

A Comparison of Commercial Carbon Fiber and Flax Fiber Under Mechanical Stress and Heat Fatigue

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ABSTRACT

This study evaluates the mechanical viability, impact resistance, and thermal resilience of a sustainable flax fiber composite as an alternative to traditional carbon fiber in performance sports equipment. A 3-point bending apparatus was created, and baseline and post fatigue specimens were tested under both room temperature and extreme heat. Quantitative results revealed carbon fiber had the highest absolute stiffness of 24.02 gigapascals, at room temperature, post-impact, it lost 14 percent of its stiffness in its flexural modulus due to microfracturing. Flax experienced a 24.1 percent decline in its modulus; however, most notably at elevated temperatures, the flax was optimized, experiencing matrix post-curing from the heat, resulting in a 257.2 percent stiffness increase, a significant change in comparison to carbon fiber. These findings demonstrate that while flax doesn't have the absolute stiffness of carbon fiber, it offers a reliable, sustainable alternative with similar stiffness retention and unique heat optimization for high-performance sports use.

Keywords: biocomposites, flax fiber, flexural modulus, carbon fiber

INTRODUCTION

The purpose of this experiment was to determine whether flax fiber could serve as a sustainable alternative to carbon fiber by testing its flexural modulus and its ability to withstand fatigue. The sports industry prioritizes materials science to find the best material for sports equipment. Carbon fiber dominates the industry as it is found in loads of equipment, including tennis rackets, hockey sticks, and pickleball paddles. This equipment is often subject to two extreme environments: cyclic velocity impacts and extreme thermal fatigue. These come in the form of repetitive hits, shots, etc., as well as being left in hot conditions outside and in cars. The industry has often turned to carbon fiber as it demonstrates a high strength-to-weight ratio and can generally withstand the common fatigue and harsh environments well(Ribeiro et al., 2018). However, carbon fiber draws its own downsides: its lack of sustainability. Carbon fiber requires high amounts of energy to produce; it is often not recyclable or biodegradable(Composites Construction, 2022). Additionally, carbon fiber is often very brittle at failure; when it exceeds its stress threshold, it just snaps. In order to address some of these issues, engineers in the

sports industry have been investigating flax fiber. Flax fiber is a natural bast fiber that comes from the flax plant(*Linum usitatissimum*). Its strength, sustainability, and light weight qualities have made it a staple in the modern engineering community(Zouhar et al., 2022). However, there is limited testing under the two outlined conditions that are essential in the sports industry. This testing gap will be bridged via addressing the question: When subject to cyclic impact fatigue and elevated temperatures to what extent can flax fiber retain stiffness in comparison to carbon fiber? In this study the independent variables that were manipulated were Fiber material(carbon v flax) and the pre conditioning(heating). The dependent variable is the baseline and post fatigue flexural modulus. The variables that were kept uniform were the support span width, the size of the strips, the resin matrix, and the drop mass.

In order to compare these materials and quantify the results 3-point mechanics principles were utilized based on Euler-Bernoulli Beam Theory. In order to convert the raw weights and deflections into material properties 3 main equations were used further detailed in the methods section(ASTM International, 2017). By comparing the flexural stress and strain, this study aims to determine whether flax fiber could serve as a viable alternative to carbon fiber in high impact sports.

METHODS

Two material types were prepared for material testing: a flax fiber composite and a carbon fiber fabric. Both materials were cut into a uniform width of 1 inch. Both materials were coated with West System G/Flex 650 Epoxy Adhesive and were left to dry at 72° F for 24 hours per G/flex instruction, this makes the later heating viable for post-cure. The length of testing as well as the thickness were recorded (Table 1). 1 strip was used per condition.

Material	Testing Length(mm)(L)	Thickness(mm)(d)
Carbon Fiber	122.9	0.700
Flax Fiber	122.9	1.320

Table 1. Thickness and Testing Lengths for Carbon and Flax Fibers

In order to simulate extreme temperature, one group of carbon fiber and flax was heated in an oven at a constant temperature of 150° F for 90 min, then left to dry at room temperature(72°F) before mechanical loads were applied, so that long-term changes to the material were tested rather than a hot, soft polymer being tested.

Before any heating or cyclic impact testing, an initial 3-point bend and deflection measurement was taken. The strips were placed on a standardized 3-point bending apparatus with a support span($L = 122.9$ mm). Static loads of different masses were placed at the midpoint of the strips; the normal forces the masses applied are shown in Table 2 below.

Oct 2026

Vol 12. No 2.

