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Mechanical Behavior of Helicoidal and Pseudo-Orthogonal Fiber Structures

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Abstract: The mechanical properties of glass-epoxy can be improved by incorporating helicoidal and pseudo orthogonal architectures observed in exoskeleton of crustaceans. When two adjacent laminas are placed with a very small angular offset, it is known as helicoidal structure and pseudo orthogonal structure is where a helical structure is placed between two unidirectional orthogonal regions.

Two helicoidal structures and one pseudo orthogonal structure is designed with considering mid-plane symmetry. A quasi-isotropic configuration is also considered as a baseline structure. Flexural modulus and shear modulus was calculated using and was compared among all the laminates. It is observed that the mechanical performance was improved for bio-inspired laminates over the baseline laminate.

Keywords: Laminates, Arthropods, Mechanical properties, Classical laminate plate theory, Flexural modulus and shear modulus.

I. INTRODUCTION

Delamination of a composite is mainly caused due to inter-laminar stresses. To overcome this delamination a helical lay-up can be used. A helicoid system consists of layers of fibers where adjacent layers have very small angular offset. Such helicoidal architecture can be seen in Arthropods such as Homarus americanus (American lobster), Callinectes sapidus (Atlantic blue crab) and Popillia japonica (Japanese beetle) which have hard exoskeletons with high structural properties [[4], [6]]. The primary components of exoskeletons are chitin, proteins, water and minerals. The exoskeletons have multi-functional capabilities including resisting external loads, filtering chemicals and supporting the body weight [[7]]. Chitin is a fibrous substance consisting polysaccharides. Lobster and crab have 3 regions epicuticle, exocuticle and endocuticle.

Epicuticle is thin, waxy protective outmost layer lacking chitin, acts as diffusion barrier. Exocuticle and endocuticle are the load carrying structures which are made of chitin protein micro fibrils. These have similar morphology but different number of layers, thickness and stacks.

The structural pattern is termed as helicoidal structure which has 180° stack, suggested by Bouligand [[1]]. Mesocuticle is an extra layer to Japanese beetle.

Helicoidal structure is present exocuticle and mesocuticle and endocuticle have pseudo-orthogonal structure where two unidirectional orthogonal layers are joined by a thin helicoidal region.

The main objective of this study is (1) to design a commercial material inspired by exoskeleton of Homarus americanus (American lobster), Callinectes sapidus (Atlantic blue crab) and Popillia japonica (Japanese beetle)[[4],[6]] ; (2) calculate the flexural and shear modulus of the bio-inspired laminates and baseline laminate using classical laminated plate theory; compare the results to conclude the advantages in bio-inspired structures over baseline structure.

II. MATERIALS AND METHODS

A. Helicoidal Structure

Adjacent layers stacked on each other with a very small angle rotation about its normal direction as shown in figure 1[[4]]. It is also known as “Bouligand structure” as it was discovered by Bouligand. Helicoidal structure is observed in exoskeleton of crustaceans i.e. lobster, blue crab, Japanese beetle and shrimp. Chitins are fibers of high tensile stiffness and strength and proteins and minerals in exoskeleton acts as matrix material [[4]].

High level of in-plane isotropy in helicoidal structure is due to high number of layers. This provides isotropic response in loading plane. The stiffness transition is smooth when compared to the cross-ply laminate as the angle between adjacent layers are very small and it also posses high interfacial strength [[4], 5]. The helicoidal structure has high stiffness, strength and is durable.

