MULTI-DIRECTIONAL HYBRID LAMINATES – STUDYING THE EFFECT OF FRAGMENTATION AND DISPERSED DELAMINATION ON STRESS-STRAIN CURVES OF UNNOTCHED LAMINATES USING ANALYTICAL MODELLING

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Keywords: Pseudo-ductility, Hybrid composites, Fragmentation, Dispersed delamination

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 pseudo-ductile strain. 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.

In this study, the behaviour of multi-directional hybrid laminates made with UD hybrid sub-laminates is studied. The final goal is to introduce pseudo-ductility to layups with wider industrial applications. The effect of layup as well as the UD building-block stress-strain curve on the final stress-strain curve of the laminate is also studied.

A new analytical approach based on Classical Laminate Theory is introduced in which the effect of different damage modes in UD hybrid laminates (fragmentation and dispersed delamination) is taken into account. The output of this method is the non-linear stress-strain curve of a multi-directional laminate with UD hybrid sub-laminates. This method is then used to study the effect of different parameters such as the mechanical properties of the constituents (low and high strain materials) and layup on the pseudo-ductility.

1 INTRODUCTION

The stress-strain curves of UD hybrids have been extensively studied using both numerical and experimental methods in previous work within the HiPerDuCT programme [1–3]. Since UD composites are not broadly applied in industrial application, it is necessary to understand and predict the behaviour of laminates made out of UD hybrid ply-blocks. In this paper, an analytical approach for investigating the effect of the main damage modes of UD hybrid composites on the tensile stress-strain response of general hybrid laminates is presented. This method is then used to compare the obtained pseudo-ductility with different layups and material combinations.

The effect of different parameters such as layup and UD stress-strain curve on the stress-strain response of multi-directional layups made with UD hybrid blocks is studied. Some of the previously tested UD hybrids [1,4–7], which have shown a favourable tensile response, are selected to study the response of different stacking sequences. The aim of this study is to provide general guidelines about pseudo-ductility in layups with UD hybrid ply-blocks. To avoid the high expense of numerical modelling and FE approaches, an analytical approach based on the nonlinear response of UD hybrids is developed. Then the response of different material combinations and also configurations are checked using the developed analytical approach.

2 ANALYTICAL APPROACH

The analytical approach presented in [2] was able to predict the tensile response of UD hybrid composites with an acceptable accuracy and is used here to find the stress-strain response of the UD hybrid blocks. Figure 1 indicates the idea behind multi-directional hybrid laminates as the main focus of this paper. Each of the plies of the $[\theta/\varphi]_s$ laminate is made up of a UD hybrid block (glass/carbon hybrid as shown in the figure for instance) with a specific configuration. In addition to the assumptions made in [2] such as uniform strength distribution, constant interfacial toughness and application of thin-plies, the following assumptions were also made to predict the stress-strain response of the multi-directional hybrid laminates with a simple but acceptably accurate model:

- The damage process does not include interlaminar cracks between the layers with different orientations. This means that free-edge delamination is ignored in this type of analysis since the applied layers are thin.
- Damage in each layer spreads uniformly over the whole specimen and therefore this method is not valid for hybrid layers with localised damage processes such as catastrophic delamination occurring within a UD hybrid ply-block.
- The damage in each sub-laminate layer does not affect the damage process in the neighbouring layers. This is a reasonable assumption, complying with the previous assumption, because the high strain material can take the load around the broken low strain material. Therefore the adjacent layers with other fibre angles do not experience the stress concentration.
- No matrix cracking is considered.
- All of the laminates are balanced and symmetric.

Based on these assumptions, it is possible to find the load direction modulus of the laminate using Classical Laminate Theory and investigate the effect of fragmentation and diffuse delamination of different layers on the overall stress-strain curve of the laminate.

