Advancing the Durability of Carbon Fiber-Reinforced Composites for Building Hollow Beams

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ABSTRACT

Additive manufacturing, a highly effective and versatile method, is widely recognized for its ability to create various structures like office and residential buildings, interior partitions, boundary walls, and architectural components. This study is centered on enhancing hollow beams through the use of fused filament fabrication (FFF) technology, utilizing carbon fiber-reinforced polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) materials. The primary focus is on investigating the vibration properties of these beams, particularly examining their stiffness and damping characteristics. Through the application of free vibration testing using an impulse hammer, an analysis was carried out on the natural frequency and damping. Notably, the outcomes reveal that carbon fiber-reinforced ABS exhibits superior damping performance compared to PLA under similar circumstances. Moreover, flexural tests were executed following ASTM standards to evaluate the stiffness of the materials when subjected to transverse vibrations. The findings suggest that ABS when reinforced with carbon fiber, showcases enhanced stiffness and damping properties in comparison to PLA. This detailed examination underscores the benefits of integrating carbon fiber-reinforced ABS into additive manufacturing practices, especially in the construction of hollow beams for diverse structural requirements.

Keywords: Additive manufacturing, Fused filament fabrication (FFF) technology, Carbon fiber-reinforced materials, Hollow beams, Vibration properties.

Introduction

Acrylonitrile Butadiene Styrene (ABS) represents a thermoplastic polymer recognized for its chemical and thermal stability, toughness, and durability. Due to its low melting point, ABS is suitable for injection molding and 3D printing, boasting a glossy finish thanks to the presence of styrene. Its robust tensile strength, along with resistance to chemical corrosion and physical impacts, positions it favorably for rigorous environments and demanding applications. Understanding the dynamics of composite structures is pivotal, especially in the examination of free vibration in 3D-printed ABS reinforced with carbon fiber. The rising usage of 3D printing technology for intricate and personalized composite structures has led to a surge in interest, notably in carbon fiber-reinforced ABS. This variant is admired for its exceptional mechanical properties and high strength-to-weight ratio.

Numerous studies have explored the mechanical facets of carbon fiber-reinforced 3D-printed ABS. Notably, Wang et al. (2020) delved into the dynamic mechanical characteristics of these composites, observing that the incorporation of carbon fiber bolstered material stiffness and strength, thereby elevating the natural frequency. Ching et al. (2020) similarly researched the influence of carbon fiber content on the mechanical aspects of 3D-printed ABS composites and highlighted improvements up to a certain threshold. In another investigation by Ali et al. (2019), the dynamic response of 3D-printed ABS reinforced with carbon fiber displayed enhanced stiffness and damping properties, resulting in increased natural frequencies and decreased vibration amplitudes. These studies underscore the potential of carbon fiber-reinforced 3D printed ABS for dynamic applications, providing valuable insights for tailored composite structures in sectors like aerospace, automotive, and medical devices.

Polylactic acid (PLA), a biopolymer derived from lactic acid, has gained recognition due to its biocompatibility and biodegradability, establishing itself as a viable alternative to conventional petroleum-based polymers. The versatility in processing PLA allows for a wide array of industrial applications encompassing textiles, packaging, biomedicine, and automotive components. PLA carbon fiber, a lightweight composite material, caters to industries seeking reduced-weight solutions such as aerospace and automotive sectors, presenting environmental advantages through biodegradability and sustainable sourcing. With enhanced 3D printing capabilities, PLA carbon fiber emerges as a feasible solution across various applications, addressing concerns like warping or breakage during printing processes. Studies like that of Venkat Agarwal have concentrated on enhancing the mechanical attributes of 3D printed materials through vibration tests to ameliorate fatigue and tensile characteristics. The comprehension and optimization of properties via free vibration analysis can lead to the creation of innovative structures with improved performance attributes.

The evolving research landscape underscores the positive outcomes associated with integrating carbon fiber into 3D printed materials, enhancing their mechanical properties, and unlocking novel avenues for diverse sectoral applications. The optimal amalgamation of carbon fiber may vary, underlining the necessity of customized solutions to meet specific application requisites.

Optimal Materials for Efficient Additive Manufacturing

DUCHOFILLA offers wire-based filaments as ideal materials for Additive Manufacturing processes. These wire filaments typically have a standard width of 1.75 mm. Studies conducted by Ahmed et al and Haque et al revealed that incorporating 15 to 20 percent short carbon fiber into ABS and PLA respectively can improve their mechanical properties. To conduct this investigation, the AbsolacTM grade filament for ABS and IngeoTM for PLA were utilized. The selection of the correct material is crucial for the success of Additive Manufacturing. By incorporating suitable filament types, such as short carbon fiber, even greater mechanical performance enhancements can be achieved for ABS and standalone PLA materials.

