EXPLORING ROUTES TO CREATE HIGH PERFORMANCE PSEUDO-DUCTILE FIBRE REINFORCED COMPOSITES

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ABSTRACT

High performance composites generally exhibit brittle failure with little or no prior warning. This paper describes research that is being conducted on strategies to introduce a more ductile failure process in these composites. Mechanisms are proposed to impart a yielding-like behaviour and to ensure this occurs in a distributed manner under uniform tensile loading. Results of modelling studies and experiments are presented for several strategies including a ‘brick and mortar’ arrangement of short composite platelets, a composite laminate containing specific patterns of ply and interface weakening and a ‘wavy’ sandwich that exhibits significant ductile-like behaviour and achieves 8% strain at final failure.

1 INTRODUCTION

Current high performance fibre reinforced polymer matrix composites offer high specific strength and stiffness, and low susceptibility to fatigue and corrosion and as a result their application in aerospace, wind energy, sporting goods and civil engineering is rapidly expanding. These materials also hold considerable potential for the future as, in addition to the ability to tailor the mechanical properties to suit particular applications, it is possible to incorporate additional functionalities such as sensing, self-repair, electrical energy storage and morphing.

Despite this progress, a fundamental limitation of current high performance composites is their inherent brittleness; failure is usually sudden and catastrophic, with little warning or residual load carrying capacity. This limitation has a very significant effect on the design and performance of composite components and structures and yet little work seems to have been done to address this issue. The only composite types in which significant ductile behaviour has been demonstrated are hybrid materials, where early work showed it was possible to achieve a gradual failure over a range of strains by mixing different types of fibres, regenerated cellulose fibre composites and all-polymer composites.

This paper describes research conducted within The Composites Centre at Imperial College as part of the High Performance Ductile Composite Technology programme (HiPerDuCT) to overcome this key limitation by introducing pseudo-ductility into the uniaxial tension failure process so that the brittle stress-strain response can be transformed as indicated in Figure 1. (Here the word *pseudo* is used to indicate that the ductility has been achieved through damage development in the composite rather than the ductile behaviour which occurs in metals which is due to sliding of layers of atoms relative to each other at dislocations.) The two ductile stress-strain curves of Figure 1 are examples of the type of behaviour being sought – the ideal would be to retain the strength and stiffness of a high performance composite system with a considerable increase in the strain to failure. With the pseudo-ductility approaches presented in this paper there is some trade-off in stiffness and/or strength but other work within HiPerDuCT is targeting new, truly ductile high performance reinforcements.

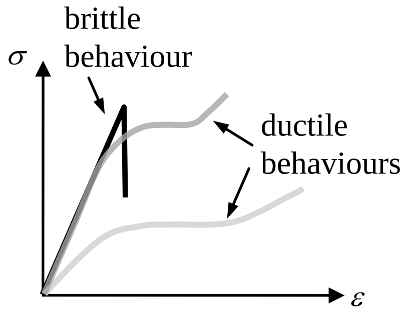


Figure 1. Brittle and desired ductile stress-strain behaviours

2 DESIRED STRESS-STRAIN RESPONSE

In order to achieve significant pseudo-ductility in a composite of the type shown in Figure 1, mechanisms are required to introduce additional extension and also to prevent failure localisation before the process providing additional extension can be achieved throughout the material. (This latter requirement must be satisfied to ensure that a pseudo-ductile stress-strain response measured in a short specimen will be achieved in a much longer specimen specimen.) To avoid premature localisation of failure, it is important that the stress-strain response of the material measured at the size of the internal length scale (e.g. the length unit cell in a material with a repeating micro-structure) exhibits a 'strain hardening' behaviour immediately prior to the maximum stress, σ_{max}, which is higher than the 'yield' stress, σ_y. Therefore unit-cell mechanisms that exhibit strain softening or elastic-perfectly plastic behaviour (Figure 2a) are unsuitable. For these cases small variations in σ_y in a series-connected set of such unit cells will result in the weakest unit cell following the elastic-softening or the elastic-perfectly plastic stress-strain curve of Figures 2a while the other unit cells in the series either, in the case of the elastic-softening behaviour, unload or, in the case of the elastic-perfectly plastic behaviour, remain at the yield stress of the weakest unit cell and then unload when that cell reaches its failure. The resulting stress-strain response of the series-connected set of such unit cells will then be dependent upon the number of unit cells in the series but will rapidly approach the initial linear elastic response (i.e. tending to exhibit no ductility) as the number of cells increases. Examples of suitable unit cell stress-strain curves are shown in Figure 2b. For these cases the stress strain curves of a series-connected set will closely follow that of the unit cell up to the strain associated with the maximum stress.

