

# Dynamic Mechanical Analysis of Carbon Fiber Reinforced Polymer Composites

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## Abstract

*This study investigates the thermal decomposition and mechanical properties of Fiber-Reinforced Polymer Composites (FRPCs) using Dynamic Mechanical Analysis (DMA). The research focuses on improving the recycling and recovery process of Carbon Fiber-Reinforced Polymers (CFRPs), addressing environmental concerns regarding their disposal. By analyzing the effects of different heating rates (5°C and 10°C per minute) and atmospheric conditions (nitrogen, oxygen, and a combination of both), the study identifies optimal parameters for maximizing fiber retention while effectively degrading the polymer matrix. The experimental procedure involved heating CFRP samples to 420°C in a nitrogen atmosphere, facilitating the decomposition of phenolic resin while maintaining fiber integrity. The most efficient recovery method was found at 540°C under oxygen, where the epoxy resin degraded completely while preserving the filament structure. The glass transition temperature (T<sub>g</sub>), storage modulus (E'), loss modulus (E''), and damping factor (Tan δ) were examined to assess the thermal and mechanical stability of different CFRP laminates. Among the tested laminates, Laminate 1 (0° stacking sequence) demonstrated superior mechanical performance, exhibiting the highest storage modulus (20,000 MPa), lowest damping factor (0.11), and highest T<sub>g</sub> (240°C), making it ideal for high-performance applications such as automotive and aerospace industries. The results confirm that optimized stacking sequences enhance both mechanical strength and thermal stability, ensuring the structural integrity of CFRP composites under varying conditions. The research underscores the importance of thermal optimization in composite recycling, providing a pathway for enhanced reuse and waste management of carbon fiber materials.*

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## INTRODUCTION

Several industries select carbon fiber-reinforced polymers (CFRPs) because these materials deliver outstanding mechanical properties united by their high strength factors and lightweight advantages and durability benefits. Environmental problems have started to appear because continued growth in CFRP applications creates barriers for composite waste disposal. The extraction of carbon fibers from used CFRP products represents a practical method to reduce environmental effects. The analysis through DMA for CFRP composites evaluates heat reactions and recovery processes for extracted carbon fibers. The fundamental analysis method

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known as dynamic mechanical analysis drives the operational activities of all laboratories that work with polymers. Just a few scientific investigations exist about this particular technique. The established thermal examination methods include TMA and both TGA and DSC. The strength of fiber-to-matrix bonds in composite materials becomes measurable through ( $E'$ ) storage moduli and ( $E''$ ) loss moduli and ( $\tan \delta$ ) damping factor examination at different stress conditions [1,2]. The polymer industry along with its sectoral components adopts dynamic mechanical approaches in their operations [3]. DTA and DMTA serve as the key testing methods for glass transition temperature measurements as stated in [4]. DMA systems empower technicians to determine the glass transition temperature of rubbery and solid materials by activation. The technique enables the detection of gelation stages and verification events as well as thermoset curing behavior. Closer evaluation of liquid resin curing performed on glass fibre tape takes place through DMA systems according to [5]. Two or more components in composite materials stay distinct entities within the overall material structure. Material science applications of composite materials yield three main advantages: improved specific strength ratios with reduced weight loads and better material stiffness along with amplified dynamic performance capabilities. These properties enable designers to achieve expansion of their capabilities. The design of composite materials includes an inferior matrix that surrounds strengthening reinforcements to serve as structural components. The resin binder protects reinforcements that are embedded in the matrix structure allowing load-bearing capabilities of the matrix material [6]. Engineers choose carbon fiber-reinforced polymers (CFRP) above all other reinforcement materials because of studies in this field [7]. Aerospace industry applications of fiber-reinforced polymer composites largely focus on carbon-fiber-reinforced polymer composites (CFRPs) since these materials have specialized use capabilities in addition to advanced structural properties. Fibre-reinforced polymer composites consist of two active elements where fibers are embedded into a polymer matrix [8]. The combination of countertops and coatings and adhesives produces multicomponent structures through the union of glass with fibers. Manufacturing used such materials but epoxy resins with fiberglass cloths enabled the production of contemporary fire-retardant FR-4 materials [9]. Although optical fiber composites are cost-effective, extensively utilized, and remarkably robust, composite materials like GFRP surpass steel in maritime applications owing to their higher strength, stiffness, and low density [10]. Ultra-thin carbon fibers within polymer matrices confer CFRP, an essential element in aviation, its superior strength-to-weight ratio, lightweight structure, unidirectional alignment, exceptional tensile strength, and little thermal expansion [11]. Lignocellulosic fibers, along with glass and carbon fibers and mineral fillers, provide several benefits to the composite. These advantages include low density, reduced machine wear compared to mineral reinforcements, lack of health hazards, and considerable flexibility [12]. The production of polymer composites through mixing reinforcing materials with a continuous polymer matrix results in their formation. The composite compounds produced by integration strengthen their capabilities while improving characteristics like strength, impact resistance and stiffness and wear resistance alongside thermal conductance and corrosion resistance and extended durability [13]. Renewable natural fibers serve as environmentally friendly alternatives to traditional reinforcing fibers, thanks to their low density, outstanding mechanical properties, abundant availability, and straightforward disposal methods [14]. The materials that exhibit durability, reliability, lightweight characteristics, and superior mechanical properties compared to traditional options are driving the increasing demand for natural fiber across multiple industries [15]. Fibre-reinforced polymer which consists of embedded fibrous materials alongside a resin mixture [16]. Optimized throughout the production process to enhance carbon fiber (CF) microstructure [17]. and exhibit unique properties such as lower carbon footprints than conventional materials like steel or concrete [18], the ability to maintain structural behavior under fire-induced tensile loading through thermal softening of fibers and matrix [19], resistance to matrix cracking due to stiff fibers [20], and excellent compressive behavior critical for polymer matrix self-healing [21], susceptibility to chemical or thermal degradation in harsh conditions [22], and reliance on testing methods like the three-point bend test to determine flexural strength [23], with epoxy thermoset polymers providing low creep and high temperature tolerance due to their crosslinked structure [24].

