Toughening Mechanisms of Bio-inspired Composites

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1 Background

- Making materials that are both strong and tough has always been one of the important problems in materials. While helicoidal structures found in biological tissues that exhibits high toughness as well as strength provide design inspiration.
- For instance, stomatopod dactyl club of the "smasher-type" mantis shrimp can impose intensive impact loads of >10 kg at a speed of 23 m/s without generating structural failure.
- By mimicking the helicoidal microstructure, composites that possess both high strength and toughness can be designed and fabricated.

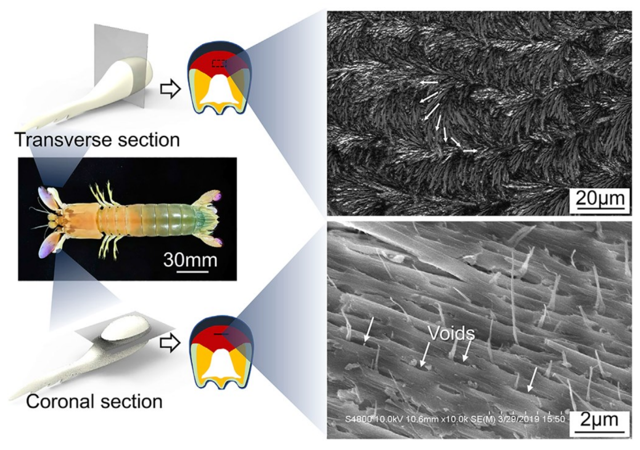

Fig. 1 Morphologies of Odontodactylus scyllarus: SEM images of cross-section and coronal section in periodic region (red).

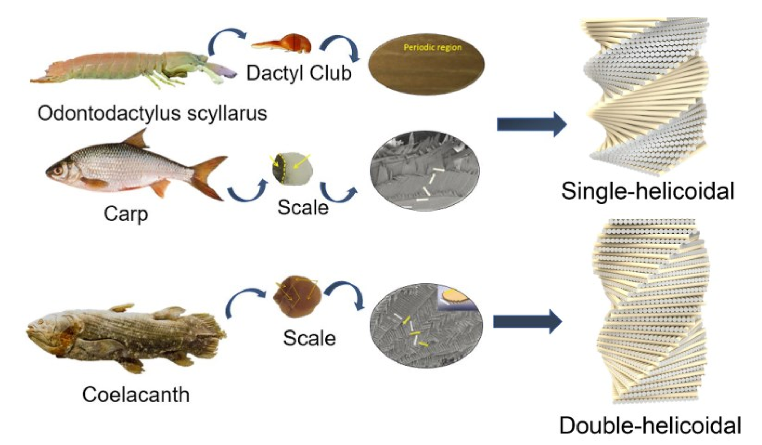

Fig. 2 Single-helicoidal structure from Odontodactylus scyllarus and carp; and double-helicoidal structure from the coelacanth

2 Design and Fabrication

- CF/PA6 helicoidal composites with voids were fabricated by continuous-fiber 3D printing technology
- Helicoidal composites WITHOUT voids were fabricated for comparison by hot pressing on the printed samples