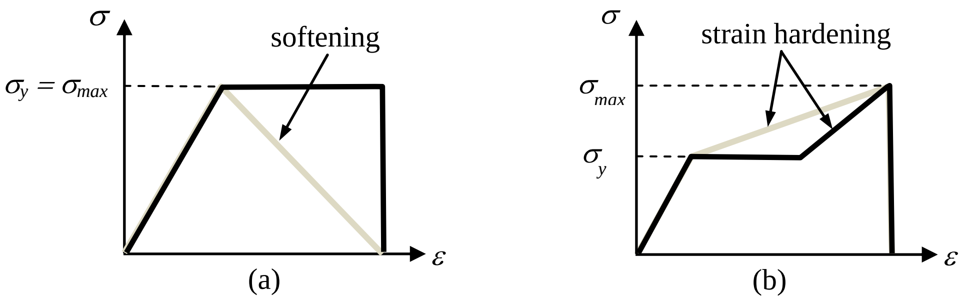


Figure 2. Potential stress-strain behaviours

2 STRATEGIES INVESTIGATED

In the absence of ductile high performance fibres the research has focussed on:

- the initiation and interaction of damage modes in the composite such that there is a gradual loss of stiffness prior to final failure;

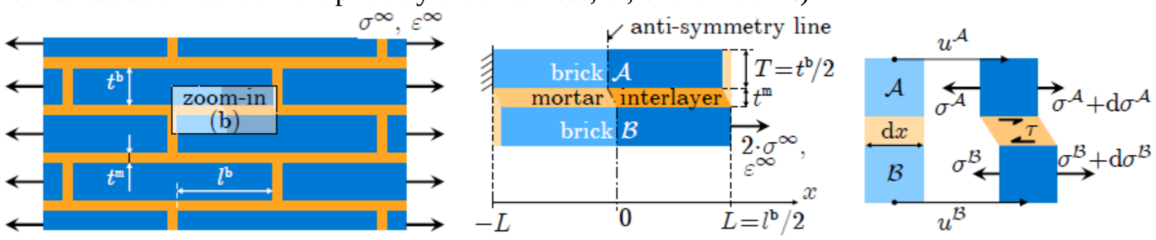
- the incorporation of waviness which can provide significant additional extension.

This section describes several of the strategies investigated so far and summarises the results from modelling and experimental studies.

2.1 Architectures exploiting discontinuities

Many natural structural materials (such as nacre, bone and spider silk) have a discontinuous brick–and–mortar architecture (see Figure 3a) with staggered stiff inclusions (i.e. the bricks) embedded in a soft matrix (i.e. the mortar) [1, 2]. When subjected to tension the resulting extension of the composite is due to the extension of the bricks (which dominates the initial stress-strain response), and to the shear deformation of the mortar (which, as the matrix yields or cracks, enables large extensions and energy absorption before final failure). It is suggested that the combination of these two mechanisms in optimised architectures is key to achieving the high stiffness, high strength and damage tolerance observed in many natural composites.

Modelling has been conducted on a composite 'brick and mortar' configuration (see Figure 3a) consisting of unidirectional carbon fibre reinforced polymer (CFRP) platelets (of length $2l^b$ and thickness t^b) bonded together by a polymer matrix (of thickness t^m) and subjected to a tensile stress [3]. Taking advantage of the antisymmetry in the unit cell, of length $2L$ (as shown in Figure 3b), a shear lag analysis has been conducted for the portion $0 \leq x \leq L$. In this analysis the matrix is assumed to resist shear only (and so distort in shear) while the bricks are assumed to carry direct stress uniformly distributed over the thickness (and so extend axially only). The shear stress-strain response of the matrix is approximated as piecewise linear and examples of the responses investigated are shown in Figure 4a. These responses all have the same initial modulus ($G^m{}_{el}$), the same maximum stress (S^m) and the same mode II toughness ($G^m{}_{IIc}$) and these properties are given in Table 1, together with those of the composite platelets (modulus E^b and strength X^b), the thicknesses of the matrix (t^m) and the half thickness of the composite platelet (T). (The mode II toughness of the matrix is equal to the area under the shear stress-strain curve multiplied by the thickness, t^m, of the matrix.)