Heating Condition	Normal Force 1(N)	Normal Force 2(N)	Normal Force 3(N)
Room Temperature	5.16006	0.41202	1.11834
Heated	5.16006	1.5696	1.11834

Table 2. The Forces applied to the heated and room temperature strips

After the initial 3-point testing, some strips were heated and others were held at room temperature, but both were subjected to cyclic velocity impacts in order to simulate shots, strikes, hits, etc. This was done by using a custom weight drop apparatus. The specimens were subjected to 100 repetitive vertical hits from a fixed height of 96.7 mm, where a .526 kg ball was dropped down a tube perpendicular with the material clamped down to a lab bench on either side to test the fatigue resistance of the materials. This created a 25.5 mm radius hemispherical strike. The apparatus contained a perpendicular tube to regulate the gravity driven drops, clamps making sure the strip stayed still and the drop mass to simulate impacts. After this, they were once again subjected to the 3-point testing to compare the materials ability to withstand fatigue. In order to make the raw weights into valuable data the following formulas were used. The formula to determine Flexural Stress is shown below (equation 1) (ASTM International, 2017).

$$\sigma = \frac{3FL}{2bd^2} \quad (1)$$

In this equation, F is the force applied to the strip, which in this case is the normal force applied by the weight. L is the length of the strip, b is the width, and d is the thickness. Equation 1 allows the stress applied to each material to be quantified.

Flexural strain is also essential to quantify the data and aids in the creation of stress-strain curves. Equation 2 details Flexural Strain (ASTM International, 2017).

$$\epsilon = \frac{6xd}{L^2} \quad (2)$$

In equation 2, x is the deflection, d is the thickness, and L is the length of the strip.

The Modulus of Elasticity was also determined in this lab for each material, which measures a material's bending stiffness. Hooke's law states that stress and strain are proportional in a region. Equation 3 is shown for the Flexural Modulus (ASTM International, 2017).

$$E = \frac{\Delta\sigma}{\Delta\epsilon} \quad (3)$$

In this experiment, the Flexural Modulus for each material was determined by using the slope from the generated scatter plots, where the vertical axis was Flexural Stress in MPa and the horizontal axis was Flexural Strain.

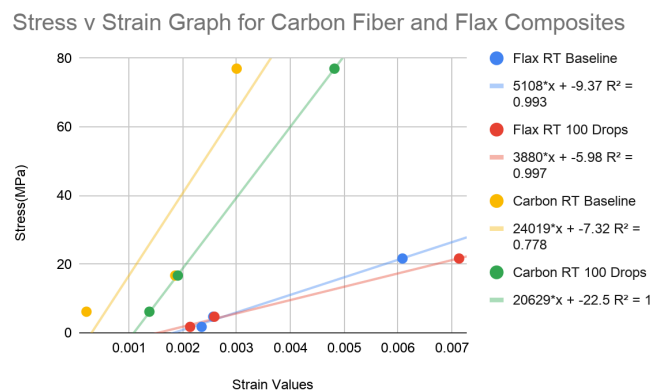
In order to determine the Stiffness Retention equation, 4 was used.

$$\text{Stiffness Retention} = \frac{\text{Final Modulus}}{\text{Initial Modulus}} \times 100 \quad (4)$$

RESULTS/DATA

The strips were subjected to 3-point testing at different weights/Forces and the deflection was recorded (Table 3).

Using this data, the equations for stress and strain (equations 1 and 2) were used to create Graph 1 for room temperature strips.

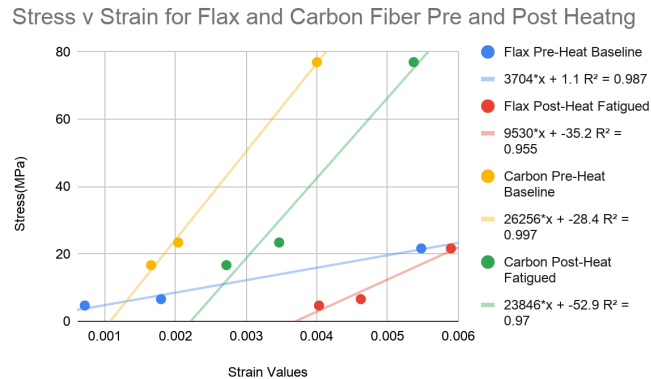


Graph 1. Stress and Strain values plotted for room temperature strips

In this graph, the slope for each line indicates the Flexural Modulus as the Y axis is Stress and the X axis is Strain. From this graph, it can be determined that the modulus for stress is 5.106 GPa initially and after

being subjected to impacts was 3.880. Using equation 4 for stiffness retention, it can be determined that the flax fiber composite at room temperature was 75.99 percent. The Carbon fiber originally had a modulus of 24.019 GPa but dropped to 20.629 GPa, making its stiffness retention at room temperature 85.89 percent. The carbon fiber RT baseline has an R^2 of .778 a low value indicating a lower best fit. This is due to a solo outlier that brought the line down. However this value is still valid as it is reinforced by the 26.25 values in graph 2.

