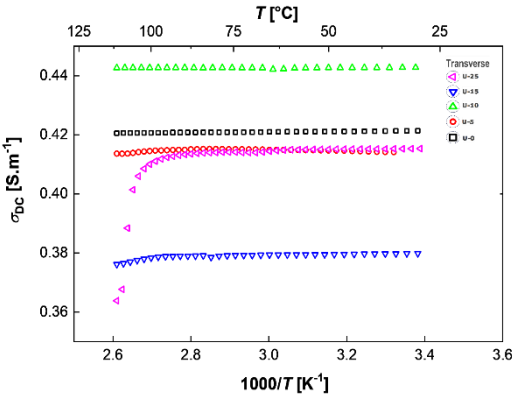

Fig. 3.10: Temperature-dependent DC conductivity of the unidirectional CFRP laminates at various prestress levels (0-25 MPa) in the transverse direction

In contrast, in the transverse direction, conductivity was considerably lower, diminishing by 4–6 orders of magnitude, emphasising the anisotropic properties of CFRPs. Transverse DC conductivity reached its highest at U-10, with U-20 showing the lowest values, demonstrating a non-linear response. Moderate prestress improves inter-fibre contact and tunnelling paths, while higher prestress seems to suppress them due to excessive compaction.

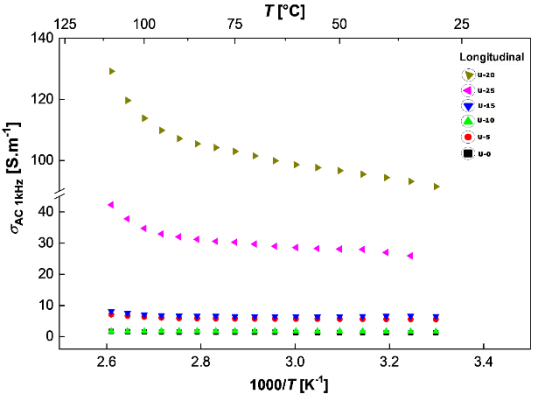

Fig. 3.11: Temperature-dependent AC conductivity of the unidirectional CFRP laminates at various prestress levels (0-25 MPa) along the longitudinal direction

AC conductivity mirrored this behaviour, peaking at U-10 (~10 S/m), but decreasing at greater prestress levels. The peak observed at U-10 can be attributed to optimal fibre-matrix coupling and interfacial polarisation, specifically Maxwell-Wagner-Sillars effects, which are vital for AC conduction in the transverse direction.

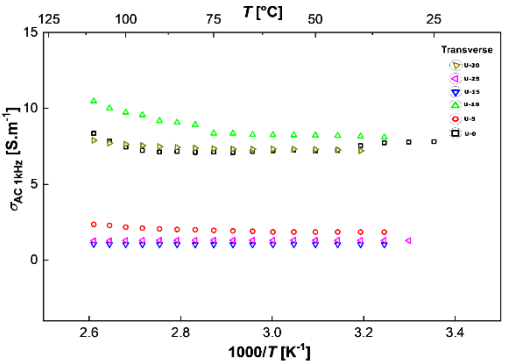

Fig. 3.12: Temperature-dependent AC conductivity of the unidirectional CFRP laminates at various prestress levels (0-25 MPa) along the transverse direction

For cross-ply CFRP laminates, DC conductivity measured along the 0° fibre direction revealed a different pattern. Conductivity was highest at B-5, but declined as prestress increased further. AC conductivity also peaked at B-5 (about 40 S/m at higher temperatures), then dropped significantly beyond B-10.

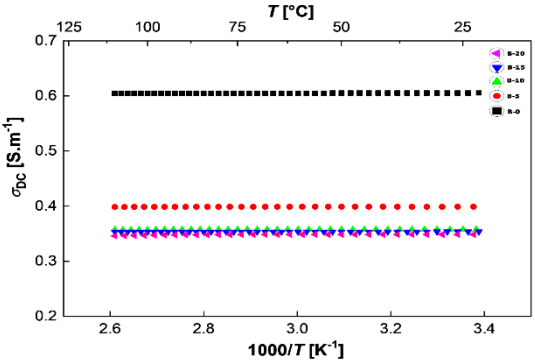

Fig. 3.13: Temperature-dependent DC conductivity of cross-ply CFRP laminates at various prestress levels (0-25 MPa) measured along the direction of prestress

These findings suggest that low prestress can enhance interlaminar contact and dielectric activity in cross-ply laminates. However, higher prestress levels might cause interfacial stress concentrations or excessive consolidation, therefore deteriorating conductive pathways. The presence of 90° plies and interlaminar boundaries limits the effectiveness of fibre prestress in enhancing conductivity compared to unidirectional laminates.

