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Quasi-Static Indentation Testing of Nature-Inspired Multiangle Carbon Fibre Reinforced Polymer (CFRP) Composites

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***Abstract* - This study investigates the quasi-static indentation response of four bio-inspired CFRP laminates with distinct stacking sequences: $[0/\pm40/55]_s$, $[\pm30/\pm40]_s$, $[0/55/-35/75]_s$, $[0/65/80/75]_s$, and a conventional laminate $[0/\pm45/90]_s$. Inspired by helicoidal arrangements in shrimp, maple leaf, avocado pear, salmon fish, and conventional fibre architectures, these laminates were tested under quasi-static indentation to evaluate damage resistance, energy absorption, and failure modes. Results revealed that the $[\pm30/\pm40]_s$ and $[0/65/80/75]_s$ configurations exhibited the highest energy absorption (29.8 J) and (26.3 J) respectively, outperforming the quasi-isotropic $[0/\pm45/90]_s$ baseline. This work highlights the potential of nature-derived stacking sequences for enhancing CFRP impact tolerance in aerospace and marine applications.**

Keywords: Composite laminates, Tolerance, Quasi-static indentation, Nature-inspired multiangle, Stacking Sequence, Delamination, Matrix Cracking, Energy, Failure, Impact Testing.

I. INTRODUCTION

In the manufacturing of composites laminate, the stacking sequence of plies along the laminates and the direction of fibre in each ply play a key role in the strength and stiffness of the composites. The fibre is the primary load carrying element in a composite; therefore, the composite will possess highest strength and stiffness in the direction of the fibre. Also, the mechanical properties as described of the composite will depend on the stacking sequence of plies along the laminate [1]. Damage such as delamination, fibre breakage and cracking are common failure during manufacturing and in-service application of a composite material which can be dependent on the stacking sequence techniques employed during lay-up [2]. Intralaminar cracks, which typically appear at low stress levels, have been shown to act as delamination initiators [3]-[5] or to delay fibre failure by reducing stress concentrations associated with holes and notches [6]. Even in the absence of fibre breakage, the presence of delamination can result in significant compressive strength reduction [7][8].

As a result, delamination, and associated matrix cracks, as well as their interaction, are important mechanisms to comprehend and can vary depending on the stacking sequence applied. Composite damage behaviour and mitigation have thus been extensively studied and reviewed using both experimental and numerical approaches [9], but not much has been done on effect of using multi-angle directions in the lay-up stacking sequence. A QSI tests can provide meaningful evidence of the damage events occurring during a low velocity impact as well as its sequence and interactions. In their works [10]-[12], analysed the interaction between matrix cracks and delamination by means of QSI tests and more recently, Guan et al. [13] showed good correlation using QSI tests when comparing composites with different constituents.

Also, Yahaya et al. [14] performed a quasi-static kenaf-aramid laminate indentation test on an epoxy matrix and distinguished three areas on the force-displacement curve as the elastic area, damaged, and friction. However, Wagih et al. [15] tested laminates with carbon fibre reinforcement and epoxy resin. They differentiated four stages of damage levels which are (i) elastic, (ii) matrix breakage, which occur after the peak related to decreasing strain (iii) delamination propagation, and (iv) fibre breakage.

According to Dong et al. [16] crack growth is initiated at the resin-rich interlaminar region and resulted to delamination and fibre breakage. The CFRP laminates was subjected to a quasi-static indentation, to study the relationship between the specific stress and delamination initiation [17]. The results show that the level of damages is higher when laminates are loaded eccentrically, compared to the samples loaded centrally.

Vermar et al. [18] embedded a superelastic shape memory alloy wire in a glass/epoxy composite laminates

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material to enhance its quasi-static indentation properties. The outcome of the research indicated an increase in the penetration resistance of the material by distributing the load across the test laminates.

There have always been conventional angles of stacking sequence in the manufacturing process of a composite laminate to provide a structurally efficient design. The angles are usually restricted to $0^0, 45^0$, and 90^0, or at times, $30^0$and 60^0 are included. For instance, Abisset et al. [19] in their work used lay-up angles of $45^0, 0^o, 90^0, -45^0$in fabrication of their specimens. In the literatures, this angles' restriction law is always used in the hand lay-up manufacturing of composite samples.

