Comparison of Tensile and Impact Absorption properties of Bio-Inspired Helicoidal stacked with Cross-Ply Stacked Carbon Fiber Laminate

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Abstract. Herrigbone structures are identified on the chitins of the Mantis shrimp. Bio-inspired helicoidal arrangement of composite layers can mimic these herringbone structures. First, the carbon composite samples are fabricated using the hand lay-up method, followed by a curing process using a hot press system. The impact absorption properties of these samples will be analyzed through a series of impact tests. The samples will also be tested for its tensile properties to compare the effect of plies arranged in helicoidal [0,45,90], [0,30,60,90] and Cross-ply orientations to form the laminate structure. The results showed that helicoidal samples have higher penetration tolerance and toughness as compared to Cross-ply samples during impact tests. It is found that the specimen with helicoidal stacking sequence has better debonding resistance and improved damage tolerance. The 6-ply helicoidal samples exhibits higher tensile strength as compared to 6-ply Cross-ply samples due to better fiber to matrix adhesion for helicoidal structure in the direction of pulling force.

1. Introduction

Mantis shrimp is a type of crustacean that has a hard-shelled body and a heavily mineralized dactyl club which it uses to attack its preys. [1] Its dactyl club and telson have shown itself to be useful tools for survival. The chitinous organic matrix of its dactyl club can withstand recurring high velocity impact forces that last in milliseconds without catastrophic failure. [2,3,4] Therefore, the mantis shrimp is a formidable hunter and fighter not to be trifled with. [5] Another interesting point to note is the telson of the mantis shrimp. During ritualized fighting, the mantis shrimp uses its telson as a defense mechanism against the extreme impact force inflicted by the appendages of the perpetuator mantis shrimp. [5,6,7] The fact that the dactyl club and telson can take this extreme impact without breaking has inspired researchers into developing and strengthening armor that mimics the structures of probably nature’s most efficient force absorbers/dissipaters. [3,6,9] In a research article by Weaver et.al and others, the bio-structure on the dactyl...
club is shown to be fibrillar and helicoidal in nature and consists of multiphase composite of oriented hydroxyapatite and amorphous calcium phosphate and carbonate. [1,3,4] Hence in the process of this study, we aimed to mimic these structures by fabricating helicoidal oriented carbon fiber composites.

2. Materials and Methods

2.1 Materials

The hot press system used for this work is supplied by LMS Technologies Pte Ltd. With this system, it assures the uniformity of the carbon fiber composite sample surface during fabrication. This system also allows for variations of temperature, pressure and duration during hot press process. The helicoidal sample is first layered by hand lay-up method with a mixture of epoxy resin to hardener in a ratio of 5:3, before the hot press process is carried out.

Plain weave carbon fiber fabrics and epoxy mix are supplied by Wee Tee Tong Chemicals Pte Ltd. Carbon fiber is a brittle material known to exhibit high tensile properties. [10,11] When infused with epoxy as the matrix, the end-product will be a carbon fiber composite with enhanced material properties.

2.2 Methods for Testing

The tensile test system from Shimadzu as shown in Figure 1a can measure tensile strength of up to 20KN with a measurement accuracy of up to 0.5%. The composite samples are cut to the required dimensions by waterjet cutting which have minimal defect causation compared to other suitable cutting methods. [12] The dimensions of the tab composite samples prepared are with adherence to ASTM D5083 standard. [13] For impact test, the semi-spherical steel impactor made of high strength steel alloy with diameter of 5cm is held by an electromagnet at a height of 1m as shown in figure 1b. The impact test results in insignificant deformation of the impactor relative to the CFRP plate. The 8-ply sample thickness for impact test is compliant to ASTM D7136 standard. [14] Both tensile and impact tests on the samples will be carried out with increasing tensile stress and impact load till they reach their point of failure or when visual defects are observed.

Figure 1 (a) Tensile machine (b) Impact Test System
2.3 Carbon Fiber Composite Fabrication

Three different orientations are explored in the making of the composite samples for this work. Their orientations are (i) Cross-ply and helicoidal stacked arrangement at (ii) $[0, 45^\circ, 90^\circ]$; and (iii) $[0^\circ, 30^\circ, 60^\circ, 90^\circ]$. These samples will be used for tensile tests and impact tests to observe the correlations between fiber orientation, tensile property and durability.

| Table 1. Number of plies corresponding to sample thickness |
|----------------------------------------------------------|
| No. of Plies | Thickness(mm) |
|--------------|---------------|
| 4            | 0.73          |
| 6            | 1.04          |
| 8            | 1.46          |

The number of plies shows a direct proportional increase in sample thickness from 4 to 8 plies.

| Table 2. Parameters for Hot Pressing |
|-------------------------------------|
| Parameters | Value & Units |
| Temperature | 80°C          |
| Pressure    | 30Bar         |
| Duration    | 3600 Seconds  |

The parameters of hot press curing were kept constant throughout the study as tabulated in Table 2. For hand lay-up method, the two caul plates applied with mold release wax were used to sandwich the prepared layers before hot pressing as shown in Figure 2.

