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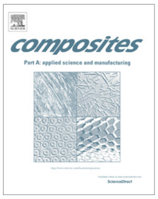

Hierarchical pseudo-ductile hybrid composites combining continuous and highly aligned discontinuous fibres

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ABSTRACT

Hybrid composites allow avoiding catastrophic failure, a key limitation of composite materials, and can provide a balanced suite of modulus, strength and ductility. The aim of this research is to manufacture hierarchical hybrid composites using a combination of continuous high elongation fibres and intermingled hybrids made out of highly aligned discontinuous fibres with lower elongation to achieve pseudo-ductility through control of failure development. The HiPerDiF (High Performance Discontinuous Fibres) method that allows a high level of fibre alignment, leading to excellent mechanical properties close to continuous fibre composites, was used to produce the intermingled hybrid discontinuous fibre preforms. The hierarchical hybrid composite configuration is composed of an intermingled hybrid discontinuous fibre layer sandwiched between continuous S-glass layers. The overall stress-strain response of the intermingled hybrid composites and the hierarchical hybrid composites was investigated for different fibre types and ratios. The analytical modelling approach previously developed by the authors for interlaminated hybrid composites was modified for this new type of hierarchical composite. The experimental results were analysed and the analytical model was used to evaluate the optimised balance of constituents to maximise pseudo-ductile strain in tension.

1. Introduction

High performance composites are typically made of continuous fibres embedded in a polymer matrix but, unlike metals, they tend to fail in a brittle manner leading to difficulties in designing structural components [1,2]. Hybridising two or more types of fibres in composites is one of the main approaches to overcome catastrophic failure.

Several researchers investigated the mechanical properties and damage modes of hybrid composites with continuous and discontinuous fibres as a function of the ratio of constituents and dispersion state. Based on the distribution of each constituent, hybrid composites are categorised into three major types, interlaminated, intraply, and intermingled hybrids, as reported and summarised in [3,4]. However, as the interlaminated hybrid configuration is easily achievable with the material forms available on the market, most of the available literature is mainly focused on this type of hybrid, where the hybridisation is achieved at lamina level by stacking plies of different constituents [3,5–7]. Yarn-by-yarn hybrid fabric prepregs are also commercially available. These give specific characteristics to composite materials, e.g. carbon/aramid hybrid fabric for protection against bullets [8] and carbon/metal hybrid fabric for electric shielding, with mechanical properties reported in [9].

Highly aligned discontinuous fibre composites allow high design freedom in the hybridisation level while achieving structural performance comparable with continuous fibre reinforced composites when the fibre aspect ratio is sufficiently high to achieve full load transfer [10]. Several flow-induced alignment techniques have achieved some success with a high fibre alignment level and a uniform fibre dispersion state in the intermingled hybrids, e.g. the MBB-VTF (Vacuum-drum-filter) alignment process, which relies on the high shear stress of a viscous liquid medium, such as glycerine, to align fibres [10–13]. The authors concluded that interlaminated and intermingled hybrid composites with the same carbon/glass ratio show approximately the same level of elastic modulus and impact strength but the intermingled hybrid composite was largely superior in flexural and tensile strength. More recently, Yu and Longana et al. [14,15] investigated the effects of the fibre mixing ratio on the overall stress-strain responses of intermingled discontinuous glass/carbon

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and recycled/virgin carbon fibre hybrid composites manufactured with the HiPerDiF (High Performance Discontinuous Fibre) method. The HiPerDiF method, invented at the University of Bristol, relies on a unique fibre orientation mechanism leading to high mechanical performance, as outlined in [16]. Thanks to the fact that a low viscosity medium, i.e. water, is used instead of the high viscosity media used in conventional fibre alignment methods, the HiPerDiF technology has the potential to be a fast and continuous process to produce highly aligned tape type preforms. The prototype machine successfully produced intermingled hybrid composites with highly aligned discontinuous fibres that showed a high level of pseudo-ductility [14].

Although hybrid composites are one of the portfolios of next generation composites development, there are few papers about the possibility to hierarchically organise the material constituents [17,18]. The hierarchical organisation of hybrid composites constituents allows a flexible tailoring of the stress-strain curves by controlling the failure mechanism of each constituent. This paper proposes an example of a new type of hierarchically organised hybrid composite which is interlaminated and where some of the layers are also hybrids with aligned discontinuous fibre intermingled preforms sandwiched between continuous S-glass layers. As previously observed in [14], intermingled hybrid composites showed a brittle linear or pseudo-ductile nonlinear tensile response depending on the type of fibres and ratio. This paper demonstrates how the behaviour of the core material affects the tensile response of the interlaminated hybrid composite and the benefits of the hierarchical organisation on pseudo-ductility. The modelling approach developed by Jalalvand et al. [19] is further developed, applied to hierarchical hybrid composites and then validated with the experimental results.