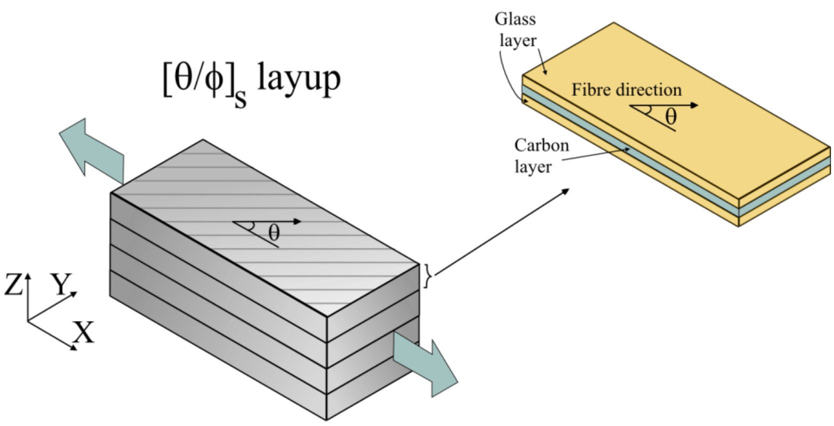


Figure 1- Schematic [θ/ϕ]s layup made out of glass/carbon UD hybrid sub-laminates

Fragmentation and dispersed delamination mainly affect the fibre direction properties of the UD hybrid block so it is necessary to consider the stiffness reduction in the fibre direction, E_1. This stiffness reduction is calculated based on the stress at the UD hybrid sub-laminate level and assuming secant stiffness at each strain. Figure 2 indicates how the reduction of fibre direction modulus is calculated based on the UD hybrid response. At ϵ_1 fibre direction strain, it is possible to find the value of stress in the UD hybrid, σ_1, and find the secant value of fibre direction modulus, E1, as equation (1).

$$E_1 = \frac{\sigma_1}{\epsilon_1} \quad (1)$$

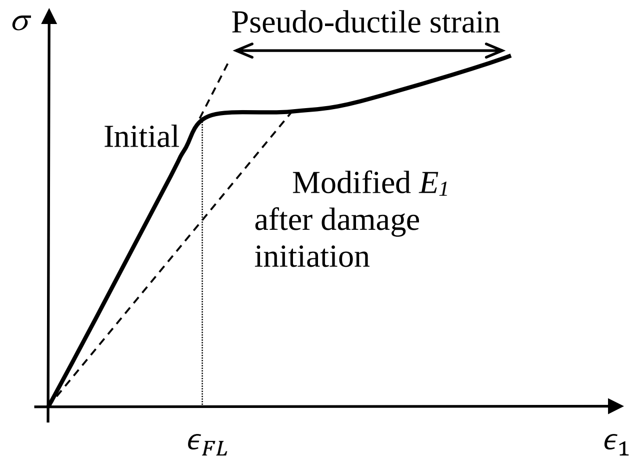


Figure 2- Schematic response of a UD hybrid sub-laminate and modified E_1 after damage initiation

3 STRESS-STRAIN RESPONSE OF HYBRID LAMINATES

In this part, different material combinations and layups are selected to draw some general conclusions about the response of hybrid laminates. Based on the ratio of the pseudo-ductile strain, ϵ_d, to the High strain material Failure strain, ϵ_{HF}, three different groups of material sets are defined as below:

1. High pseudo-ductile strain ratio when $\frac{\epsilon_d}{\epsilon_{HF}} > 50\%$,
2. Medium pseudo-ductile strain ratio when $30\% > \frac{\epsilon_d}{\epsilon_{HF}} > 50\%$,
3. Low pseudo-ductile strain when $30\% > \frac{\epsilon_d}{\epsilon_{HF}}$.

To achieve different pseudo-ductile strain ratios, different low strain materials are assumed to be hybridised with S-glass/epoxy as high strain materials.

Figure 3 indicates the predicted analytical stress-strain response of four UD hybrid composite layups using the analytical method discussed in [2] that show a good variety of pseudo-ductile responses. The thickness of these layups is 0.35 mm to 0.38 mm which might be slightly thick to supress edge delamination and interlaminar damage. However, these responses are selected here for this theoretical study. Three dimensional effects such as free edge delamination can be suppressed later using the same hybrid ratio and thinner constituent layers.

