AVOIDING FREE EDGE DELAMINATION IN QUASI-ISOTROPIC PSEUDO-DUCTILE HYBRID LAMINATES – BY MATERIAL DISPERSION OR LAYER ANGLE DISPERSION?

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Abstract

Hybridisation is one of the approaches to introduce pseudo-ductility to brittle composite materials. In this approach, two or more different types of fibre are combined and if the configuration and material constituents are well selected, the tensile response shows a gradual failure and a metal-like stress-strain curve with a pseudo-yeild point. Different types of hybrid composites with continuous layers have been studied to produce pseudo-ductile tensile behaviour. However, most hybrid material studies to date have been focused on Uni-Directional (UD) laminates which are not usually applied in industry due to poor transverse mechanical properties.
To make a multi-directional hybrid laminate, different approaches can be selected to mix different fibre types with different fibre orientations. In this paper, two approaches are presented and compared: (i) UD hybrid sublaminates used as the building blocks of hybrid laminates and (ii) dispersed orientation in which non-hybrid multi-directional sublaminates with different fibre types are stacked up . It is shown that the method of dispersed orientation significantly helps to reduce interlaminar stresses at the free edges of the tensile samples and therefore supresses free-edge delamination.

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1. Introduction

Fibrous composites are strong and have a good potential for structural applications but they suffer from lack of ductility. The failure of composite materials is usually catastrophic with little or no warning. Therefore, large safety margins are applied in the design procedure, reducing the benefits of composite materials. Achieving gradual failure and pseudo ductility can help composite structures to maintain functionality even when they are over- loaded, improve safety and reduce the applied safety factors.

One of the successful approaches for introducing pseudo-ductility into composite materials is hybridisation with thin plies, combining fibres with different mechanical properties to achieve a gradual failure. The mechanical response of UD hybrids has been extensively studied using both numerical and analytical methods in previous work within the HiPerDuCT programme [1,2] and a new simple and powerful method based on the 'damage mode map' of hybrids has been proposed to achieve optimal

UD hybrid configurations [3,4]. This approach was then used in designing advanced UD hybrid laminates with significant pseudo-ductility [5] and high initial modulus and strength.

Most of the studies on hybrid composites have been focused on UD hybrids. However, UD composites are not broadly applied in industry because of their poor transverse properties. Therefore, it is necessary to move towards multi-directional hybrid laminates and be able to understand and predict their behaviour.

In this paper, two different approaches of combining layers with different fibre orientations and fibre types are presented. In the first approach (‘UD hybrid sublaminates’), the successful UD hybrid laminates developed in previous studies e.g. [5] are used as the building blocks or sublaminates of the multi-directional hybrid laminate [6]. Whereas in the second approach (‘orientation dispersed’), multi-directional laminates are hybridised.

It will be shown that by using the dispersed orientation layups, it is possible to avoid free-edge delamination, which is an important failure mode in composite materials and results in loss of integrity of the laminate. The average interlaminar stresses are significantly lower in these layups and therefore, this method of hybridisation is recommended for achieving multi-directional hybrid composites.

2. Quasi-Isotropic hybrid composites – two different approaches

Among many different approaches to build a multi-directional (quasi-isotropic specifically in this paper) hybrid laminate, the two different lay-up methods based on fibre orientation and material are:

1. Using ‘UD hybrid sub-laminates’ to build a Quasi-Isotropic (QI) laminate where the low strain material is embedded in high strain material layers with the same angle. In this approach the low and high strain materials are uniformly dispersed through the thickness and thick blocks of similar material is avoided.

2. Interlaying quasi-isotropic sub-laminates made with similar fibres to achieve hybrid quasi-isotropic laminates where the layer orientations are uniformly dispersed through the thickness and thick blocks with similar fibre orientations are avoided.

