ANALYSIS OF FAILURE MECHANISMS IN HYBRID CARBON FIBRE/SELF-REINFORCED POLYPROPYLENE COMPOSITES

Marina Selezneva[1], Yentl Swolfs[1], Tomoko Ichikawa[2], Ignaas Verpoest[1], Larissa Gorbatikh[1]

[1]Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44, 3001 Leuven, Belgium
Email: Marina.Selezneva@mtm.kuleuven.be
[2]Composite materials research laboratories, Toray Industries, Inc., 1515, Tsutsui, Masaki-cho, Iyo-gun, Ehime, Japan, 791-3193
Email: Tomoko_Ichikawa2@nts.toray.co.jp

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Abstract
The present work investigates the tensile properties of a novel type of hybrid composites that contain stiff but brittle webs of discontinuous carbon fibres, and tough but compliant plies of self-reinforced polypropylene (SRPP). The goal is to achieve a better balance between stiffness, strength and toughness. In the scope of this study, the effect of fibre volume fraction on the ductility of the hybrid was evaluated, and failure mechanisms that govern the transition between brittle and ductile behaviour were assessed. Hybrids with volume fraction of less than 7 % exhibited quasi-ductile response, while reaching the modulus of 6.1 GPa and the failure strain of 10 %. Through the modelling work it was shown that the initial elastic behaviour of the hybrid can be estimated using the incremental rule-of-mixtures. It was found that catastrophic interply delamination is not a dominant failure mode, and consequentially, the strength of the hybrid can be predicted from the failure strengths of the web and the SRPP. Overall, this family of hybrids has attractive properties that can be tuned to specific applications by controlling the fibre volume fraction.

1. Introduction

The high specific properties of carbon fibre composites make them attractive for a wide range of applications from sporting goods to aircraft components. However, such components are typically over-designed, because they fail in a brittle manner with little or no warning before final failure. There is significant industrial interest in prolonging damage development in carbon fibre composites by designing quasi-ductile layups. It has been previously shown [1 - 5] that pseudo-ductile behaviour can be achieved by interlayer hybrids that consist of layers of low elongation (brittle) and high elongation (ductile) plies. Effective design of ductile hybrids is challenging and requires a thorough understanding of the failure mechanisms that occur during loading [3 - 5]. The damage scenarios that can occur in hybrids were outlined by Czel *et al.* [1 - 4] and Swofls *et al.* [2] and are shown in Figure 1. The possible damage events that can occur after the initial failure of the low elongation layer are [1 - 5]:

a) instant failure of the high elongation layer as it cannot sustain the load that is transferred to it,
b) catastrophic delamination, which is then followed by the failure of the high elongation material,
c) stable fragmentation of the low elongation material until saturation and then failure of the high elongation material.

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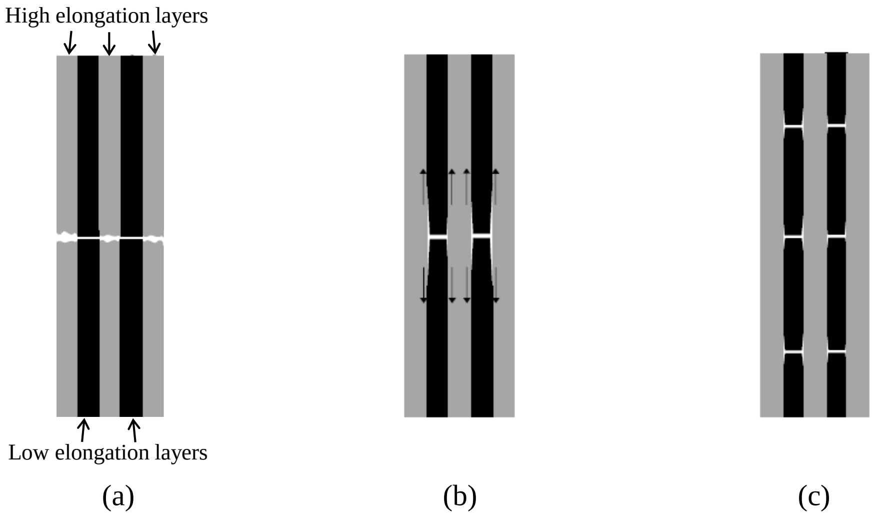

Figure 1. Possible failure scenarios in interlayer hybrid composites: (a) instantaneous failure of the high elongation layer, (b) delamination (c) stable fragmentation of the low elongation material (adapted from [2]).