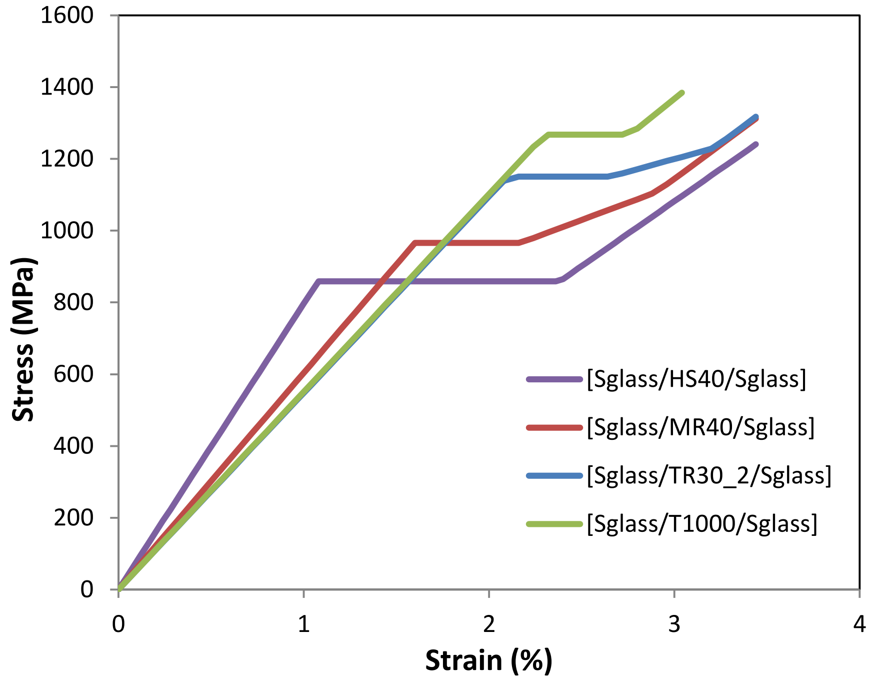


Figure 3- Predicted stress-strain curves of typical samples of four UD glass/carbon hybrid sub-laminates