Parameters	Range
Bed size (mm)	200 x 200 x 200
Printing speed	3600 mm/min
x/y axis movement speed	4000 mm/min
Z axis movement speed	1000 mm/min

Table 1 Printing parameters

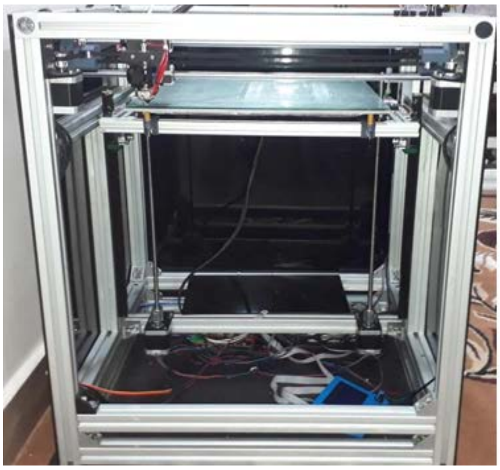


Figure 1a. Fused filament fabrication of composites

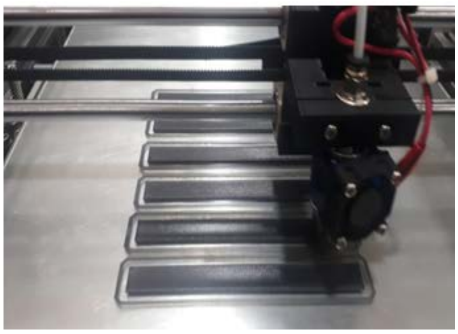


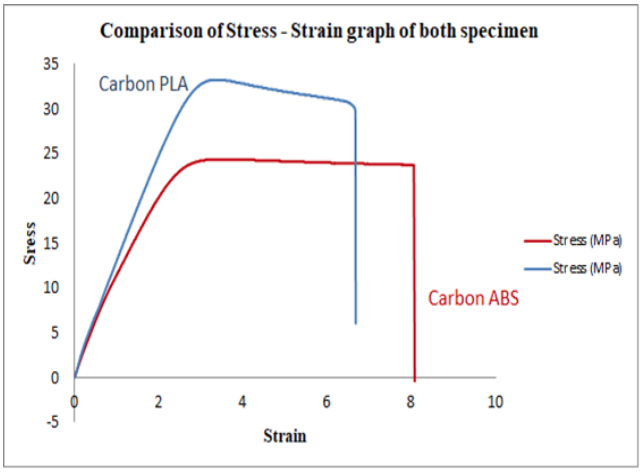
Figure 1b. Tensile test Specimens

Methodology for Tensile and Flexural Testing Based on ASTM Standards

The focus of the study is to utilize a well-known desktop FDM 3D printer for experimentation. Both ABS and PLA filaments will be employed for producing standard test samples, following the recommended printing configurations for each material. The specimen measurements will adhere to the standards specified in the ASTM D 3039 guideline, which sets the dimensions for both tensile and flexural test samples. The tensile test specimens will have measurements of 250 mm x 13 mm x 4 mm, while the flexural specimens will have dimensions of 125 mm x 13 mm x 4 mm. A recent study detailed in the Journal of Reinforced Plastics and Composites investigated the mechanical properties of 3D printed PLA and PLA with short carbon fibers. The results showed a significant enhancement in the tensile and flexural strengths of the PLA composite with the addition of carbon fibers. Specifically, the tensile strength experienced a 35% boost, while the flexural strength displayed a 56% improvement compared to pure PLA. Additionally, the research emphasized that incorporating carbon fibers also increased the impact resistance and hardness of the PLA composite (Jiang et al., 2020).

Figure 2a. Tensile test

Figure 2b. Flexural test



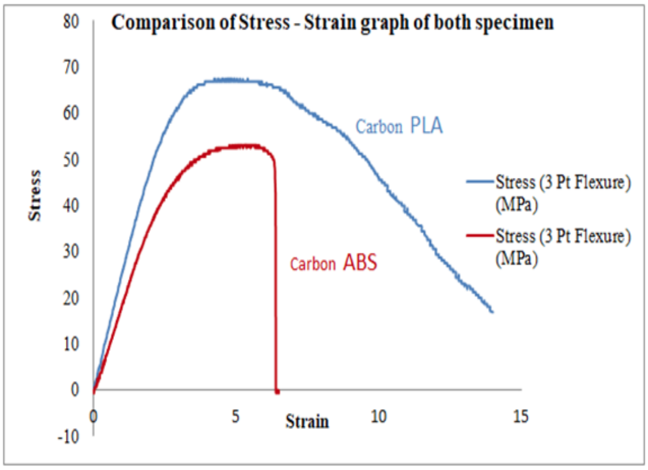


Figure 2c. Tensile strength

Figure 2d. Flexural strength

Figure 2. Comparative Analysis of Tensile and Flexural Strengths for Carbon Reinforced Plastics

