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Bio-inspired laminate design exhibiting pseudo-ductile (graceful) failure during flexural loading

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ABSTRACT

Discontinuous reinforcement phases are often observed in high toughness natural materials, for example, nacre. The aim of this study is to introduce a degree of 'pseudo-ductility' to fibre reinforced polymer materials by exploiting such discontinuities. The work presented aims to take a simple concept of discrete material sections and apply it in the form of ply cuts in a carbon fibre reinforced polymer. A variety of specimen types which encompass the principles inspired by the architecture of nacre were tested in four point bend flexure and the failure processes investigated. Finite element analysis was also carried out to understand stress conditions around ply cuts and their role in the observed failure. It was observed that ply cut spacing and ply cut density were important parameters in achieving 'pseudo-ductile' failure.

1. Introduction

1.1. Nacre

Nacre is a composite material found in the inner layers of mollusc exoskeleton and features a highly discontinuous structure. The main function of this exoskeleton is the protection of the inner soft tissue from external damage. Nacre is a hierarchical material and it's remarkable physical properties are the subject of ongoing debate [1–7]. The structure of nacre comprises lamellae of discontinuous platelets. The platelets are discrete hexagonal calcium carbonate (aragonite) tiles, embedded in a viscoelastic protein matrix arranged in a 'brick and mortar' microstructure, resulting in two levels of hierarchy [8], shown in Fig. 1 (adapted from [9]). The tiles of aragonite are typically 300–500 nm thick with the organic layer being 20–30 nm in thickness. An interesting feature of nacre is the very high percentage of the mineral phase, with values of around 95% of the total weight. In nacre, the unique viscoplastic deformation of the organic interface and the crack delocalisation of the layered microstructure of the inorganic aragonite leads to an increase in fracture toughness; this is typically 20–30 times that of synthetic aragonite and fracture strength three orders of magnitude higher than monolithic calcium carbonate [10]. This remarkable toughness and strength, from a relatively simple arrangement of 'tiles' and 'glue', demonstrates the importance of structural design over base material properties. As observed by Knipprath et al. [11], an exact representation of nacre, experimentally or with finite element analysis (FEA) is extremely challenging due to the multi-level hierarchy material intricacies and complex pseudo-ductile failure mechanisms at different length scales, such as interlayer deformation, crack deflection, microbuckling and delamination [12]. Direct mimicry of this system is currently beyond the scope of engineering composite materials but the synthesis of these 'design rules' to yield 'graceful degradation' within a brittle based system is possible and the motivation behind this study.

1.2. Fibre reinforced polymers

Unidirectional (UD) fibre and reinforced polymers (FRP) are generally considered to be continuous in nature, with the reinforcing fibre tows essentially uninterrupted along the length of the laminate. There are exceptions to having a continuous fibre arrangement, which are a necessity of real component design and manufacture (Fig. 2).

- Automatic lay up; during manufacture of large components, the spool of pre-impregnated tape will need periodic replacement resulting in a discontinuous ply region, often a butt joint. Fig. 2a shows two ply terminations sandwiched between two continuous plies.
- Tapering; if a reduction in component thickness is required, this is achieved by a series of ply-drops. Fig. 2b shows a single ply drop reducing the thickness of the laminate by one lamina.

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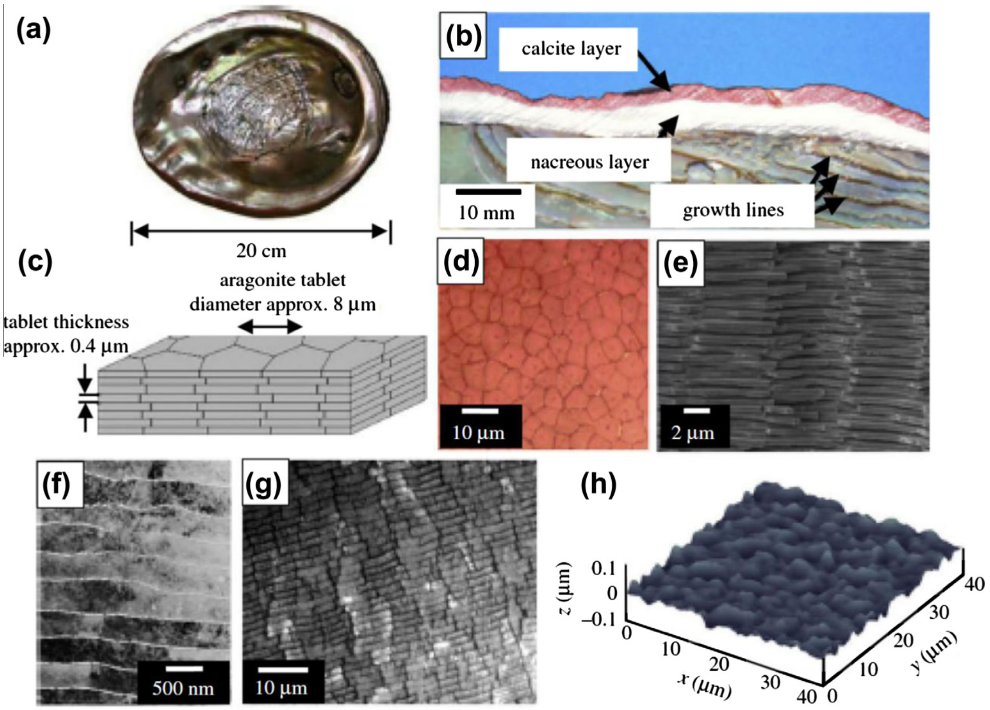

