International Journal on Science and Technology (IJSAT)
E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Comparative Study of Carbon Fiber-Reinforced Thermoplastics

Mr. Uddipan Pathak

Student, Mechanical Engineering, National Institute of Technology Karnataka Surathkal

ABSTRACT

This study presents a comparative analysis of the mechanical and vibrational properties of carbon fiber-reinforced thermoplastics—specifically PLA, ABS, and PETG—with a fixed carbon fiber (CF) content of 10% by weight. The primary objective is to evaluate the suitability of these composites for functional, load-bearing applications produced via Fused Deposition Modeling (FDM), a popular additive manufacturing method.

Mechanical testing was conducted using a Universal Testing Machine to determine tensile strength and stiffness. Among the tested materials, CF-ABS exhibited the highest stiffness (930 MPa), while CF-PLA achieved the highest ultimate stress (31.1 MPa), indicating strong resistance to mechanical failure. CF-PETG demonstrated the lowest performance in both metrics, attributed to its inherent ductility and weaker fiber-matrix bonding.

Vibrational analysis was performed using free vibration testing in a cantilever configuration. CF-PLA displayed the highest natural frequencies, suggesting superior stiffness, whereas CF-ABS showed a favorable balance between stiffness and damping (3.99%), making it well-suited for dynamic applications. Pure CF unexpectedly exhibited low stiffness and high damping, likely due to manufacturing-related inconsistencies.

These findings highlight how carbon fiber reinforcement enhances specific properties of thermoplastics and emphasize the importance of selecting an appropriate matrix based on application requirements. Future work will involve modal analysis and further exploration into the design of adaptive structures with tunable dynamic responses.

CHAPTER 1
INTRODUCTION

The evolution of lightweight, high-strength composites has revolutionized modern design and engineering practices. These materials provide tailored mechanical and thermal performance to meet the growing needs of the aerospace, biomedical, robotics, and automotive industries. However, the real frontier lies in their application within **additive manufacturing (AM)**—a paradigm shift in how we design, prototype, and manufacture parts.

Among the AM techniques, **Fused Deposition Modeling (FDM)** is the most accessible and widely adopted due to its simplicity, affordability, and design flexibility. While FDM excels in rapid prototyping, its utilization for functional and load-bearing parts is often questioned due to inherent material and process limitations. These include poor interlayer adhesion, anisotropic mechanical behavior, and sensitivity to vibrational and thermal loading.

To overcome these limitations, the integration of high-performance fibers, specifically **carbon fibers**

(CF), into thermoplastic matrices has emerged as a promising strategy. Carbon fibers offer exceptional tensile modulus, fatigue resistance, and damping capabilities, making them ideal for reinforcement purposes. When integrated into materials like **PLA, ABS,** and **PETG**, they significantly alter the composite's structural and dynamic characteristics.

This study delves into the structural and vibrational characterization of **CF-reinforced thermoplastics**, with a fixed CF content of **10%**. It seeks to uncover not just how strong these materials are under mechanical loads, but how well they perform under dynamic excitation, an often overlooked but critically important factor in real-world engineering applications.

CHAPTER 2
DEEP DIVE: OBJECTIVES OF THE STUDY

The study is structured with multi-tiered objectives that aim to bridge the gap between material characterization and practical implementation. These objectives address not only the mechanical and vibrational behavior of carbon fiber-reinforced thermoplastics but also expand into process-performance relationships, design applicability, and future engineering pathways. The goals span fundamental analysis, applied engineering utility, and additive manufacturing optimization.

A. Mechanical Objectives — Static Load Performance Quantitative Evaluation of Reinforcement Impact

- Analyze how the integration of **10% carbon fiber** affects the tensile strength, modulus of elasticity (stiffness), and strain at break (ductility) of **PLA, ABS,** and **PETG**.
- Understand the direction and magnitude of property changes introduced by **CF** in each polymer matrix.

Assessment of Mechanical Performance Trade-offs

Investigate the **stiffness–ductility trade-off**, which is common in fiber-reinforced systems where increasing stiffness often leads to reduced elongation and toughness.