Figure 2 Schematic diagram of prepared layers by Hand Lay-up method

3. Results and Discussion

3.1 Drop test results on the Cross-ply and Helicoidal samples

The impact test results show an increasing trend of resilience to deformation with increase in number of layers. The nature of resilience to deformation is drastic especially when the number of layers is increased.
from 6 to 8. Helicoidal samples showed better toughness and penetration resistance as compared to 0°/90° samples. The reason for this behavior is due to the different fiber orientations which prevent continuous matrix cracking that has occurred on Cross-ply samples. Therefore, helicoidal orientation allows for optimal dissipation of energy in every fiber direction [15].

![Figure 3](image.png)

Figure 3 Impact test results for amount of impact energy for sample failure

3.2 Sample Failure Analysis

3.2.1 Impact tested samples

![Figure 4](image.png)

Figure 4 (A) 4 ply failure in 0°/90° orientation and (B) 6 ply

![Figure 5](image.png)

Figure 5 (A) 6 ply failure in 0°/90° orientation and (B) 6 ply helicoidal orientation

![Figure 6](image.png)

Figure 6 (A) 8 ply failure in 0°/90° orientation and (B) 6 ply helicoidal orientation
4 ply and 6 ply samples are used for tensile tests and impact tests in order to find the correlation between number of layers to toughness and different angular orientation. Based on Figure 4 to 6, crack propagation is observed on Cross-ply samples while global indentations are more prominent on helicoidal samples. The reason for the crack propagation to occur on the Cross-ply sample is due to the impact wave being able to readily traverse along the plane. Whereas for helicoidal samples, the orientation of the fibers allows for a larger surface area per unit crack length in the main direction of projectile impact [15]. The high shear resistance from the difference in minute angle between laminas can disrupt the flow of impact wave along a plane and instead evenly distributes the impact force propagation along planar orientations of the helicoidal arrangement. [1,15]

3.2.2 Tensile Test Results

![Figure 7 Plot of Tensile force applied and ultimate tensile strength until sample failure](image)

![Figure 8 Young's Modulus and Yield Strength until sample failure](image)

![Figure 9 Schematic diagram showing multiple points of resistance](image)
It is clear from the results that Cross-ply samples is better than helicoidal sample in terms of tensile strength. However, it is an exception for 6 ply composites; \([0, 45, 90]_2\). 2 layers of carbon fiber fabrics are pointing 45° away from the direction of 90°. The two plies of 45° deviation carbon fiber complements the shear strength and tensile properties of the epoxy matrix as the sample is being pulled in the longitudinal direction. It prevents the phenomenon of carbon fibre pullout from the epoxy matrix which can occur in the case when the fibers are arranged in Cross-ply orientation. The helicoidal orientation of the fibers samples enables it to exhibit higher shear resistance between lamina [16]. The shear resistance to delamination between the orientated lamina by the epoxy interaction with the 45° orientated fibers give rise to higher ultimate tensile strength as compared to Cross-ply samples as shown in Figure 9. During the tensile test on helicoidal samples, delamination begins to occur first at the mid-plane where there are higher traverse shear stresses. The drastic failure suggested by J.L.Liu et al. occurs when the fiber failure meets the delamination point at the mid-plane.[17] From Figures 7 and 8, the increase in the tensile force and the ultimate tensile strength is gradual when the plies were increased from 4 to 6 plies but more significant when it increases to 8 plies.

An observation from the failure analysis of the carbon fiber helicoidal composite that undergoes the tensile test is that there is little delamination, but more signs of drastic fiber breakage. The reason was that the epoxy matrix can adhere to the carbon fiber well, and distribution of force can be consistent throughout the sample during pulling. This optimizes the tensile performance of the helicoidal composite. However, the carbon fiber will reach its breaking point first as it has higher Young’s Modulus compared to epoxy. This also suggests that the tensile strength of the sample is based largely on the carbon fiber instead of the epoxy matrix. An observation of failure for cross-ply samples is that there are many signs of delamination traverse to the pulling force after sample failure. Cracking of the epoxy matrix already begins to form at an early stage of the tensile test before the pull out phenomenal of carbon fiber takes place [18,19,20].

More studies can be carried out on the correlations of orientations using different angles in helicoidal samples to better optimize the tensile force transition from one fiber orientation to another. This may allow the elastic properties of both carbon fiber and epoxy matrix to match closely, thereby reducing the chances of delamination between each layer [15].

4. Conclusion

From the results, we can identify that helicoidal orientations of different step angles can further enhance tensile performance of the carbon fiber composite as seen in Figures 7 and 8. Although samples with helicoidal orientations have inferior tensile properties, impact absorption properties are enhanced, and crack propagation is significantly reduced as compared to Cross-ply samples. Helicoidal samples, when compared to Cross-ply samples, have the potential to exhibit higher energy absorption threshold during tensile pulling when accompanied with appropriate step angles that are close to the pulling force.

5. Reference

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