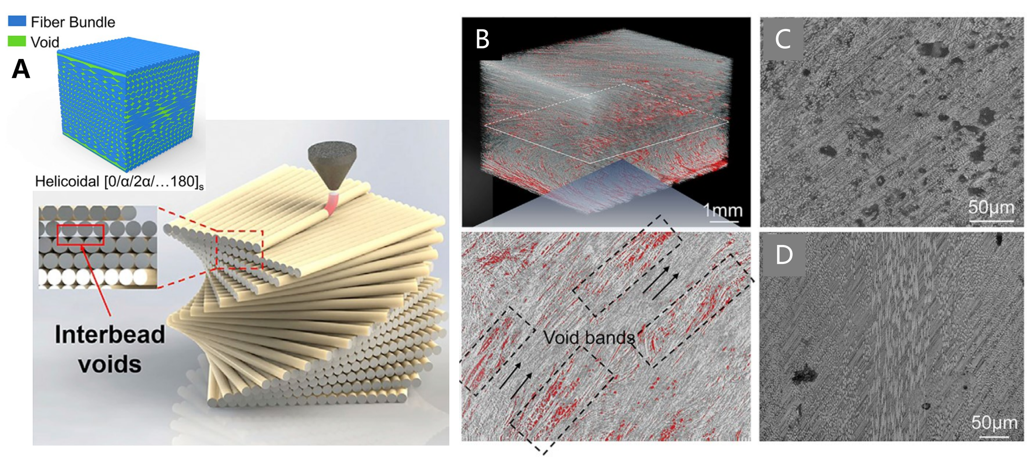

Fig. 3 (A) Illustration of 3D-printed helicoidal composites with voids. (B) 3D micro-CT image and a sectional view of helicoidal composites showing void marked in red. Micrographs of voids in the polished sections of the helicoidal composites: (C) without hot pressing and (D) after hot pressing

- Two layers with vertical fiber orientation combined as a group. The groups then stack up helicoidally to form double helicoidal composites
- CF/PA6 double helicoidal composites were fabricated by hot pressing of CF/PA6 prepreg

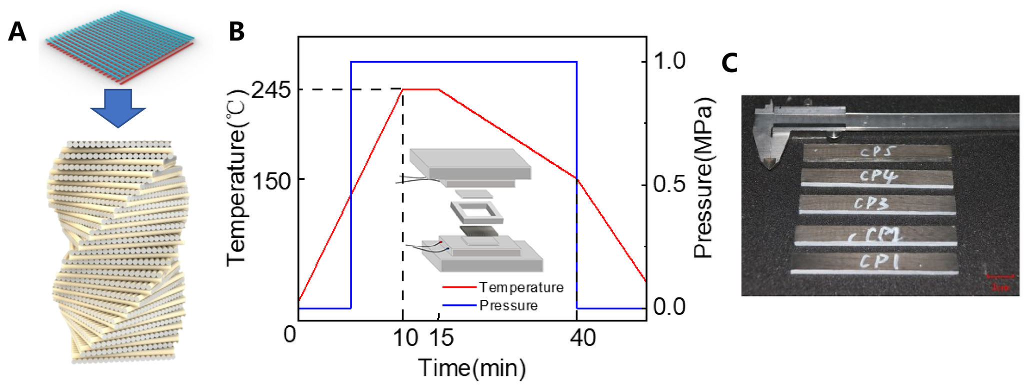

Fig. 4 (A) Illustration of double helicoidal composites. (B) temperature and pressure curves for thermoplastic composites manufacturing. (C) Samples for testing.

Group	Twisting angel	Stacking
A-1	16.36	$[0/16.36/32.72…/163.6/180]_s$
B-1	9.47	$[0/9.47/18.95…/170.53/180]_s$
Single 10°(SH-10)	10°	$[0/10°/20°/…/80°/90°]_s$
Single 20°(SH-20)	20°	$[0/20°/40°/…/160°/180°]_s$
Double 10°(DH-10)	10°	[0/90°/10°/100°/…/90°/180°]
Double 20°(DH-20)	20°	[0/90°/20°/110°/…/180°/90°]

Tab. 1 Summary of Fabricated Samples with Different Stacking Sequences

3 Experiments and Results of 3D-printed Helicoidal Composites

- Three-point-bending tests were conducted to evaluate the quasi-static mechanical properties and deformation history of the composites. And Charpy pendulum tests were conducted to evaluate the impact resisting of the composites.
- Deformation history for three-point-bending: Elastic region → curves dropped sharply due to fiber breakage, which was apparent in the lower layers → cracks rapidly penetrated several layers → cracks be arrested
- Twisted crack can be clearly observed from the failed samples.
- Voids inside the composites can guide the tip of crack to propagate along the ideal crack trajectory.