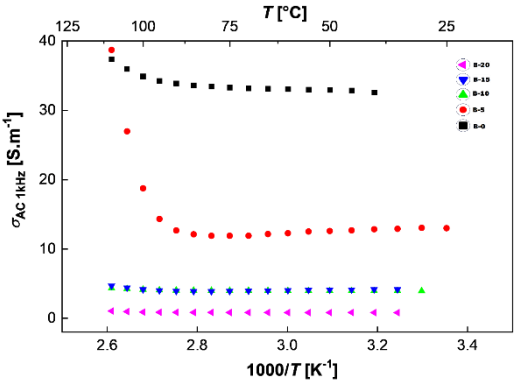

Fig. 3.14: Temperature-dependent AC conductivity of cross-ply CFRP laminates at various prestress levels (0-25 MPa) measured along the direction of prestress

In conclusion, elastic fibre prestressing significantly boosts in-plane (longitudinal) electrical conductivity in unidirectional CFRPs, especially with U-20 showing optimal performance. Cross-ply and transverse conduction are more sensitive to microstructural changes, peaking at moderate prestress (U-10 or B-5) before declining.

These findings highlight prestressing as an effective method for adjusting the electrical properties of CFRP laminates for multifaceted applications such as EMI shielding or structural health monitoring.

4. CONCLUSION AND RECOMMENDATION

This study investigated the influence of elastic fibre prestressing on the mechanical, thermal and electrical behaviour of carbon fibre reinforced polymer (CFRP) composite laminates. The aim is to explore the possibility that tensile prestressing applied during laminate fabrication could be utilised to improve material performance and multifunctionality. The study employed a systematic method involving sample fabrication utilising a custom-designed jig, standardised mechanical testing (tensile, flexural and impact), dynamic mechanical analysis (DMA), and in-depth electrical characterisation (both DC and AC regimes). Also,

post-fracture morphological assessment was utilised to support the quantitative findings.

The experimental investigations showed that elastic fibre prestressing significantly influences CFRP laminate microstructural development and performance. The mechanical properties of the unidirectional laminates consistently improved with increasing prestressing level up to 25 MPa. The tensile modulus increased by up to 32.8%, and tensile strength improved by 67.3 %. Flexural modulus and strength increased by 32.1 % and 34.4 %, respectively. Impact performance improved, with absorbed energy rising by 41.2 % and impact strength by 55.7 %. The samples prestressed at 15-20 MPa showed the most distributed, matrix-intensive failure modes, which indicate enhanced interfacial strength and fibre bridging. The DMA analysis further confirmed these improvements: U-25 showed storage modulus rise by 6.1 % and Tg elevation from 97 °C to 117 °C (20.6 %), reflecting restricted polymer mobility due to densification and fibre-matrix interaction.

However, the cross-ply CFRP laminates presented more subdued mechanical improvements. Tensile modulus rose to 32.6 %, and tensile strength increased by 52.1 %, with gains progressing steadily to 20 MPa and a slight fall at 25 MPa. Flexural modulus also rose by 61.6 %, and flexural strength improved by 23.5 %. Likewise, the impact toughness rose by 60.4 % and impact strength improved to 79.8 %, peaking at 20 MPa. DMA further showed storage modulus increases by 63.0 % while Tg shifts by 29.8 %.

Also, the electrical characterisation of the laminates revealed a more complex behaviour. In the longitudinal direction, unidirectional laminates presented a sharp rise in both DC and AC conductivity by 1500% and 1400%, respectively, while increasing the prestress level, with a peak at U-20. This is driven by improved fibre alignment and reduced inter-bundle voids. However, in the transverse direction, the electrical conductivity (AC and DC) exhibited a non-monotonic behaviour with a peak at U-10 and declining at higher prestress levels (-14.3 % DC, -33.3 % AC at U-25) due to high fibre straightening and reduced cross-fibre contact. This shows that even though fibre prestressing enhances in-plane conductivity through an improved percolation, it may disrupt the through-thickness pathway essential for transverse conduction.

