Bio-inspired armour: CFRP with scales for perforation resistance

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Abstract

This paper proposes a novel biomimetic Carbon Fibre Reinforced Polymer (CFRP) with a microstructure inspired by fish scales. The aim of the novel microstructure is to improve the perforation resistance of CFRP without compromising its flexibility. To this end, we prototype the first ever CFRP laminate with scales and test it in quasi-static indentation on a soft backing material. We compare the mechanical behaviour of the CFRP with scales to two baseline configurations with conventional lay-ups. The results presented in this paper suggest that the CFRP with scales significantly outperforms the two baseline configurations in terms of force and displacement at penetration, while being flexible. This makes CFRPs with scales an attractive alternative for applications where perforation resistance is paramount, such as body armour against low velocity strikes.

Keywords: Biomimetic; Microstructure; Composite materials; Deformation and fracture; Polymeric composites; Penetration resistance

1. Introduction

Nature has many interesting composite materials with outstanding mechanical properties, which has inspired researchers to design new generations of high-performance materials [1-3]. One example of a natural composite with excellent mechanical properties is fish skin. It combines low weight, high flexibility, and penetration resistance to allow for unrestricted movement while providing protection against predatory attacks [4, 5]. These features make fish skin one of the most effective protective systems without compromising mobility [6].

Fish skin consists of hard, finite-sized scales that attach to soft and flexible dermis to form an overlapping, imbricated, arrangement [6]. The individual scales have a Bouligand

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microstructure [7], and the soft dermis is covered by approximately three scales at each point [6].

The overlapping structure provides the fish with many strategies for protection. The main deformation mechanisms associated with fish skin are bending of individual scales, rotation of the scales at the contact point with the dermis, shearing of the dermis, and strain-stiffening when the scales start to interact with each other upon bending [8]. When the fish is under attack, the overlapping scales also distribute the penetration force on a larger area when compared with a monolithic structure [4]. Furthermore, because the scales overlap, the failure of one scale does not lead to catastrophic failure on the macroscopic scale [5].

Despite its interesting mechanical properties, few attempts have been made to mimic the deformation mechanisms of fish skin in synthetic composites, and none using CFRP. The synthetic composites inspired by fish skin reported in the literature include studies using 3D printed polymers [8-11], ceramics [12], and glass [13].

In this work, we propose the first ever CFRP laminate with scales in the literature and compare its mechanical behaviour to two baseline configurations with conventional lay-ups. We test the CFRP with scales and the baseline configurations in quasi-static indentation on a soft foundation, and demonstrate that the CFRP with scales can be loaded up to higher load and displacement before failure than the baselines, while retaining its compliance. The CFRP microstructure presented here therefore has potential for applications that need to be flexible and penetration resistant, such as protective armour.

2. Methods

2.1. Design and prototyping

We designed an original imbricated CFRP microstructure with dimensions based on natural scaled composites and relevant manufacturing considerations (see Figure 1). The CFRP with scales consisted of a quasi-isotropic laminated base plate (lay-up sequence $[0°/+45°/90°/-45°]_S$) and cross-ply scales (lay-up sequence $[0°/90°]_S$), each scale measuring 10 mm x 10 mm. The scale overlap was designed such that the ratios followed the ratios in natural teleost fish skin [8], and such that, at each point of the microstructure, the base plate was covered by three scales on average.