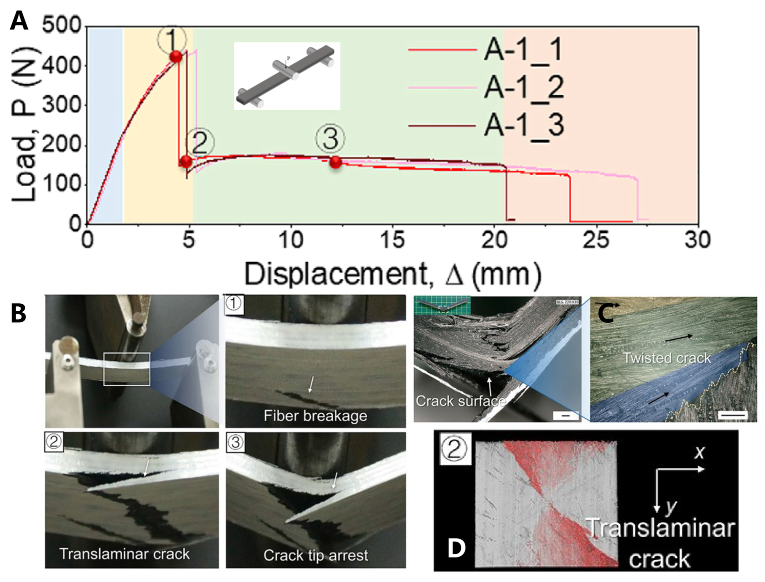

Fig. 5 (A) Load-displacement curves for helicoidal composites with voids. (B) deformation history and failure modes from the side view. (C) Micrograph observations for various crack morphologies for helicoidal. (D) Micro-CT images for helicoidal samples from the nonlinear and failure regions with voids or crack paths highlighted in red

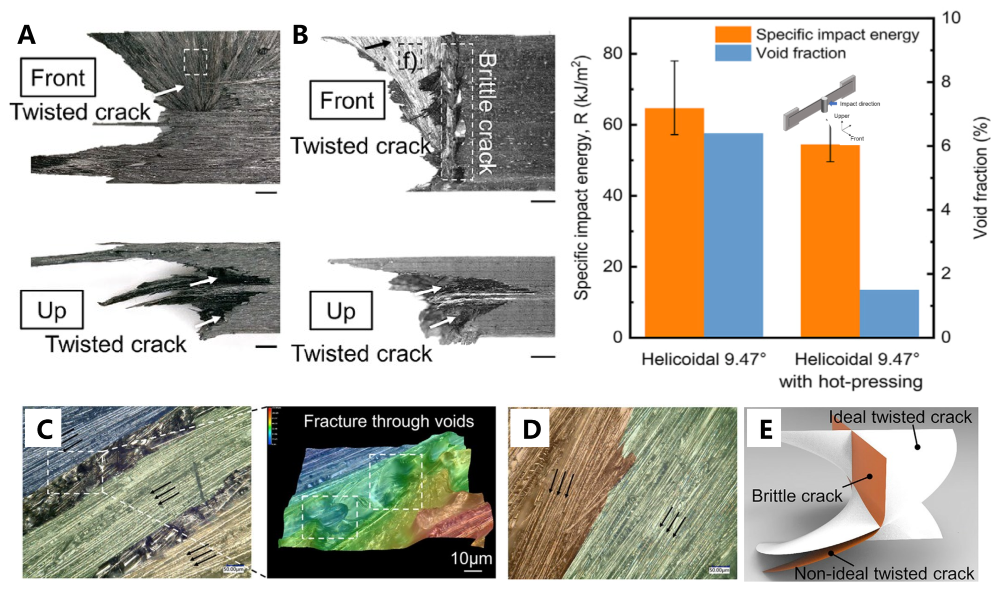

Fig. 6 Fracture mode of (A) helicoidal 9.47 ° composite beams and (B) helicoidal composite beams after hot pressing. (C) Comparison of mechanical properties. Observation of crack surface in samples without hot-pressing (D) shows that cracked layers on crack surfaces were divided by voids bands. This phenomenon couldn't be observed in those of samples after hot pressing (E). (F) A schematic comparison of ideal and non-ideal twisted crack paths

- The lack of guidance from the interbead voids would result in a non-ideal twisted crack path with a smaller surface area, which leads a low energy absorption. This is typical of the helicoidal laminates after hot pressing.