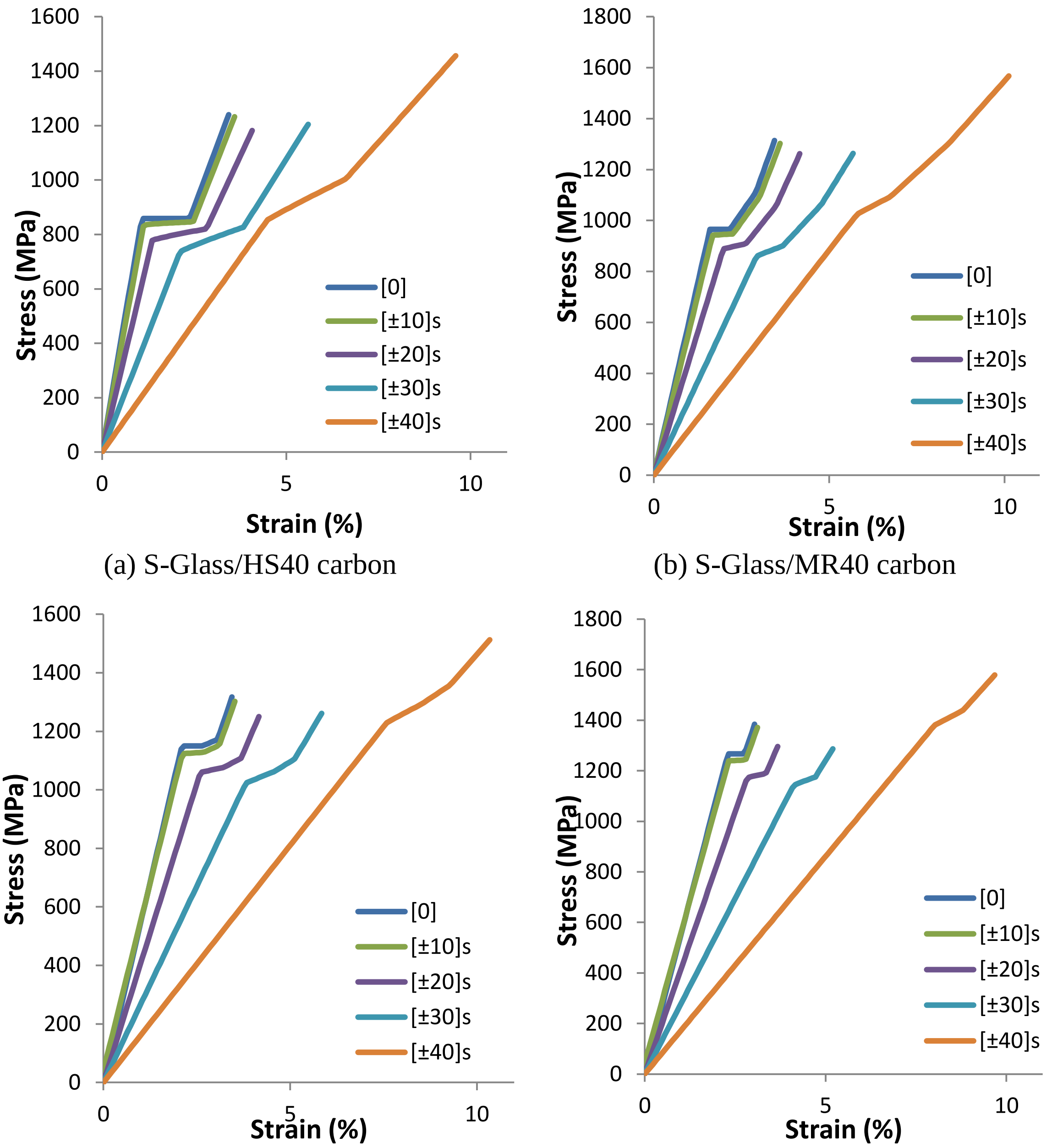
3.1 ANGLE-PLY RESPONSE

To show the effect of fragmentation and dispersed delamination in off-axis layers on the stress-strain curve, $[\pm\theta]_s$ angle-ply laminates made by orienting UD hybrid sub-laminates are examined in this section. The plastic shear behaviour of the layers, fibre reorientation as well as the matrix dominated damage modes are not considered in this study so the obtained results can only reflect the pseudo-ductility due to fragmentation and dispersed delamination. The assumed mechanical properties of the S-Glass, HS40, MR40, TR30, T1000 layers are given in Table 1. The stress-strain curves of the four material combinations with five different angle-ply layups, θ=0, 10°, 20°, 30° and 40 are shown in Figure 4 (a-d).

Table 1- Mechanical properties of the glass/carbon hybrid constituents

	S-Glass/ epoxy	HS40/ epoxy	MR40/ epoxy	TR30/ epoxy	T1000/ epoxy
E_1 (GPa)	45.7	206.6	134.6	101.7	149
E_2 (GPa)	15.4	7*	7*	6	7*
G_{12} (GPa)	4.34	4.6*	4.6*	2.4	4.6*
ν_{12}	0.3	0.31*	0.31*	0.3	0.31*
ϵ_F (%)	4.0	1.0	1.5*	1.9	2.0
ϵ_{Frag} (%)	-	1.1	1.6	2.1	2.3
Ply thickness (mm)	0.155	0.083	0.061	0.030	0.031

*Typical values assumed based on M55J NorthThinPly properties [8].



(a) S-Glass/HS40 carbon
(b) S-Glass/MR40 carbon
(c) S-Glass/TR30 carbon
(d) S-Glass/T1000 carbon

Figure 4- Stress-strain curves of (a) S-Glass/HS40, (b) S-Glass/MR40, (c) S-Glass/TR30 and (d) S-Glass/T1000 hybrids for different angle-ply layups and predicted UD response

