Research Article

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Finite element-based buckling analysis of bio-inspired laminated composite plates

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Highlights

- Buckling behavior of bio-inspired laminates
- Analysis carried out using finite element method
- Lamination schemes inspired from mantis shrimp
- Lamination scheme affects free vibration behavior

Abstract

The helicoidal structures can cater to the loads effectively and efficiently without large deflections or stresses. These structures can even sustain environmental loads without failing. Also, these structures can take impact loads without failing. The present work aims to carry out buckling analysis of bio-inspired helicoidal laminated composite plates using finite element-based model within the framework of ANSYS. The plate is modeled using SOLID191 finite element (20-node 3D layered structural solid). The present model is validated by comparing the present results with those available in the literature. Influence of end conditions over the buckling behavior of bio-inspired helicoidal laminated composite plates is explored. Some new results are also presented in the present work, which will serve as the benchmark for future studies.

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1. Introduction

Laminated configurations are used in constructing various structures in the fields of civil, automobile, aerospace, marine, defense industries, etc. as the engineering properties in laminated structures can be modified by changing the ply-angle and thickness of each layer [1]. Thus, due to the property of tailorability possessed by laminated composite structures, these structures can sustain the loads effectively. Conventionally, the angle and the number of the ply are chosen randomly and then analyzed for different conditions under the required loading conditions.

The arrangement of tissues in the layers in the biological creatures helps in sustaining the loads in an efficient manner to which they are encountered. The venation in the leaves of the trees helps in connecting them with the branches without encountering large stresses. The elliptical shape of the shell and the material from which it is made up help in protecting him from adverse conditions and prey. The helicoidal structure is present in the various living organisms and helps in withstanding impact loading [2,3]. Even the basic life form, i.e., DNA present in the creatures possesses helicoidal structures. The beetles can even withstand the puncture load of 23 N in its forewing area which is much higher than its fighting force [4] (Figure 1).

Several theories are available in the literature for the bending, free vibration, and buckling analysis of laminated composite and sandwich plates under various loading conditions [5–12]. Mohamed et al. [13] carried out buckling analysis of 32-layered laminated composite plate made up of helicoidal scheme using first-order shear deformation theory (FSDT). Sharma et al. [14] predicted the bending behavior of helicoidal laminated composite plates using higher order shear deformation theory. Garg et al. [15] predicted the free vibration behavior of helicoidal laminated composite plates using higher-order zigzag theory. Garg et al. [16] predicted the free vibration and buckling behavior of helicoidal laminated sandwich plates using finite element based higher-order zigzag theory. Sharma et al. [17] predicted first-ply failure load for cross- and double-helicoidal laminated sandwich plates. Due to the presence of the helicoidal schemes, the crack propagation becomes difficult within the laminate and a higher strength can be achieved.

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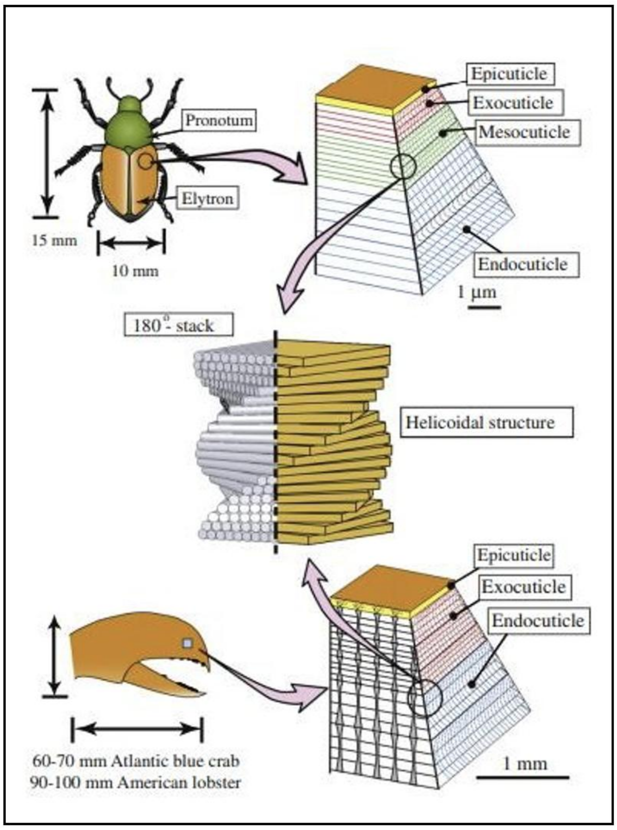


