CFRP COMPOSITE WITH NACRE-INSPIRED MICRO-STRUCTURE AND FRACTAL-TEXTURED INTERFACE

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Keywords: Damage tolerance, Biomimetics, Nacre, Thermoplastic, Micro-structural design

ABSTRACT

In this work, a nacre-inspired carbon/epoxy composite is designed, prototyped and tested. A tiled micro-structure, designed via analytical and numerical models, is laser-engraved in the laminate plies, in order to mimic the staggered arrangement of ceramic platelets in nacre. Geometrical interlocks are also exploited to reproduce a nacre-like crack deflection behaviour. In order to increase the damage spreading capability of the composite, the interface between tiles is modified with the addition of a thin layer of PLA via film-casting, both as a continuous film and as discontinuous fractal-shaped patches. Results from 3-point bend tests show that the nacre micro-structure succeeded in deflecting damage. Furthermore, with respect to the pure epoxy interface, the added PLA layer is demonstrated to facilitate the progressive unlocking of tiles, thus increasing damage diffusion without significantly increasing the material thickness.

1 INTRODUCTION

As the use of Carbon-Fibre Reinforced Polymers (CFRP) increases in the automotive and aerospace industry, several efforts are being made to overcome the brittleness of such material, which typically undergoes sudden failure without prior warning. In order to increase the damage tolerance of CFRP, the properties can be designed at the micro-structural level, and on these grounds biological materials provide a valuable source of inspiration. Several natural composites (namely bone, wood and shells) exhibit common toughening mechanisms [1], such as crack bridging, crack deflection and damage diffusion, which in principle can all be exploited in synthetic composites via micro-structural design [2].

In particular, nacre, with its characteristic staggered arrangement of hard ceramic platelets in a soft protein matrix (Figure 1), provides a remarkable trade-off between strength and toughness [4,5]. Despite being mostly made of a brittle ceramic phase (95% weight), nacre proves to be up to 30 times tougher than its main constituent. Researchers have attempted to reproduce its discontinuous 'brick-and-mortar' micro-structure with various materials (including glass and ceramics [4,6]), with the aim of achieving a damage-tolerant behaviour in traditionally brittle materials.

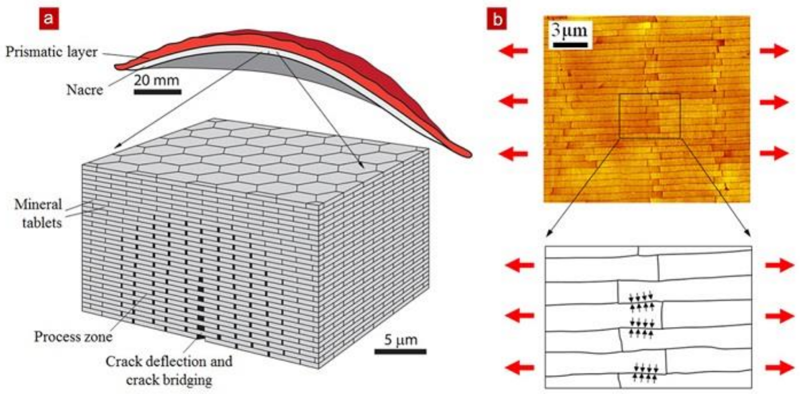


Figure 1: (a) Tiled arrangement of nacre and (b) detail of tile interlock, from ref. [3].