Figure 1 (a-d) indicates these two concepts where two different QI hybrid layups are coloured in two different ways: (i) based on the material of the plies and (ii) based on the orientation of the layers. The two layups shown in this figure are $[45_H/45_L/45_H/90_H/90_L/90_H/-45_H/-45_L/-45_H/0_H/0_L/0_H]_s$ and $[45_H/90_H/-45_H/0_H/45_L/-90_L/-45_L/0_L/45_H/90_H/-45_H/0_H]_s$ where the H and L stand for High strain material and Low strain material. For instance, for a glass/carbon hybrid, these laminates will be $[45_G/45_C/45_G/90_G/90_C/90_G/-45_G/-45_C/-45_G/0_G/0_C/0_G]_s$ and $[45_G/90_G/-45_G/0_G/45_C/-90_C/-45_C/0_C/45_G/90_G/-45_G/0_G]_s$ where the G and C stand for Glass and Carbon respectively showing the fibre type of the layer as examples for the high and low strain materials.

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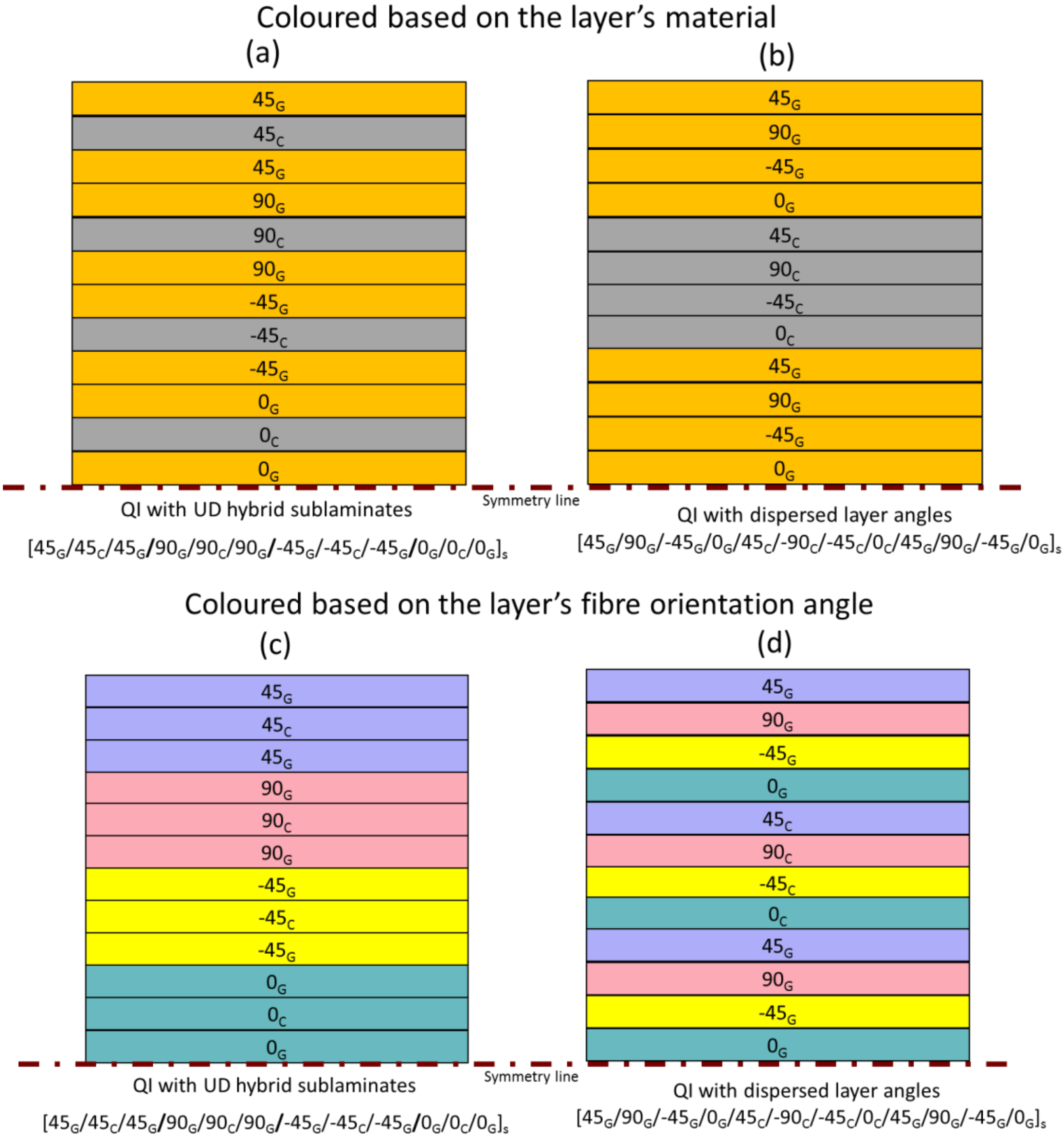