The response of the angle-ply laminates has some similarities to the predicted UD stress-strain curves. The effect of material combination can be distinguished easily within the overall results. The S-Glass/HS40 hybrid demonstrates the highest pseudo-ductile strain and lowest yield stress of the different angle-ply layups. On the other hand, the off-axis angle also has a significant effect. In angles with θ<30, the damage initiation strain is postponed and the yield stress value is slightly reduced. But for the θ =40, both stress and strain at damage initiation are increased and the stiffness is decreased significantly. Since for higher angles like θ =40 the damage mode is usually matrix dominated, it is believed that other damage modes probably will occur before the predicted $[\pm 40]_s$ fragmentation and dispersed delamination and the layer fails earlier.

3.2 QUASI-ISOTROPIC LAYUPS

To cover a range of possible quasi-isotropic layups, $[\pm60/0]_s$, $[90/\pm45/0]_s$, $[0/90/\pm60/\pm30]_s$, $[0/90/\pm67.5/\pm45/\pm22.5]_s$ and $[0/90/\pm10/\pm20/\pm30/\pm40/\pm50/\pm60/\pm70/\pm80]_s$ stacking sequences are studied in this section. Since the proposed method is based on 2D Classical Laminate Theory, interlaminar damage modes such as free edge delamination are not included and the stacking sequence is not important. So the response of a $[\theta/\varphi]_s$ layup is the same as $[\varphi/\theta]_s$ in this approach. This means that the obtained stress-strain curve represents the best possible stress-strain curve if no plastic-shear deformation, fibre rotation or delamination takes place.