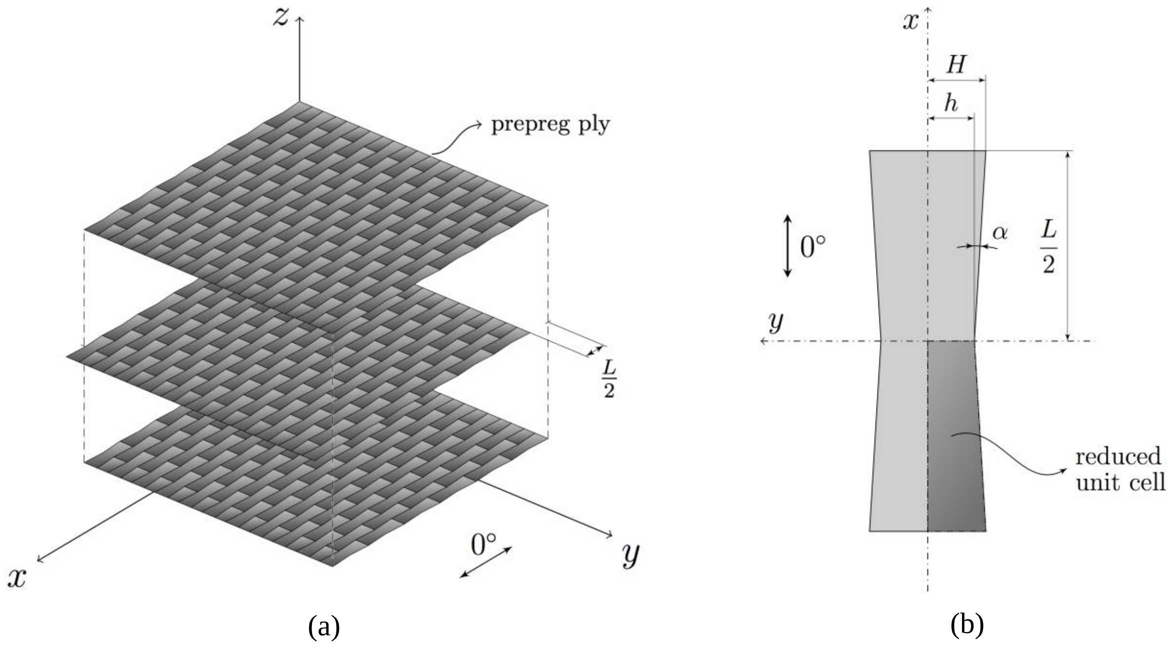


Figure 2: (a) micro-structure of the laminate and (b) detail of the unit cell used for the modelling.

In this work, we seek to design a nacre-like CFRP composite. The aim is to investigate the potential of such nacre-inspired micro-structure for deflecting cracks and spreading damage. Of the various attempts made in the literature to design materials with nacre-inspired structure [4], few have directly utilised CFRP for this purpose [7]. Section 2 contains the design of the micro-structure, whereas the synthesising process is described in Section 3. Results are presented and discussed in Section 4, whereas concluding remarks are summarised in Section 5.

2 MICRO-STRUCTURAL DESIGN

We aim to design a nacre-inspired laminate as the one showed in Figure 2(a), where each prepreg ply is cut at specific locations in order to reproduce an interlocking array of hourglass-shaped tiles that overlap by half of their length. The tile geometry (see Figure 2(b)) is defined using a suitably developed model [8,9], which provides a design length for tiles of around 0.66 mm.