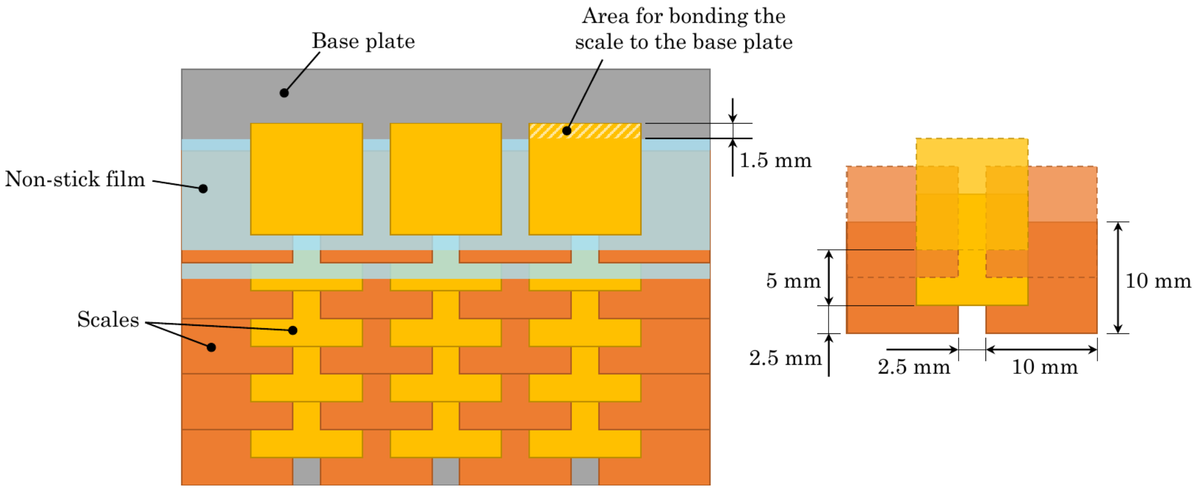


Figure 1. Dimensions and prototyping procedure for fish scale inspired CFRP.

We subsequently prototyped the CFRP with scales using SkyFlex USN020A thin-ply prepreg. The rows of scales were sequentially laid on the base plate, leaving 1.5 mm of the scale for attaching it to the base and placing non-stick film between each layer of the scales to keep them separated during curing (see Figure 1).

In order to evaluate the effectiveness of the imbricated CFRP microstructure, we also manufactured two baseline configurations using SkyFlex USN020A thin-ply prepreg – a baseline with quasi-isotropic lay-up [0°/+45°/90°/-45°]$_S$ and a baseline with quasi-isotropic lay-up sandwiched between a cross-ply: [0°/90°/0°/+45°/90°/-45°]$_S$. The baseline configurations were chosen such that the expected stiffness of the CFRP with scales would lie between the stiffness of the two baseline configurations. All configurations were cured in the autoclave according to the prepreg manufacturer's recommendations (125 °C, 6 bar). The densities of the CFRP with scales, the quasi-isotropic baseline and the quasi-isotropic/cross-ply baseline were 930 kg/m^3, 840 kg/m^3 and 970 kg/m^3, respectively.