2. Analytical model

Jalalvand's analytical model developed in [19] predicts the stress-strain curve of layer-by-layer hybrid composites with a low elongation material in the middle layer sandwiched between high elongation materials. The model offers three damage mode criteria: (i) fragmentation in the low elongation material; (ii) delamination between the low elongation material and high elongation material; (iii) failure in the high elongation material. The model also offers analytical predictions for the corresponding stress levels at which these damage modes are expected to occur.

In this paper, the hierarchical hybrid composites consist of three types of materials, i.e. the mixture of low and intermediate elongation materials (LE, IE) in the middle and the high elongation material (HE) in the outer layers as shown in Fig. 1. The Jalalvand model was further developed to predict the stress-strain curve for hierarchical hybrid composites. The procedure for finding the damage process is shown in Figs. 2 and 3 as the stress-strain curves of the intermingled hybrid composites in tension are categorised into two cases based on the mechanical properties of the low and intermediate elongation materials and their ratio in the hybrid; linear (elastic) and nonlinear (pseudo-ductile) behaviours.

2.1. Linear-elastic behaviour of intermingled hybrids

When the intermingled layer shows a linear stress-strain curve, the intermingled layer can be considered as a homogenised unit (Fig. 2(a)). When the low elongation material fails in the intermingled layer, the intermediate elongation material cannot withstand the load therefore these instantly cause cracking of the intermingled layer and the appearance of a sequence of fragmentations over the specimen length. Its failure process therefore follows that of the interlaminated hybrid composites with 2 types of material as investigated in [19]. The tensile response of the hierarchically organised interlaminated hybrid composite can be predicted by comparing the fragmentation stress in the intermingled layer ($\sigma_{@itmF}$), the delamination stress between the intermingled layer and the high elongation material ($\sigma_{@del}$), and the final failure stress of the high elongation material ($\sigma_{@HF}$). These stress levels denote the average stress in the laminate. As shown in Fig. 2(b), the stress-strain responses can be drawn using the characteristic points given in Table 1, connected by straight lines from the origin (0, 0) up to high elongation material failure [19]. In this paper, the stress at which the first crack occurs, $\sigma_{@itmF}$, in the intermingled layer was assumed to be the same as the stress at which fragmentation progresses, $\sigma_{@frag}$,

$$\sigma_{@itmF} = \sigma_{@frag} = S_L \frac{\alpha\beta + 1}{\alpha(\beta + 1)} \tag{1}$$

where α and β are the modulus and thickness ratios of the intermingled layer to the high elongation composites respectively ($\alpha = \frac{E_{L+I}}{E_H}, \beta = \frac{t_{itm}}{t_H}$); E_{L+I} is the elastic modulus of intermingled layer made of low and intermediate elongation materials and E_H is the elastic modulus of the high elongation material, t_{itm} and t_H denote the half thickness of the intermingled layer and high elongation materials. In order to calculate the strain of the saturated fragmentation knee point (P3 in the case of L2) and L3) in Table 1 and Fig. 2(b)), the modulus of the laminate with randomly saturated fragmentation in the intermingled layer, E_{sat}, [19] is derived as:

$$E_{sat} = E_H \frac{1 + \alpha\beta}{(1 + \beta)(1 + \frac{11}{18}\alpha\beta)} \tag{2}$$

$\sigma_{@del}$ is calculated using Eq. (3) in an aspect of fracture mechanics and $\sigma_{@HF}$ using Eq. (4) respectively [19],

$$\sigma_{@del} = \frac{1}{1 + \beta}\sqrt{\frac{1 + \alpha\beta}{\alpha\beta}\frac{2G_{IIc}E_H}{t_H}} \tag{3}$$

$$\sigma_{@HF} = \frac{S_H}{K_t(1 + \beta)} \tag{4}$$

where G_{IIc} is the mode II fracture toughness and S_H is the high elongation material failure strength. A stress concentration factor, K_t, is

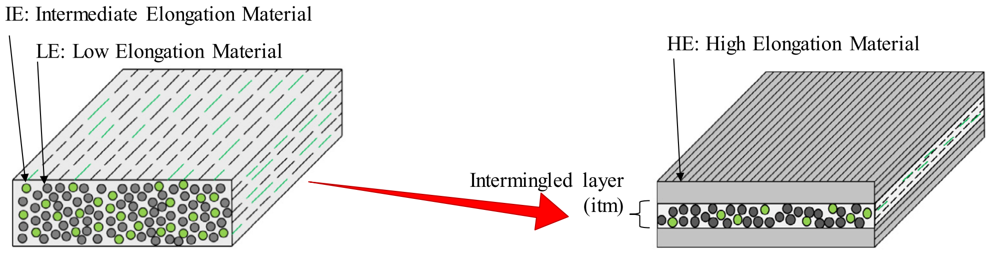

Fig. 1. Schematic of intermingled hybrid composite and hierarchical interlaminated hybrid composite specimens. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)