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Identifying optimal rotating pitch angles in composites with Bouligand structure

Wenting Ouyang ^{a,1}, Bowen Gong ^{a,1}, Huan Wang ^{a,*}, Fabrizio Scarpa ^b, Bo Su ^c,

Hua-Xin Peng ^{a,*}

^a Institute for Composites Science Innovation (InCSI), School of Materials Science and Engineering, Zhejiang University, Hangzhou 310027, PR China

^b Bristol Composites Institute (ACCIS), University of Bristol, Bristol, UK

^c Biomaterials Engineering Group (bioMEG), Bristol Dental School, University of Bristol, Bristol, UK

*corresponding author: hwang2014@zju.edu.cn; hxpengwork@zju.edu.cn

¹ Authors contributed equally to this work.

Abstract

The Bouligand structure is a typical helicoidal architecture found in various crustaceans in which each layer rotates by a small angle relative to the adjacent one. We present a theoretical analysis to relate the rotation pitch angle to the mechanical performance (interlaminar shear property in this case) of laminas mimicking the Bouligand architecture. For a given laminate, there exists an optimal pitch angle which yields the lowest shear stress. Theoretical models are compared against experimental tests carried out on 32-layer helicoidal carbon fibre laminates with pitch angles of 6°, 9.1°, 12°, 25.7° where the 9.1° is the predicted optimal angle. The results show that this particular architecture with a pitch angle of 9.1° indeed attains the highest load-bearing capability and delays any catastrophic delamination. This provides a fundamental basis to the design of helicoidal structures mimicking the Bouligand architecture.

Keywords: Bouligand structure, Pitch angle, Helicoidal laminates, Interlaminar shear.

1. Introduction

Several species featuring exoskeletons with Bouligand structures [1-7] such as the peacock mantis shrimp (Fig.1a) have attracted the attention of researchers for their excellent mechanical properties and versatility. For instance, the peacock mantis shrimp uses its feeding appendage to attack prey by reaching speeds between 14-23m/s and astonishing levels of accelerations up to 6628-10600 g [8]. Despite these bewildering values of speed and acceleration, the damage-resistant part of the mantis shrimp's dactyl club hammer-like appendage can withstand thousands of high-intensity strikes because of its Bouligand architecture (Fig.1b). Each layer has chitin fibers and it is offset from adjacent layers to form a helicoidal structure (Fig.1c) [5, 7]. Researchers have therefore attempted to explore the helicoidal structure topologies for the design and manufacture of engineering composite laminates with focuses on the mechanical response from uniaxial tensile [9], plate bending [9-12], three-point bending [13-15], low-velocity impact [5, 9, 16, 17] and compression tests after impact [5, 16, 17]. Delamination represents one of the most critical failure modes of laminates [18]. Interlaminar shear stress is the essential trigger of delamination (i.e., interfacial debonding or matrix failure) when the laminates are subjected to shear loads. Enhancement of delamination resistance provided by helicoidal arrangements in CFRPs structures has been observed and explained by Liu et al. [11, 12]. Since a significant mismatch of the angle between two consecutive layers in traditional laminates leads to a non-uniform distribution of the interlaminar shear stress; this can be alleviated by using helicoidally-stacked

designs [17] that induce a smooth change of in-plane stiffness.

Fig.1. (a) Photograph of the peacock mantis shrimp and the hunting weapon in which the area surrounded by full black lines is the location of the dactyl club. (b) SEM micrograph of the periodic region in the fractured surface [5]. (c) 3D schematic diagram of the helicoidal architecture in the periodic area.

Here, for the first time we present a simple theoretical approach to the identification of an optimal helicoidal laminate with superior interlaminar shear property. A short-beam shear test is carried out to validate the theoretical prediction and to investigate the effect of the rotation angle on the interlaminar shear behavior. The distribution of the interlaminar shear stresses obtained by the theoretical model also sheds insights on the failure mechanisms.