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The incorporation of silicon carbide filler into composite materials occurs because of its exceptional mechanical alongside electromagnetic properties [25]. A conversion of activated carbon fibres through silicon monoxide produced silicon carbide fibres. A mixture of silicon dioxide with silicon produced the silicon monoxide. The chemical reaction occurred between 1200 and 1300°C under argon conditions which maintained inert conditions [26, 27]. Phenolic resin emerges from phenolic compounds interaction with aldehyde substances at controlled temperatures through acid-based or alkaline catalysis mechanisms. Manufacturers commonly choose this material for their plastic products and coating and adhesive applications since its production costs are low while its mechanical strength is high and it maintains its stability when exposed to heat and chemicals and offers excellent electrical insulation and fire resistance properties [28-30].

The research highlights the importance of heating speed and atmospheric conditions in achieving a balance between effective polymer matrix degradation and fibre preservation. The findings contribute to sustainable CFRP recycling solutions while offering insights for industrial applications and material characterization, particularly in the development of eco-friendly composites. By accounting for both dry and moisture-conditioned states, the study provides a comprehensive evaluation of the thermal behavior and structural performance of CFRP composites under varying conditions, ensuring reliable and accurate determination of glass transition temperature ( $T_g$ ). These findings contribute to the advancement of sustainable recycling practices for CFRPs, offering insights that can be applied in material characterization, industrial applications, and the development of eco-friendly solutions for CFRP waste management.

## MATERIALS AND METHODS

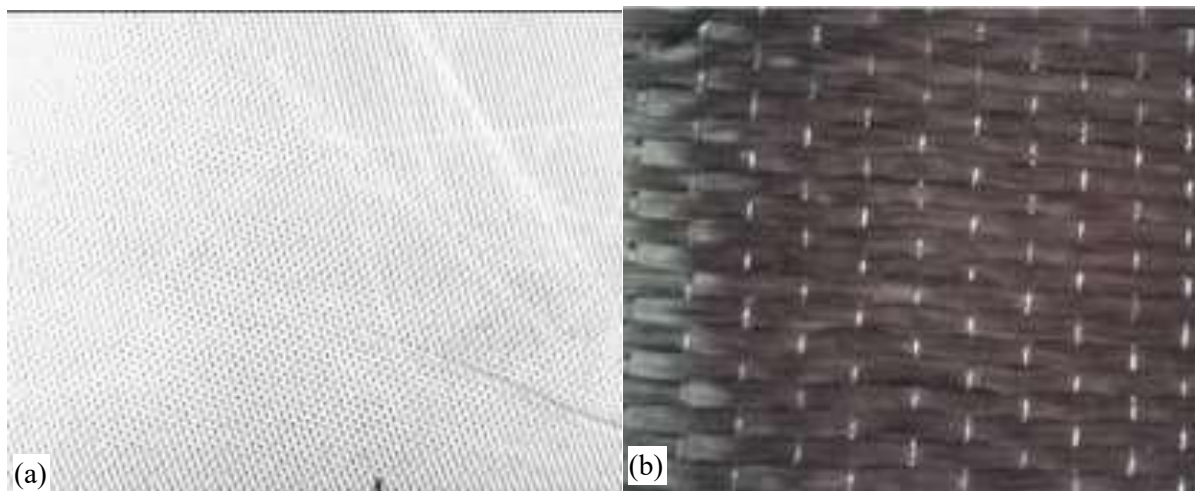
Composite materials reinforced with carbon fibre serve as a common choice due to their excellent durability and strength and resistance to corrosion. CFRP exhibits outstanding creep and fatigue resistance which supports its widespread applications in sports applications and aerospace uses and automotive industry and construction sector. Civil engineering professionals are starting to utilize Glass Fibre Reinforced Polymer (GFRP) rebar's as their preference increases. These materials are preferred over steel reinforcement because they exhibit great corrosion resistance along with a superior strength-to-weight ratio as well as longer durability. In Figure 1, we observe two types of fibers: carbon fiber and glass fiber.