4 Experiments and Results of Double Helicoidal Composites

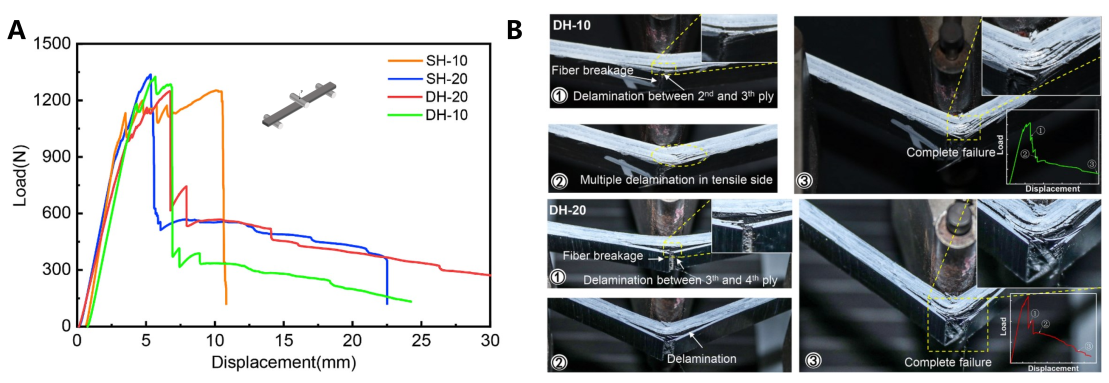

Fig. 7 (A) Load-displacement curves for double helicoidal composites. (B) Deformation history accompanied with the failure modes for DH-10 and DH-20

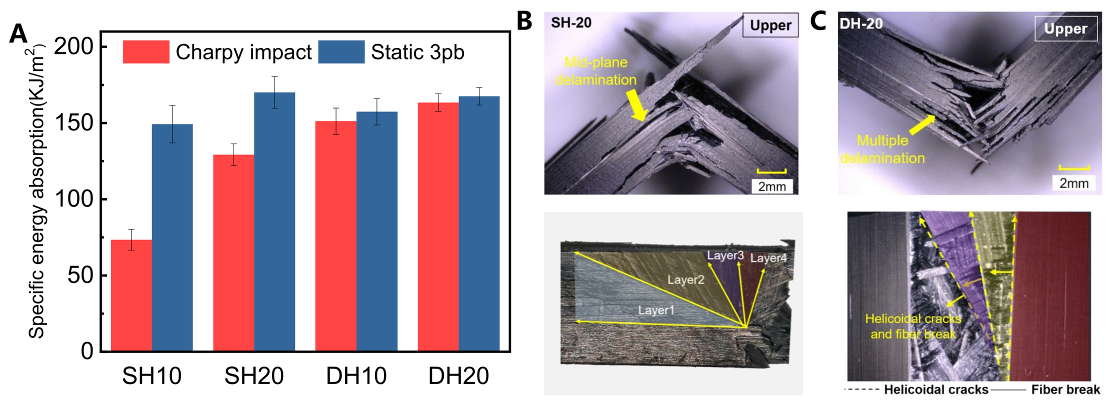

Fig. 8 (A) the specific energy absorption of different helicoidal composites under static and dynamic conditions. Images of samples after impact: (B) SH-20 (C) DH-20

- Instead of twisted intralaminar cracks, dominant failure mode of double helicoidal composites is delamination.
- Interlayer interfaces caused by delamination inhibit the propagation of intralaminar cracks tip, leading to larger failure displacement.
- Under impact, the failure mode of double helicoidal composites including twisted cracks, fiber breakage and delamination. The mixed failure modes contribute to the higher energy absorption during failure.