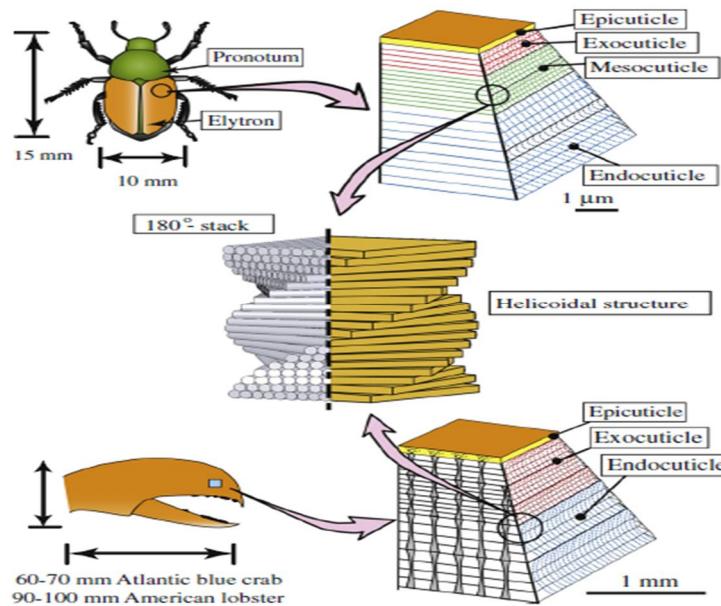


Fig 1 Helicoidal structure in exoskeletons of American lobster Atlantic blue crab and Japanese beetle [[7]].

B. Pseudo Orthogonal Structure

When a helicoidal layer is between two unidirectional orthogonal regions it is called as pseudo orthogonal structure. This structure is found in locust and Japanese beetle cuticle. Pseudo orthogonal structure is considered because it leads to uniform stress and strain distribution in its cross section and also results in reduced maximum tensile stress and transverse shear stress. This provides an overall isotropic structure with an acceptable interfacial strength [[6]].

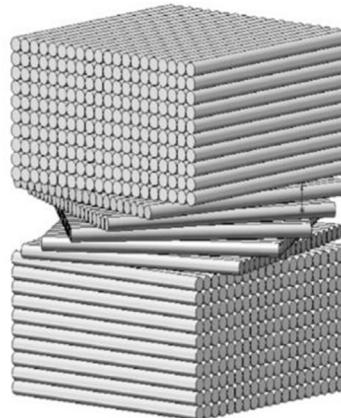


Fig 2 Pseudo-orthogonal structure of chitin-protein fibers in endocuticle in Japanese beetle [[6]].

C. Mechanical Properties

According to ASTM standards a rectangular plate of dimensions 80X10 mm with thickness of 0.25mm per lamina is considered. The mechanical properties of E-glass epoxy composites are shown in table 3. The nominal strength of the GFRP is 800MPa.

E11 (GPa)	E22 (GPa)	E33 (GPa)	G12 (GPa)	G13 (GPa)	G23 (GPa)	v 12	v 13	v 23
45.95	14.56	14.56	4.50	4.50	5.51	0.25	0.25	0.3

Table 1 Mechanical properties of E-glass epoxy where E11 and E22 are the young's modulus along the direction of fiber and orthogonal to fiber, respectively. G12 and G23 are the shear modulus; v 12 and v23 are the Poisson's ratio [[9]].

D. Bio-Inspired Design

Four laminate configurations of 20 plies and dimensions 80X10X5mm with different lay-up sequences were calculated and designed by using MATLAB of each 20 number of plies. The four laminates include one baseline and 3 bio-inspired structures. In these 3 bio-inspired structures, 2 helicoidal laminates and one pseudo orthogonal laminate.

- 1) *Baseline structure (BL)*, symmetric laminate used in industry as quasi-isotropic structure, stacking sequences $[0^\circ 45^\circ -90^\circ 45^\circ 0^\circ]_{2S}$.
- 2) *Single helicoidal (SH)*, anti-symmetric laminate which was directly replicated from nature designed helicoidal structure. 20 numbers of plies are taken of each ply of thickness 0.25mm where each ply requires a 9° rotation. Stacking sequence $[0^\circ/9^\circ.....171^\circ]$.
- 3) *Pseudo orthogonal (PO)*, have 20 number of plies where the first and last 8 plies are 0° and 90° respectively, and in between these two unidirectional plies a helicoidal structure of 4 plies where each ply has a 18° rotation. This structure provides overall isotropic structure. Stacking sequence, $[0^\circ_8/18^\circ_4/36^\circ_4/54^\circ_4/72^\circ_4/90^\circ_8]$
- 4) *Single helicoidal mid-plane symmetric laminate (SHMS)*, the upper half of 10 plies is same as single helicoidal laminate and its lower half is mirrored with respect to mid-plane of laminate. Thus, it enforces mid-plane symmetry. Stacking sequence $[0^\circ/9^\circ.....81^\circ]_S$.