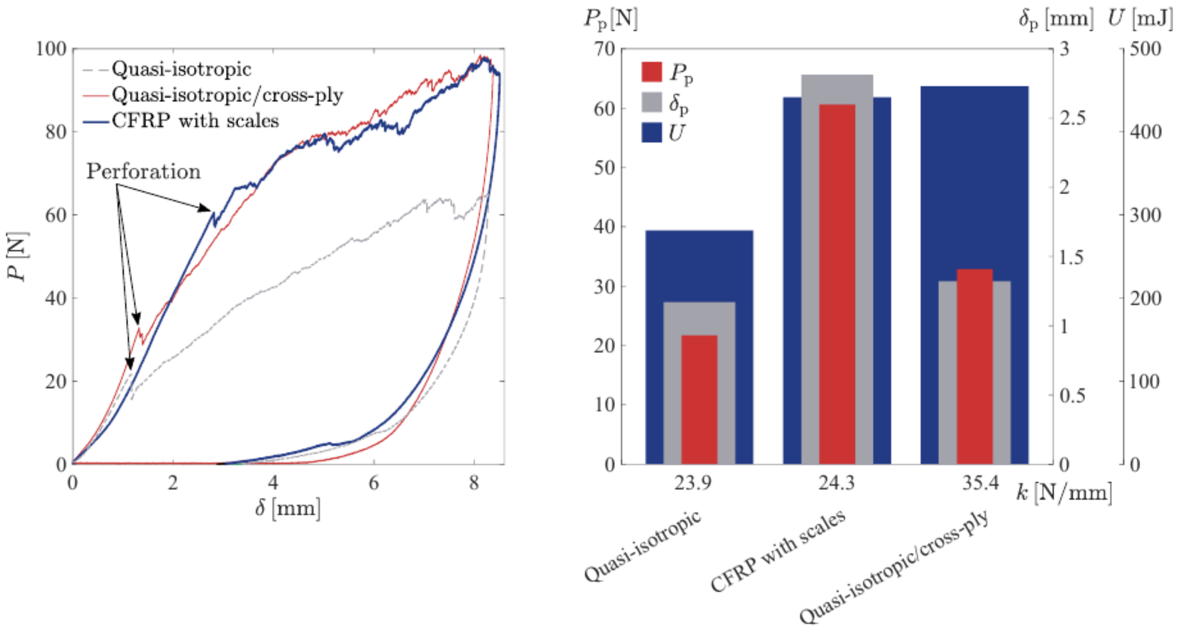
2.2. Mechanical testing

One specimen for each configuration (i.e., the two baselines and the CFRP with scales) was tested in quasi-static indentation on a soft backing material. The chosen test configuration was based on the stab vest testing standards outlined by the UK Home Office [14], and on other quasi-static tests in the literature [15].

The specimens, each measuring 83 mm x 83 mm, were placed in a contained filled with Plastiline 40 modelling clay acting as the soft backing material. The specimens were tested using a sharp indenter with a constant displacement rate of 1 mm/min. The displacement was reversed at the displacement of 8.5 mm.

3. Results

The results of the tests are summarised in Figure 2 and 3. Figure 2(a) shows the load, P, vs displacement, δ, curves of the two baselines and the CFRP with scales. Figure 2(b) shows the stiffness, k, of the tested specimens measured from the linear part before specimen perforation (seen as the first load drop in Figure 2(a)) as categorical values, the force P_{p} and displacement δ_{p} at perforation, as well as the total energy (area under the load vs displacement curve) of the specimens, U.

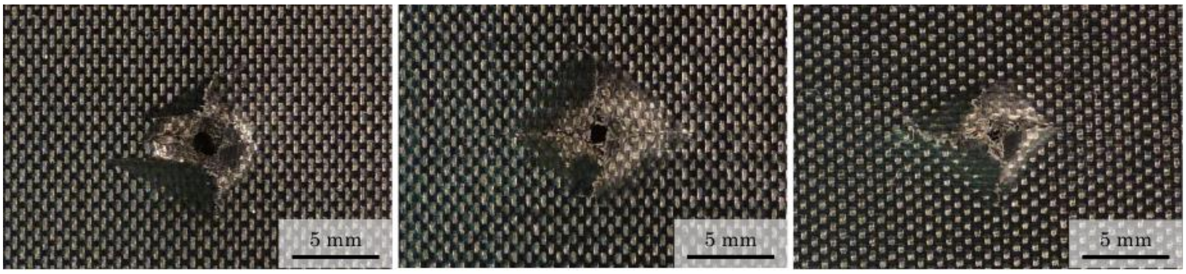


(a) (b)

