

Influence of Stacking Sequence on the Mechanical Behavior of Hybrid Carbon–Flax Fiber Composite Laminates for Lightweight Structural Applications

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Abstract This paper presents an experimental study on hybrid carbon–flax fiber reinforced epoxy laminates developed for lightweight structural use, with special relevance to bicycle frame applications. Four laminate configurations were examined: Carbon/Carbon/Carbon, Flax/Flax/Flax, Carbon/Flax/Carbon, and Flax/Carbon/Flax. The aim of the work is to understand how fiber hybridization and layer arrangement influence the overall mechanical response of the composite. Carbon fiber was selected for its rigidity and load-bearing capability, while flax fiber was included to introduce sustainability, reduced density, and improved damping characteristics. A series of mechanical tests was carried out to study tensile, compressive, and flexural behavior, along with additional evaluations for impact resistance and material durability. The experimental observations were supported by finite element analysis to better interpret stress distribution and deformation behavior under loading. The study shows that laminate architecture strongly affects performance, and that hybrid composites can provide a practical balance between structural efficiency, weight reduction, and environmental responsibility.

Keywords Hybrid composites, carbon fiber, flax fiber, stacking sequence, epoxy laminate, bicycle frame, mechanical testing, finite element analysis

1. Introduction

Lightweight materials with high strength and good durability are increasingly important in transportation, sports equipment, and structural engineering. Fiber-reinforced polymer composites are widely used because they combine low weight with excellent mechanical efficiency and design flexibility. Carbon fiber composites are especially valued for their stiffness and load-carrying ability, but their higher cost and low environmental friendliness encourage the search for alternative or complementary reinforcement systems. Natural fibers such as flax offer an attractive route toward more sustainable composites because they are renewable, lightweight, and

capable of absorbing vibration energy effectively. Hybrid composites provide a way to combine the advantages of both synthetic and natural fibers in one laminate. In this project, carbon and flax fibers are used together in an epoxy matrix so that the composite can benefit from carbon's structural strength and flax's damping and sustainability. Since the outer layers of a laminate carry higher stress in bending and loading, the stacking order becomes an important design variable. For this reason, four different layer arrangements were selected to compare pure carbon, pure flax, and two hybrid forms with reversed surface compositions. This makes the study useful not only for

material

comparison, but also for understanding how sequence design affects real structural performance.

2. Literature Review

According to Shah, Schubel and Clifford (2013), natural fiber reinforced composites such as flax fiber have gained attention in engineering applications due to their low density, renewable nature and good vibration damping properties, making them suitable for lightweight structural components.

According to Amiri, Banks and Pullen (2017), hybrid composites combining carbon fiber and flax fiber can achieve high strength and stiffness while also improving vibration damping characteristics, which make them suitable for applications such as bicycle frames.

According to Yan, Chou and Jayaraman (2014), flax fiber reinforced composites provide good energy absorption and impact resistance compared to many synthetic fiber composites, which improves structural durability in hybrid composite systems.

According to Fiore, Scalici and Valenza (2014), hybridization of natural fibers with synthetic fibers such as carbon fiber significantly improves the mechanical properties of composites, including tensile strength, flexural strength and stiffness.

According to Jawaid and Abdul Khalil (2011), the stacking sequence of fibers in hybrid composites plays an important role in determining the mechanical behavior, impact resistance and overall structural performance of laminated composites.

According to Pickering, Efendy and Le (2016), natural fiber hybrid composites offer an effective balance between mechanical performance, environmental sustainability and cost reduction when compared to fully synthetic fiber composites.

3. Materials and Methodology

The composite specimens were prepared using carbon fiber, flax fiber, and epoxy resin. The laminates were produced by hand lay-up, which allowed the layers to be placed according to the intended stacking sequence before curing. The four configurations studied were Carbon/Carbon/Carbon, Flax/Flax/Flax, Carbon/Flax/Carbon, and Flax/Carbon/Flax. These layups were selected to establish a comparison between a carbon-dominant laminate, a flax-dominant laminate, and two hybrid cases in which the surface and core layers are arranged differently. The laminate design itself was intended to reveal how the position of each fiber type influences strength, toughness, and surface protection.