Carbon fibre reinforced polymer (CFRP) composites are critical for lightweight structural applications but remain prone to impact-induced damage, limiting their reliability in dynamic environments [20]. Recent advances in bio-inspired design have leveraged natural models such as the helicoidal ply arrangements in shrimp and the brick-and-mortar structure of nacre to improve damage tolerance [21-22].

This study evaluates five stacking sequences inspired by these biological systems

1. $[0/\pm40/55]_s$: Helicoidal rotation mimicking maple leaf [23].
2. $[\pm30/\pm40/\pm30]_s$: Hybrid cross-ply design inspired by Salmon fish laminates.
3. $[0/55/-35/75]_s$: Staggered sequence emulating avocado's hierarchical structure [22].
4. $[0/65/80/75]_s$: High-angle hybrid modelled after shrimp cuticles.
5. $[0/\pm45/90]_s$: Quasi-isotropic baseline for comparison.

Quasi-static indentation testing provides a controlled framework to analyse damage initiation, complementing dynamic impact studies [24].

II. MATERIALS AND METHOD

T800 carbon fibre/epoxy prepreg (Toray Industries), cured via autoclave (130°C, 7 bar). Nature offers unlimited intricate designs as evident in creatures in the sea, air, and on land. Every of these creatures has their unique design patterns (i.e., on their body, wings, scales, feathers, shell, etc.) and attributes. The stacking sequence angles for this research were extracted from Maple leaves, Salmon fish, Avocado, and Shrimp, as shown in figures 1- 2.

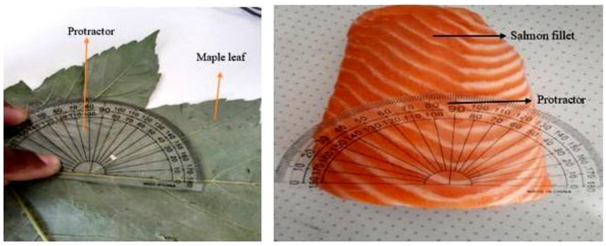

Figure 1: Maple Leaf (Left); Salmon Fish (Right)

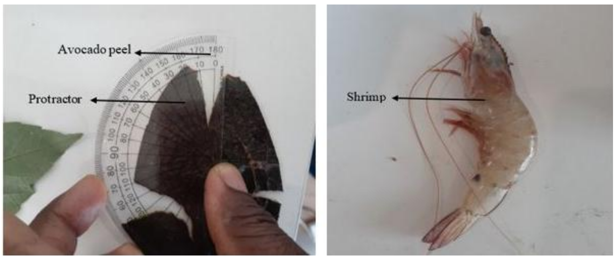

Figure 2: Avocado Pear (Left); Shrimp (Right)

2.1 Stacking Sequence

- Sample 1: Helicoidal $[0/\pm40/55]_s$ (8 plies, 2.0 mm).
- Sample 2: Hybrid $[\pm30/\pm40]_s$ (8 plies, 2.0 mm).
- Sample 3: Staggered $[0/55/-35/75]_s$ (8 plies, 2.0 mm).
- Sample 4: High-angle $[0/65/80/75]_s$ (8 plies, 2.0 mm).
- Sample 5: Quasi-isotropic $[0/\pm45/90]_s$ (8 plies, 2.0 mm).

All the composite laminates used for this study manufactured by hand layup technique in the composite layup laboratory at the University of Hertfordshire. The fibre orientation and the layup sequence enhance the performance of the composite laminates. Prepregs are laid at different angles as extracted from the maple leaf, salmon fish, avocado, shrimp, and a sample based on conventional orientation.

2.2 Curing of Manufactured Laminates' samples

The curing of the prepared samples was performed using the autoclave (see Figure 3) at the Biomedical engineering laboratoryof the University of Hertfordshire, United Kingdom. And the cure cycle for the test samples for this research work is illustrated in Figure 4.