Structure Designation	Specification	Number of Laminas	Stacking Sequence
BL	Baseline	20	$[0^\circ 45^\circ 90^\circ -45^\circ 0^\circ]_S$
SH	Single Helicoidal	20	$[0^\circ/9^\circ.....171^\circ]$
PO	Pseudo Orthogonal	20	$[0^\circ_8/18^\circ_4/36^\circ_4/54^\circ_4/72^\circ_4/90^\circ_8]$
SHMS	Single Helicoidal Mid-Plane Symmetric	20	$[0^\circ/9^\circ.....81^\circ]_S$

Table 2 Investigated laminate structures and their stacking sequences

E. Classic Laminate Plate Theory

According to classical laminate theory the ABD matrix is calculated [APPENDIX]. Matrices of extensional stiffness A (N/m), bending extensional coupling stiffness B (N) and bending stiffness D (N/mm²) of

- 1) Baseline

$$A = \begin{bmatrix} 147.69 & 41.22 & 0 \\ 41.22 & 115.66 & 0 \\ 0 & 0 & 67.80 \end{bmatrix}, B = 0 \text{ and } D = \begin{bmatrix} 0.0003 & 0.0001 & 0 \\ 0.0001 & 0.0002 & 0 \\ 0 & 0 & 0.0001 \end{bmatrix}$$

- 2) Single helicoidal

$$A = \begin{bmatrix} 126.01 & 46.88 & 0 \\ 46.88 & 126.01 & 0 \\ 0 & 0 & 79.13 \end{bmatrix}, B = \begin{bmatrix} -0.135 & 0.0035 & -0.085 \\ 0.0035 & 0.0065 & -0.0414 \\ -0.085 & -0.0414 & 0.0071 \end{bmatrix} \text{ and } D = \begin{bmatrix} 0.0004 & 0.0001 & 0 \\ 0.0001 & 0.0002 & 0 \\ 0 & 0 & 0.0001 \end{bmatrix}$$

- 3) Pseudo orthogonal

$$A = \begin{bmatrix} 147.25 & 25.64 & 12.32 \\ 25.64 & 147.25 & 6.16 \\ 12.32 & 6.16 & 36.65 \end{bmatrix}, B = \begin{bmatrix} -0.098 & 0 & -0.0024 \\ 0 & 0.0988 & 0.0012 \\ -0.0024 & 0.0012 & 0 \end{bmatrix} \text{ and } D = \begin{bmatrix} 0.0003 & 0 & 0 \\ 0.0001 & 0.0003 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

- 4) Single helicoidal mid-plane symmetric

$$A = \begin{bmatrix} 134.02 & 46.88 & 50.54 \\ 46.88 & 147.25 & 25.27 \\ 50.54 & 25.27 & 79.13 \end{bmatrix}, B = 0 \text{ and } D = \begin{bmatrix} 0.0004 & 0.0001 & 0 \\ 0.0001 & 0.0002 & 0 \\ 0 & 0 & 0.0001 \end{bmatrix}$$

III. RESULTS

A. Flexural Modulus

Flexural modulus gives the stiffness of the structure. A stiffer material has high flexural modulus. From the classic laminate theory, the equivalent flexural modulus for a laminate is calculated for the given material properties and stacking sequences. The D matrix is calculated as shown in Appendix A.

$$\text{The equivalent flexural modulus } [3] \text{ is } E_{BE} = \frac{12D_{11}}{h^3}$$

Where, h is the total thickness of the laminate.

The normalized flexural moduli for different laminates are shown in figure 3. The normalized flexural stiffness of bio-inspired laminates are high than the baseline structure. Pseudo orthogonal have less flexural modulus than the single helicoidal mid plane symmetry laminate and single helicoidal, because these two have very small angle ply rotation. Single helicoidal mid plane symmetry has the highest flexural modulus due to its small angle ply rotation and also its mid plane symmetry.