The experimental program included tensile testing, compression testing, flexural testing, impact evaluation, wear assessment, and water absorption observation. Selected specimens were also intended for microscopic examination to study fracture behavior and fiber-matrix

bonding. In parallel, finite element analysis was used to simulate the structural response and to examine deformation and stress concentration under applied loads. This combined experimental and numerical approach supports a more complete interpretation of laminate behavior and helps connect specimen-level results with structural design needs.

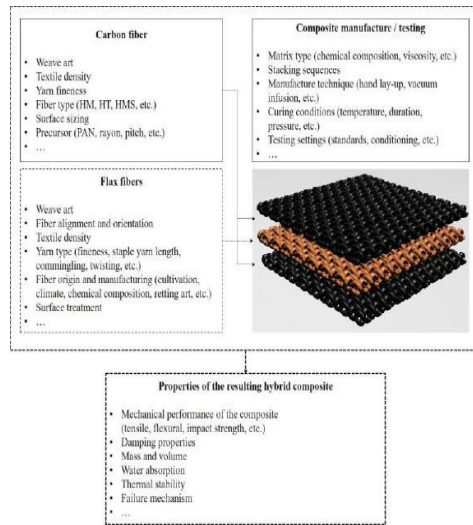


Figure 1: Factors affecting the properties of the resulting hybrid carbon/flax composites.

4. Laminate Design Logic

The fully carbon laminate was included as the reference configuration because it represents the highest-strength reinforcement condition in the study. It serves as the benchmark for comparing the performance of hybrid and natural-fiber systems. The fully flax laminate was introduced to evaluate the behavior of a natural-fiber composite and to highlight the advantages and limitations of a sustainable reinforcement system. The two hybrid laminates were then used to study the effect of placing carbon on the outside or the inside of the stack. Carbon on the outer surfaces is expected to improve surface durability and bending resistance, while flax in the core can contribute to damage tolerance and energy absorption. Reversing the order allows comparison of how natural fibers behave when they are exposed at the surface.

5. Experimental Overview

The test observations indicate that the mechanical response of the composite depends strongly on fiber type and laminate sequence. The carbon-dominant specimen acts as the stiffest baseline and reflects the high load-bearing character expected from carbon

reinforcement. In contrast, the flax-dominant laminate represents a more compliant structure with greater emphasis on energy dissipation and sustainability, but with lower rigidity than the carbon system. The hybrid laminates fall between these two extremes and demonstrate how performance can be tailored by choosing the right stacking sequence.

For tensile and compressive loading, the laminates with carbon placed in the outer layers are expected to carry stress more efficiently because the surface plies experience the highest internal loading in structural service.

This arrangement also improves resistance to damage initiation at the exposed surfaces. The flax-containing layers help moderate brittle behavior and contribute to a more balanced response. In bending-related loading, the difference between the layups becomes more visible, since the outer plies dominate the laminate response. This makes the effect of sequence especially important for frame-type applications where bending and repeated loading are common.

The impact-related observations support the idea that flax layers can improve energy absorption and delay crack growth, while carbon layers provide surface protection and stiffness. The hybrid structures therefore offer a compromise between rigidity and damage tolerance. This balance is particularly valuable

bleinabicycleframecontext,wherethematerial must remain light but still resist repeated service loads, vibration, and occasional local impacts. The combined results suggest that hybridization is not simply a way to mix two materials, but a design strategy for tuning structural behavior.

The qualitative outcome also supports the importance of environmental performance. Natural fiber inclusion improves the sustainability profile of the laminate, while the carbon layers help compensate for the natural fiber's limitations in stiffness and moisture sensitivity. As a result, the hybrid system offers a more practical engineering route than either carbon alone or flax alone when the design goal is a balanced combination of performance, weight reduction, and eco-friendliness.

Conclusion

This study demonstrates that carbon–flax hybrid laminates can be designed to deliver a useful balance of structural performance and sustainability. The comparison between pure carbon, pure flax, and the two hybrid stacking sequences shows that laminate architecture has a major influence on mechanical behavior. Carbon-rich outer layers improve load-carrying efficiency and surface durability, while flax layers contribute to damping and damage tolerance. The experimental program, together with finite element analysis, provides a strong basis for selecting a suitable laminate configuration for lightweight structural components such as bicycle frames. Overall, the work supports hybrid composites as a promising material solution for future sustainable engineering applications.

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