B. Vibrational Objectives — Dynamic Load Behavior Characterization of Free Vibration Behavior

- Analyze the modal behavior of each composite under free vibration conditions.
- Extract parameters such as **natural frequency, damping ratio (ξ), storage modulus (E′), and loss modulus (E″)** through frequency response analysis.

Understanding the Effect of CF on Vibration Response

- Study how **CF** increases stiffness and therefore alters the resonant frequency of the material system.
- Examine the damping characteristics—does **CF** amplify or reduce internal energy dissipation? How does this vary with matrix type?

CHAPTER 3
DETAILED MECHANICAL TESTING APPROACH

The mechanical testing phase of this study is central to understanding the influence of 10% carbon fiber reinforcement on the static behavior of thermoplastic materials. It provides the foundation for evaluating material suitability in load-bearing and structural applications. This section details the entire methodology—from specimen fabrication to post-failure inspection—integrating best practices in materials testing and additive manufacturing research.

A. Specimen Design and Fabrication 3D Printing Parameters:

1. Printing was carried out using **Fused Deposition Modeling (FDM)** on a consistent platform.
2. **Filament Type**: Pre-compounded carbon fiber-reinforced PLA, ABS, and PETG (10% CF by weight).
3. **Layer Height**: Typically 0.2 mm to ensure dimensional accuracy.
4. **Nozzle Diameter**: 0.4 mm brass or hardened steel (CF is abrasive).
5. **Infill Density**: 100% for consistent comparison.
6. **Raster Angle**: ±45° alternating pattern for isotropic in-plane properties.
7. **Print Orientation**: Flat orientation to replicate real-world part performance.
8. All specimens were printed with **identical parameters** to ensure that variations in results could be attributed solely to the material and not the process.

Post-Processing:

All specimens were **conditioned for 24–48 hours** in a controlled environment (23°C, 50% RH) before testing to eliminate moisture and temperature-related variability. Edges were deburred and surfaces lightly cleaned to remove stringing or printing artifacts.

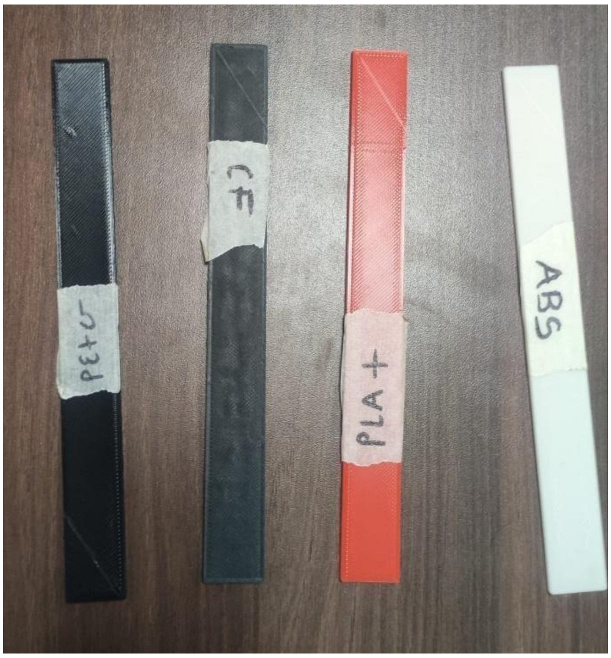


Fig 1: 3D Printed Beams

B. Testing Setup and Execution Equipment:

- A Universal Testing Machine (UTM) with a minimum load capacity of 10 kN was used.
- High-resolution extensometers or non-contact Digital Image Correlation (DIC) systems were used for accurate strain measurement.

Test Conditions:

- **Strain rate**: 5 mm/min to match ASTM D638 guidance for plastics.
- **Room temperature testing**: Ensures compatibility with literature for baseline comparison.
- Specimens were aligned carefully to ensure axial loading and avoid premature failure due to bending or grip-induced stress.