Figure 5 indicates the stress-strain curves of the above mentioned stacking sequences made out of S-Glass/HS40 hybrid sub-laminates. The initial slope and the strain at which nonlinear response initiates for all of the laminates are the same. The predicted stresses at which the 0° glass layer fails are also close to each other, all between 694 MPa for $[\pm60/0]_s$ and 796 for $[90/\pm45/0]_s$. Although at the failure point of the 0° glass layer, it is likely that there will be final failure of the whole laminate, the rest of the stress-strain curves showing the contribution of other layers are plotted to help understand the difference between the laminates. This means that the obtained pseudo-ductility due to fragmentation and dispersed delamination ignoring any shear plastic deformation for all of these cases are similar.

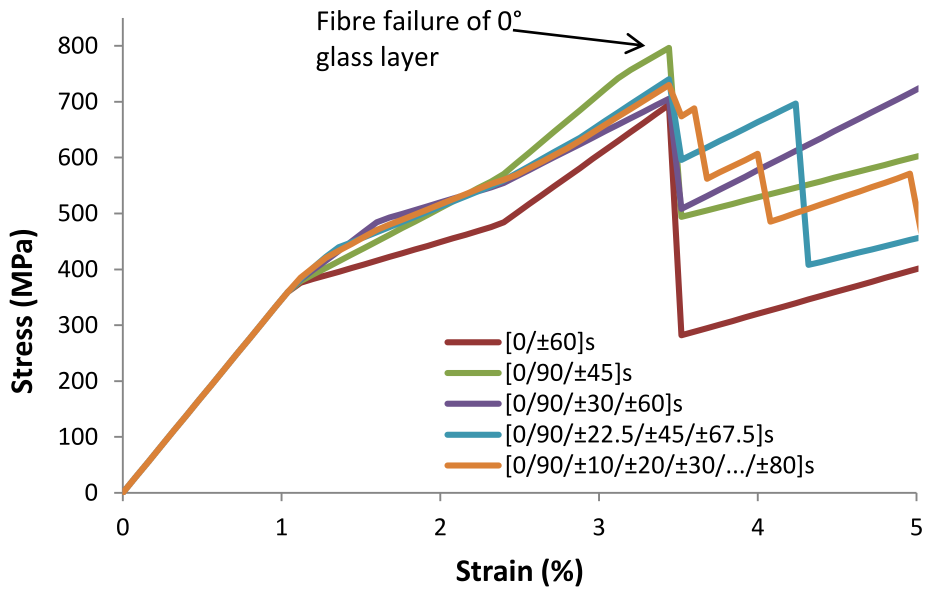
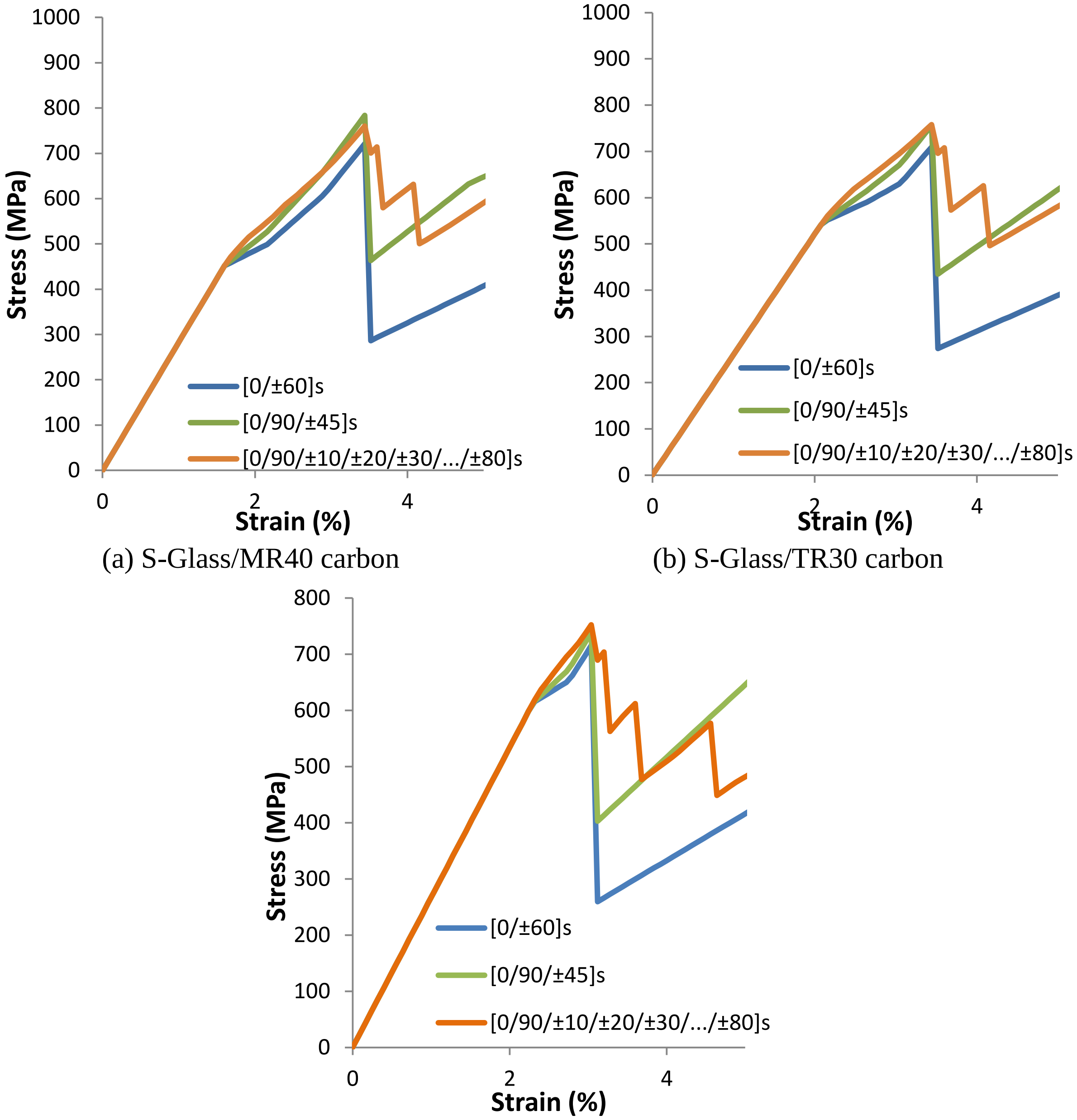