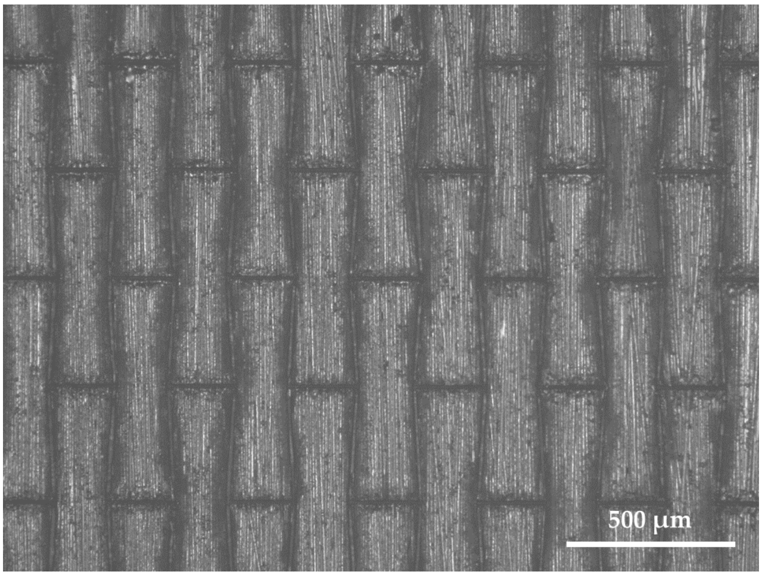
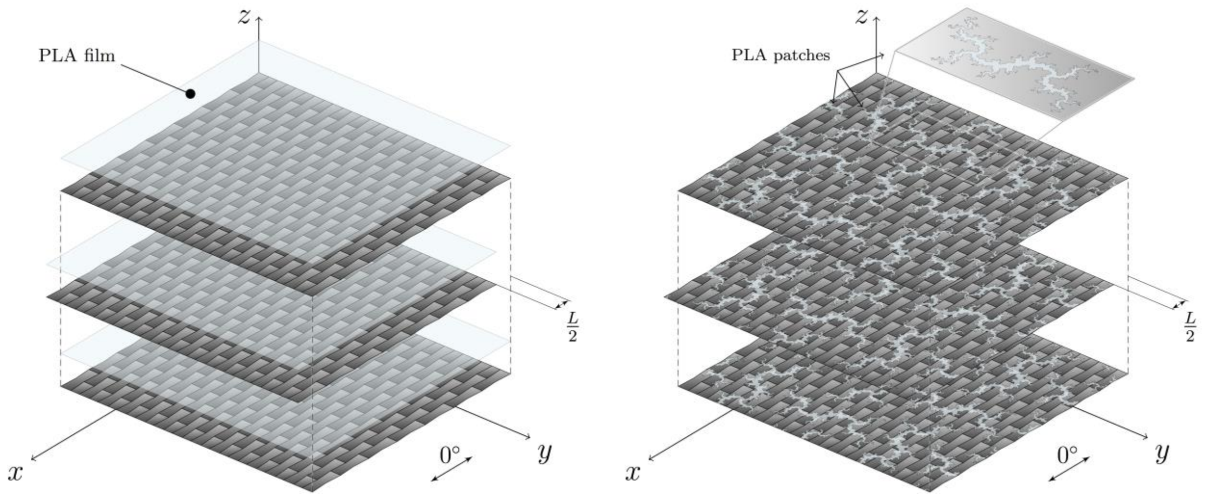


Figure 3: Optical micrograph of a ply with the laser-cut pattern of interlocking tiles.



(a) (b)

Figure 4: PLA-patterned nacre-like CFRP: (a) full film and (b) fractal patches of PLA.

3 EXPERIMENTAL

3.1 Material

A Skyflex™ USN020A carbon/epoxy prepreg was used to manufacture the nacre-like laminate, with a 43% fibre volume fraction and an average cured ply thickness of 0.022 mm. The tiled micro-structure was laser-engraved in the uncured prepreg plies prior to layup, using an Oxford Lasers Diode Pumped Solid State (DPSS) micromachining system. The laser-cut array of tiles is shown in Figure 3.

3.2 Interface modification

In order to promote the unlocking of tiles and enhance diffusion of damage, the interface of some specimens was modified by adding a thermoplastic phase. A film-casting technique [10] was used to deposit a thin layer of PLA on the interface of the laser-cut plies [11] (Figures 2(a) and 4(a)-(b)).

Three types of interface were investigated, with different area fraction (A_f) of PLA:

1) **epoxy**: no addition of PLA between layers, corresponding to $A_\mathrm{f} = 0\%$;
2) **full film of PLA**: a continuous film of thermoplastic extending all over the tile region, corresponding to $A_\mathrm{f} = 100\%$;
3) **fractal PLA patches**: discontinuous patches of PLA with $A_\mathrm{f} = 33\%$ and a fractal shape, derived from the Julia set of fractals, with complex rational function $f = z^2 + 0.8\,i$ [10].