Figure 1- Two different QI layups of :$[45_G/45_C/45_G/90_G/90_C/90_G/-45_G/-45_C/-45_G/0_G/0_C/0_G]_s$ and $[45_G/90_G/-45_G/0_G/45_C/-90_C/-45_C/0_C/45_G/90_G/-45_G/0_G]_s$ coloured in two different ways based on (a-b) fibre type and (c-d) fibre orientation angles. C and G stand for Carbon/epoxy and Glass/epoxy as examples for the high and low strain materials.

Obviously, the plies used and their orientation in these two type of hybrid composites are exactly the same and the only difference is the stacking sequence. In the UD hybrid sublaminate hybridisation, the materials are dispersed through the thickness (Figure 1 a) but the fibre orientations are blocked (Figure 1 c). On the other hand, in the orientation dispersed laminate, the laminate is blocked in terms of material type but fibre orientations are well dispersed through the thickness.

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3. Interlaminar stresses

Interlaminar stresses, σ_z, σ_{xz} and σ_{yz}, are the main reason for free-edge delamination, so to study the difference between the two suggested hybrid layups, (UD hybrid sub-laminates and orientation dispersed), we can compare the variation of interlaminar stresses at the interface. However, due to the singularity at the free-edge, the local point stress values are not applicable. As the aim of this study is only to compare these two laminates, the averaging stress method along the interface proposed by Kim and Soni [7] and further developed by Brewer and Lagace [8] is applied. In this approach, the interlaminar stress components are averaged over a characteristic length which is experimentally determined and then compared against the interlaminar strength values of the material. Equation (1) indicates the definition of average normal stress, $\overline{\sigma}_z$ over the characterstic length b_0, suggested in [7]. Similarly, the average interlaminar shear stresses for $\overline{\sigma}_{xz}$ and $\overline{\sigma}_{yz}$ can be found by averaging the interlaminar shear stresses, σ_{xz} and σ_{yz}, close to the free edge and can be used in the quadratic criterion, equation (2), suggested in [8].

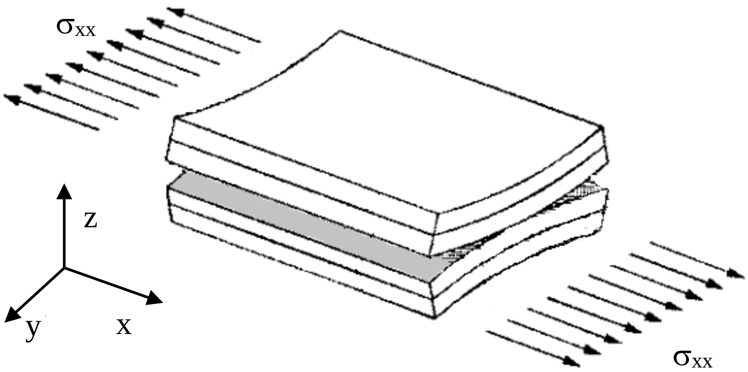

Figure 2- Schematic free-edge delamination and coordinate definition (Adapted from [9]).

$$\overline{\sigma}_z = \frac{1}{b_0}\int_0^{b_0} \sigma_z(y,0)dy \tag{1}$$

$$\left(\frac{\overline{\sigma}_{xz}}{s_{xz}}\right)^2 + \left(\frac{\overline{\sigma}_{yz}}{s_{yz}}\right)^2 + \left(\frac{\overline{\sigma}_z^{\,t}}{s_z^{(+)}}\right)^2 + \left(\frac{\overline{\sigma}_z^{\,c}}{s_z^{(-)}}\right)^2 = 1 \tag{2}$$

To calculate the interlaminar stresses, the slice modelling technique discussed in [10] with 3D 20 node elements was applied. In this method, both sides of the slice are constrained in a way that longitudinal strain along the x-axis is constant over the whole model and the other components of deformation in the y- and z-directions are equated. The low and high strain materials are high mudulus carbon fibre XN80/epoxy and high strength carbon fibre T1000/ epoxy layers respectively [11]. The main material properties are given in [5].