Fig 2: UTM Setup

Data Acquisition:

- Real-time force and displacement data were recorded.
- The stress–strain curve was automatically generated, from which the following mechanical properties were derived
- **Ultimate Tensile Strength (UTS):** The maximum stress before failure.
- **Young's Modulus (E):** The slope of the stress–strain curve in the elastic region.
- **Yield Strength (if applicable):** For materials like ABS with a distinct yield point.

C. Results

The results we obtained are as follows:

1. Pure Carbon Fiber:

Modulus of Elasticity: 815 MPa Ultimate Stress: 30.9 MPa

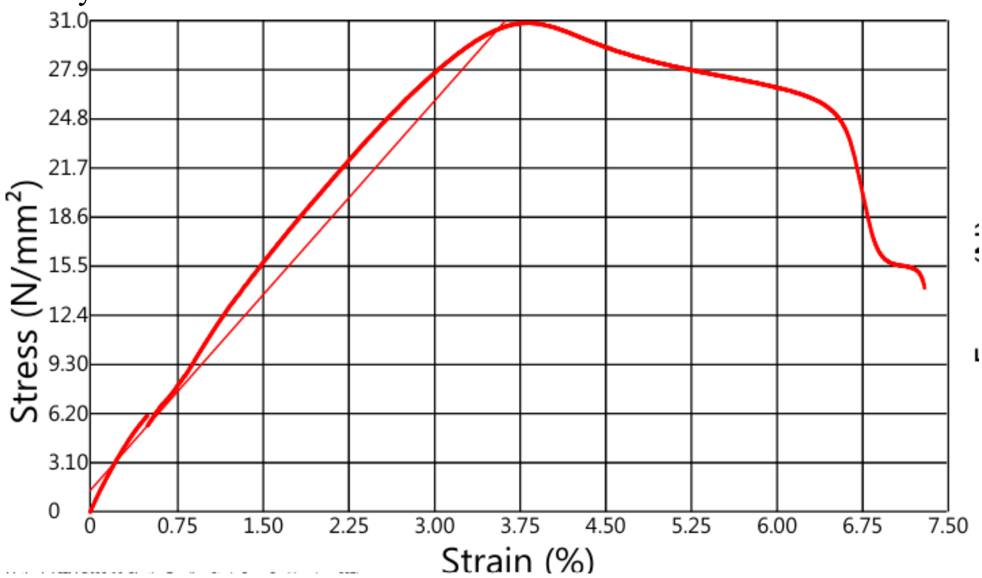


Fig 3: Pure Carbon Fiber Stress Strain Curve

2. ABS + 10% CF:

Modulus of Elasticity: 930 MPa Ultimate Stress: 22.9 MPa

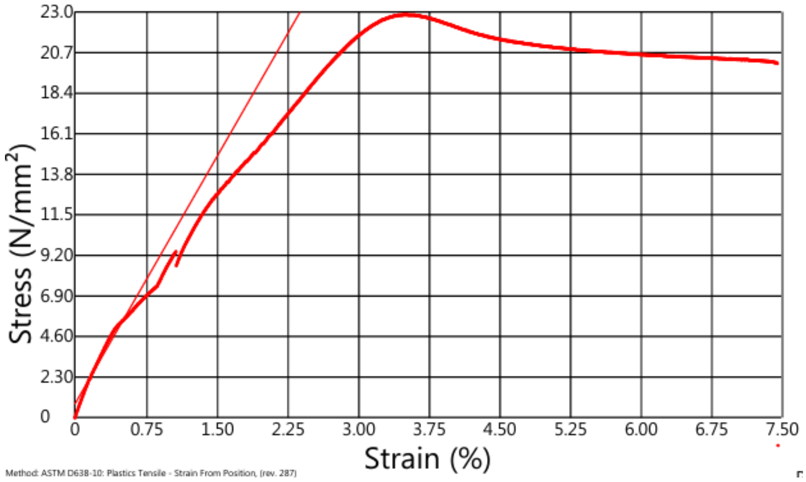


Fig 4: ABS + 10% CF Stress Strain Curve

3. PLA + 10% CF:

Modulus of Elasticity: 633 MPa Ultimate Stress: 31.1 MPa

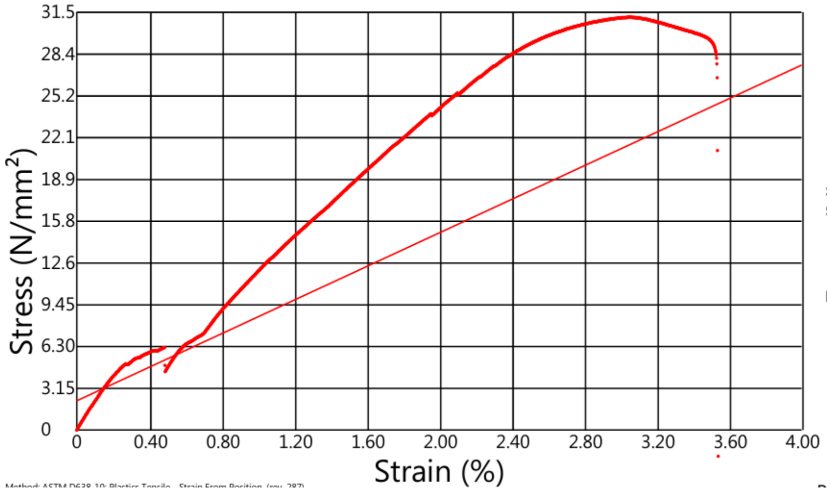


Fig 5: PLA + 10% CF Stress Strain Curve

4. PETG + 10% CF:

Modulus of Elasticity: 322 MPa Ultimate Stress: 20.4 MPa

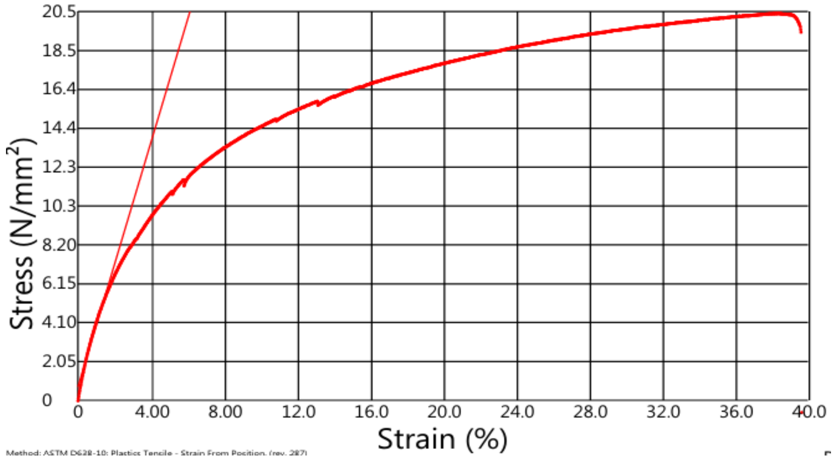


Fig 6: PETG + 10% CF Stress Strain Curve

CHAPTER 4
VIBRATIONAL ANALYSIS METHODOLOGY

Understanding how materials behave under dynamic loading is essential for designing reliable components in systems subject to oscillations, shocks, or cyclic stress. While static tensile testing reveals a material's capacity to bear load, vibrational analysis uncovers how that material responds to energy input, dissipates that energy, and whether it may resonate dangerously under specific conditions.

In this study, the vibrational properties of **PLA, ABS, and PETG**, each reinforced with 10% carbon fiber, were analyzed using free vibration testing techniques. The goal was to determine each composite's **natural frequency, damping behavior, and energy dissipation profile**, enabling informed material selection for dynamic environments such as aerospace brackets, robotic limbs, and automotive mounts

A. Purpose and Scope

The vibrational testing aims to:

- Determine the **natural frequency** of each composite material.
- Measure the **damping ratio** to assess how quickly the material stops vibrating.

B. Experimental Configuration

1. Test Setup

The specimens were tested in a **cantilever beam configuration**, which is widely used in vibrational testing due to its simplicity and well-defined boundary conditions.