The selected patch shape was previously demonstrated to provide a significant increase in interlaminar toughness [10] and it was therefore chosen in order to increase the ductility of the interface between tiles, with the aim to facilitate their progressive sliding and enhance diffusion of damage under bending loading.

3.3 Layup and specimen preparation

A uni-directional panel of 62 plies was laid up to produce one 3-point-bend (3PB) specimen for each of the three types in Section 3.2. The bottom 30 plies (tensile region) were laser-engraved with a nacre pattern. The central two plies (31st and 32nd) were only laser-cut with a partial array of tiles, in order to provide a smoother transition between tensile and compression region. The top 30 plies (in compression) were left untouched with long fibres. The resulting 3PB setup is sketched in Figure 5, where the specimen width is $w_\mathrm{s} = 10$ mm, the span is $d = 20$ mm and the thickness t_s depends on the interface type. The effect of PLA on the overall thickness is reported in Table 1. All specimens were polished on the side surfaces (to make the tile details more visible) and subsequently gold-sputtered.

Interface type	Specimen thickness t_s	PLA equivalent thickness $t_{\mathrm{eq.}}^{\mathrm{PLA}}$
Epoxy	1.33 mm	-
PLA full film	1.35 mm	0.28 μm
PLA patches	1.51 mm	3 μm

Table 1: Average specimen thickness and effect of adding PLA to the interface.

3.4 Testing

Tests were carried out in 3PB configuration with a Deben Microtest Module, which allowed testing in a SEM environment. Specimens were loaded at a displacement rate of 0.1 mm/min, with a load and displacement acquisition time of 200 ms. Displacements were measured with the built-in extensometer and subsequently corrected for machine compliance. The tests were run discontinuously in order to allow for SEM image capturing. During the initial elastic loading, the motor was stopped at equal intervals of 40 N. After damage initiation, the test was instead stopped as soon as sudden load drops were observed or when a new feature of failure became visible.

4 RESULTS AND DISCUSSION

Figure 6 shows the load-deflection curves for the three specimens, until onset of compression failure at the contact point with the loading pin. For all the three patterns, failure started at the outer tensile region and then progressed along a staircase pattern, following tile boundaries.

For the specimen with full film of PLA, the cracks stopped at the compression region (hitting the long fibres) and subsequently led to complete splitting along the ply interface (Figure 7(c)). For the other two specimens, the interface was strong enough to avoid such delamination, and loading could therefore continue until compression failure started at the contact point with the central loading pin.

Whilst the specimen with pure epoxy interface led to some limited damage diffusion (Figure 7(b)), the PLA-patterned ones exhibited a more diffuse pull-out of tiles (Figure 7(d) and (f)). With a full film of PLA, crack propagation was accompanied by a considerable amount of tile opening ahead of the crack (red arrows in Figure 7(d)); however, such initiation sites did not manage to open completely and to lead to diffuse pull-out of tiles.