5 Effect of Voids

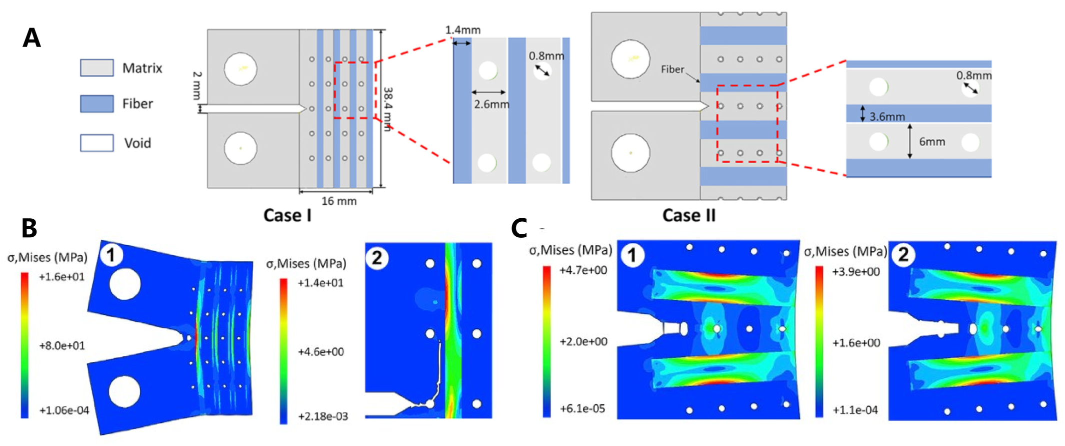

Fig. 9 (A) Two cases are shown for a matrix crack propagating in a composite containing voids. Variations in stress contours as the matrix crack propagates that (B) perpendicular to the fibers and (C) parallel to the fibers

- The voids were found to deform or to coalesce when the matrix crack propagated perpendicular to the fibers or parallel to the fibers, with the voids between them.

6 Interlaminar stress analysis

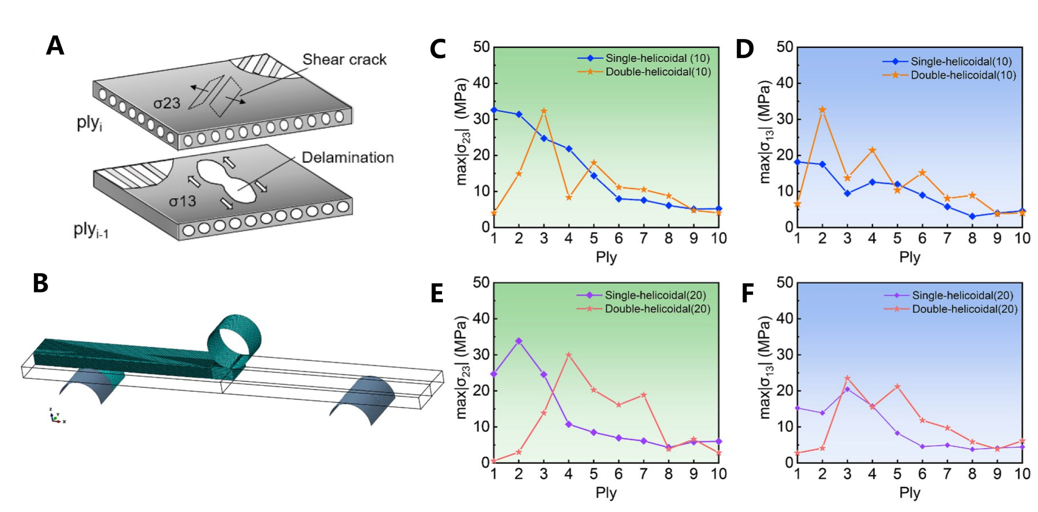

Fig. 10 (A) Schematic description of the delamination growth mechanism induced by shear cracks; (B) Finite element model; comparisons of the interlaminar stress σ_{23} and σ_{13} between (C–D) DH-10 and SH-10; (E–F) DH-20 and SH-20.

- The interlaminar stress model can accurately predict the delamination location
- $\sigma_{13}^{DH} > \sigma_{13}^{SH}$ caused different damage modes of the two structural

7 Conclusion

- helicoidal laminated composites were designed and fabricated by continuous-fiber 3D printing technology to mimic the periodic region of the dactyl club, with the presence of interbead voids distributed helicoidally
- The voids, which were introduced by a lack of consolidation during printing, can contribute to toughness by void collapse and associated microcracking
- Double-helicoidal composites mimicking the coelacanth fish scale were designed and fabricated through hot pressing
- Double-helicoidal composites have excellent impact resistance under dynamic conditions, the complex failure mode increases energy absorption.
- The progressive delamination of the double-helicoidal composites hinders the propagation of interlayer cracks and prolongs the failure displacement.