The critical delaminating interface for the orientation blocked layup is at the $90_{T1000}/\text{-}45_{XN80}$ interface whereas for the orientation dispersed, it is at the $90_{XN80}/\text{-}45_{XN80}$ interface. This has been found through plotting the distribution of stresses over the whole model. Interestingly, both of these interfaces are at

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the same z-direction distance from the mid-plane.

Figure 3 compares the interlaminar stresses σ_{zz}, σ_{xz} and σ_{yz}, at the critical interfaces. Due to the singularity at the free edge (y=0), the stress gradient is high close to the free edge and comparing the maximum value of the stresses for initiation investigation is not correct.. However, the average values can show which of these two laminates are more susceptible to free-edge delamination. Since the characteristic length of this material, b_0, is not known, the integration of the interlaminar stresses, $\int_0^y \sigma_z(y,0)dy$, $\int_0^y \sigma_{xz}(y,0)dy$ and $\int_0^y \sigma_{yz}(y,0)dy$ are calculated and plotted in Figure 4 for different values. These integral results are directly associated to the average stress values of $\bar{\sigma}_z, \bar{\sigma}_{xz}$ and $\bar{\sigma}_{yz}$ so will help to qualitatively decide which layup is less prone to free-edge delamination.

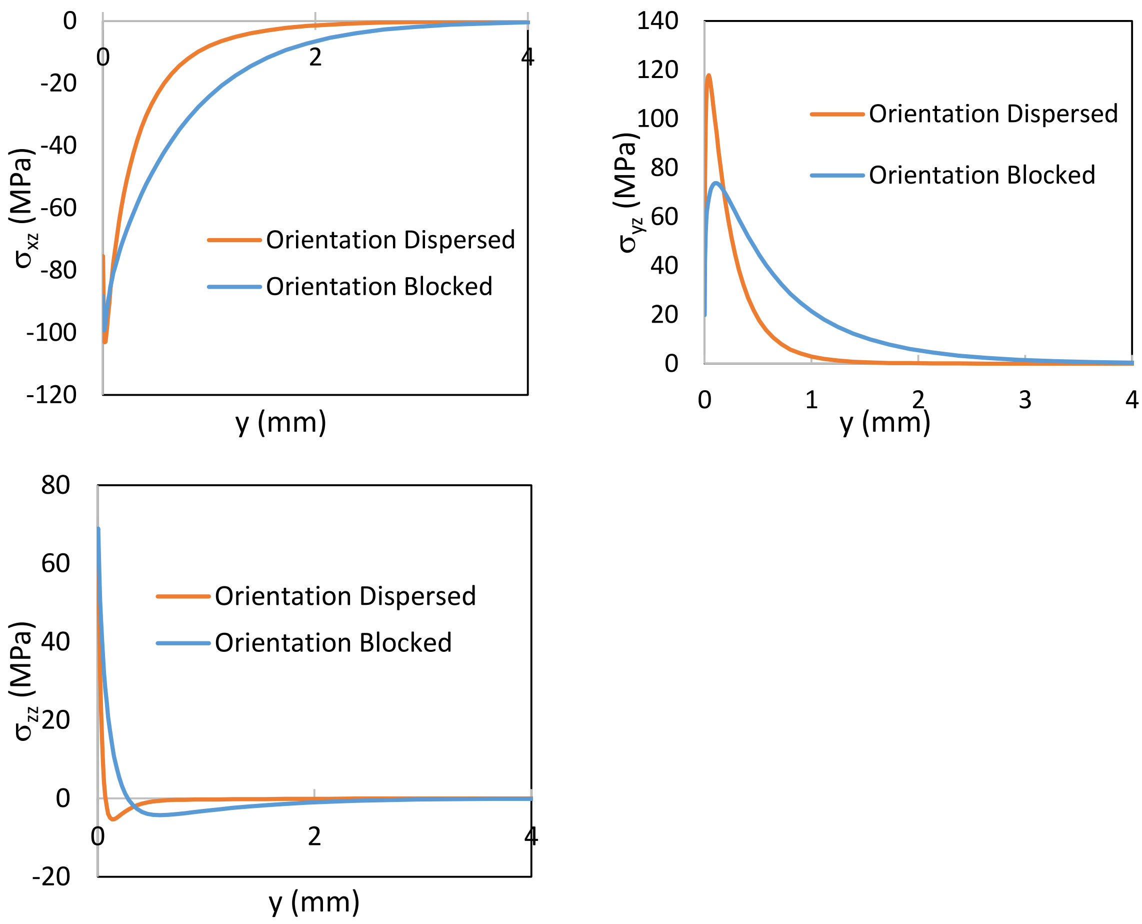

Figure 3- The interlaminar stresses σ_z, σ_{xz} and σ_{yz} at the critical interface of the UD hybrid sublaminate and orientation dispersed laminates.

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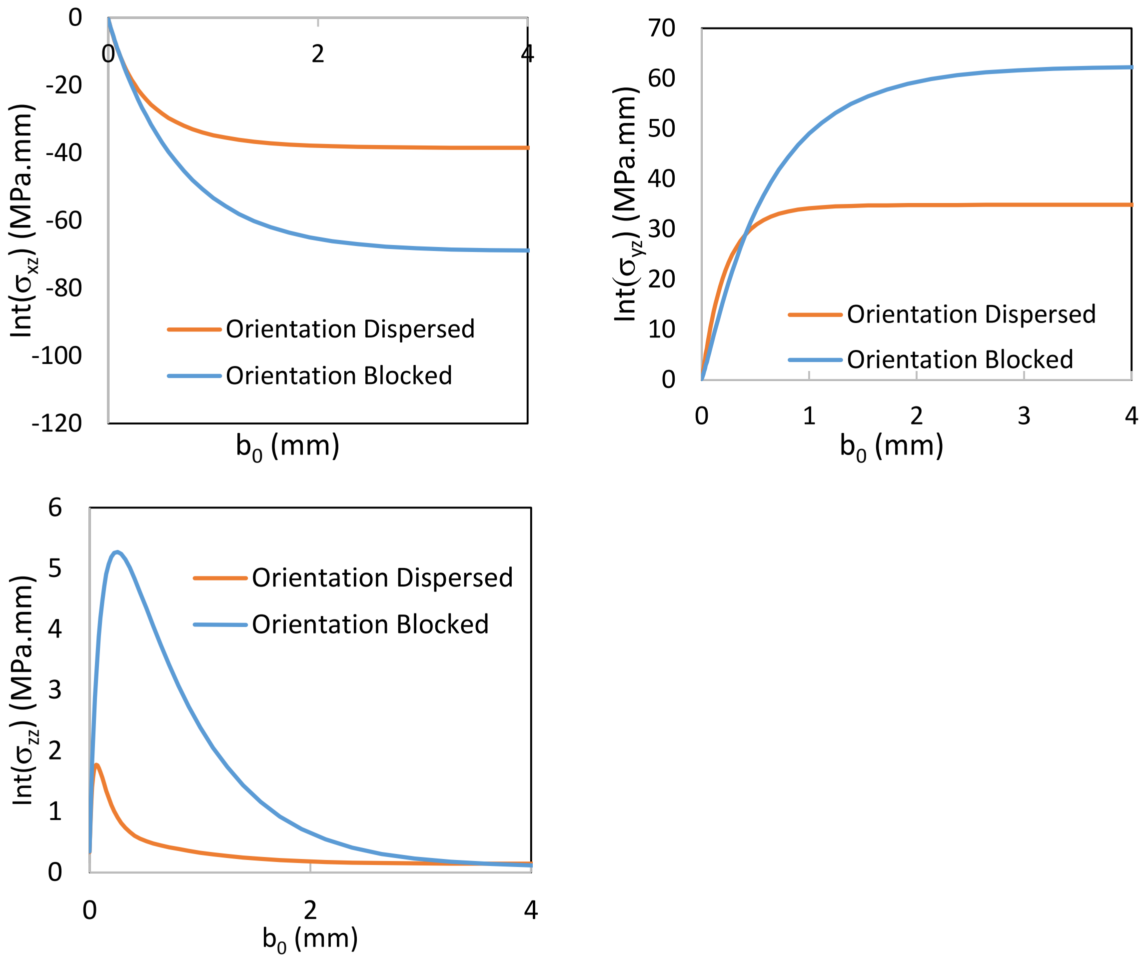