Initiation and propagation of damage depend primarily on the strength, stiffness, volume fractions of the ductile and brittle layers, their lay up as well as the interlaminar fracture toughness of the interface between them. Depending on the combination of these properties, failure can be either gradual or abrupt. Hence, the right combination of parameters is required to achieve a pseudo-ductile response.

This paper explores the design of hybrids that consist of brittle carbon fibre webs (discontinuous, randomly-oriented fibres) and ductile woven self-reinforced polypropylene (SRPP). The aim of this study is to investigate the fundamental load-sharing and failure mechanisms particular to these hybrids. Finally, conclusions will be drawn regarding the dominant failure mechanisms that govern the brittle-ductile transition.

1. Experiemental

1.1. Materials and processing

The moulded hybrid panels consist of outer SRPP layers and an inner web layer. The precursor material to SRPP is balanced 2/2 twill PP tape fabric provided by Propex Fabrics GmbH. Upon heating, the outer sheath of the PP tapes melts, while the inner core maintains its orientation. During the cool-down, the molten PP consolidates and forms the “matrix” component of the SRPP layer. The web layer of the hybrid effectively consists of randomly oriented 6 mm long carbon fibres (Toray Industries, Inc) that are impregnated by PP films (Propex Fabrics GmbH) during hot compaction. During the layup, 30 gsm dry carbon fibre webs are interleaved with 20 µm PP films in order to achieve good impregnation. Different overall carbon fibre volume fractions (V_f = 4.4 – 9.8 %) were achieved by varying the number of webs and PP films, while the same internal V_f in the impregnated web layer was maintained. Based on the areal densities of the films and the webs, the internal V_f was calculated to be 16.7 %. Pure-web and pure-SRPP panels were produced as reference materials. Panels were manufactured by hot compaction at 188°C with a hold time of 5 min at 40 bar, and an average cooling rate of 35°/min. Additional information on the manufacturing process and the optimisation of the processing conditions can be found in [6].

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1.2. Test methodology

To measure tensile properties the ASTM D3039 standard was followed. Specimens were 250 mm long and 25 mm wide, and had a gauge section of 150 x 25 mm. Specimens were not tabbed, but instead a piece of emery cloth was placed between the specimen and the grips to prevent slippage. Specimens were loaded at a rate of 2 mm/min or 7.5 mm/min, depending on whether their response was brittle or ductile. Strain was measured using the 2D digital image correlation (DIC) technique and data was analysed using the VIC-2D software from Correlated Solutions.

1.3. Results

The stress-strain curves of the pure-web, pure-SRPP and hybrid composites are shown in Figure 2. Pseudo-ductility with failure strains above 10 % is achievable when the total V_f of carbon fibres is lower than 7 %. At the same time these hybrids offer a twofold increase of modulus over that of SRPP (6.1±0.4 vs. 3.06±0.06 GPa) . It is anticipated that further improvements to the ductility and stiffness combination can be achieved by optimising the stacking sequence, which is the focus of ongoing work.

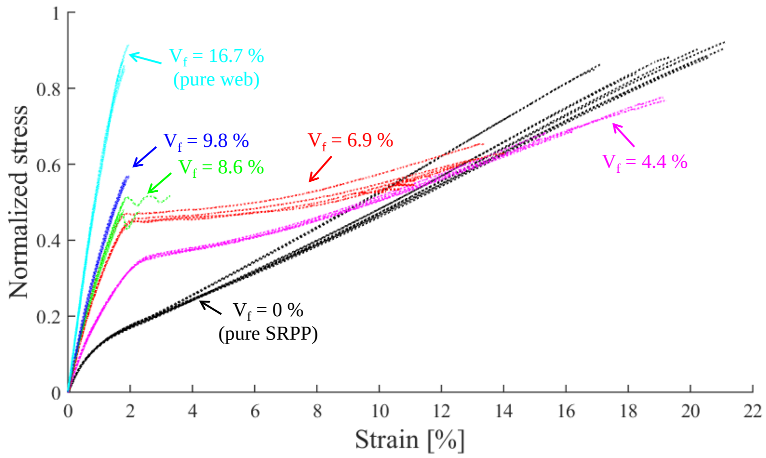

Figure 2. Tensile stress-strain curves of pure-web, pure-SRPP and hybrid composites.