Figure 1. The hierarchical structures of the exoskeletons from Homarus americanus, Callinectes sapidus, and Popillia japonica. The Helicoidal structural pattern is observed in different regions of all the exoskeletons [18].

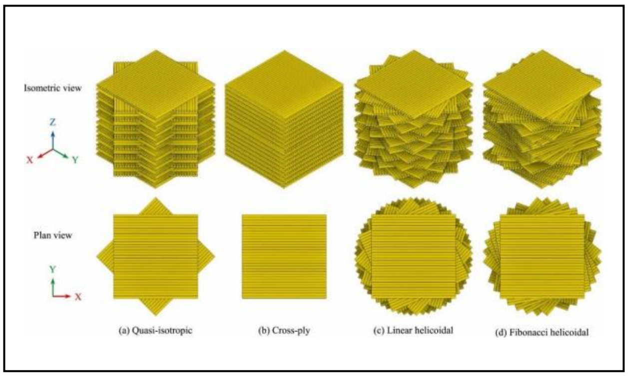


Figure 2. Different lay-up configurations of (a) quasi-isotropic (QI), (b) cross-ply (CP), (c) linear helicoidal (LH), and (d) Fibonacci helicoidal (FH) bio-inspired laminated configurations employed during the present study [4].

Singh et al. [18] in their work reported that by adopting the helicoidal schemes in laminated composite structures, the buckling strength of the plate can be increased. From the review work it has been observed that the influence of end conditions on the buckling behavior of bio-inspired helicoidal laminated composite plates is not fully explored. In the present work, an attempt has been made to carry out the buckling analysis of laminated composite plates containing bio-inspired helicoidal scheme using ANSYS. The efficiency of the present model is demonstrated by comparing the obtained results with those available obtained by Mohamed et al. [13]. Several new results are also reported, which will serve as a benchmark for future studies in a similar direction.

2. Materials and Geometric Modeling

For modeling the helicoidal bio-inspired 32-layered laminated composite plate in ANSYS, SOLID191 finite element (20-node 3D layered structural solid) is employed as this element is specially used for modeling the laminated structures. The helicoidal schemes used during the present study are shown in Table 1 and Figure 2.

The accuracy of the results obtained using the finite element method (FEM), depends on the number of elements adopted. Therefore, at first convergence study is carried out. The material properties used for the same are: $E1/E2$ = Open, $E2$ = $E3$ = 1E6, $G12$ = $G13$ = 0.5E6, $G23$ = 0.2E6, $\nu12$ = $\nu13$ = $\nu23$ = $\nu32$ = 0.25, $\nu21$ = 0.01, $\nu31$ = 0.01. The value for *a/h* = 20 with all edges clamped is taken during the analysis. The results of the buckling for the convergence study are presented in Table 2 for different helicoidal schemes. The present results converges when the mesh size reaches 24 × 24. Therefore, in further studies, the same mesh size is adopted. The present results are in good agreement with those reported by Mohamed et al. [13] and Garg et al. [16]. Some deviation in the present results compared to those reported by Mohamed et al. [13] because of the application of FSDT. FSDT is not able to predict the behavior of laminated structures effectively as this theory assumes constant transverse shear stresses across the thickness of the plate [20].