5. CONTRIBUTION TO KNOWLEDGE

This study offers several unique contributions to the field of fibre-reinforced polymer composites, particularly focusing on the use of elastic fibre prestressing as a multifunctional method for performance improvement. The innovative findings and methodological advances presented in this work enrich current understanding in notable ways, as stated as follows:

i. Development of a Controlled Prestressing Fabrication Method:
A custom-built jig was successfully applied to provide accurate elastic fibre prestress levels (0-25MPa) during CFRP laminate curing. The technique allowed for repeatable prestressing across many specimens while also introducing a scalable, filler-free way for influencing the inner composite microstructure.

ii. Comprehensive Quantification of Prestress Effects Across Multiple Domains:
Unlike previous studies, which focused on isolated characteristics, this study examined the mechanical (tensile, flexural, and impact), thermal (DMA) and electrical (AC/DC conductivity) responses of CFRP laminates as a function of prestress level. This comprehensive methodology offered a multifunctional performance profile that was not created in the current literature.

iii. Architecture-Specific Optimisation of Prestress Levels:
The study revealed that optimal prestress levels for performance enhancement are highly dependent on laminate architecture. For unidirectional laminates, prestress levels between 15-20 MPa maximise in-plane mechanical and electrical properties. For cross-ply laminates, moderate prestress levels (5-10 MPa) offered the best balance between stiffness, impact resistance, and conductivity. This architectural specificity provides new design guidelines for tailored composite manufacturing.

iv. Identification of Prestress-Induced Trends in Transverse and Through-Thickness Properties:
This study is one of the first to assess how improving fibre alignment by prestress may negatively influence transverse conduction and inter-bundle energy dissipation using transverse electrical conductivity and Charpy impact analysis. These findings provide a more detailed view of the trade-offs involved in prestressing techniques.

v. Validation of Long-Term Functional Potential Without Additive Modification:
The reported improvements in mechanical, thermal, and electrical characteristics were obtained without the addition of fillers, nanomaterials, or chemical surface treatments. This confirms elastic prestressing as a low-complexity, high-impact strategy for increasing CFRP performance that requires little additional processing or cost.

vi. Contribution of Post-Failure Analysis to Failure Mode Understanding:
Detailed post-fracture investigations of tensile, flexural, and impact specimens showed architecture-specific damage progression patterns (for example, fibre pull-out, delamination modes, and matrix fragmentation). This gives vital

information on the failure mechanics of prestressed CFRP under various loading regimes.

Overall, this study advances the fundamental and practical understanding of elastic fibre prestressing in CFRP laminates, establishing the framework for future multifunctional composite designs. The work also acts as a resource for engineers and material scientists looking to improve composite behaviour using mechanical prestressing approaches rather than chemical modifications.

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List of Abbreviations and Symbols

EPPMC	Elastically prestressed polymer matrix composite
VPPMC	Viscoelastically prestressed polymer matrix composite
FRP	Fibre-reinforced polymer
CTE	Coefficient of thermal expansion
UD	Unidirectional
DSC	Differential Scanning Calorimetry
DMA	Dynamic Mechanical Analysis
RTM	Resin transfer moulding
VARI	Vacuum-assisted resin infusion
OOA	Out-of-autoclave
VARTM	Vacuum-assisted resin transfer moulding
SEM	Scanning electron microscope
CT	Computed Tomography
NCFs	Non-crimp fabrics
CAI	Compression-after-impact
AFP	Automated fibre placement
ATL	Automated tape laying
DIC	Dynamic Image Correlation
DT	Destructive techniques
NDT	Non-destructive testing
FBG	Fibre Bragg Grating
U	Unidirectional laminate
B	Cross-ply laminate
U-0	Unidirectional laminate with 0 MPa prestress level
U-5	Unidirectional laminate with 5 MPa prestress level
U-10	Unidirectional laminate with 10 MPa prestress level
U-15	Unidirectional laminate with 15 MPa prestress level
U-20	Unidirectional laminate with 20 MPa prestress level
U-25	Unidirectional laminate with 25 MPa prestress level
B-0	Cross-ply laminate with 0 MPa prestress level
B-5	Cross-ply laminate with 5 MPa prestress level
B-10	Cross-ply laminate with 10 MPa prestress level
B-15	Cross-ply laminate with 15 MPa prestress level
B-20	Cross-ply laminate with 20 MPa prestress level
B-25	Cross-ply laminate with 25 MPa prestress level
ISO	International Standard Organisation
DC	Direct current
AC	Alternating current
TGA	Thermogravimetric analysis