Better understanding of the origin of pseudo-ductility in these hybrids is obtained by monitoring damage development. Fragmentation of the web is clearly visible during loading, due to the colour difference between carbon and SRPP layers (Figure 3). Interestingly, fragmentation is accompanied by the "checkered-pattern" whitening of the specimen (Figure 4 (a) and (b)). Microscopic analysis (Figure 4 (c)) revealed that this whitening is caused by debonding between the longitudinal and the transverse PP tapes. Propagation of the debond is then impeded by the web/SRPP interface (Figure 4 (b) and (c)). Hence, it can be concluded that the web/SRPP interface is tougher than the intralayer bond between the SRPP tapes. Dimensions of the checkered-pattern (≈ 3 x 3 mm) corresponds to the width of two longitudinal tapes that form the twill 2/2 unit cell of SRPP.

The final failure of both ductile and brittle hybrids occurs due to the fracture of SRPP and is accompanied by debonding or pull-out of the longitudinal PP tape. Interestingly, no delamination, in its classic sense, between the web and the SRPP layers is observed.

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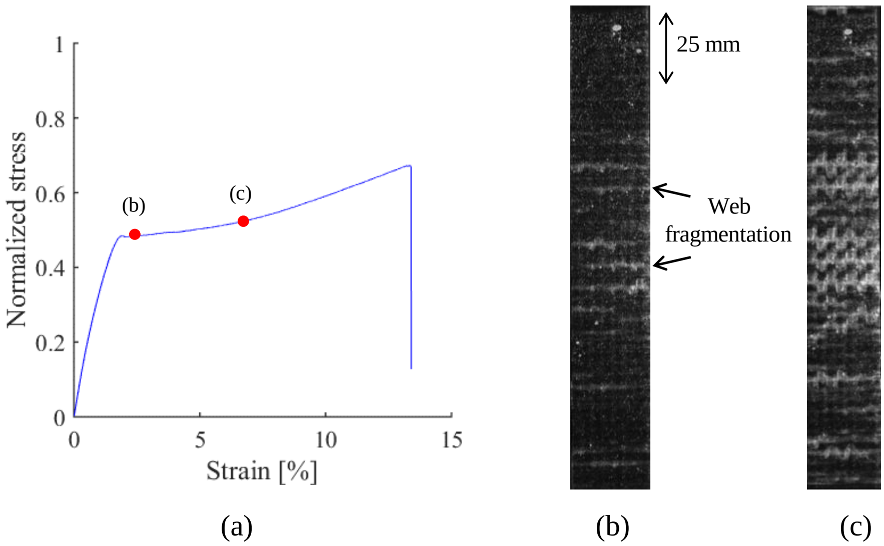

Figure 3. Correlation between tensile behaviour and damage development in pseudo-ductile hybrids: (a) typical stress-strain curve, and (b) and (c) photos that capture specimen appearance during fragmentation.

