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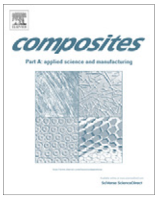

Control of unstable crack propagation through bio-inspired interface modification

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A B S T R A C T

Selective toughening can be used to improve specific interfaces in a fibre reinforced polymer (FRP) component which may otherwise act as crack initiation sites. Interfacial tougheners (such as interleaves and powder treatments) have typically been deployed in a simplistic manner. However, by discretely and judiciously introducing toughening agents, taking inspiration from nature, a step change in toughness characteristics can be demonstrated. Cracks propagating through these toughened regions give rise to interesting fracture phenomena. The work presented herein shows that by incorporating regions of variable toughness, unstable crack propagation can be avoided and graceful degradation to failure demonstrated. Using both Mode I double cantilever beam testing and finite element modelling this study shows how selective toughening can be used without unstable crack growth.

1. Introduction

Fibre reinforced polymer composite laminate interfaces can be selectively toughened to increase damage tolerance, where selective toughening is said to be “the application of a interlayer at critical locations that are potential sites for premature composite failure” [1]. Selective toughening can be applied to areas which require local toughening, such as free-edges, holes and highly stresses regions. Selective toughening has also been used to improve adhesive delamination resistance [2], as well as constraining composite delamination caused by impact loading [3]. A well known application of selective toughening is in the composite wings of the Bell Boeing V-22 Osprey [4].

Research into localised toughening began in the mid-1970s resulting in a promising outlook. For unknown reasons it was not fully developed, a situation possibly attributed to the development of increasingly tough resin systems to address the inadequacies of early systems. Much of the research into selective toughening considered the inclusion of adhesive strips between plies of pre-preg tape prior to cure [5–9].

Localised toughening is an alternative to global toughening as it can reduce manufacturing cost/complexity, maintain weight/dimension requirements or minimise any adverse effects of introducing toughening enhancements. While selective toughening can result in increased damage tolerance there is a consequence from its application. The concept of toughening is based on increasing critical strain energy release rate (G_c) over the baseline toughness. If we consider the use of an interleave material on a single ply interface, the resulting toughening is highly discretised between a region of high and low toughness, separated by a ‘step’ change. The consequence of this arrangement is manifest when a crack propagates across this boundary. The ‘excess’ strain energy released when propagating from high to low toughness will result in unstable crack jumping. Therefore, it is of interest to investigate methods where selective toughening may still be used but without this associated problem. This work investigates a method of transforming the discrete change in toughness described above to a ‘pseudo-continuous’ effect, thereby promoting stable crack propagation from high to low toughness regions of a laminate interface. The design of the interface was inspired by observing the interfaces between different materials in biological structures. Such as root systems in tree’s, root interface between tooth and jaw, tapered finger joints in woodwork and more specifically the interface between tissues in horse hoofs, as shown in Fig. 1.

In the engineering community there are limited examples of selective toughening to control damage propagation. However, one example which has proved successful is the control of crack propagation in sandwich panels with functionally graded interior core junctions or the inclusion of sub-structural components [10–14].

Sandwich materials are layered structural components composed of thin strong face layers separated and bonded to light-weight (typically foam) core materials. Different core materials are often selected depending on the structural loading and level of integrity required. Due to the layered composition of sandwich structures, face–core interface delamination is a commonly observed failure mode, often referred to as peeling failure, which drastically diminishes the structural integrity of the structure. In

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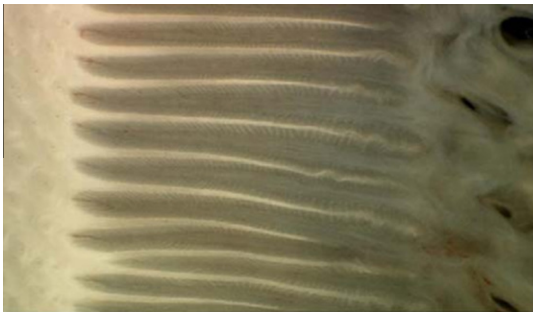

Fig. 1. Interface between high toughness (left) and low toughness (right) epidermal layers of horse hoof showing interdigitated transition region, image courtesy of Dr. Chris Pollitt, University of Queensland. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

recent years there has been a desire by the designer to 'blend' different core materials within the sandwich to minimise weight and maximise structural integrity in selective zones. This methodology has resulted in the formation of highly stressed tri-material regions with inherently different elastic material properties. In an effort to diminish the local failure at these junctions, the concept of 'functionally graded' cores, where the mechanical properties of the functionally graded cores vary gradually with the location within the material, have been investigated [11,12]. In these investigations it was observed structurally graded core junction fatigue life was up to 30% higher sandwich beams with the conventional junction design [12]. An alternative method for crack deflection is the inclusion of a sub-structural component embedded into the sandwich panel [11,12]. The key purpose of this feature (see Fig. 2) is to arrest face–core interface crack propagation by rerouting the crack path into a closed/restricted area of the sandwich panel, thus preventing the catastrophic failure of the sandwich structure. This approach, which utilises the available space in the through-thickness direction between the two skins, has been shown experimentally to retain at least 10% of their initial beam bending stiffness, while the conventional beams retained none [13].