Phenol formaldehyde resins which go by the name phenolic resins emerge from mixing phenol or comparable substances with formaldehyde to produce synthetic materials. Bakelite originated from phenolic resins which became the leading synthetic plastics introduced to commerce. These materials serve numerous applications that cover billiard ball molding's in addition to laboratory equipment manufacturing while benefiting from use in countertops and provide coating ingredients with adhesive functionality.

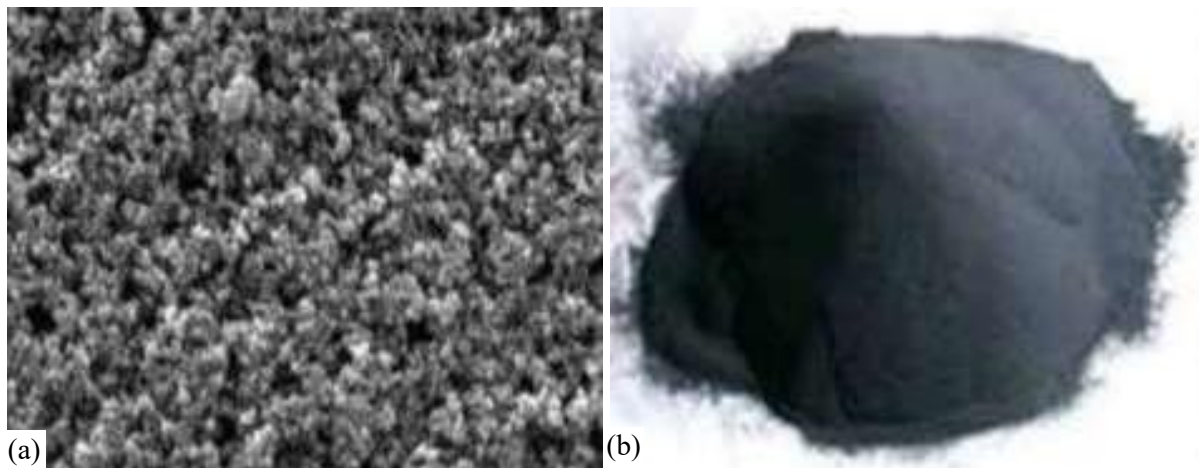
Silicon carbide (SiC) is a robust ceramic material composed of silicon and carbon, known for its exceptional hardness, thermal conductivity, and chemical stability, making it ideal for applications such as abrasives, semiconductors, high-performance ceramics, and heat-resistant components in industrial and aerospace industries. In Figure 2, we can see two illustrations: SiC powder and an SEM image of SiC. Table 1 presents the properties of four materials: carbon fiber, glass fiber, silicon carbide, and phenolic resin.

**Table 1.** Properties of Carbon Fibre, Glass Fibre, Silicon Carbide, Phenolic Resin.

Properties	Glass Fibre	Carbon Fibre	Phenolic Resin	Silicon Carbide
Density (g/cm <sup>3</sup> )	2.4 – 2.6	1.6 – 2.0	1.3 – 1.4	3.1 – 3.2
Young's Modulus (Gpa)	50 - 90	70 - 300	2 - 6	300 - 450