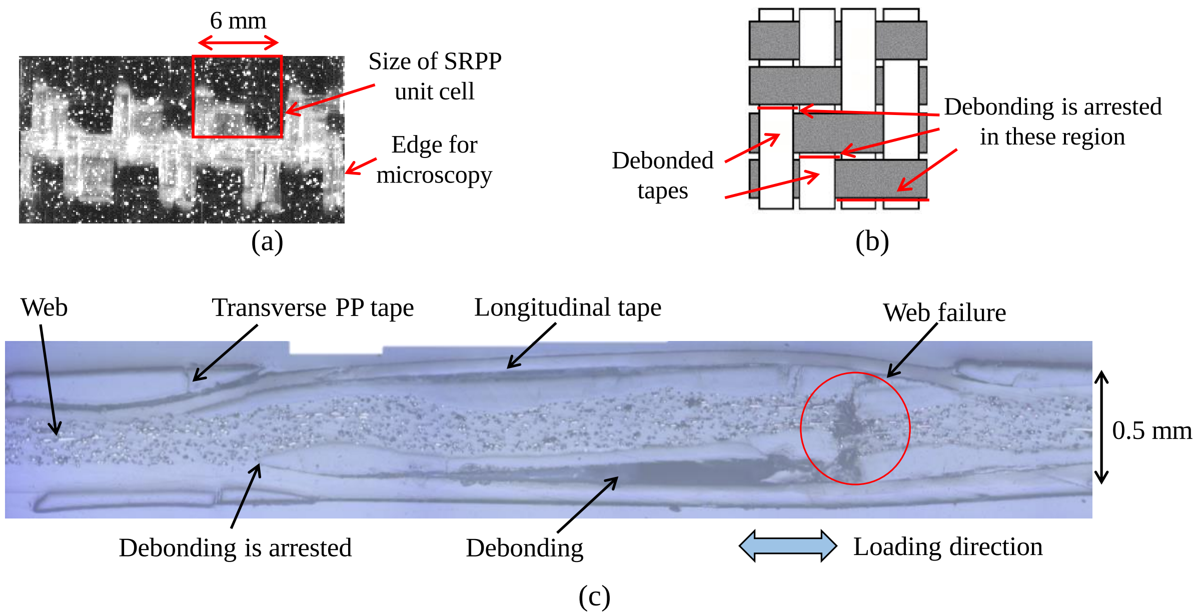

Figure 4. Checkered-pattern debonding: (a) what it looks like on the specimen surface, (b) how it is related to the material architecture and (c) as it appears in the cross-sectional micrograph.

2. Modelling

2.1. Approach

One of the goals was to develop a simple analytical model that would capture the entire stress-strain response of any hybrid consisting of a self-reinforced polymer and a web. The first step in attaining such a model is to examine the elastic behaviour of a hybrid before any failure initiates. Elastic properties can typically be estimated using the rule-of-mixtures. In order to account for the non-linear behaviour

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of SRPP, stress-strain curve of a hybrid can be calculated by applying the rule-of-mixtures at incremental values of strain (ε_i), as shown in Eq. 1.

$$\sigma_i = \frac{(\sigma_H)_i t_H + (\sigma_L)_i t_L}{t_H + t_L}, \tag{1}$$

where σ_H and σ_L are stresses in the high elongation layer (SRPP) and low elongation layer (web) at strain ε_i, σ_i is global stress in the hybrid at strain ε_i, and t_H and t_L are thickness of the high and low elongation layers.

From the experimental results it can be seen that the drop in the load-bearing capacity of the hybrid is associated with the failure of SRPP, and not with catastrophic delamination. Hence, it is possible to estimate the strength of the hybrid by simply considering the strength of SRPP (S_H), as shown in Eq. 2.

$$\sigma = \frac{S_H t_H}{t_H + t_L} \tag{2}$$

Ongoing work is focused on incorporating the load redistribution between the fragmented web layer and partially debonded SRPP layers into the model in order to properly capture the shape of the stress-strain curve during damage development.

2.2. Results

Comparison between the experimental and the modelling results for the part before failure of the carbon layer is presented in Figure 5. The initial response of these hybrids is well predicted by the incremental rule-of-mixtures.

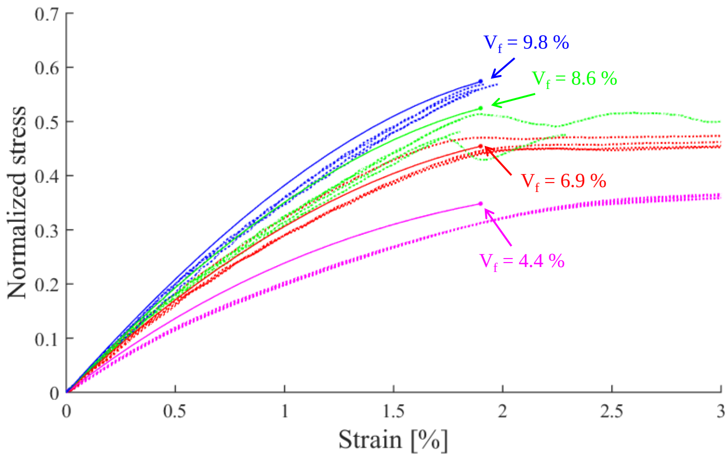

Figure 5. Experimental (dotted lines) and modelling (solid lines) results of the initial elastic portion of the stress-strain curves.