- **Support**: One end of the specimen was rigidly clamped in a fixture to prevent translational and rotational motion.
- **Free End**: The other end was left free to oscillate upon excitation.
- **Excitation Method**: A light, controlled impulse was applied at the free end using either a modal impact hammer (with a piezoelectric force sensor), or manual deflection and release method for low-frequency damping studies.

2. Measurement Instrumentation

- **Sensor**: A high-sensitivity **accelerometer** or **laser Doppler vibrometer** (LDV) was mounted or aimed near the free end to capture vibrational motion.
- **Data Acquisition System**: A high-speed DAQ module (e.g., NI USB-4431) was used for analog-to-digital signal conversion.
- **Software**: Signal processing was carried out using tools like **MATLAB**, **SignalExpress**, or **LabVIEW** to extract time-domain and frequency-domain data.

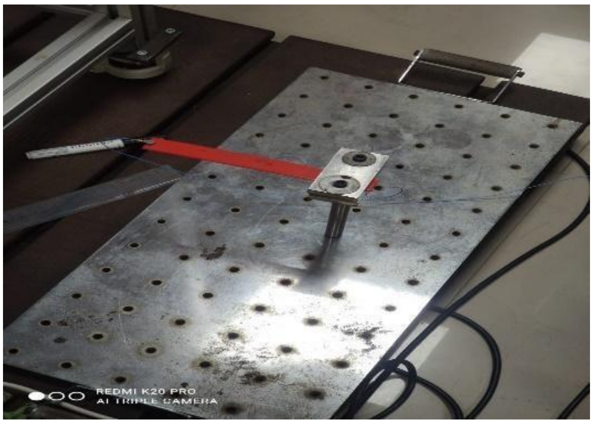


Fig 7: Vibration Analysis Setup

C. Signal Analysis and Parameter Extraction

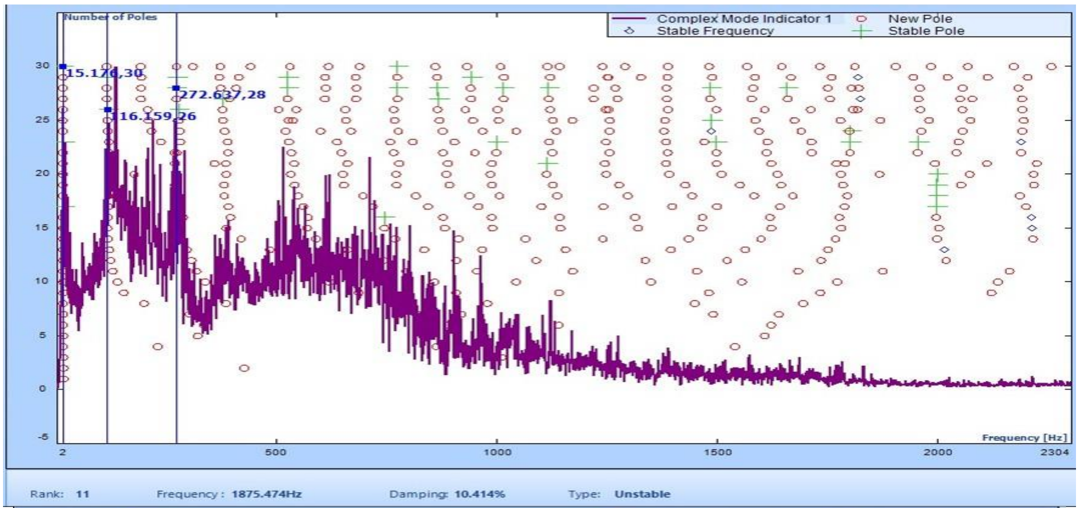
1. **Natural Frequency (fn)**

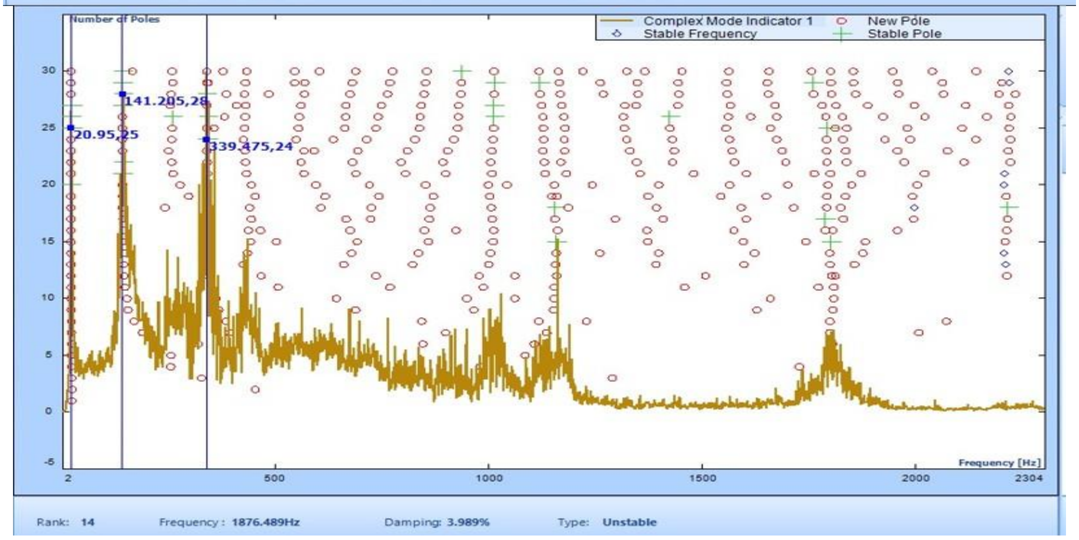
- **Time-Domain Observation**: Oscillation cycles after the initial impulse were recorded.
- **FFT Analysis**: Time-domain signals were transformed into the frequency domain using Fast Fourier Transform to isolate the dominant frequency peaks.
- **Fundamental Mode**: The **first peak** in the FFT spectrum corresponds to the **first natural frequency (fn),** a critical factor in resonance avoidance during design.

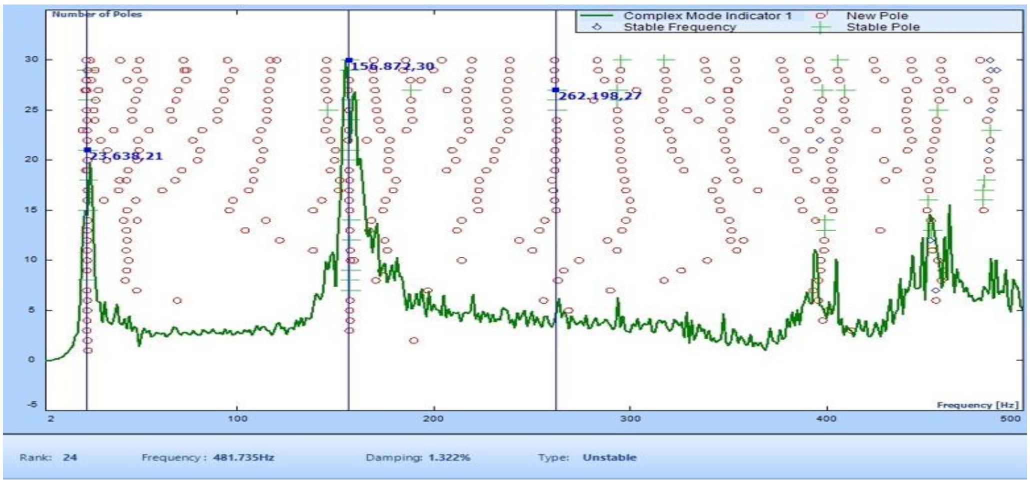
2. **Damping Ratio (ξ)**

The **damping ratio** is a dimensionless measure of how quickly the system loses energy