**Figure 1.** a) Carbon fiber b) Glass fiber.



**Figure 2.** a) SiC powder b) SEM image of SiC

## EXPERIMENTAL METHODS

A release gel distributes on the mould surface first as an initial step for stopping polymer from sticking to the mould. Improving the surface finish of the composite requires thin plastic sheets to be installed between the top and bottom of the mould. The mould process requires exact cutting of woven mats or chopped strand mats to fit the mould surface before placing them with great precision. A thermosetting polymer mixed with curing agent (hardener) at the correct proportion receives a uniform application on the reinforcement through brushing. Polymer and reinforcement layers build up in succession on top of each other. The roller serves two purposes: it smoothes the material layers while simultaneously displacing trapped air and redistributing excessive polymer. You should apply pressure after stacking required layers by placing a top mould plate with release gel coating. Different polymers require curing through specific temperature conditions which may either be room temperature or elevated above. Room temperature conditions require epoxy-based systems to cure during 24 to 48 hours. Once the curing phase finishes the final composite is taken out from its mould to proceed with additional processing steps. The creation of composites utilizes hand-layup materials as their main manufacturing approach. Noise-free compression moulding employs heated hydraulic presses to combine composite products at high pressure under specific metal tool satisfaction. The material serves as an essential component to produce thermosetting prepress as well as fiber-reinforced thermoplastic sheets and Sheet Moulding Compound (SMC) among other molding compounds. Technical staff places organized sheets or tapes of material inside a mould prior to heating and pressurization stage that begins

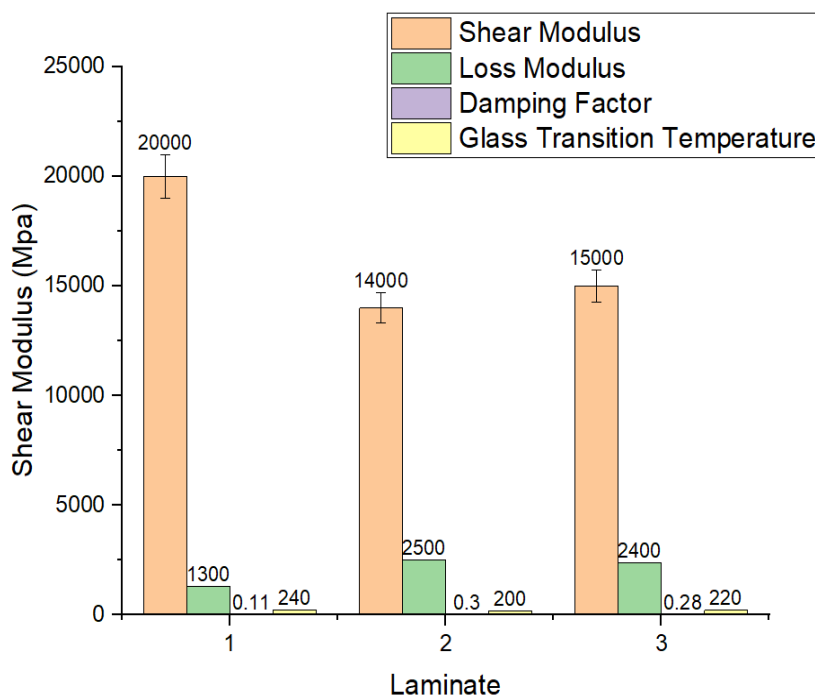
the consolidation or curing reaction. Sanitation of pressure during processing demonstrates essential importance because it protects foam or honeycomb core materials used in sandwich structures. Aerospace and automotive and industrial industries benefit from this method as it provides powerful lightweight components together with exceptional performance. Several post-processing techniques apply to components to achieve their final requirements. Due to its automatic features compression moulding delivers reliable outcomes through uniform production which makes it suitable for large-scale manufacturing of sophisticated high-quality composite products. In composite manufacturing operations the hand lay-up method joins with compression moulding as essential manufacturing techniques. The hand lay-up approach delivers extensive application in quick custom production but compression moulding excels for mass production of precise components. Lightweight components producing large and strength-driven products remains vital to modern manufacturing requirements. The developed methods create an enduring solution that works well for different industrial sectors. In Figure 3, we see three different laminates: Laminate 1 at 0 degrees, Laminate 2 at 45 degrees, and Laminate 3 at 30 degrees.