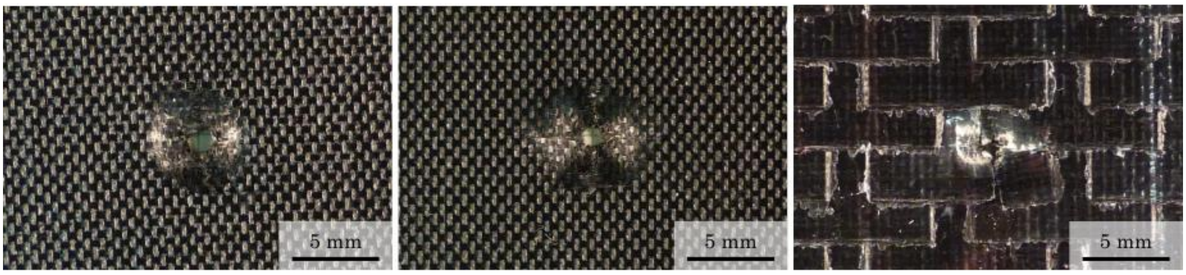
Figure 2. (a) The load vs displacement graphs of the tested specimens; (b) the force at perforation, P_{p}, displacement, **δ_{p}**, and energy, U, for the different stiffnesses k of the tested specimens. The stiffness k was measured from the linear part before the first load drop.

The mechanical response of all specimens is initially non-linear when the sharp indenter pushes the specimen against the soft backing material (Figure 2(a)). This is followed by a linear region and a load drop associated with specimen perforation. Following the first load drop, the load has an increasing trend until the displacement is reversed at $\delta = 8.5$ mm.

Figure 3 shows the back face (Figure 3(a)-(c)) and the strike face (Figure 3(d)-(f)) of the quasi-isotropic baseline, the quasi-isotropic/cross-ply baseline and the CFRP with scales, respectively. Figure 3(g) shows the strike face of the CFRP with scales at an angle, showing out-of-plane damage on the specimen.



(a) Back face, quasi-isotropic (b) Back face, quasi-isotropic/cross-ply (c) Back face, CFRP with scales



(d) Strike face, quasi-isotropic (e) Strike face, quasi-isotropic/cross-ply (f) Strike face, CFRP with scales

(g) Out-of-plane damage on the strike face of the CFRP with scales.

Figure 3. Damage on the conventional baseline CFRPs and the CFRP with scales after testing.

4. Discussion

The load vs displacement curves are qualitatively similar for all tested specimens (Figure 2(a)). The load grew until the first load drop, which is caused by the sharp indenter perforating the test specimen. After perforating the specimen, the indenter pushed further into the soft backing material and enlarged the hole in the specimen, which is seen as predominantly increasing load in the load vs displacement curve.

With respect to the quasi-isotropic baseline and the quasi-isotropic/cross-ply baseline, the CFRP with scales led to an increase in perforation load of 64% and 46%, respectively, and in perforation displacement of 58% and 53%, respectively, while having a stiffness close to that of the softer quasi-isotropic baseline and dissipating as much energy as the stiffer quasi-isotropic/cross-ply baseline (Figure 2(b)). This indicates that the scaled microstructure in CFRP enhances the penetration resistance without making the structure significantly stiffer.

The damage in all tested specimens is concentrated on a relatively small area (Figure 3), with the quasi-isotropic/cross-ply baseline having the largest damaged area on the back face. The quasi-isotropic and the quasi-isotropic/cross-ply specimens have a distinct hole from the indentation visible on the back and front faces of the tested specimens, while no distinct hole is visible on the CFRP with scales. Furthermore, the damage on the strike face of the CFRP with scales (Figure 3(f)) shows a smaller indented area than those of the quasi-isotropic and quasi-isotropic/cross-ply specimens (Figure 3(d) and (e), respectively). Figure 3(g) shows diffuse out-of-plane damage on the CFRP with scales, suggesting that the scales have interacted during deformation and distributed the load on a large area, leading to enhanced perforation resistance.

5. Conclusions

This paper investigated the first biomimetic CFRP composite inspired by fish scales in order to achieve a microstructure that resists penetration damage without compromising flexibility. It can be concluded that:

- the first ever prototyping route to synthesise the scaled CFRP microstructure was conceived and the microstructure was subsequently successfully prototyped;
- the scaled microstructure is resistant to penetration, leading to increase in penetration load and displacement when compared with baseline configurations with conventional lay-ups;
- the scales in the biomimetic CFRP distribute the point load in quasi-isotropic indentation on a large area, demonstrated as out-of-plane deformation on the specimen.