Table 1. Layup configuration adopted taken from Wang et al [4].

Representation	Number of layers	Stacking sequence
UD	32	[0°/0°.../0°]
CP	32	[0°/90°/0°/90°/.../0°/90°]
QI	32	[0°/45°/90°/-45°]4s
LH	32	[0°/24°/.../360°]s
FH	32	[0°/10°/10°/20°/30°/50°/ 80°/130°/210°/340°/190°/ 170°/360°/170°/170/340°] s

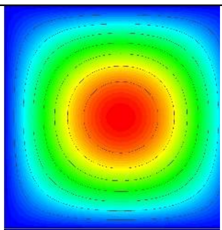
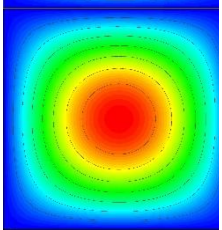
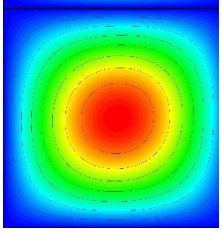
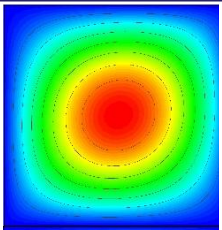
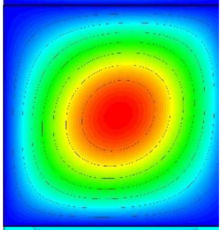
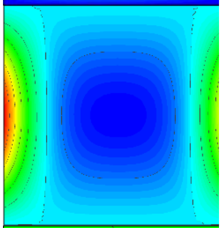
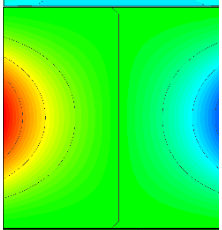
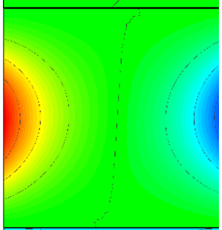
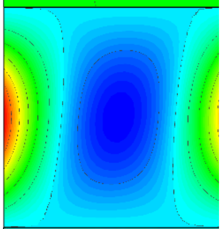
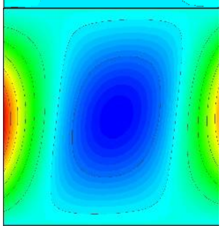
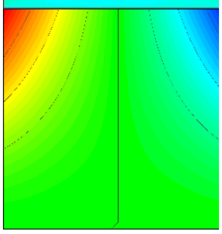
Table 2. Validation study on buckling load $\bar{\lambda} = \lambda a^2/E_2h^3$ of bio-inspired helicoidal laminated composite plate.

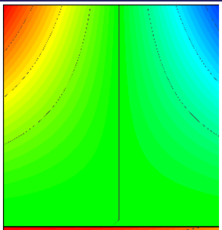
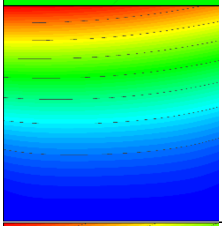
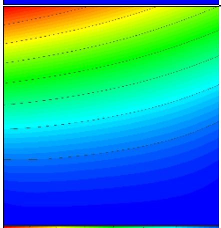
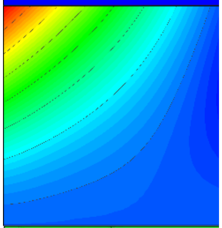
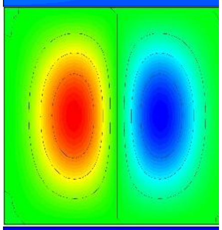
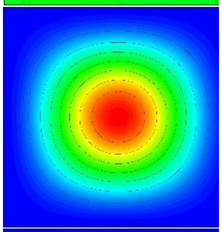
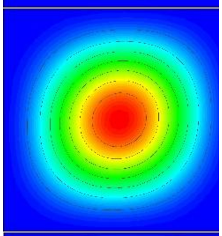
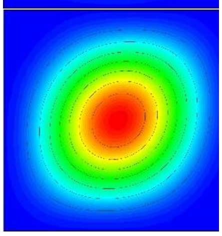
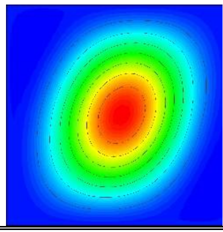
Source	UD	LH	FH
Present (16 × 16)	13.6957	18.2253	17.0588
Present (20 × 20)	12.1025	16.9875	15.8840
Present (24 × 24)	11.8259	15.4124	14.5007
Present (28 × 28)	11.8259	15.4124	14.5007
Mohamed et al. [13]	11.7802	16.2265	15.3801
Garg et al. [16]	11.7480	15.5931	14.9292