2. Theoretical method and experiments

2.1. Theoretical derivation of the interlaminar shear stress in the short-beam configuration

The short-beam shear test is widely used to characterize the interlaminar fracture resistance of fiber-reinforced composites because of its simplicity. The results of the

test are usually based on the homogeneous beam equation. For laminates, these formulas need to be modified on account of the stacking sequence of the individual layers [19]. Following Whitney's theoretical framework [20], the displacement v along the width direction y is approximately zero, and the axial and transverse displacements (u and w , respectively) are independent of the y coordinate (Supplementary Fig.S1). The interlaminar shear stress $\tau_{xz}^{(k)}$ can be written as:

$$\tau_{xz}^{(k)} = \alpha^{(k)} \frac{3P}{4bh} \quad (1)$$

Details of the derivation of $\tau_{xz}^{(k)}$ and the overall geometry of the beam can be found in Supporting Information. Essentially, in this work we introduce an interlaminar shear stress factor $\alpha^{(k)}$ on the original homogeneous beam equation; this factor considers the effect of the fiber on interlaminar shear stress. Under bending load $\alpha^{(k)}$ can be expressed as:

$$\alpha^{(k)} = \frac{(N * z) \sum_{i=k}^{\frac{N}{2}} \bar{Q}_{11}^{(i)} (z_i^2 - z_{i-1}^2)}{\sum_{i=1}^N \bar{Q}_{11}^{(i)} (z_i^3 - z_{i-1}^3)} \quad (2)$$

For laminates with the same N (the total number of layers) and z (single-layer thickness) values, $\alpha^{(k)}$ depends only on the stiffnesses $\bar{Q}_{11}^{(k)}$ that are functions of the fiber orientation angle (see Supporting Information). Eq. (1) can be applied to calculate the interlaminar shear stress distribution of symmetrical laminates with arbitrary layups. Specific cases we have covered in this work relate to the relationship between the rotation angle θ and a normalized maximum interlaminar shear stress for three architectures: 24-layer, 32-layer, and 48-layer helicoidal laminates with a stacking sequence of $[0/\theta/2\theta/\dots/(N/2-1)\theta]_s$.

Fig.2. Under the premise of a specific number of layers (i.e., 24 layers, 32 layers, 48 layers), the relationship between rotation angle and normalized maximum interlaminar shear stress for laminates with different number of layers.

Table 1 The optimal angles corresponding to laminates with different elastic properties.

Material properties details	Optimal angles		
	24 layers	32 layers	48 layers
CFRP (Sky flex USN20A) [17]	12.4°	9.18°	6.03°
CFRP (T800/M21) [16]	12.36°	9.15°	6.01°
CFRP (USN 15000/6511/RC33) Thickness per layer (mm): 0.141	12.3°	9.1°	6.0°
$E_{11}=115\text{GPa}$, $E_{22}=14\text{GPa}$, $G_{12}=4.12\text{GPa}$, $\nu_{12}=0.25$			

We have normalized each maximum τ_{xz}^θ per configuration with the maximum interlaminar shear stress in the unidirectional laminate of the same layer number N , τ_{xz}^0 . As shown in Fig.2a, the normalized maximum interlaminar shear stress firstly decreases with increasing rotation angle θ and reaches a minima at $\theta = 6^\circ$, $\theta = 9.1^\circ$ and $\theta = 12.3^\circ$, respectively for different layer numbers, and then increases as θ increases. With further increase of θ , the $\tau_{xz}^\theta \sim \theta$ curves fluctuate with several peaks.

Additionally, Table.1 shows that the elastic properties have little effect on the determination of the optimal angle of the structure with a specific number of layers. The theoretical results suggest that, for a given Bouligand architecture, there is an optimal helicoidal configuration with the lowest maximum τ_{xz}^{θ} value that can provide an improved interlaminar shear property. These conclusions are however based on an ideal situation that the shear strength of the composite is mainly dependent on the matrix – i.e., the smaller the maximum interlaminar shear stress caused by the same shearing force, the higher the load-bearing capacity of the optimal structure at the beginning of the delamination.

2.2.Experimental verification

For the experimental verification, we have selected 32-layers helicoidal laminates with pitch angles of 6°, 9.1°, 12°, 25.7° where the 9.1° is the predicted optimal angle. Table.2 displays in detail the stacking sequences used in this experimental part. The mechanical properties of the prepreps (USN 15000/6511/RC33) are listed in Table.1. A GERBER cutter DCS 2600 has been used to cut each ply at the specific angle. The prepreg stacks have been vacuum-bagged and cured in autoclave following the manufacturer recommended cure cycle. Essentially, at a pressure of 7 bars, the temperature was initially raised to 80°C at a constant rate of 2°C/min, then slowly increased to 120°C at a rate of 0.5°C /min, and maintained at this temperature for 90mins. The temperature was finally reduced to 60°C at a rate of 2°C /min.

Table 2 Summary of laminates configuration.