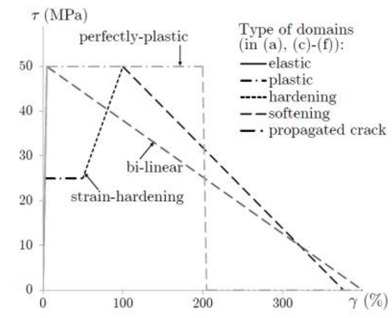
a. Brick–and–mortar composite. b. Unit cell (zoom-in from (a)). c. Infinitesimal element.

Figure 3 'Brick and mortar' architecture and model overview

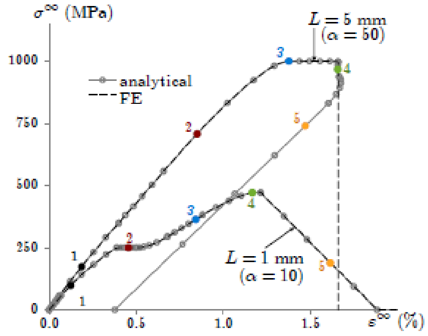
Geometry		platelet properties		Matrix properties		
T (mm)	t^m (mm)	E^b (GPa)	X^b (MPa)	G^m_{el} (GPa)	S^m (MPa)	$\mathcal{G}^m_{IIc}$ (kJ/m^2)
0.100	0.010	100	2500	1.0	50	1.0

Table 1 Dimensions and properties for the overlap models

The predicted stress-strain response determined from the analysis of the unit cell for the strain-hardening matrix of Figure 4a is presented in Figure 4b for two values of L, the half overlap length. For short overlaps the predicted tensile stress-strain behaviour exhibits the same characteristics as the shear response of the matrix, i.e. the stress-strain response possesses a plateau at an intermediate stress, a strain-hardening phase up to a maximum stress and then a softening phase to final failure. Similarly, when the other shear stress-strain responses of Figure 4a are used, their characteristic features are present in the stress-strain behaviour predicted for the short unit cell. For a sufficiently long overlap, the process zone associated with failure of the matrix is relatively small and fully contained within the half-overlap. In this situation, the model predicts the response expected for propagation of a crack from each end of the overlap and so, as shown in Figure 4b, the stress-strain curve rises to a maximum stress which is significantly higher than that of achieved with a small overlap and then remains constant at that value as the cracks propagate from the two ends towards the centre of the overlap. Using one of the other shear stress-strain responses of Figure 4b will not change the maximum stress associated with the plateau (as long as the fracture toughness remains the same) but will effect, to a small extent, the shape of the curve as it approaches this plateau stress value as well as the shape of the curve at the end of the plateau (which corresponds to the stage as the process zones associated with the two cracks merge, after which the overlap progressively separates).



a. Matrix shear responses considered in this study, with coordinates ($\gamma[\%], \tau[\text{MPa}]$) as follows:
strain–hard.: (2.5,25); (50,25); (100,50); (376,0);
bi-linear: (5,50); (400,0);
perfectly–plastic: (5,50); (200,50); (205,0).



b. Global stress–strain response of composites with a strain–hardening matrix, as predicted by the analytical and plane–stress FE models.

Figure 4 Matrix shear stress-strain behaviours and predicted stress-strain response from unit cell

Recalling that a unit cell with a strain hardening characteristic is required to ensure that a series of such unit cells will exhibit significant ductility, it is clear that although the long overlap case will exhibit relatively high strength and stiffness, the lack of significant strain hardening will mean that a composite composed of a series of such overlaps will not possess significant ductility. However, for short overlaps and matrix shear stress-strain responses with strain hardening, significant ductility could be achieved in the composite.