FLUCTURAL STRENGTH COMPARISON

Carbon fibers are well-known for their high stiffness and strength, which can improve the stiffness and strength of the composite material. This is because the carbon fibers are capable of bearing load and reinforcing the polymer matrix, resulting in a more durable and rigid material. Additionally, the inclusion of carbon fiber can improve the bonding between the fiber and the polymer matrix. This is because of the high surface energy of carbon fibers, allowing for the development of strong chemical bonds with the polymer matrix. This enhanced adhesion can prevent fiber pull-out, thereby improving the toughness and longevity of the composite material.

In summary, the addition of carbon fiber to ABS or PLA can greatly enhance the mechanical properties of the composite material, such as increased stiffness, strength, toughness, and thermal stability. However, it is crucial to consider that the specific properties of the composite will vary depending on the type, length, and concentration of the carbon fiber used.

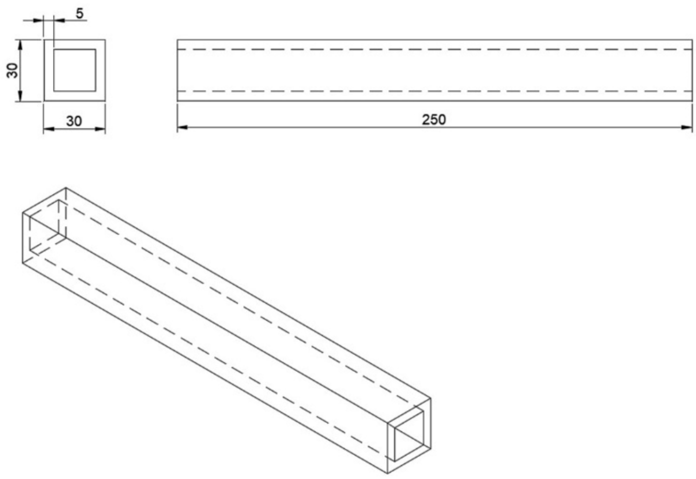


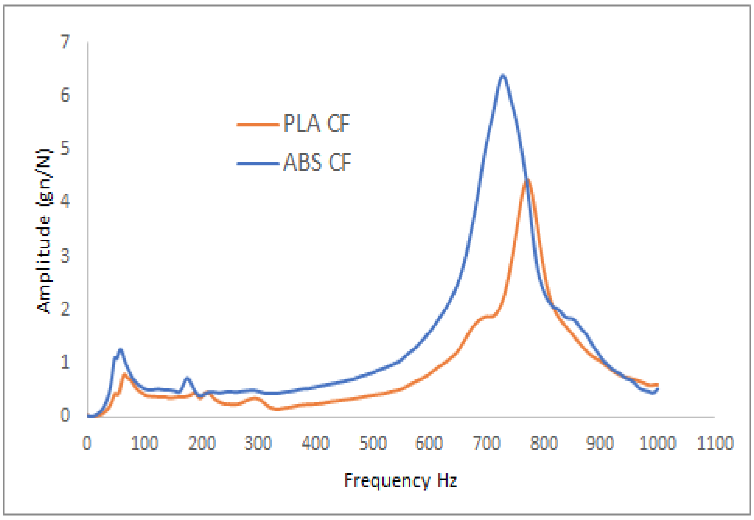
Fig. 3. Fabrication Dimensions of Hollow Shaped Beam (All Dimensions are in mm).

FREE VIBRATION TESTING

Vibration tests without restraint were conducted on beams with fixed or cantilever boundaries using impulse frequency response examinations. An impulse hammer was utilized to impact a composite beam with constraints through a force transducer device (Dytron model 5800B3), while the ensuing vibration was gauged with a piezoelectric accelerometer (Dytron model 3055B2). The captured signal was processed using an FFT analyzer data acquisition system (Dytron model Photon 200) and saved on a computer. The vibration data from the tests were used to formulate the frequency response function (FRF) utilizing the RT-Pro application software, which was then scrutinized to detect the original natural frequency, following resonance frequencies, and their corresponding damping coefficients. Multiple consistent test trials, ranging between eight to ten, were conducted to ensure the dependability of the vibration response pattern.

