Composites Science and Technology 165 (2018) 282–289

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

Effects of inter-ply angles on the failure mechanisms in bioinspired helicoidal laminates

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ARTICLE INFO

Keywords:
Laminate (A)
Delamination (B)
Matrix cracking (B)
Mechanical properties (B)
Biomimicry

ABSTRACT

Following encouraging findings on the potential of helicoidal laminates under transverse loads to significantly outperform cross-ply laminates, a more extensive study was undertaken to include thicker helicoidal laminates with the greater range of variation in inter-ply angles. Previous research has shown that thin helicoidal laminates outperform cross-ply laminates when the inter-ply angle is less than 10°. It was reported that the small inter-ply angles in helicoidal laminates make them more resistant to delamination. Consequently, less delamination occurs and they are deeper inside the laminates. This delays catastrophic failure, which occurs when transverse cracks propagating from the surface of the laminates merges with the delamination. The current study shows that thick helicoidal laminates with small inter-ply angles promote a different damage mechanism not apparent in thin laminates. Hence reducing inter-ply angles does not always lead to higher transverse load bearing capability. Observations from CT scan images of thick helicoidal laminates suggest that higher delamination resistance offered by small inter-ply angles is offset by the ease with which cracks between fibers propagates transversely when the angle is too small. Hence, helicoidal laminates comprising 73 plies of unidirectional carbon fiber reinforced laminas with 2.5° inter-ply angle could not achieve the peak loads of 73-ply laminates with 10° inter-ply angle. The optimal inter-ply angle to achieve high peak load appears to be between 5° to 10°. This study shows that the peak transverse load for helicoidal laminates can be up to 73% higher than that of cross-ply laminates when they are optimized.

1. Introduction

Inspired by the exoskeletal structure of crustaceans by Bouligand [1], investigations into stacking unidirectional carbon fiber composite helicoidally with small inter-ply angles showed that helicoidal laminates can carry significantly higher transverse load as reported by Liu et al. [2], Shang et al. [3], Apichattrabrut and Ravi-Chandar [4] and Cheng et al. [5]. Shang et al. [3] determined the load bearing capacities for 11-ply and 19-ply helicoidal laminates and suggested that helicoidal laminates perform better with smaller ply rotation angle. Liu et al. [2] showed that under transverse loads, there are fewer large delamination within helicoidal laminates in contrast to the multiple large delamination in cross-ply laminates. The better delamination resistance due to the small inter-ply angles of helicoidal laminates was credited for their improved transverse loading performance. Different from Shang et al. [3] and Liu et al. [2] who studied the thin helicoidal laminates of up to 19 plies and thicknesses of up to 1.5 mm, Apichattrabrut and Ravi-Chandar [4] studied 6.35 mm thick helicoidal laminates. Cheng et al. [5] studied helicoidal laminates with different inter-ply mismatch angles (24-ply single helicoidal with 6.8° inter-ply mismatch angle and 24-ply double helicoidal with 16.4° inter-ply mismatch angle) and concluded that helicoidal laminates with smaller inter-ply mismatch angle performed better, which was also suggested by Liu et al. [2] and Shang et al. [3]. Besides fiber reinforced composites, there have also been many insightful reports on mechanical properties of Bouligand structures in general by de Obaldia et al. [14] Weaver et al. [15] and Suksangpanya et al. [16] in general.

While reports to date have shed much light on the potential of helicoidal laminates, most studies are limited to only a few or ad-hoc helicoidal configurations. There are many other helicoidal configurations yet to be investigated. This investigation attempts to document observations of helicoidal laminates ranging from 19 to 73 plies with inter-ply angles reduced systematically from 40° to 2.5°. The aim is to identify the dominant damage mechanism responsible for the load bearing capabilities of helicoidal laminates as their thickness and inter-ply angles change.

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https://doi.org/10.1016/j.compscitech.2018.07.017
Received 19 May 2018; Received in revised form 4 July 2018; Accepted 7 July 2018

Table 1
Laminate configurations.

Designation	Description	No. of plies (inter-ply angle)	Configuration
CP19	Cross-ply	19 (90°)	$[(0^\circ/90^\circ)_9/0^\circ]$
SH19	Single Helicoidal	19 (10°)	[0°/-10°/-20° …/-180°]
DH19	Double Helicoidal	19 (20°)	[0°/-20°/-40° …/-360°]
TH19	Triple Helicoidal	19 (30°)	[0°/-30°/-60° …/-540°]
QH19	Quadruple Helicoidal	19 (40°)	[0°/-40°/-80° …/-720°]
CP37	Cross-ply	37 (90°)	$[(0^\circ/90^\circ)_{18}/0^\circ]$
SH37	Single Helicoidal	37 (5°)	[0°/-5°/-10° …/-180°]
DH37	Double Helicoidal	37 (10°)	[0°/-10°/-20° …/-360°]
QH37	Quadruple Helicoidal	37 (20°)	[0°/-20°/-40° …/-720°]
CP73	Cross-ply	73 (90°)	$[(0^\circ/90^\circ)_{36}/0^\circ]$
SH73	Single Helicoidal	73 (2.5°)	[0°/-2.5°/-5° …/-180°]
DH73	Double Helicoidal	73 (5°)	[0°/-5°/-10° …/-360°]
QH73	Quadruple Helicoidal	73 (10°)	[0°/-10°/-20° …/-720°]
OH73	Octuple helicoidal	73 (20°)	[0°/-20°/-40° …/-1440°]
DPSH73	Double ply Single Helicoidal	73 (5°)	[0°/0°/-5°/-5°/-10°/−10° … −175°/-175°/-180°]
DPDH73	Double ply Double Helicoidal	73 (10°)	[0°/0°/-10°/-10°/-20°/−20° … −350°/-350°/-360°]