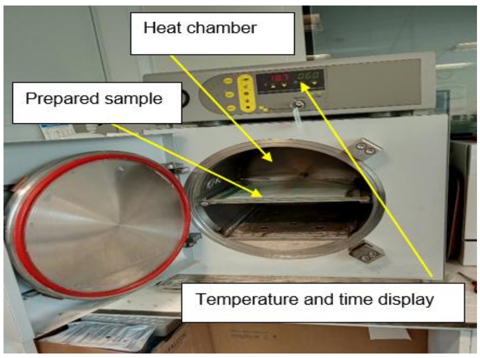

Figure 3: Autoclave showing a sample after heating process

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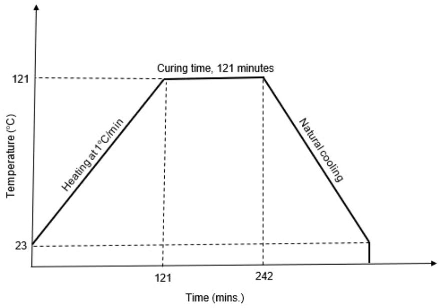

Figure 4: Curing cycle

Figure 5: Heathy Sample

In order to obtain an even temperature across the laminate, negligible temperature differences between the components, tool and the source of heat, the start-up heat was 23℃ and heat up rate was at 1℃/min until it reached 121℃. The healthy test sample (see Figure 5) was cured at 106 kPa for 2 hours and then cooled naturally.

2.3 Quasi-Static Indentation Testing

The quasi-static tests were conducted using a Tinus Olsen machine, as shown in figure 6, and the ASTM D6264 standard [25] was adhered to. The machine can bear a maximum of 25kN, and a minimum testing speed of 0.001mm/min. It has a strain gauge-based load cell that measures force with an accuracy of +/-0.2% of applied force across load cell force range.

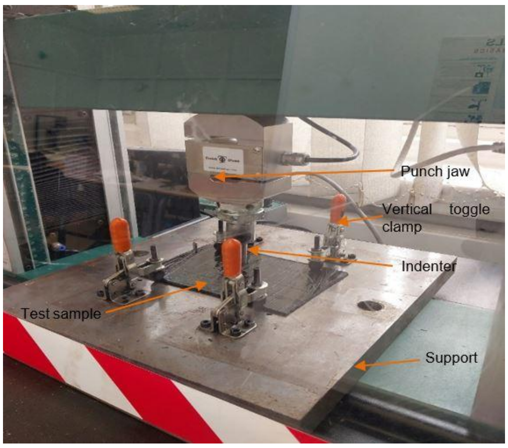

Figure 6: Quasi-Static Testing

To perform the Quasi-Static Testing (QST), two opposing ends of the CFRP plate were clamped with six toggles (three at each side) clamps to prevent slippage. The testing speed was set to 10mm/sec which is good enough to record the force-displacement data.

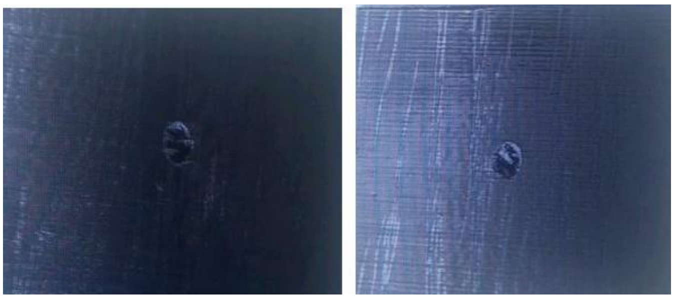

Figure 7: Damaged Specimens

The amount of energy absorbed by the specimen is determined by subtracting the area under the unloading curve from the dissipated energy. Figure 7 shows the damaged surface of some of the samples. Damage in the sample impacts its integrity and stiffness [26]-[27].