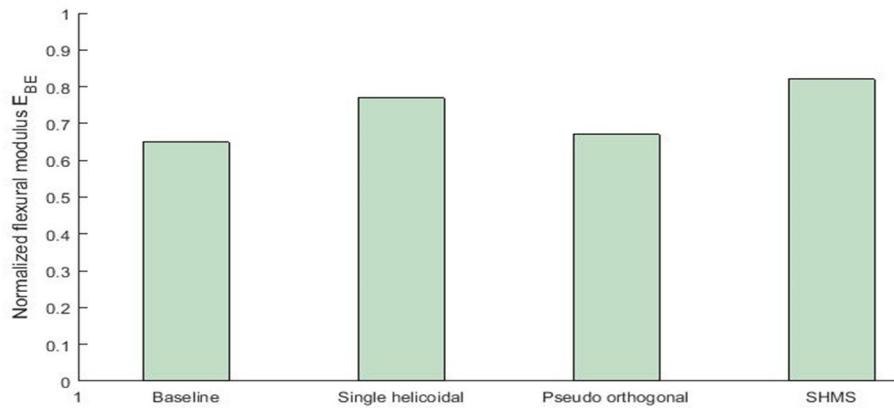


Fig 3 Normalized flexural modulus for baseline(BL), single helicoidal (SH), pseudo orthogonal (PO) and single helicoidal mid-plane symmetry

Structure Designation	Specification	Normalized Flexural Modulus
BL	Baseline	0.65
SH	Single Helicoidal	0.77
PO	Pseudo Orthogonal	0.67
SHMS	Single Helicoidal Mid-Plane Symmetric	0.82

Table 3 Normalized flexural modulus

Table 4

B. Transverse Shear Modulus

Transverse shear modulus shows the material response to the shear stress. When load is applied on one surface of a laminate, its opposite surface experience opposing force like friction than deformation occurs. Shear modulus is concerned with this deformation. Transverse shear modulus is obtained from classic laminate theory with given material properties and stacking sequences.

$$\text{Transverse shear modulus } [3] \text{ is } G_{TE} = \frac{A_{11}}{h}$$

Normalized transverse shear modulus is high in single helicoidal than the other laminates. This depends on both material properties and stacking sequences. Pseudo orthogonal has the least shear modulus as a helicoidal structure is between of two unidirectional laminas.

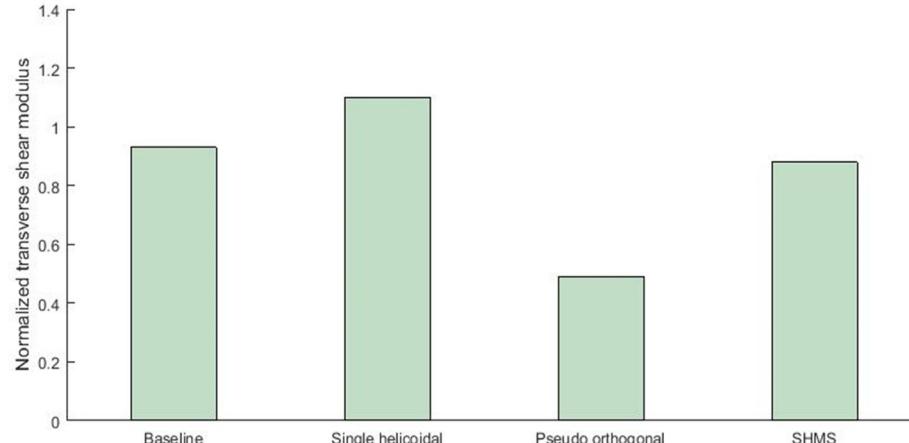


Fig 4 Normalized transverse shear modulus for baseline(BL), single helicoidal (SH), pseudo orthogonal (PO) and single helicoidal mid-plane symmetry

Structure Designation	Specification	Normalized Flexural Modulus
BL	Baseline	0.93
SH	Single Helicoidal	1.1
PO	Pseudo Orthogonal	0.49
SHMS	Single Helicoidal Mid-Plane Symmetric	0.88

Table 4 Normalized transverse shear modulus

As the angle ply rotation is very less and pure 180° stack is present, rigidity is more in single helicoidal. The transverse shear modulus is normalized with the transverse modulus. The table shows the normalized transverse shear modulus for different laminates.