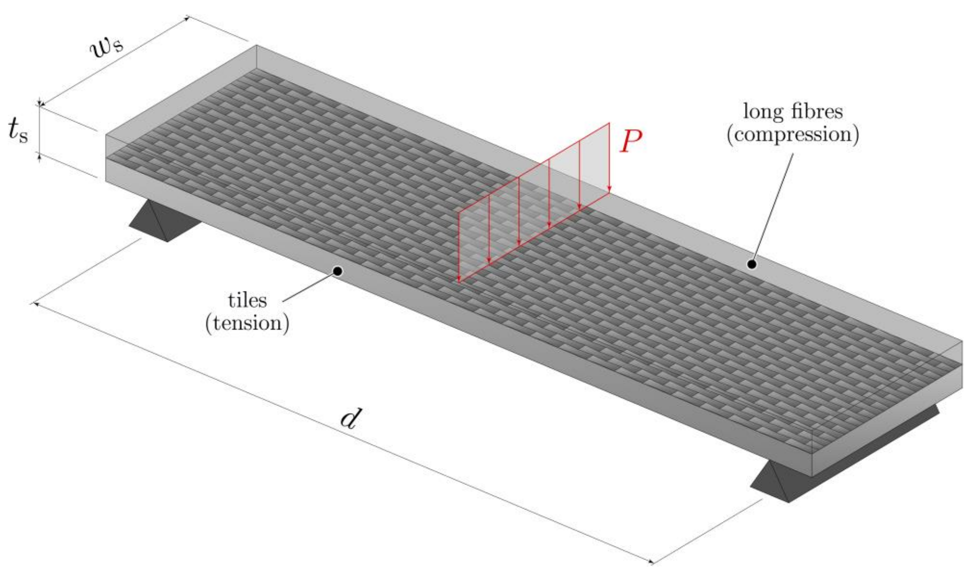


Figure 5: Sketch of the 3PB setup, showing the arrangement of tiles.

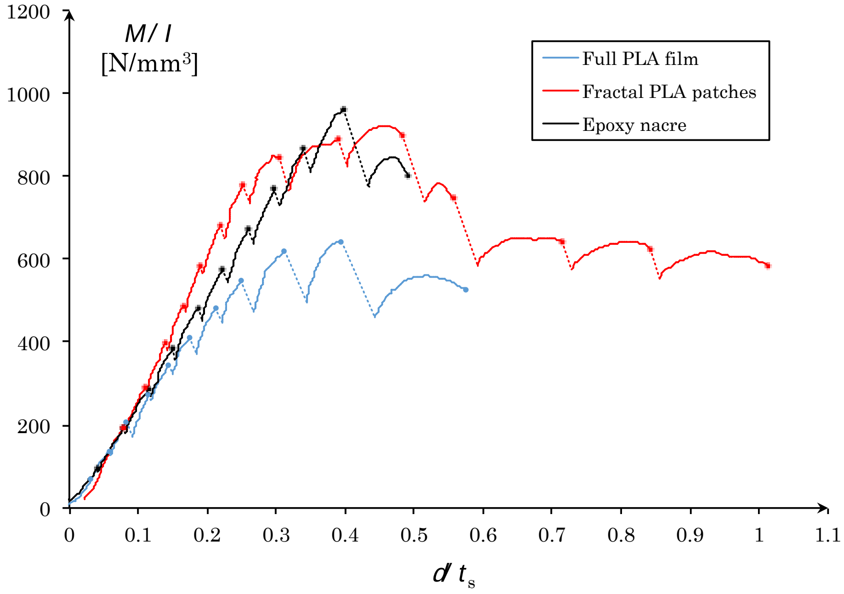


Figure 6: Load-deflection curves until start of compression failure. The bending moment M is normalised to the second moment of area I, and the beam deflection δ to the specimen thickness t_s.

5 CONCLUSIONS

This work investigated the concept of exploiting nacre-inspired micro-structures in CFRP laminates in order to achieve crack deflection and damage diffusion. It can be concluded that:

- with a pure epoxy interface, it is possible to achieve crack deflection and avoid localised failure in the most loaded cross-section of the specimen. In addition, this occurs with some limited spreading of damage;
- by film-casting a thin layer of PLA on the nacre-like ply interface, the opening of inter-tile gaps appears to be enhanced, with slightly greater damage diffusion;
- by film-casting discontinuous patches of PLA with fractal shape, the increased ductility of the interface leads to a significantly higher amount of damage diffusion, with negligible amount of added material, and hence with negligible increase in specimen thickness.

ACKNOWLEDGEMENTS

The authors acknowledge funding from EPSRC under grant EP/M002500/1, Dr Steve Harrison from Triple H Composites Ltd for providing the Skyflex prepreg, and Martin Hervy (Aeronautics, Imperial College) for providing the PLA solution for film-casting.