Figure 5- Stress-strain response of different quasi-isotropic layups made of S-Glass/HS40 carbon UD sub-laminates

The response of the other material combinations, S-Glass/MR40, S-Glass/TR30 and S-Glass/T1000, are shown in Figure 6 for $[\pm60/0]_s$, $[90/\pm45/0]_s$ and $[0/90/\pm10/\pm20/\pm30/\pm40/\pm50/\pm60/\pm70/\pm80]_s$ quasi-isotropic layups. Similar to the S-Glass/HS40 quasi-isotropic layups, the stress-strain curves and pseudo ductile strains of different stacking sequences for each material combination are similar up to the 0° glass layer failure strain. Additionally, the peak stress values of all different quasi-isotropic laminates with different material combinations are similar to each other because it is dependent on the final failure strength of the UD hybrid sub-laminates, shown in Figure 3, which were all similar.



(a) S-Glass/MR40 carbon

(b) S-Glass/TR30 carbon

(c) S-Glass/T1000 carbon

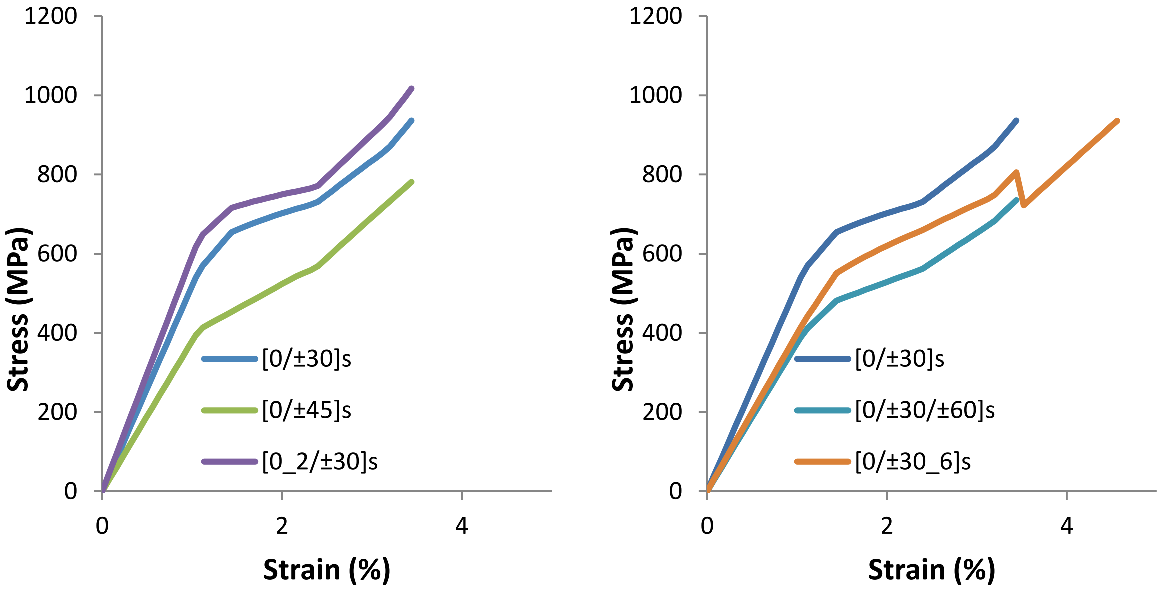
Figure 6- Stress-strain response of different quasi-isotropic layups made out of (a) S-Glass/MR40 (b) S-Glass/TR30 and (c) S-Glass/T1000 ply-blocks

3.3 GENERAL LAYUPS

After studying the effect of angle-ply laminates and quasi-isotropic stacking sequences on the stress-strain curve, other layups with fewer restrictions are studied in this part. The balanced and symmetric layups studied are $[0/\pm30]_s$, $[0/\pm45]_s$, $[0_2/\pm30]_s$, $[0/\pm30/\pm60]_s$, $[0/\pm30_6]_s$. Figure 7 (a) shows the tensile response of $[0/\pm30]_s$, $[0/\pm45]_s$ and $[0_2/\pm30]_s$ laminates with S-Glass/HS40 hybrid as ply-blocks. This combination was selected between the four hybrid combinations due to its better pseudo-ductile response.

Obviously the laminate with ±45 layers shows lower initial stiffness and strength compared with the other two laminates. The nonlinearity of the response of the layup with ±45 layers due to fragmentation and dispersed delamination is also less than the other layups with ±30 layers since the fragmentation of the ±30 layers initiates just after the 0 layers. A better response in terms of stiffness, strength and pseudo-ductility can be achieved by increasing the proportion of 0 layers in the $[0_2/\pm30]_s$ laminate.

In Figure 7 (b), the $[0/\pm30]_s$ layup's response is compared with $[0/\pm30/\pm60]_s$, $[0/\pm30_6]_s$ laminates. Addition of the ±60 layers to the $[0/\pm30]_s$ laminate as the baseline has resulted in lower stiffness and strength but has not significantly changed the nonlinearity of the curve and the achievable pseudo-ductile strain. Application of a higher volume ratio of ±30 layers in the $[0/\pm30_6]_s$ laminate compared with $[0/\pm30]_s$ has resulted in a higher second peak after the 0° layer failure. This means that using higher ratios of off-axis angle layers may lead to failure strains higher than the 0° layer failure strain. However, more detailed studies are necessary to confirm that the failure of the S-glass fibres in the 0° layers does not result in either premature failure or delamination.



(a) $[0/\pm30]_s$, $[0/\pm45]_s$, $[0_2/\pm30]_s$ (b) $[0/\pm30]_s$, $[0/\pm30/\pm60]_s$, $[0/\pm30_6]_s$

Figure 7- The stress-strain response of $[0/\pm30]_s$, $[0/\pm45]_s$, $[0_2/\pm30]_s$, $[0/\pm30/\pm60]_s$, $[0/\pm30_6]_s$ laminates made of HS40/S-glass UD hybrid sub-laminates

A summary of the stress-strain response of the different laminates made with S-Glass/HS40 hybrid sub-laminates is given in Table 2. The pseudo-ductile strain (as defined in [9]) is reduced from 1.88% in [0] to about 1.14% for the $[0/90/\pm45]_s$ quasi-isotropic laminate and the pseudo-ductile strain ratio ($\frac{\epsilon_d}{\epsilon_{HF}}$) is changed from 47% to about 28%. More significant changes are seen in the maximum stress, stiffness and yield stress from 1240 MPa, 79.7 GPa and 859 MPa respectively to about 796 MPa, 34.6 GPa and 359 MPa. A similar trend can be seen in other layups as well: the pseudo-ductile strain is less changed compared with the stiffness, strength and yield stress.