IV. CONCLUSION

This report is to show the mechanical properties of fiber structures which are influenced by nature. A man-made material is designed by studying the properties of helicoidal structure in exoskeleton of arthropods like Homarus americanus (American lobster), Callinectes sapidus (Atlantic blue crab) and Popillia japonica (Japanese beetle) and pseudo orthogonal structure in Japanese beetle. By using classical laminate plate theory, deflection was calculated for different layup sequences of each 20 number of laminas, the layup sequence which got least the deflection was considered to form 4 configurations where 3 were bio-inspired laminates and one cross-ply laminate. These four configurations are (1) baseline (2) single helicoidal (3) pseudo orthogonal and (4) single helicoidal mid plane symmetry. Mid plane symmetry is considered in to avoid warping.

Each laminate is designed as rectangle plate of 80X10X5 mm. Flexural modulus and transverse shear modulus were evaluated from classic laminate theory. These flexural modulus and transverse shear modulus were normalized with longitudinal and transverse modulus, respectively. These results showed that the helicoidal structures mechanical properties are better than the baseline in both flexural modulus and transverse shear modulus. Normalized flexural and transverse shear modulus are high in helicoidal structures which means these are stiffer than the baseline structure and also helicoidal structure is more durable. There is uniform distribution of stress and strain in pseudo orthogonal structure and its deflection is less than the baseline. The mechanical properties in bio-inspired structure showed that the advantage of helicoidal structure with mid-plane symmetry possesses great potential in future applications.

V. APPENDIX

Classical laminate theory used to find strains and curvatures for each lamina or a whole laminate. The main three conditions used are stress-strain relationship, strain-displacement relationship and equilibrium equations. E11, E22 and G12 are young's modulus and shear modulus along the lamina's principle axis. v12 and v21 are Poisson's ratio. The stiffness matrix Q is expressed as,

$$[Q] = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix}$$

$$Q_{11} = \frac{E_{11}}{1 - v_{12}v_{21}}, \quad Q_{22} = \frac{E_{22}}{1 - v_{12}v_{21}}, \quad Q_{22} = \frac{v_{12}E_{22}}{1 - v_{12}v_{21}} = \frac{v_{21}E_{11}}{1 - v_{12}v_{21}} \text{ and } Q_{66} = G_{12}$$

To form the elastic properties of laminea with different orientations when local coordinates of lamina are not aligned with the global coordinates, transformed matrix is necessary. The transformed stiffness matrix \bar{Q}

$$[\bar{Q}] = [T]^{-1} [Q] [T]^T$$

where $m = \cos \theta$ and $n = \sin \theta$, θ is the angle from global axis to the lamina's orientation, transformed matrix T is expressed as,

$$[T] = \begin{bmatrix} m^2 & n^2 & 2mn \\ n^2 & m^2 & -2mn \\ -mn & mn & m^2 - n^2 \end{bmatrix}$$

$$A_{ij} = \sum_{k=1}^N Q_{ij}^k (Z_k - Z_{k-1}), \quad B_{ij} = \frac{1}{2} \sum_{k=1}^N Q_{ij}^k (Z_k^2 - Z_{k-1}^2) \text{ and } D_{ij} = \frac{1}{3} \sum_{k=1}^N Q_{ij}^k (Z_k^3 - Z_{k-1}^3) \quad i, j = 1, 2, 6$$

Aij are the extensional stiffness, Bij are bending-extension coupling stiffness and Dij are bending stiffness. N is the number of lamina, Z_k and Z_{k-1} are the distance from laminate mid surface to upper end and lower end of the kth lamina, respectively.

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