DTA	Differential thermal analysis
G_{ref}	Glass fibre-reinforced epoxy sample
MWS	Maxwell-Wagner-Sillars
MPa	megapascal
GPa	gigapascal
g	gram
cm^3	cubic centimetre
^oC	degree celsius
T_g	glass transition temperature
atm	atmosphere
σ_f^P	target fibre prestressing level
F	applied force
A_f	effective fibre cross-sectional area
mm^2	millimetre square
V_f	fibre volume fraction
A_l	total cross-sectional area of the laminate
w	laminate width
t	laminate thickness
N	newton
W	energy absorbed
J	joules
b	width at notch
mm	millimeters
h	laminate thickness
E''	storage modulus
E''	loss modulus
δ	delta
V	volts
I	current
σ_{DC}	DC conductivity
kHz	Kilo hertz
σ_{AC}	AC conductivity
G	conductance (the reciprocal of resistance)
kJ	kilo joules
E*	complex modulus

APPENDICES

Table 1: Statistical summary of tensile strength and modulus of unidirectional CFRP laminates at various prestress levels (n = 10)

Prestress Level	Tensile Strength (MPa)			Tensile Modulus (GPa)		
	Mean (μ)	StDev (σ)	SE Mean (SE)	Mean (μ)	StDev (σ)	SE Mean (SE)
U-0	942.07	0.98	0.31	96.73	0.99	0.31
U-5	1154.07	2.80	0.89	111.42	1.07	0.34
U-10	1207.81	2.49	0.79	115.46	1.50	0.47
U-15	1253.01	16.91	5.35	116.91	1.60	0.51
U-20	1395.08	4.68	1.48	128.53	0.85	0.27
U-25	1575.80	11.92	3.77	123.17	1.91	0.60

Notes: μ = mean; σ = standard deviation; SE = standard error of the mean n = 10 replicates per group

Table 2: Statistical summary of tensile strength and modulus of cross-ply CFRP laminates at various prestress levels (n = 10)

Prestress Level	Tensile Strength (MPa)			Tensile Modulus (GPa)		
	Mean (μ)	StDev (σ)	SE Mean (SE)	Mean (μ)	StDev (σ)	SE Mean (SE)
B-0	606.4	2.15	0.68	51.55	0.621	0.20
B-5	608.8	1.30	0.41	59.94	0.817	0.26
B-10	822.4	1.23	0.39	59.96	0.177	0.06
B-15	871.7	0.62	0.20	65.64	0.388	0.12
B-20	925.5	1.00	0.32	66.05	0.204	0.06
B-25	921.7	0.68	0.22	67.70	1.585	0.50

Notes: μ = mean; σ = standard deviation; SE = standard error of the mean n = 10 replicates per group

Table 3: Statistical summary of flexural strength and modulus of unidirectional CFRP laminates at various prestress levels (n = 10)

Prestress Level	Flexural Strength (MPa)			Flexural Modulus (GPa)		
	Mean (μ)	StDev (σ)	SE Mean (SE)	Mean (μ)	StDev (σ)	SE Mean (SE)
U-0	1004.6	3.62	1.14	103.32	0.947	0.299
U-5	1046.4	2.51	0.79	115.15	2.21	0.699
U-10	1198.9	0.584	0.18	115.90	2.18	0.689
U-15	1198.2	2.04	0.65	121.60	0.353	0.112
U-20	1380.0	10.9	3.45	126.66	2.05	0.648
U-25	1365.6	18.5	5.85	137.15	1.45	0.459

Notes: μ = mean; σ = standard deviation; SE = standard error of the mean
n = 10 replicates per group

Table 4: Statistical summary of flexural strength and modulus of cross-ply CFRP laminates at various prestress levels (n = 10)

Prestress Level	Flexural Strength (MPa)			Flexural Modulus (GPa)		
	Mean (μ)	StDev (σ)	SE Mean (SE)	Mean (μ)	StDev (σ)	SE Mean (SE)
B-0	716.30	1.88	0.595	66.42	0.266	0.084
B-5	719.70	0.53	0.168	77.95	0.183	0.058
B-10	845.10	1.21	0.383	78.84	0.206	0.065
B-15	846.90	0.27	0.085	86.90	0.236	0.075
B-20	852.80	0.71	0.225	100.53	2.720	0.860
B-25	884.80	1.88	0.595	68.05	0.861	0.272

Notes: μ = mean; σ = standard deviation; SE = standard error of the mean n = 10 replicates per group

Table 5: Statistical summary of charpy impact response of the unidirectional CFRP laminates at various prestress levels (n = 10)