The Heated strips were also recorded identically, and the slopes are shown in Graph 2.



Graph 2. Stress and Strain values plotted for strips heated at 150° F for 90 minutes

This graph indicates that the flax's stiffness increased after being heated, as the modulus went from 3.704 GPa to 9.530 GPa, a 257.28 percent increase. Carbon fiber additionally showed a higher stiffness retention compared to its room temperature retention at 90.82 percent. All of these values are recorded in (Table 4)

Specimen Group	Calculated Modulus(E)(GPa)
Flax RT Baseline	5.108
Flax RT 100 Drops	3.880
Carbon RT Baseline	24.02
Carbon RT 100 Drops	20.63
Flax Pre-Heat Baseline	3.704
Flax Post Heat 100 Drops	9.53
Carbon Fiber Pre-Heat Baseline	26.26

Carbon Fiber Post Heat 100 Drops	23.846
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Table 4.

DISCUSSION

The data collected displays carbon fibers with higher absolute stiffness with a flexural modulus of 24.02 GPa and a 14.11 percent stiffness reduction after the impacts where flax had a lower absolute stiffness and also displayed a 24 percent stiffness reduction. This suggests that at room temperature carbon fiber is not only stiffer but retains its stiffness better. However the degree at which stiffness is reduced is similar to the flax fiber.

The most intriguing takeaway from the data is flax's 257.2 percent stiffness retention when heated. For reference Carbon fiber retained 90.8 percent of its stiffness at this temperature. The increase in stiffness from the flax came as a result of a phenomenon called matrix post-curing. At room temperature, when hand-cured, the resin can overlap and be left fully reacted. The heat provides the activation energy needed to fully react and create a higher density matrix, which locks the fibers of the flax in place, increasing its rigidity(Silva et al., 2020). This discovery displays the attributes of flax that make it a possibly lucrative alternative to carbon fiber. Flax has the ability to regain stiffness via heat because of its natural fibers, making it an extremely intriguing material in sports.

ERROR ANALYSIS/LIMITATIONS

The data collected had very good linearity, leading to overall R's very close to if not 1, which gives reason for confidence in the results due to the cohesiveness. However, there were constraints in the experiment and places of error. Firstly, because the strips were cured by hand, it led to obscure edges and thicker and thinner parts of the strip. The measurements used for the stress and strain calculations, however, were generalized for one strip. This led to anomalies and slightly lower or higher values based on whether the tested strip was thicker or thinner than the measured value. This could be prevented by utilizing a more mechanical curing process. Secondly, the experiment relied heavily on placing the weights at the mathematical center of the strip, while this center was measured out and marked, slight deviation when done by hand could lead to the weights being off by millimeters, ultimately leading to different measurements in stress and strain. Lastly, an engineering term describing how a material deforms over a period of time was not taken into account, so the measurements happened at different time periods. This led to certain strips seeming stronger than they actually were because of the shortened time period. This could have been prevented by creating a procedure where the weight stays on the material for 10 seconds before the measurement to create uniformity and adjust for creep. Additionally the data is exploratory, due to limited resources only 1 trial could be done per condition. However the preliminary observations can be used to further research, through higher # of trials. Despite these constraints and minor errors, the data

Oct 2026

Vol 12. No 2.

remains valid, because these variances were kept uniform, and the data maintained proper trends, making the conclusions of this experiment reliable.

CONCLUSION

This experiment tested whether a flax fiber composite could serve as a reliable alternative to carbon fiber in sports equipment. Through 3-point bending testing, it was quantitatively determined that carbon fiber had the highest absolute stiffness at 24.02 GPa, after 100 impacts, it suffered a 14.1 percent decline. Flax fiber, after 100 impacts, declined 24.1 percent. Under intense heating conditions and impacts carbon fiber's stiffness was retained at a rate of 90 percent, whereas flax actually became stiffer, increasing at 257.2 percent. This is a result of matrix post curing from the heat. Since flax is an organic material and not static, heat can actually increase its stiffness due to the similar pre heat decline difference of roughly 10 percent and the abilities of flax to become stiffer post cure. Flax could serve as a viable alternative to carbon fiber in high impact extreme temperature conditions when more innovation to its absolute stiffness makes it a more sustainable alternative.

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