Table 2- Stress-strain curve characteristics of different layups made out of S-Glass/HS40 hybrid

	[0]	$[0/\pm60]_s$	$[0/90/\pm45]_s$	$[0/90/\pm30/\pm60]_s$	$[0/90/\pm22.5/\pm45/\pm67.5]_s$	$[0/90/\pm10/\pm20/\pm30/\ldots/\pm80]_s$	$[0/\pm30]_s$	$[0/\pm45]_s$	$[0_2/\pm30]_s$	$[0/\pm30/\pm60]_s$	$[0/\pm30_6]_s$
Strength (MPa)	1240	694	796	705	740	730	948	800	1019	730	906
Yield stress (MPa)	859	359	359	359	359	359	532	387	613	383	402
Ex (GPa)	79.7	34.6	34.6	34.6	34.6	34.6	51.2	37.2	58.9	36.8	38.7
Ey (GPa)	13.6	34.6	34.6	34.6	34.6	34.6	13.7	19.5	14.1	25.5	12.5
Gxy (GPa)	4.4	13.0	13.0	13.0	13.0	13.0	13.0	15.9	10.8	14.7	16.3
Final failure strain (%)	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	4.6
Pseudo-ductile strain (%)	1.88	1.43	1.14	1.40	1.30	1.33	1.59	1.29	1.71	1.46	2.26
Pseudo-ductile ratio (%)	47	36	28	35	32	33	40	32	43	36	56

4 DISCUSSION, CONCLUSION AND FUTURE STUDIES

The effect of fibre fragmentation and dispersed delamination on the nonlinear response of laminates made of UD hybrid sub-laminates with different off-axis angle layers has been studied in this paper using an analytical approach. The proposed method is based on uniformly dispersed damage in each layer as well as ignoring interlaminar cracks between layers with different fibre directions and fibre reorientation/rotation. It is believed that if the UD hybrid sub-laminates are thin enough, interlaminar cracks will be suppressed.

The stress-strain responses of angle-ply laminates showed that damage initiates at higher strains in the layers with higher off-axis angles. Based on the studied angle-ply laminates, layers with off-axis angles higher than 30° are not expected to produce much nonlinearity from the low strain material fragmentation and dispersed delamination. This issue is not studied in detail and should depend on the material properties but the fact that layers with more than 30° off-axis angle have higher yield stresses than those of UD sub-laminates supports this argument. The material combination was also found to affect the final stress-strain response significantly. In laminates with the same layup, those with higher pseudo-ductile ratio of the UD hybrid sub-laminate gave better pseudo-ductility. Although layup orientation has been found to be an important factor, the stress-strain responses of different quasi-isotropic laminates were similar up to the failure of the 0° layers.

One of the main aims of using laminates rather than UD composites is to provide acceptable mechanical properties in more than one loading direction. So lower mechanical characteristics for a laminate is expected compared with a UD plate loaded parallel to the fibres. For instance, both stiffness and strength of quasi-isotropic laminates are lower than UD hybrid layers. However, the reduction in the pseudo-ductility of general hybrid laminates has been found to be lower than the reduction in the strength and stiffness and in some special cases, higher pseudo-ductile strains might be achieved.

Further numerical modelling to study the interaction of fragmentation and free-edge delamination is planned. To model both fragmentation and delamination as explicit discontinuities, a Finite Element approach with cohesive elements similar to [10–12] will be used. Experimental studies will be also performed and the results will be compared against the predictions.

ACKNOWLEDGEMENTS

This work was funded under the UK Engineering and Physical Sciences Research Council Programme Grant EP/I02946X/1 on High Performance Ductile Composite Technology in collaboration with Imperial College, London. Gergely Czél acknowledges the Hungarian Academy of Sciences for funding through the Post-Doctoral Researcher Programme fellowship scheme.

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