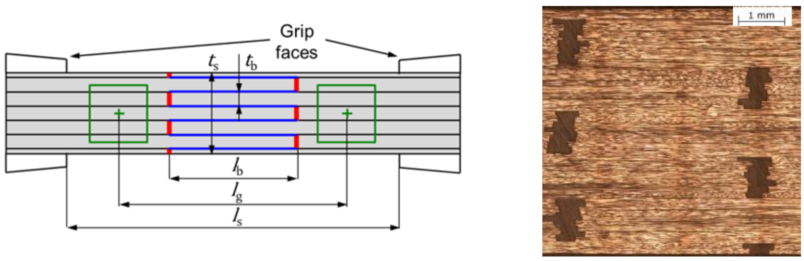
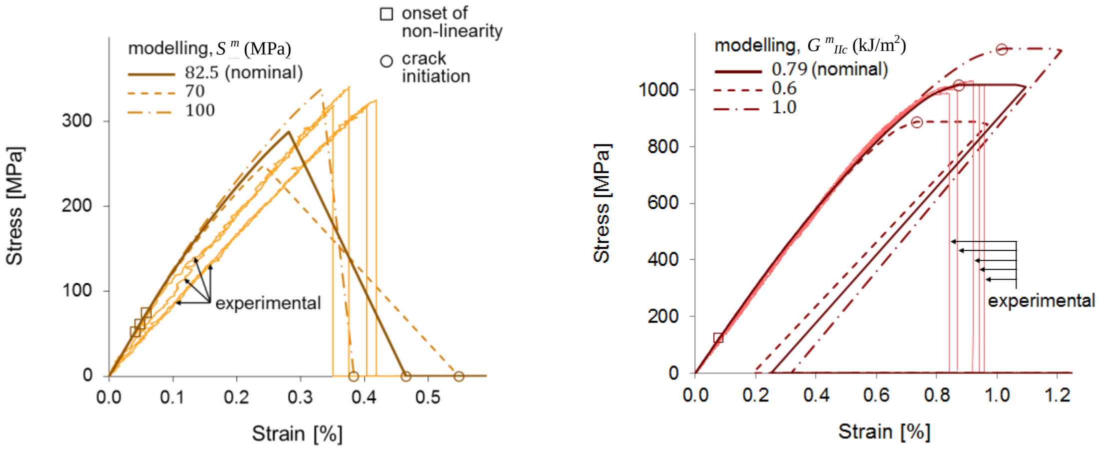


Figure 5 (a) Schematic of overlap test specimen (b) Micrograph of overlap region of short overlap specimen.

Experiments have been performed by colleagues at Bristol University using IM7/8552 for both short and long overlap configurations and the results were compared to the analysis predictions which assumed a simple bi-linear shear stress-strain response (i.e. no strain hardening) [4]. The specimen consisted of a single set of overlaps arranged in a parallel fashion as shown in Figure 5. The experimental stress-strain plots and the predicted responses for both the short and long overlap specimens are shown in Figure 6. For the short overlap case, the agreement between the experiment and the predictions (shown for several different) is reasonable and there is no benefit in terms of ductility. For the long overlap case there is good agreement with the predicted stress to cause crack growth and for the non-linear behaviour preceding it, but the extent of the associated plateau is much less than predicted (probably due to variations in the overlap lengths within a specimen). To demonstrate the benefits of using a more ductile matrix material in a discontinuous composite, short overlap tests using a specimen similar to that of Figure 5 were also performed by the Imperial College team on a carbon fibre PEEK system, but in this case additional PEEK films were incorporated at the interfaces within the overlap zone [5]. These specimens were rather more variable in the cured geometry, but the typical stress-strain plot shown in Figure 7 confirms that the ductile shear stress-strain behaviour of the matrix does result in a ductile tensile performance in a composite consisting of a single set of parallel overlaps (as in Figure 5).



a) *Short overlap* configuration   b) *Long overlap* configuration.

Figure 6 Modelling predictions and experimental results for the stress-strain curves of IM7/8552 discontinuous-ply specimens.

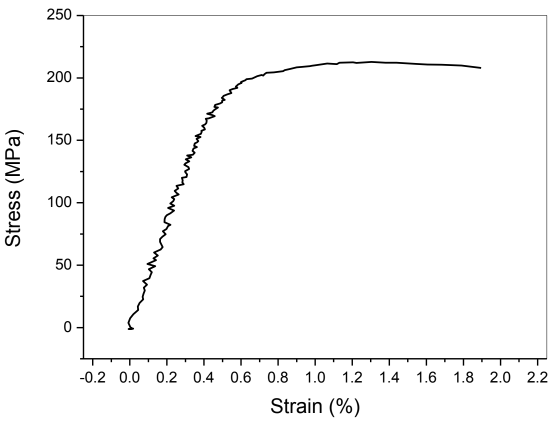


Figure 7 Experimental stress-strain curve of discontinuous-ply carbon-PEEK specimen with an overlap length of 2 mm

Unfortunately neither of the systems tested experimentally exhibits the strain-hardening necessary to ensure that a composite consisting of many of these overlapping elements connected in series will exhibit significant ductility. One way to achieve a strain hardening response is to combine a discontinuous architecture with continuous plies in a parallel arrangement as shown in Figure 8a. Provided the configuration has been suitably designed, the continuous plies will support a further increase in load after the interface with the adjacent platelet has completely failed (i.e. the unit cell can be designed to possess a ductile strain-hardening response) and so a series-connected set of such unit cells will also display a strain hardening response. Such an approach has been already been demonstrated by colleagues working in the HiPerDuCT programme at Bristol University [6], and other approaches to incorporate a strain hardening response in a discontinuous architecture are being explored at Imperial College.