Fig. 1. The multiscale structure of nacre: (a) inside view of shell; (b) cross-section of a red abalone shell; (c) schematic of brick wall like microstructure; (d) optical micrograph showing tiling of tablets; and (e) SEM of fracture surface. (Adapted from [9].) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

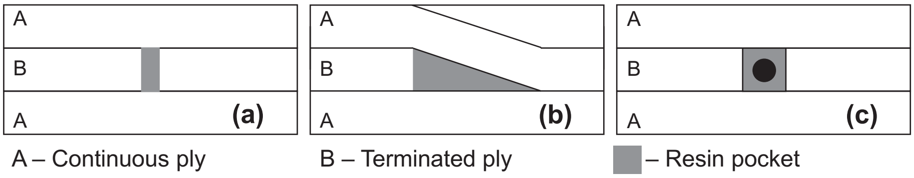

Fig. 2. Ply terminations (a) butted ply ends, (b) single ply drop and (c) feature in butted joint. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Embedment; occasionally features such as health monitoring devices (e.g. fibre optics or strain measurement), Fig. 2c.

The work presented herein discusses research conducted into the effect of ply terminations on the fracture behaviour of laminated FRPs. By selectively introducing controlled discontinuities it has been shown that the catastrophic failure commonly observed in UD composites can be reduced by creating a number of sub-critical fractures sites distributed throughout the structure.

In contrast to continuous FRPs, discontinuous FRP systems in the form of sheet-moulding compounds (e.g. Hexcel HexMC) consist of short 'chips' of pre-preg cut to various sizes and oriented in various directions. The benefit of such a material architecture is an ability to mould very complex 3D components which would not be possible with continuous fibre systems. The nature of discontinuous fibre systems means that there are many ply terminations and resin rich areas. Work by Feraboli et al. [13] identified resin rich areas as well as resin-starved areas to be causes of laminate failure. The work herein takes a fundamental approach to understanding ply discontinuities and their effect on fracture properties.

1.3. The influence of ply cuts on fracture behaviour

Within a laminate, resin rich areas are often avoided as they can act as crack initiation sites due to localised stress concentrations [9,10]. However, this property can be utilised to control the location of crack initiation as well as controlling the subsequent propagation. If a ply cut is introduced within a laminate there will be a resin pocket at the location of the cut, as seen in Fig. 2. To the authors knowledge the effect of this resin pocket geometry/ply cut spacing on flexural fracture properties of a FRP laminate has not been investigated. By altering the width of separation between the two ply ends a simple way of understanding the resin pocket's influence on fracture behaviour can be studied. It is believed that these ply terminations essentially introduce a number of 'weak' links within the laminate. By correctly coordinating these 'weak' links it is possible to generate sequential or 'graceful' failure by replacing a single large catastrophic crack with a number of smaller sub-critical cracks.

Literature shows that cut plies can be used to understand tapering effects, therefore, the work presented may be applicable to tapered laminates as well as those with a uniform thickness [14]. The idea of a 'weak link', which essentially states that each ply cut acts independently unless the distance separating adjacent cuts is less than a critical value, has also been suggested [15–17]. Richards et al. [16] determined a loss in tensile strength of about 15% in CFRP irrespective of the number of ply cuts, given that the separation distance between ply cuts was above this critical value. The work of Darby et al. [15] would suggest that for IM7/8552 (the material used in this study) this length would be approximately 0.15 mm. This criticality may, therefore, be exploited and allow