Prestress Level	Absorbed Energy (J)			Impact Strength (kJ/m²)		
	Mean (μ)	StDev (σ)	SE Mean (SE)	Mean (μ)	StDev (σ)	SE Mean (SE)
U-0	1.36	0.00892	0.0028	76.30	0.638	0.2018
U-5	1.49	0.0193	0.0061	70.60	0.699	0.2210
U-10	1.67	0.0266	0.0084	112.90	0.766	0.2422
U-15	1.85	0.0322	0.0102	118.80	0.745	0.2356
U-20	1.92	0.0256	0.0081	108.60	1.010	0.3194
U-25	1.91	0.00739	0.0023	102.40	0.609	0.1926

Notes: μ = mean; σ = standard deviation; SE = standard error of the mean n = 10 replicates per group

Table 6: Statistical summary of charpy impact response of the cross-ply CFRP laminates at various prestress levels (n = 10)

Prestress Level	Absorbed Energy (J)			Impact Strength (kJ/m²)		
	Mean (μ)	StDev (σ)	SE Mean (SE)	Mean (μ)	StDev (σ)	SE Mean (SE)
B-0	1.343	0.0153	0.0048	75.56	0.773	0.2444
B-5	1.462	0.0066	0.0021	70.79	0.491	0.1553
B-10	1.634	0.0282	0.0089	110.83	0.655	0.2071
B-15	1.831	0.0269	0.0085	118.36	0.404	0.1278
B-20	1.883	0.00808	0.0026	107.13	0.827	0.2615
B-25	1.894	0.0103	0.0033	101.57	0.566	0.1790

Notes: μ = mean; σ = standard deviation; SE = standard error of the mean n = 10 replicates per group

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Kotlánová, B., Rusnáková, S., Ogunleye, R. O., & Javořík, J. (2023). Volume changes measurement of elastomers using 3D DIC. In D. Kytýř, T. Doktor, & P. Zlámal (Eds.), 18th Youth Symposium on Experimental Solid Mechanics (pp. 46–50). Polytechnica CTU Proceedings. https://doi.org/10.14311/APP.2023.42.0046

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Education

2021- Present	Ph.D. Process Engineering Department of Production Engineering Tomas Bata University in Zlin, Czech Republic
2015 - 2019	MTech Chemical Engineering Ladoke Akintola University of Technology, Ogbomoso, Nigeria
2006 - 2011	BTech Chemical Engineering Ladoke Akintola University of Technology, Ogbomoso, Nigeria

WORK EXPERIENCE
Doctoral student
Composite Laboratory, Department of Production Engineering, *Tomas Bata University* [04/2021 – Present]
Supervisor: Assoc. Prof. Sona Rusnakova
• Tooling design for composite part fabrication and assembly
• Engagement in various development projects to test the feasibility of composite part designs
• Responsible for various composite process specifications, drafting and development
• Design, conduct scientific experiments and evaluate test data
• Preparation and maintenance of research environment and equipment, including cleaning and setup duties

Doctoral Research Intern
Division of Ceramic Materials and Polymers, Faculty of Materials Science and Engineering, Warsaw University of Technology [10/2023 – 12/2023]
Supervisor: Dr. Kamil Dydek
• Fabrication of carbon-based sensors, characterisation (SEM, TGA, electrical conductivities) and evaluation of their performance
• Preparation of CFRP composites with embedded sensors using out-of-autoclave (OOA) and vacuum infusion method
• Investigation of the morphology and thermal properties of the composite structure by performing SEM and TGA, respectively
• Mechanical and electrical properties evaluation and failure mode analysis of the composite structure
• Reporting and documentation of the project

Graduate Assistant
Polymer Processing Group, Department of Chemical Engineering, Ladoke Akintola University of Technology [03/2017 – 06/2019]
Advisor: Prof. G.K. Latinwo; Assoc. Prof. Abbas Alade
• Provided research support, project writing and data analysis, and mentored five undergraduate students in designing experiments using statistical tools (DOE and Minitab)
• Drafted a successful project proposal for funding from Unifoam Group and Vitafoam on the development of filled flexible polyurethane foam
• Provided research support on the optimisation of soybean oil using an azeotropic solvent mixture
• Collaborated with the technologist in the Gas Chromatography lab in preparation of samples for GC-MS analysis
• Investigation of new renewable materials for the advancement of green polymer technology

HONOURS AND AWARDS
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Erasmus+ Scholarship
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SKILLS AND COMPETENCE

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Doctoral Thesis Summary

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