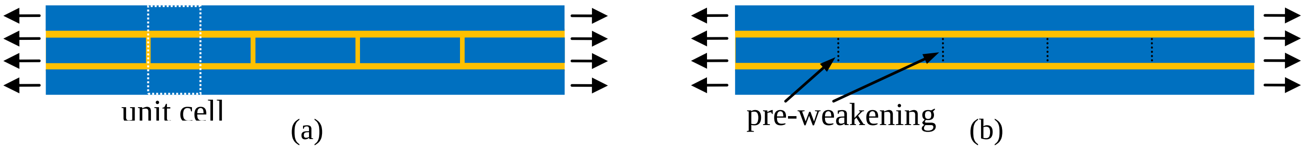


Figure 8 Discontinuous platelets combined with continuous plies: (a) manufactured with discontinuities in place (b) discontinuities produced by failure at pre-weakened sites

2.2 Pre-weakening to create a discontinuous composite in-situ

By suitably pre-weakening the internal ply of a continuous ply composite as indicated in Figure 8b, the architecture of Figure 8a can be produced in-situ when the composite is loaded in tension. It is anticipated that in a suitably designed system the weakened plies will fail first, a higher load will be required to delaminate the resulting platelets from the pristine plies and then an even higher load will be required to fail the pristine plies. (The increasing load associated with the progression through these failure modes will ensure that a composite plate containing a series of ply weakenings, as shown in Figure 8b, will exhibit the intended ductile response.) Finite element (FE) modelling studies have been conducted to investigate the tensile response of a 12 ply M21/T800S carbon epoxy laminate with a layup of $[0°/0°_w/0°]_4$ in which the subscript *w* indicates that the ply is weakened [7]. Weakening of the interface between the weakened ply and the adjacent pristine plies was also investigated. In this case, rather than examine the response of a unit cell, the modelling results are presented for a specimen of length 150 mm and thickness 2.2 mm. Cohesive elements were inserted between the plies to capture delamination and at 300 evenly spaced planes to capture tensile failure of the plies. Weakening was introduced at specific locations by reducing the strength and critical energy release rate of the interface elements to one third and 10% of the pristine values for ply weakening and interface weakening respectively. Ply weakening was chosen to be uniformly spaced along the length of the specimen and arranged in a chessboard pattern and interface weakening was centred on the location of each ply weakening as shown in Figure 9. Various spacings, *D*, of ply weakenings and lengths, *W*, of interface weakening were investigated and selected results are shown in Figure 10 for the case of $D = 4$ mm.

For the case without interface weakening (Figure 10a) the model predicts that the stress-strain response of the modified composite departs from the pristine response as expected at around 1/3 of the pristine strength (i.e. matching the strength of the weakened plies) and follows a non-linear path to an ultimate failure load of just less than 2/3 the pristine strength (again as expected since 2/3 of the thickness consists of pristine, unweakened plies). The non-linear path has a plateau at a stress of approximately 1520 N/mm^2 before a short rising section to the ultimate failure stress. The case with interface weakening (Figure 10b) shows similar characteristics except that the departure from the pristine response is much more distinct with a larger loss in stiffness and the ductile strain is significantly larger. A detailed investigation is currently being performed into the development and interaction of the ply and interface failure modes in the FE models that result in these predicted behaviours. Specimens are also being prepared to establish if the predicted pseudo-ductile responses can be achieved in practice.