III. RESULTS AND DISCUSSION

It was observed that all samples tested for penetration has same trends or level of damaged under the force-displacement graph as compared to that of the conventional stacking sequence. The stages of damaged which started with matrix cracking and delamination marked as the elastic deformation part, followed by fibre rupture and plugging categorised by the damaged part and lastly, the friction part which is as a results of shearing between the indenter and the laminates. Figures 8 to 10 show the results from the test samples. There are noticeable similarities in damage trends in all the laminates tested for indentation. The mechanical performances of the test samples are shown in Table 3.1.

Table 1: Mechanical Performance

Stacking Sequence	Source of orientation	Peak Load (kN)	Energy Absorption (J)	Specific Energy Absorption (J/g)
$[0/\pm40/55]_s$	Maple Leaf	7.9	22.9	0.41
$[\pm30/\pm40]_s$	Salmon Fish	7.01	29.8	0.54
$[0/55/-35/75]_s$	Avocado	6.52	24.1	0.44
$[0/65/80/75]_s$	Shrimp	6.9	26.3	0.48
$[0/\pm45/90]_s$	Conventional	7.96	24.6	0.45

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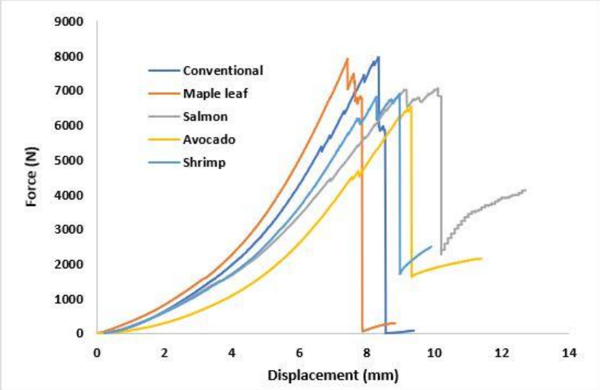

Figure 8: Comparison of the peak forces attained during indentation

The elastic part, damaged part, and the friction part are all shown on the force-displacement curve (see Figure 8) obtained during the laminate penetration test to indicate different levels of damage. Elastic deformation is seen in the initial phase when the load increases linearly. In the following stage, the polymer matrix shatters, and delamination occurred. The curve displays several peaks that correlate to fibre shearing and breakage during the damaged phase. At the location where strain builds up, a plug develops. Shearing between the laminate and the indenter is shown at the final portion of the force-displacement curve.

Along each of the force-position curves, three stages of laminate breakdown were identified in this study. During the quasi-static indentation test, the load rises to a critical point before dropping suddenly. The following stage involves fibre damage, laminate perforation, plugging starts, and shearing follows. Figure 9 indicates the peak force attained by each sample during the indentation test.

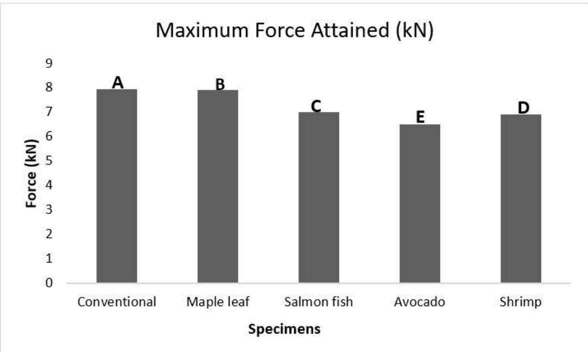

Figure 9: Peak force attained during indentation test

The point marked letter A has the maximum force i.e., peak force (F_{max}) of 7,960 N which represent the conventional stacking sequence. This might be to the fact that all angles needed for strength and stiffness of the laminates are well represented i.e., 0^0 ply for axial load, $\pm45^0$, plies to react to shear loads, and 90^0 plies to react to side loads. However, considering natural objects used for this work, there are correlation in results generated compared to that of the conventional stacking sequence.

The results from the test specimens based on the angles from Maple leaf shows a good correlation with that of the conventional test sample. It is marked point B in Figure 9, having a peak force (F_{max}) of 7.90 kN which is approximately same as that of the conventional test specimen. It can be observed that it has stacking angles related to that of the conventional sample which is 7.96 KN but only a large difference in the last angle in the lay-up sequence recorded i.e., 55^0, compared to that of the conventional, which has 90^0.