Next, to predict whether a particular hybrid will have a brittle or a ductile behaviour, the strength criterion given by Eq. 2 is considered. The manner in which the hybrid fails depends on whether the global stress that can be sustained by the SRPP layers on their own is higher or lower than the global stress required to break the web. In the case of ductile hybrids (Figure 6a), SRPP layers can sustain a higher load than that at which the web fracture occurs, and the hybrid continues to carry load until the max value as predicted by Eq. 2. In the case of brittle hybrids (Figure 6b), the SRPP plies cannot carry all the load that is transferred to them after the failure of the web, which leads to an abrupt load drop in the stress-strain curve. Depending on the ductility of the high elongation ply, it can either break or

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continue stretching at this load. Nonethless, the specimen would not be able to attain a higher load than that at which the web broke and for practical reasons can be considered as failed. Hence, the strength of these brittle hybrids is determined by the load at which the web fails.

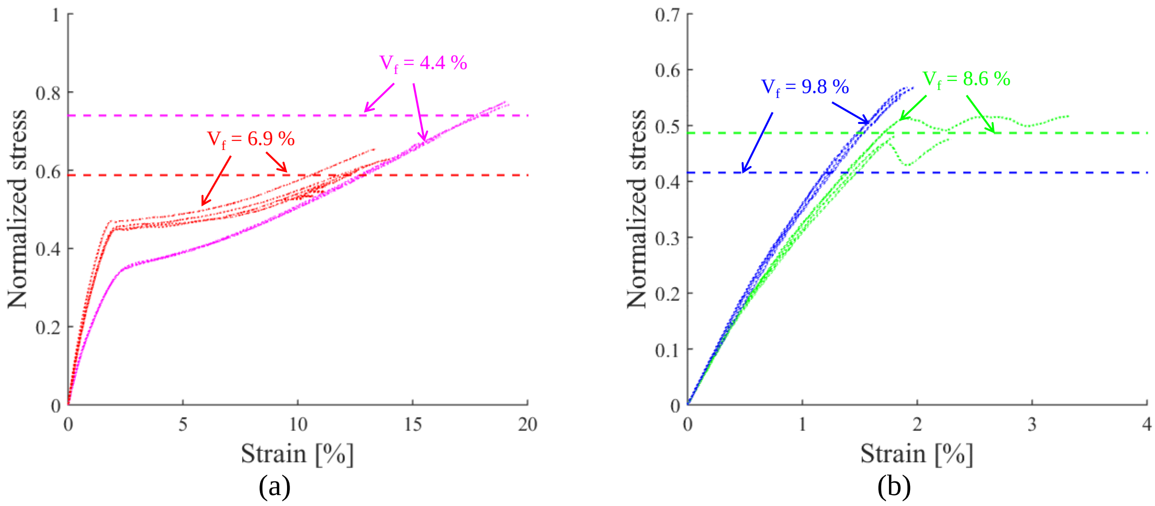

Figure 6. Experimental (dotted lines) stress-strain curves up to failure and the predicted global stress levels (dashed lines) at which SRPP plies are expected to fail: (a) pseudo-ductile and (b) brittle hybrids.

Thus far, it seems that for this family of hybrids the failure criterion for unstable delamination, which is prominent to hybrids with UD fibres [1, 2, 4, 5], is not required to predict the peak stress and the transition between the brittle and the ductile behaviour. Nonetheless, the fracture toughnes the web/SRPP interface cannot be completely ignored in the analysis, as they are expected to play a role in the stress-strain response of the material up to final failure.

4. Conclusions

The development and the potential of a novel pseudo-ductile hybrid that consists of SRPP/carbon-web were discussed. It was shown that tensile properties of these hybrids can be tuned by adjusting the fibre volume fraction and that pseudo-ductile behaviour is attainted for $V_f < 7$ %. Interestingly, this material develops a distinct checkered-pattern damage zone during failure. Formation of this pattern is attributed to the woven architecture of the SRPP layers and the tough interface between the SRPP and the web that impedes the debonding of longitudinal PP tapes. Overall, a good combination of stiffness (6.1 GPa) and ductility (10 %) was achieved, which makes these hybrids competitive with bulk moulding and sheet moulding compounds. It is anticipated that further improvements can be achieved by modifying the stacking sequence and the interface properties.

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