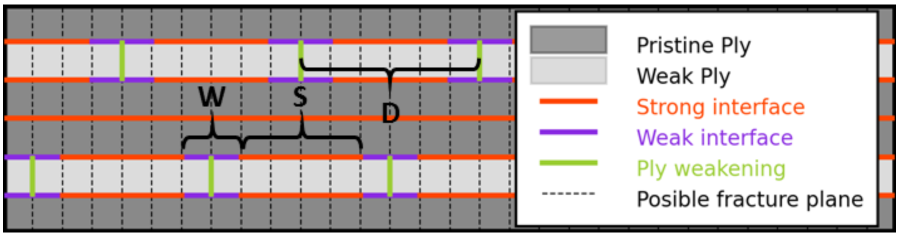
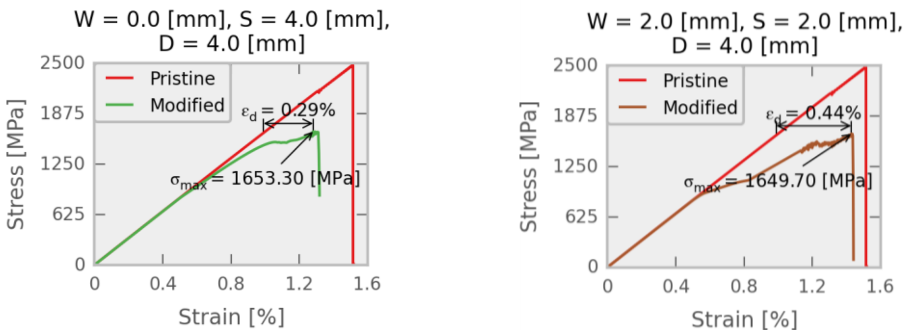


Figure 9 Small section of model showing ply and ply interface weakening scenario



(a) (b)

Figure 10. Predicted stress-strain response for D = 4 mm a) no weakened interfaces, b) weakened interfaces with W = 2 mm

2.3 Waviness

Waviness of fibres and plies has been explored as another means of introducing ductility in a composite. The idea is to take advantage of the high extension exhibited by a wavy fibre or thin wavy ply loaded in tension and also to exploit the increase in stiffness (i.e. strain-hardening response) as the fibre (or ply) becomes straighter. One study has investigated techniques for introducing waviness into the fibres of a unidirectional composite and a second study has investigated the behaviour of a sandwich panel with wavy skins.

2.3.1 Achieving fibre waviness in a unidirectional composite

Two techniques were used to introduce fibre waviness in a unidirectional carbon fibre (IM7 by Hexcel)/PA-12 (Vestosint®-2159 by Evonik Degusa) tape. In both cases the tape was manufactured using a modular custom-built composite production line in which two fibre tows under tension-control are drawn sequentially through a suspension of PA12 (5% by wt. in water containing a surfactant), a drying oven to remove the water, a melt oven to melt the PA12, heated shear pins to smooth the tape and finally through steel rollers to consolidate the tape to produce a uniform thickness of 0.08 mm and width of 6-8 mm [8].

In one case the dry tows were gas-textured by passing them over a perforated bobbin through which nitrogen gas was blown causing the tows to separate into filaments and small bundles with some degree of misalignment and then processed on the production line as described above. The resulting tape was cut into 200 mm lengths and end-tabbed to produce tension specimens [9].

In the other case the standard tape (produced without gas-texturing) was cut into 200 mm lengths and each length was sandwiched between release films and placed between two steel plates. The whole assembly was heated in a pre-heated hot press at 220°C with contact-only pressure (i.e. no actual pressure applied) for 2 h. It was slowly cooled down to room temperature over 8 hours. After this non-constrained annealing process, some visible fibre misalignment was introduced into the carbon fibre/PA-12 tape, as seen in Figure 11. The tape lengths were then end-tabbed to produce tension specimens.

Figure 11 Carbon fibre / PA-12 tape after non-constrained annealing

Measurements of fibre misalignment angles confirmed that both techniques had increased the range of misalignment angles compared to control (i.e. pristine material) specimens. The tensile behaviour of the manufactured composite tapes are shown in Figure 12 which includes the behaviour of the control specimens.