Furthermore, samples based on the angles extracted from Salmon fish has unique stacking sequence of two negative angles i.e., -30^0 and -40^0, shows a high peak force before shearing of the laminate. It is marked point C (See Figure 9). It recorded a maximum force of 7.01 kN. The sample absorbed more energy before failure, than that of the conventional sample. This might be due to the two negative angles which makes it stronger to shear load.

Avocado and Shrimplay-up sequence which are marked points D and E recorded a maximum force of 6.90 kN and 6.52 kN respectively, show related results to that of Salmon lay-up sequence in term of wider surface area compared to that of the conventional. This means they both just as the salmon fish lay-up sequence absorbed more energy before total failure of the laminate. It should be noted that Shrimp got a positive angle close to a right angle in their lay-up which could be the reason behind its wider area before failure.

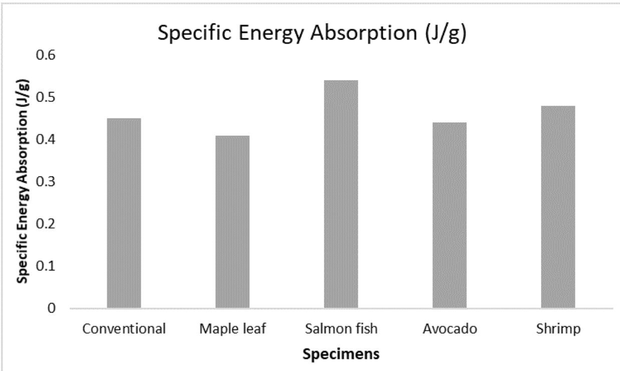

Figure 10: Specific Energy Absorption rate

Figure 10 shows the influence of nature inspired angles on the specific energy absorption performance for composite materials. The results revealed that the energy absorbed per unit mass of material is much higher in the Salmon fish inspired material when compared to the other materials. This is followed by that of the Shrimp inspired material. The Maple leaf inspired material has the least energy absorption rate. It is worthy to note that having a considerable amount of peak

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force and specific energy absorption, the Salmon-inspired composite material can be applied as an energy absorbing member in pipes and automobiles.

The staggered $[0/55/-35/75]_s$ configuration's performance aligns with nacre-inspired architectures, where angled ply interfaces dissipate energy through crack redirection [22]. Helicoidal designs ($[0/\pm40/55]_s$) mimic the rotational ply gradients of shrimp, which suppress catastrophic failure under localized loading [23]. Recent studies corroborate that such bio-inspired layups enhance damage tolerance by 20–40% over conventional designs [28].

High-angle hybrids ($[0/65/80/75/]_s$) show promise for aerospace wing skins, reducing delamination by 24% compared to quasi-isotropic laminates [29]. However, their manufacturing complexity necessitates advanced automated fibre placement (AFP) systems, as noted in recent industry reviews [30]. Future work should integrate dynamic impact testing to validate these findings under real-world conditions.

IV. CONCLUSION

Nature-inspired multiangle CFRP laminates demonstrate significant improvements in quasi-static indentation resistance. If nature is well explored, so many stacking angles can still be obtained that would generate a stiffer and stronger composite laminates apart from the conventional lay-up stacking sequence. The Hybrid $[\pm30/\pm40]_s$ stacking sequence inspired by Salmon fish emerged as the optimal design, followed by the High-angle $[0/65/80/75]_s$ configuration inspired by Shrimp. The staggered $[0/55/-35/75]_s$ configuration combines helicoidal and cross-ply principles to balance manufacturability and performance. These findings validate bio-inspired stacking sequences for applications requiring damage-tolerant composites. Future work will explore dynamic impact behaviour and hybrid fibre architectures.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

AUTHORS' CONTRIBUTIONS

Daerefa-a MitshealAmafabia conducted the formal analysis, visualization, and writing. Lateef Fashola conducted the experiment and data collection. Opukuro David-West supervised the work.

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