Figure.4.Experimental Investigation of Free Vibration Testing on Hollow Shaped Beams and Beam Fabrication

Figure.5. Comparative Analysis of Tensile Specimens Post-Failure: ABS versus PLA with Carbon Fiber



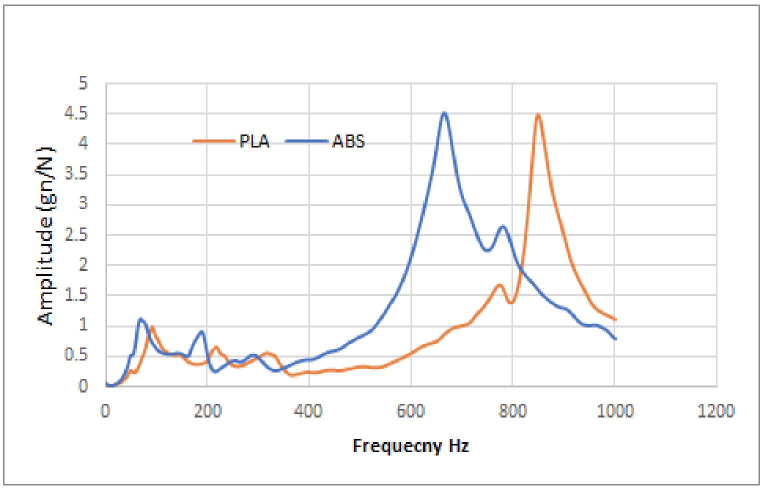


Figure.6. Comparison of Frequency Response Functions (FRF) for Carbon Fiber Reinforced Composites and Virgin Composites

	Material	ABS	PLA	PLA CF	ABS CF
Set 1	Frequency Hz	68	92.39	28	66
	Damping	4.2	5.1	5.74	6.62
	Amplitude gn/N	1.1	0.9	1.26	0.794
Set 2	Frequency Hz	664	848	728	772
	Damping	2.67	4.95	2.07	6.39
	Amplitude gn/N	4.5	4.47	5.38	4.42

Table 2: Analysis of Resonant Frequency Sets and Damping Values in Composite Beams

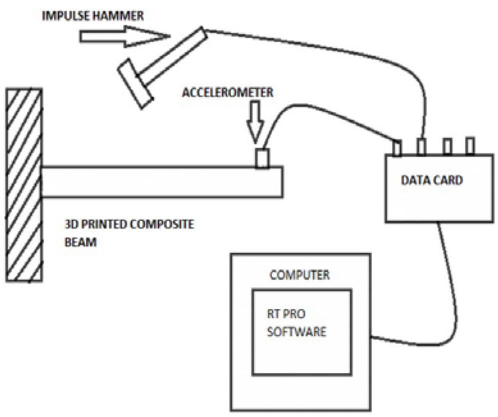


Figure.7. A Visual Representation Structural Testing of Composite Materials:

Vibration Analysis and Carbon Fiber Impact Study

Incorporating carbon fiber into PLA or ABS materials has been found to decrease resonance levels and improve damping properties significantly. This improvement is evident in the frequency response chart, showing a marked decrease in amplitude compared to pure plastics. A research conducted by Senthamarai Kannan et al in 2019 emphasized that the addition of carbon fiber increases the composite's flexibility due to the damping effect, leading to higher flexural strength in comparison to unmodified composites. The outcomes of free vibration tests further support this relationship, demonstrating that factors such as orientation, carbon fiber volume percentage, and operational variables affect frequencies and test results.

Enhanced flexibility and strength play crucial in maintaining overall physical well-being. Flexibility enables the free movement of muscles and joints, reducing the chances of injuries and enhancing performance in physical activities. Regular inclusion of stretching and mobility exercises in our exercise routine can improve flexibility and range of motion. Conversely, gaining strength through resistance training can lead to increased muscle mass, better bone density, and a faster metabolism. Combining flexibility and strength training not only boosts resilience to physical challenges but also elevates the overall quality of life.

Prioritizing flexibility and strength in our fitness regimen, whether through yoga, Pilates, weightlifting, or bodyweight exercises, is essential for achieving a holistic and healthy body.

Conclusion

The study outcomes illuminate the vibration features of composite sheets composed of polylactic acid (PLA) strengthened with carbon fibers. These resources reveal promising potential for vibration-sensitive applications. The introduction of carbon fibers leads to reduced vibration magnitudes and enhanced damping features in comparison to standard PLA material.

Moreover, an inquiry accentuates a significant rise in both tensile and bending strength of the PLA-carbon fiber composites, a tendency that matches with preceding investigations. This remarkable surge in bending strength shines, indirectly supporting the superior damping features observed in beams produced from these composite supplies.

Overall, these findings highlight the practicality of utilizing carbon fiber-reinforced PLA composites in vibration-sensitive uses, offering enhanced mechanical features and damping abilities. These strides bear implications for various sectors like aviation, automotive, and construction engineering, where reducing vibrations is crucial for optimum performance and safety. Further research in this domain could delve into additional parameters influencing the vibration conduct of these composites and refine their operation for precise applications.

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