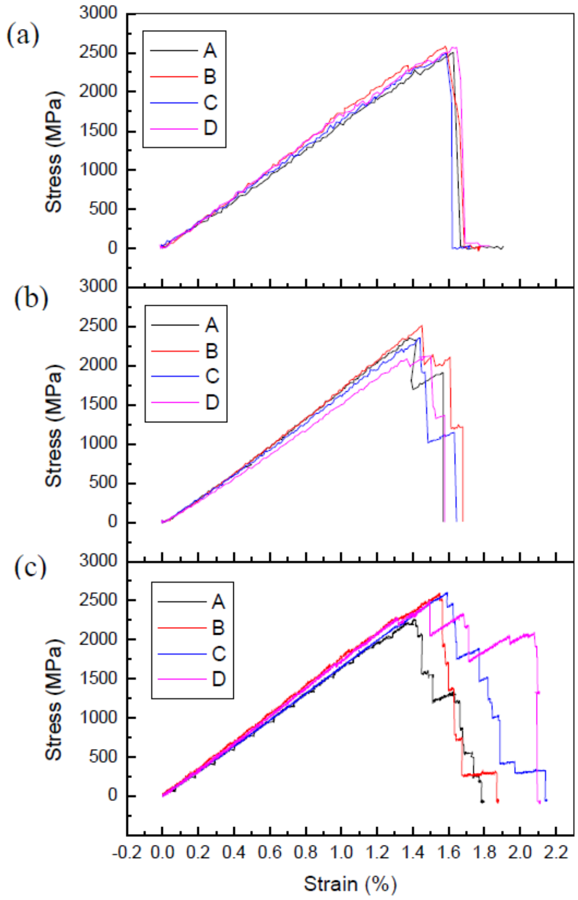


Figure 12 Tensile stress-strain curves of (a) control, (b) gas-textured and (c) non-constrained annealed carbon fibre/PA-12 tapes

Figure 12 shows that fibre waviness resulted in a more gradual tensile failure mode of the modified composites under uniaxial tension rather than the single, catastrophic failure which was observed for the control samples. This was particularly the case for the specimens produced by non-constrained annealing where the ultimate tensile failure strain was increased in comparison to the control sample. In the case of the gas-textured samples there was no improvement in failure strain of gas-textured carbon fibre/PA-12 and it is believed that this is due to damage of the carbon fibres caused by the gas-texturing process. Further studies will investigate how fibre waviness can be introduced in a more controlled manner with a pre-defined range of waviness and how such waviness can be manipulated to achieve a strain hardening response.

2.3.2 Wavy skin sandwich panel

An investigation has been conducted into the behaviour of the sandwich panel configuration shown in Figure 13a consisting of T800-M21 carbon-epoxy skins and a Rohacell core [10]. The desired behaviour is that, as the sandwich is subjected to a tensile load, the core will develop through-thickness compression stresses which will lead to it crushing and enable the skins to straighten as indicated in Figure 13b.

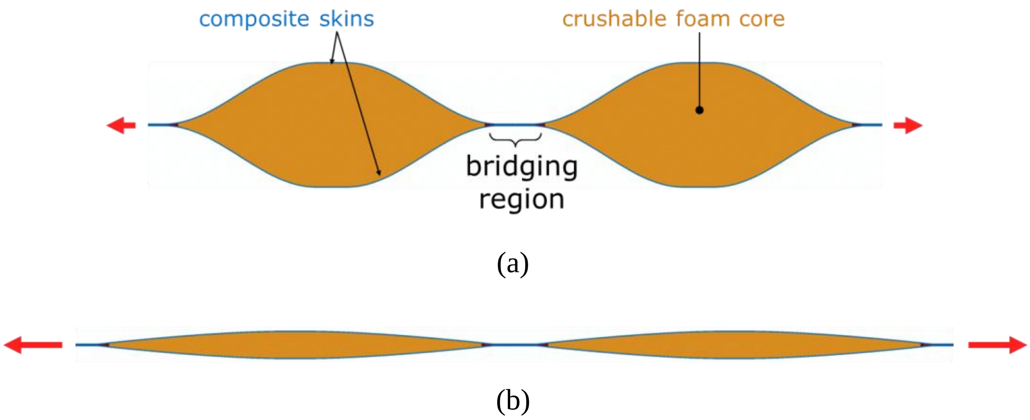


Figure 13 Wavy skin sandwich panel (a) initial state, (b) deformed state

Finite element modelling of a unit cell confirmed that this behaviour can be achieved as long as suitable strengths are chosen for the core and for the bridging region where the skins join. Predicted stress-strain curves are shown in Figure 14a for configurations with three distinct foam densities, but in all cases using skins formed of a single unidirectional ply (thickness of 0.193 mm) and a wave geometry with a period of 60 mm and a total height of 20 mm (more details of the geometry and material properties are given in reference 10). It can be seen that the densest foam causes premature delamination of the bridging region, but for the two other foam densities failure strains of over 8% with very significant ductility are achieved. The response shows a smooth behaviour, with an early softening region as the foam crushes but finally increasing in stiffness as the core densification occurs and the skins become straighter. (This strain hardening response of the unit cell will ensure that a series of these unit cells will exhibit the same overall stress-strain response as that predicted for the unit cell.) Experimental results (see Figure 14b) for the nominal foam density confirm the FE predictions but also show that the bridging region is a critical zone as two of the eight specimens failed by delamination at this position.