3. Results and Discussion

After validating the present model, the new results are presented in this section on the buckling analysis of helicoidal laminated composite plates having different boundary conditions. The material properties used for the same are as follows: $E1$ = 131 GPa, $E2$ = $E3$ = 10.34 GPa, $G12$ = $G13$ = 6.895 GPa, $G23$ = 6.205 GPa, $\nu12$ = $\nu13$ = 0.22, $\nu23$ = $\nu32$ = 0.49, $\nu21$ = $\nu31$ = 0.017. The first buckling mode shape along with the non-dimensional critical buckling load are presented in Table 3. The influence of four different boundary conditions, namely SSSS (all edges simply supported), CCCC (all edges clamped), CCFF (edges parallel to X-axis are simply supported and edges parallel to Y- axis are free), and CFFF (one edge parallel to X-axis is clamped and remaining three edges are free) on the buckling behavior of 32-layered bio-inspired laminated composite plate is studied for the different layup schemes as reported in Table 1. The maximum value for the non-dimensional critical buckling load is observed for CCCC boundary conditions and minimum for CFFF end conditions as expected. For bio-inspired laminated lay-ups, the buckling mode shape is slightly different when compared with the conventional lay-up schemes (UD, CP, and QI). Due to the presence of the corrugations, the crack propagation becomes difficult within the laminate and a higher strength can be achieved. Because of the symmetric helicoidal schemes with respect to the middle-axis of the plate, the mode shapes obtained are symmetric in nature with symmetric end conditions.

Table 3. Mode shape and non-dimensional critical buckling load for square shaped bio-inspired laminated composite plates with different layup schemes and boundary conditions (a/h = 10).

Boundary condition	Layup scheme	Mode shape	Non-dimensional buckling load
	UD		5.9473
SSSS	CP		6.3195
	QI		7.7598
	LH		7.6236
	FH		6.9483
	UD		5.2493
	CP		8.2359
CCFF	QI		8.678
	LH		8.5283
	FH		6.9050
CFFF	UD		1.2803

	CP		1.0103
	QI		1.2278
	LH		1.2073
	FH		1.3756
CCCC	UD		11.0739
	CP		16.6993
	QI		16.2983
	LH		16.0779
	FH		14.4713

4. Conclusion

In the present article, buckling analysis of 32-layered bio-inspired helicoidal laminated composite plate is carried out using ANSYS. Following important points are noted down during the present study:

1. Bio-inspired helicoidal laminated composite plate is found to perform better than the conventional lay-up schemes.

2. Boundary conditions widely determine the buckling behavior of bio-inspired laminated composite plates.

3. CCCC ended plate gives maximum value for non-dimensional critical buckling load, whereas CFFF end condition gives the minimum value.

4. The mode shape for bio-inspired helicoidal scheme is symmetric about the diagonal of the square, for UD, CP, and QI, the same is symmetric about the mid edge-axis and diagonals (for SSSS and CCCC boundary conditions).

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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