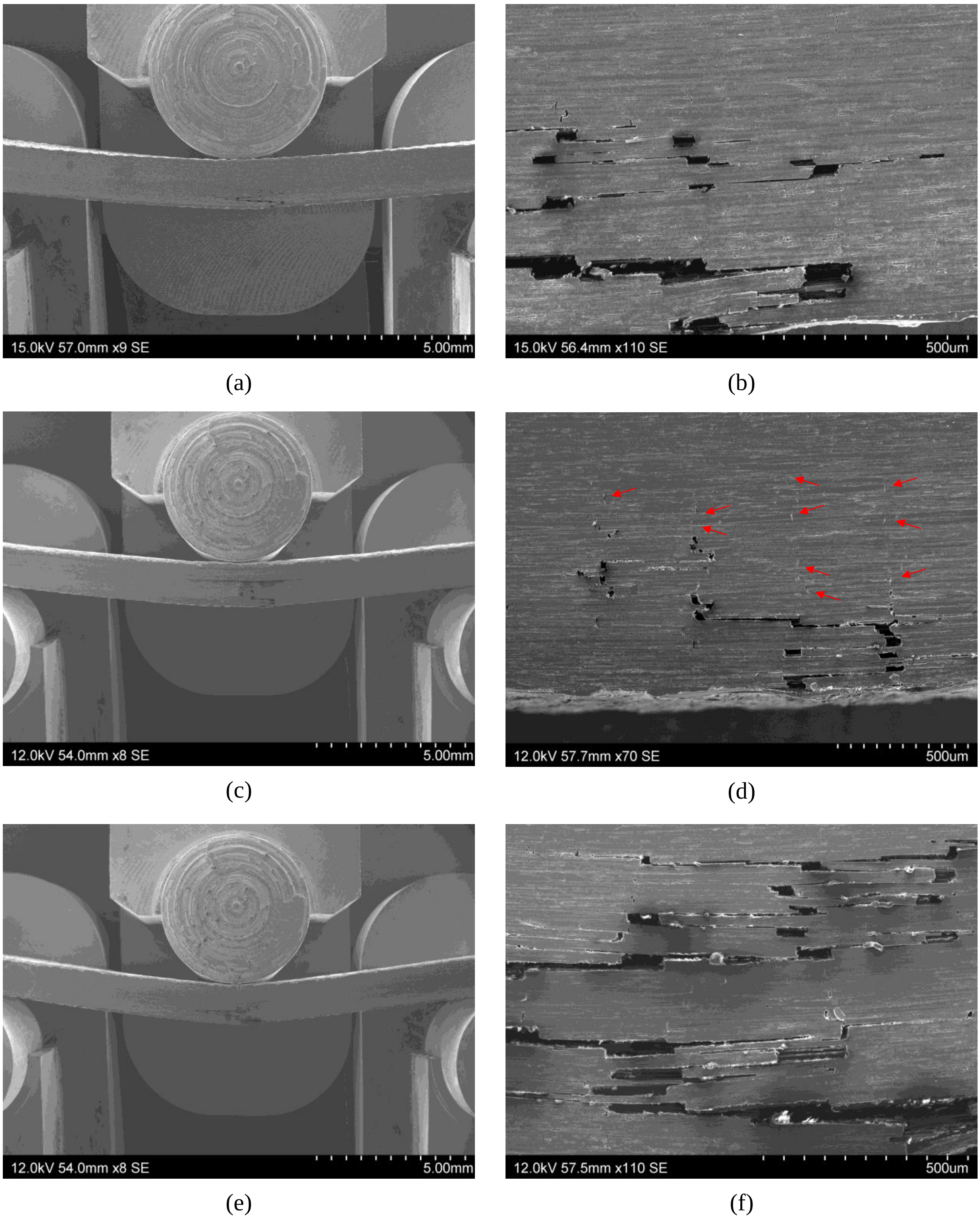


Figure 7: SEM images of the 3PB specimen failure (left: specimen failure pattern; right: failure details). From top to bottom: (a-b) epoxy, (c-d) full PLA film and (e-f) fractal PLA patches.

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