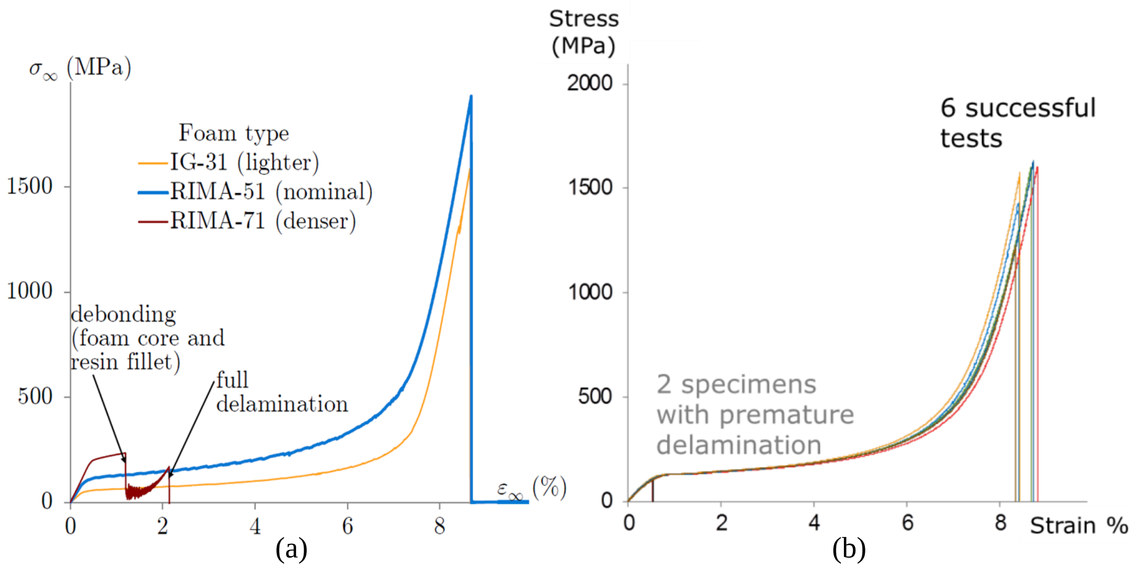


Figure 14 Stress-strain response of wavy sandwich panel a) FE predictions, b) experimental results

9 CONCLUSIONS AND FURTHER WORK

This paper has described several approaches that are being explored for introducing pseudo-ductlity into high performance composites.

Modelling and experimental studies of the discontinuous ‘brick and mortar’ configuration have shown that for short platelets the unit cell exhibits a load-displacement response that reflects the shear stress-strain behaviour of the matrix (or adhesive) between the overlapping platelets i.e. strain hardening is observed in the unit cell response for a matrix which possesses shear strain hardening. However the stiffness and strength of the unit cell are predicted to be relatively low and a matrix with a suitable strain hardening characteristic has yet to be identified and so, in a composite comprising many of the overlapping units in series, the failure will localise and exhibit very little overall ductility. For sufficiently long overlaps, higher stiffnesses and strengths can be achieved and in this case the failure is by propagation of cracks inwards from the ends of an overlap. This crack propagation occurs at a constant load (for a matrix material with a constant fracture toughness) and so again a composite consisting of a series of long overlaps will localise and show little overall ductility. Matrix materials that exhibit shear-strain hardening and methods of arresting the crack growth prior to complete failure of an overlap are being investigated.

Pre-weakening of plies and ply interfaces offer the potential to modify the brittle response of a unidirectional carbon composite. Finite element modelling has shown that the ‘yield’ stress can be modified by adjusting the magnitude of the ply weakening and a satisfactory strain-hardening behaviour beyond the ‘yield’ stress can be achieved by careful positioning of the ply and ply interface weakenings. These pre-weakened composites have the advantage that the initial elastic modulus is the same as that of the pristine composite but the upper bound to the failure strain will always be the failure strain of the pristine unidirectional composite and so for significant ductility the ‘yield’ stress must be considerably lower than the pristine strength. Experimental testing is underway to validate the modelling predictions and further explore the practical potential of this strategy.

Waviness has been explored at both the fibre and ply levels. Unconstrained annealing of a carbon fibre thermoplastic composite has been shown to cause significant fibre waviness which results in a more gradual failure process and an increase in the ultimate failure strain of the composite. Further studies will examine how the fibre wave geometry can be controlled and investigate the influence of this on the stress-strain behaviour of the composite. A sandwich panel with wavy skins has been shown to achieve high pseudo ductility with good ultimate strength and a failure strain in excess of 8%. Future work will focus on optimising the performance of the wavy-ply sandwich configuration and exploring the potential of the concept for blast-protection structures and protective layers in pressurised vessels.

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