Structure designation	Number of layers	Stacking sequence
Helicoidal (6°)	32	[0/6/12/.../84/90] _s
Helicoidal (9.1°)	32	[0/9.1/18.2/...127.4/136.5] _s
Helicoidal (12°)	32	[0/12/24/.../168/180] _s
Helicoidal (25.7°)	32	[0/25.7/51.4/.../154.2/180] _{2s}

The size of the samples was 30mm×9mm×4.5mm (length×width×thickness). The span-to-thickness ratio was four based on the ASTM D2344 standard guidelines [21]. A Zwick/Roell tensile machine with a 5KN load cell and equipped with a 3mm support roller and 6mm diameter loading roller was used to perform the three-point bending test. The loading was applied in displacement control at a cross-head speed of 1mm/min. After the test, the failed specimens were analyzed using a Nikon XT H225/320 LC x-ray Computer Tomography (CT) scanner to observe the internal damage distribution.

3. Results and discussion

3.1. Load-bearing capability of four sets of helicoidal composites

Five samples for each stacking sequence have been tested. All the helicoidal composites showed a brittle fracture (Fig.3a). The 9.1° helicoidal architecture led to a 11% increase in maximum load-bearing capability compared with the laminate with the 25.7° rotation angle (Fig.3b). The helicoidal 6° and 12° architectures also show a small decrease in peak load (4% and 7.5% respectively) with respect to the 9.1° rotation angle configuration. According to the theoretical prediction, the order of maximum interlaminar shear stress induced by the same shear force from low to high is: helicoidal 9.1°, helicoidal 6°, helicoidal 12° and helicoidal 25.7° structure (see the red curve in Fig.2a). Conversely, the theoretical force to induce the shear delamination of these

laminates increases in turn. The load-displacement trends (Fig.3b) amongst the different architectures are consistent with the results provided by the theory.

Fig.3. (a) Experimental load-displacements on the helicoidal (6°), (9.1°), (12°) and (25.7°) composites. (b) Mean peak load of four sets of helicoidal composites.

3.2 Failure modes and damage characteristics

CT scanner was used to capture the three-dimensional damage distribution and thus can obtain more intuitive information about the internal crack paths of the helicoidal composites. Fig.4 shows that the increase of the rotation angle from 6° to 25.7° resulted in a catastrophic delamination failure but less dominated by crack twisting, crack branching, and sub-critical damage. The activation of additional failure mechanisms led to an increase of the driving force after the occurrence of shear cracks in the configuration with the 9.1° rotation angle [14]. The smaller rotation angle, the larger the number of plies that participated in the redirection of the shear cracks. Cracks were distributed helicoidally, following the fiber orientation and forming continuous tortuous crack paths with a smooth helicoidal damage pattern (see Fig.4a-c).

Fig.4. CT-scan images (front view of the damaged region) for the (a) helicoidal (6°), (b) helicoidal (9.1°), (c) helicoidal (12°), and (d) helicoidal (25.7°) composites. The colored areas in the CT images refer to delamination at a certain ply-interface. (e) Through-the-thickness distribution of the interlaminar shear stress for different rotation angles.

The through-the-thickness distribution of the damage can be inferred from the distribution of the intralaminar shear stress, which dominates the formation of shearing matrix cracks in the laminate [17]. Fig.4e shows the distribution of the interlaminar shear stress of Eq. (1) varies with the change of the rotation angle. Quite interestingly, the helicoidal structure with small pitch angles (such as $\theta = 6^\circ$ and $\theta = 9.1^\circ$ in this work), features an intralaminar shear stress distribution with a stress plateau in the mid-plane. This stress is expected to cause the simultaneously failure of several interfaces, and this finding correlates well with experimental evidence of diffused through-the-thickness shear cracks of the helicoidal (6°) and (9.1°) composites (see Fig.4a and b). In contrast to laminates with large rotation angles ($\theta = 12^\circ$ and $\theta = 25.7^\circ$), the delamination is expected to appear on the few interfaces at the mid-plane, which is also

observed experimentally. In this case, once delamination occurs in the middle of the specimen, the shear stress is re-arranged along the thickness direction, which results in a significant shear delamination present in several regions (see Fig.4c and d).

4. Conclusions

We have shown here a combined theoretical and experimental analysis to evaluate the interlaminar shear behavior of a bio-inspired helicoidal composite based on the Bouligand structure present in the mantis shrimp's dactyl club. The theoretical model has successfully captured the relationship between the mechanical properties and the characteristic pitch angle. The failure mechanism progressively changes from being dominated by shear delamination in configurations with a large rotation angle, to being characterized by sub-critical damage and crack twisting in structures with small pitch angles. Both crack twisting and branching mechanisms have slowed catastrophic failure, especially in case of the laminate with 9.1° rotation angles. The theoretical analysis here presented provides a further insight about the damage mechanism in helicoidal composites.

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