In summary, this paper presented the first ever CFRP with scales in the literature, and demonstrated that it is effective in redistributing forces from a point load, thus improving its penetration resistance. The microstructure presented here therefore has potential for applications that need to be both flexible and penetration resistant, such as body armour.

Acknowledgments

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References

[1] M. Mirkhalaf, A. K. Dastjerdi and F. Barthelat, “Overcoming the brittleness of glass through bio-inspiration and micro-architecture,” *Nature communications,* 5, 2014.

[2] R. Malkin, M. Yasaee, R. S. Trask and I. P. Bond, “Bio-inspired laminate design exhibiting pseudo-ductile (graceful) failure during flexural loading,” *Composites Part A: Applied Science and Manufacturing,* 54:107-116, 2013.

[3] F. Narducci and S. T. Pinho, “Exploiting nacre-inspired crack deflection mechanisms in CFRP via micro-structural design,” *Composites Science and Technology,* 153:178-189, 2017.

[4] F. J. Vernerey and F. Barthelat, “On the mechanics of fishscale structures,” *International Journal of Solids and Structures,* 47:2268-2275, 2010.

[5] F. J. Vernerey and F. Barthelat, “Skin and scales of teleost fish: Simple structure but high performance and multiple functions,” *Journal of the Mechanics and Physics of Solids* 68:66-76, 2014.

[6] D. Zhu, L. Szewciw, F. Vernerey and F. Barthelat, “Puncture resistance of the scaled skin from striped bass: Collective mechanisms and inspiration for new flexible armor designs,” *Journal of the Mechanical Behavior of Biomedical Materials,* 24:30-40, 2013.

[7] H. Quan, W. Yang, E. Schaible, R. O. Ritchie and M. A. Meyers, “Novel Defense Mechanisms in the Armor of the Scales of the “Living Fossil” Coelacanth Fish,” *Advanced Functional Materials,* 28:1804237, 2018.

[8] A. Browning, C. Ortiz and M. C. Boyce, “Mechanics of composite elasmoid fish scale assemblies and their bioinspired analogues,” *Journal of the Mechanical Behavior of Biomedical Materials,* 19:75-86, 2013.

[9] S. Rudykh, C. Ortiz and M. C. Boyce, “Flexibility and protection by design: imbricated hybrid microstructures of bio-inspired armor,” *Soft Matter,* 11:2547-2554, 2015.

[10] R. Martini, Y. Balit and F. Barthelat, “A comparative study of bio-inspired protective scales using 3D printing and mechanical testing,” *Acta Biomaterialia,* 55:360-372, 2017.

[11] M. M. Porter, N. Ravikumar, F. Barthelat and R. Martini, “3D-printing and mechanics of bio-inspired articulated and multi-material structures,” *Journal of the Mechanical Behavior of Biomedical Materials,* 73:114-126, 2017.

[12] R. Martini and F. Barthelat, “Stretch-and-release fabrication, testing and optimization of a flexible ceramic armor inspired from fish scales,” *Bioinspiration & Biomimetics,* 11:066001, 2016.

[13] R. K. Chintapalli, M. Mirkhalaf, A. K. Dastjerdi and F. Barthelat, “Fabrication, testing and modeling of a new flexible armor inspired from natural fish scales and osteoderms,” *Bioinspiration & Biomimetics,* 9:036005, 2014.

[14] T. Payne, S. O'Rourke and C. Malbon, “Body armour standard (2017),” *Home Office,* 2017.

[15] D. P. Kalman, J. B. Schein, J. M. Houghton, C. H. N. Laufer, E. D. Wetzel and N. J. Wagner, “Polymer dispersion based shear thickening fluid-fabrics for protective applications” *Proceedings of SAMPE 2007,* Baltimore, MD, 3-7 June 2007.