## RESULTS AND DISCUSSION

Dynamic mechanical analysis (DMA) was performed on three composite laminates with varying stacking sequences to evaluate their viscoelastic and thermal properties. Conducted under flexural oscillation mode from 40°C to 300°C in a nitrogen atmosphere, the study revealed significant differences in the mechanical and thermal performance of the laminates. Among the configurations, Laminate 1 exhibited the most advantageous combination of properties, indicating its superior suitability for high-performance applications. The storage modulus ( $E'$ ), a critical measure of structural rigidity and load-bearing capacity, was highest for Laminate 1, measured at 20,000 MPa. This value was significantly greater than that of Laminate 2, which showed a storage modulus of 14,000 MPa, and Laminate 3, with 15,000 MPa. The elevated  $E'$  of Laminate 1 highlights its enhanced structural stiffness, suggesting that its stacking sequence effectively optimized its mechanical properties. This stiffness is particularly valuable for applications requiring durable and rigid composite materials. Damping characteristics, represented by the loss modulus ( $E''$ ) and  $\tan \delta$  values, further differentiated the laminates. Laminate 1 demonstrated the lowest  $\tan \delta$  value of 0.11, indicating minimal energy dissipation during mechanical deformation. In contrast, Laminate 2 and Laminate 3 exhibited higher  $\tan \delta$  values of 0.3 and 0.28, respectively, reflecting greater energy loss and reduced damping efficiency. The reduced damping in Laminate 1 implies superior vibrational performance, critical for maintaining stability under dynamic loading conditions. Thermal stability was assessed through the glass transition temperature ( $T_g$ ), a key parameter denoting the onset of significant molecular mobility within the polymer matrix. Laminate 1 showed the highest  $T_g$  at 240°C, outperforming Laminate 3, which had a  $T_g$  of 220°C, and Laminate 2, at 200°C. The elevated  $T_g$  of Laminate 1 highlights its superior thermal resistance, making it more suitable for high-temperature environments. The combination of high storage modulus, low damping behavior, and elevated  $T_g$  in Laminate 1 can be attributed to its optimized stacking sequence, which likely enhanced the interlayer bonding and stiffness of the composite.



**Figure 3.** a) Laminate 1(0 Degree) b) Laminate2(45 Degree) c) Laminate (30 Degree).



**Figure 4.** DMA Analysis of Different Laminates

**Table 2.** Results for the Dynamic Mechanical Analysis

Laminate	Shear modulus (E' MPa)	Loss modulus (E'' Mpa)	Damping factor (Tan δ)	Glass transition temperature (T <sub>g</sub> °C)
1	20000	1300	0.11	240
2	14000	2500	0.3	200
3	15000	2400	0.28	220

These properties make Laminate 1 an ideal candidate for demanding applications such as high-temperature automotive components, where both structural integrity and thermal stability are critical. Table 2 provides the results of the Dynamic Mechanical Analysis. In Figure 4, we present the DMA analysis of different laminates.

**CONCLUSION**

The Dynamic Mechanical Analysis (DMA) of fibre reinforced polymer composites has provided valuable insights into the thermal and mechanical performance of carbon fibre reinforced polymer (CFRP) materials, specifically in relation to the recovery and reuse of carbon fibres (CF). The study demonstrates that a lower heating rate (5 °C/min) in a nitrogen atmosphere effectively breaks down epoxy resin, ensuring the retention of fibre structure while enabling efficient recovery of reclaimed CF at a final temperature of 540 °C. The comprehensive evaluation, considering both dry and moisture-conditioned states, contributes to a reliable assessment of the thermal properties of CFRP composites, which is essential for material characterization and industrial applications. The results from the DMA of three composite laminates with varying stacking sequences reveal distinct differences in their mechanical and thermal properties. Laminate 1 exhibited the highest storage modulus, demonstrating superior structural rigidity and stiffness, which is critical for high-performance applications. Furthermore, Laminate 1 displayed the lowest tan δ value, indicating minimal energy dissipation and enhanced vibrational performance, ideal for dynamic loading conditions. Additionally, the elevated glass transition temperature (T<sub>g</sub>) of Laminate 1 (240°C) further underscores its superior thermal stability, making it more suitable for high-temperature environments. These findings highlight the significance of stacking sequence optimization in enhancing both mechanical strength and thermal

stability, positioning Laminate 1 as an ideal candidate for demanding applications, such as high-temperature automotive components. This research not only offers a promising method for CF recovery but also emphasizes the potential for further improvements in the performance of CFRP composites for various industrial applications.

### **Declaration of Interest**

The authors(s) have disclosed no conflicts of interest.

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Not Applicable

### **Data Availability Statement**

This study does not develop nor examines any new data

### **Ethics Statement**

This material was created by the author alone, hasn't been published anywhere else, and isn't currently being considered for publishing anywhere. It fully and properly reflects the study and analysis of the author or authors.

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