2. Experimental set up

Cross-ply and helicoidal laminates were fabricated from unidirectional T700/2510 carbon-epoxy prepregs. Individual plies were cut into 100 × 100 mm squares and laid manually to the required configurations. Specimens are then cured in an oven under 30 kPa pressure. The temperature is raised from room temperature to 140 °C over 2 h and maintained for 2 h. The specimens are then cooled over 8 h to room temperature. Table 1 provides a list of the laminates that were prepared and tested as well as the abbreviations used to denote them. In addition, $[0^\circ_9/90^\circ_{10}]$ laminates were tested to explain certain features observed in other specimens.

The specimens were subjected to transverse point loads using the experimental setup following procedures described previously [2,3]. The specimens are simply supported on one end of a circular cylinder with 75 mm internal diameter allowing the specimen to flex under transverse loading while providing an out-of-plane constraint that is independent of in-plane orientation. The point load is applied at the center of the specimen at a rate of 1 mm/min using a 12 mm diameter hemispherical indenter attached to a mechanical tester (AG-25TB, Shimadzu).

The transverse load vs displacement curves are used to evaluate the performance of the specimens. Most specimens are loaded until failure - defined as a load drop of more than 30% from the peak load. Five specimens were produced and tested for each configuration to ascertain specimen consistency. CT-scans were then performed on the specimens to observe the damage within (see Fig. 1).

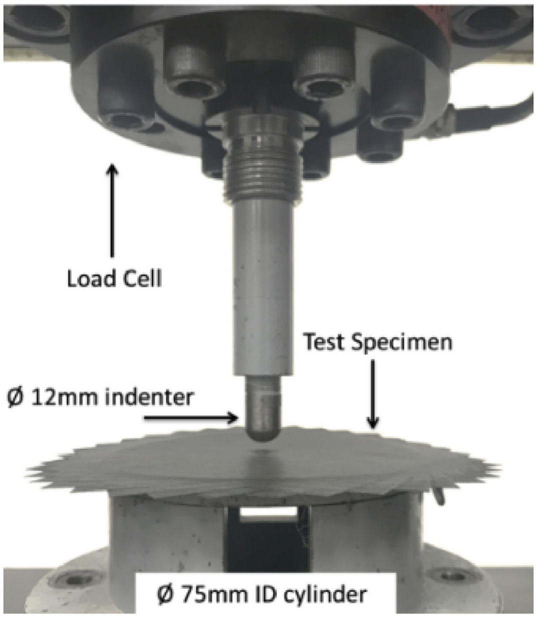

Fig. 1. Transverse loading experimental setup.

3. Results for 19-ply and 37-ply laminates

The load vs displacement curves of all 19-ply specimens are shown in Fig. 2. It is seen that as ply angle increases from 10° (SH19) to 90° (CP19), the peak load decreases. It was reported in earlier works involving single helicoidal (SH) and cross-ply (CP) laminates [2,3] that SH laminates experience a single and abrupt load drop only upon attaining the maximum peak load. The load-displacement curve for SH19 in Fig. 2 is typical of SH laminates reported previously. In contrast, cross-ply laminates (CP19) experience multiple load drops before final failure. With the addition of DH19, TH19 and QH19 laminates from the current work, it can be seen that there is a transition from a single load drop to multiple load drops in the load displacement curves. DH19 and TH19 still show a single load drop only, albeit with a lower peak load than SH19. However, when the inter-ply angle increases to 40° in QH19, several small load drops start to appear before QH19 specimens experience a large and catastrophic load drop. Not surprisingly the $[0^\circ_9/90^\circ_{10}]$ laminate has the lowest peak load as a transverse crack forms easily between the fibers of the 0° block at the bottom during bending.

The load vs displacement curves of 37-ply specimens are plotted in Fig. 3. Many of the observations for the load-displacement curves of the 19-ply specimens are also reflected in those of the 37-ply specimens. Again, the peak load is highest for the single helicoidal laminate (smallest inter-ply angle) and lowest for the cross-ply laminate – a difference of 73%. As before, DH37, with its smaller inter-ply angle, has a higher peak load than QH37. One notable difference from the 19-ply results is that multiple load drops occur in DH37 but not in SH19 although both DH37 and SH19 have the same inter-ply angle of 10°.

It was observed and explained by Lesser and Filippov [6], Liu et al. [7], Hong and Liu [8], Kim and Mayer [9] Andersons and König [10], Sebaey et al. [11] Ma and Liu [12], that laminates with smaller inter-ply mismatch angles are more resistant to delamination. Consequently, SH19 outperforms CP19 because the helicoidal configuration has smaller inter-ply angles. This results in only a few large delamination at middle of the laminate. It was previously suggested that catastrophic load drops in SH19 laminates under transverse loading occur when cracks propagating from the bottom surface reaches the large mid-plane delamination [2]. Both fiber and matrix damage initiating from the bottom surface in SH19 has to grow further to reach the delamination layer located at middle before any load drop occurs. In the case of cross-