The approach for selective toughening in composite sandwich panels is very unique to the geometry and material combinations employed. Whilst functionally graded core interfaces and different material combinations have been used to reroute the critical crack path, the concept of promoting stable crack propagation from high to low toughness regions of a composite laminate interface has not yet been considered. The aim of this study is to improve specific interfaces within a fibre reinforced polymer (FRP) component which may otherwise act as crack initiation sites. Ideally through discretely and judiciously introduction of toughening agents, taking inspiration from nature, unstable crack propagation can be avoided and graceful degradation of inherently brittle composite materials demonstrated.

2. Experimental methodology

As the aim of this study was to develop a method of varying the interfacial toughness over a distance, the type of modifier was of importance. It was felt that a particulate toughener was suitable as the small particle sizes would allow the toughener to be deposited in varying densities. In essence, particulate modifiers can be applied in variable areal densities whereas film inserts are discrete in their toughening ability. A commercially available elastomer particulate, Duomod DP5045 (Zeon Chemicals LP, USA), has previously been shown to increase the interlaminar fracture toughness in carbon FRP, thus was selected for the study of interface modification [15]. The cross-linked carboxyl-functional particulate is supplied as a fine powder with a typical particulate size of 10 μm.

It was observed in the early stages of the study that the amount of particulate deposited on an interface has a large effect on the fracture toughness. A relatively small deposition of the particulate would result in a toughness increase but if the interface became saturated by too much particulate the toughness would be drastically reduced. Thus, the quantity of toughener deposited was an important parameter, albeit practically challenging to control.

2.1. Experimental design

In order to assess the effect of the Duomod particulate on the interlaminar fracture behaviour Mode I double cantilever beam (DCB) testing was carried out. IM7-8552 carbon fibre/epoxy prepreg tape (Hexcel UK) was chosen as the baseline material system. The Mode I fracture properties were tested according to ASTM Standard 5528 [16]. The generic DCB specimen is shown in Fig. 3.

All specimens were tested on an Instron 3343 screw driven electromechanical test machine (fitted with a 1 kN load-cell) under displacement control at crack-opening displacement of 1 mm/min. The location of the crack was recorded during the test using a digital video macro camera. Specimens were clamped via piano hinges attached in the fixtures. The Mode I strain energy release

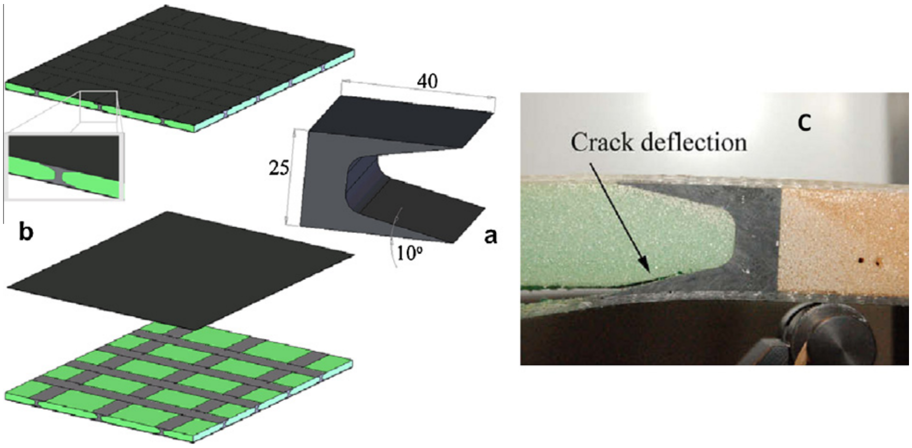

Fig. 2. Proposed design of the peel stopper [13] (a). The case shown displays a crack rerouting angle of 10°. A suggested implementation of the proposed peel stoppers in a sandwich plate is shown in (b) where the grid type pattern will confine damage to the grid mesh. (c) Photo of a peel stopper has been embedded between the two foam cores. The wedge of the peel stopper deflects the interface crack into the core, where the crack was finally arrested and thereby confining the delamination propagation [14]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)