D. Result







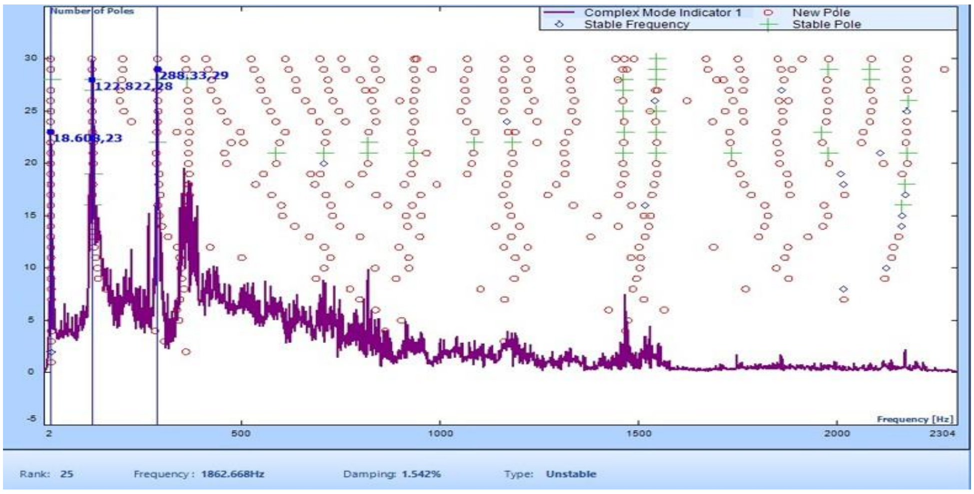


Fig 8: Amplitude vs Frequency Graph of Beams

Beams	Natural frequency 1(hz)	Natural frequency 2(hz)	Natural frequency 3(hz)	Damping (%)
CF	15.176	116.15	272.63	10.414
CF + ABS	20.95	141.20	339.47	3.989
CF + PLA	23.638	156.872	262.198	1.322
CF + PETG	18.608	122.022	288.33	1.542

CHAPTER 5 CONCLUSION

Among the four tested composite beams, **ABS + 10%** Carbon Fiber exhibited the highest stiffness (**930 MPa**) and moderate damping (**3.99%**), making it the most rigid and well-balanced material for structural applications requiring dimensional stability and energy dissipation under dynamic loading. This high stiffness is further supported by its relatively high natural frequencies, suggesting good bonding between ABS and carbon fiber and possibly a denser printed structure.

PLA + 10% Carbon Fiber showed the highest ultimate stress (**31.1 MPa**), indicating the best strength performance under load. It also had the highest natural frequencies, confirming its high stiffness, but with very low damping (**1.3%**). This makes it suitable for components needing high rigidity but where vibration damping is less critical.

Pure Carbon Fiber, surprisingly, did not outperform the composites in either stiffness or strength. It also showed low natural frequencies and unusually high damping (**10.4%**). These results suggest that the sample may not be a standard unidirectional prepreg and could contain defects, voids, or chopped fibers, which reduced its expected performance.

PETG + 10% Carbon Fiber had the lowest stiffness and strength, as well as low natural frequency and damping. Its ductile nature and poor fiber bonding likely caused this, making it unsuitable for load-bearing applications but potentially useful where impact resistance and flexibility are needed.

Overall, the study highlights how material composition and manufacturing method significantly influence mechanical properties. For applications requiring stiffness and structural integrity, **ABS + CF** stands out. For strength-focused use, **PLA + CF** is preferable. The performance of **pure CF** depends heavily on its form, while **PETG + CF** is better reserved for flexible, non-critical components.

CHAPTER 10 REFERENCES

1. Bhaskar Dhiman, Vijay Guleria, Parikshit Sharma (2022). "Applications and Future Trends of Carbon Fiber Reinforced Polymer Composites", researchgate
2. Alaa M. Almushaikeh a, Saleh O. Alaswad a, Mohammed S. Alsuhybani a, Bandar M. AlOtaibi b, Ibrahim M. Alarifi c,(2023) "Recent Advancements in Carbon Fiber-Reinforced Polymer Composites: Material Design and Structural Applications" , ScienceDirect – Composites Part B: Engineering
3. Basheer A Alshammari (2021) "Carbon Fiber Reinforced Polymer (CFRP) Composites for Aerospace and Automotive Applications: A Review"**,** PubMed Central (PMC)