Figure 4- The integration of interlaminar stresses, Int(σ_z), Int(σ_{xz}) and Int(σ_{yz}) at the critical interface of the UD hybrid sublaminate and orientation dispersed laminates for different values of averaging distance (b_0).

It is obvious from Figure 4 that the integration of all of the interlaminar stresses over the critical interface is significantly larger in the orientation blocked layups. This clearly shows that this type of hybridisation is more prone to free-edge delamination and therefore is less favourable. On the other hand, the lower values of integration of interlaminar stresses in the orientation dispersed layups indicate that this laminate is less likely to delaminate at the free edges and is therefore a better choice.

4. Conclusions

Two different methods of laminating to achieve multi-directional pseudo-ductile hybrid composites are proposed: i) hybrid laminates with blocked ply orientations where UD hybrids are used as sublaminates, and ii) dispersed orientation laminates in which non-hybrid multi-directional laminates are stacked up. The first approach is based on dispersing materials uniformly through the thickness and the second method is based on dispersing the orientation of the layers. It was shown that the dispersed orientation method was significantly better to avoid or postpone free edge delamination than dispersing the materials.

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References

[1] Czél G, Wisnom MR. Demonstration of pseudo-ductility in high performance glass-epoxy composites by hybridisation with thin-ply carbon prepreg. Compos Part A Appl Sci Manuf 2013;52:23–30.

[2] Jalalvand M, Czél G, Wisnom MR. Numerical modelling of the damage modes in UD thin carbon/glass hybrid laminates. Compos Sci Technol 2014;94:39–47.

[3] Jalalvand M, Czél G, Wisnom MR. Damage analysis of pseudo-ductile thin-ply UD hybrid composites - a new analytical method. Compos Part A Appl Sci Manuf 2015;69:83–93.

[4] Jalalvand M, Czél G, Wisnom MR. Parametric study of failure mechanisms and optimal configurations of pseudo-ductile thin-ply UD hybrid composites. Compos Part A Appl Sci Manuf 2015;74:123–31.

[5] Czél G, Jalalvand M, Wisnom MR. Design and characterisation of advanced pseudo-ductile unidirectional thin-ply carbon/epoxy–glass/epoxy hybrid composites. Compos Struct 2016;143:362–70.

[6] Jalalvand M, Czél G, Wisnom MR. Multi-directional hybrid laminates - Styding the effect of fragmentation and dispersed delamination on stress-strain curves of unnotched laminates using analysiscal modelling. 20th Int. Conf. Compos. Mater. ICCM-20, 2015.

[7] Kim RY, Soni SR. Experimental and Analytical Studies On the Onset of Delamination in Laminated Composites. J Compos Mater 1984;18:70–80.

[8] Brewer JC, Lagace P a. Quadratic Stress Criterion for Initiation of Delamination. J Compos Mater 1988;22:1141–55.

[9] Mittelstedt C, Becker W. Free-Edge Effects in Composite Laminates. Appl Mech Rev 2007;60:217.

[10] Jiang W, Henshall JL. Analysis of Composite Laminate Beams Using Coupling Cross-Section Finite Element Method. Appl Math Mech 2006;27:1709–18.

[11] Czél G, Jalalvand M, Wisnom MR. Pseudo-ductile carbon/epoxy hybrid composites. 20th Int. Conf. Compos. Mater. ICCM-20, Copenhagen: 2015.

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