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DAMAGE MODE MAPS AND PARAMETRIC STUDY OF THIN UD HYBRID COMPOSITES

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Abstract
Hybridisation is one of the approaches to introduce pseudo-ductility to brittle composite materials. In this approach, two layers with different types of fibre are combined and a new stress-strain response which depends on the material properties of the components and thickness of the constituents is produced. In this paper, an analytical method of predicting the damage progress of UD hybrids is proposed which has an acceptable accuracy and is significantly faster than numerical methods such as FE. A new chart called a "damage mode map" is produced that relates the configuration of a UD hybrid to its predicted damage scenario straightaway. This map has been found to be a very useful tool to find the optimum configuration in designing new hybrid composites.

1. Introduction

Brittle failure is one of the main problems of fibrous composite materials that obliges designers to use high safety margins and results in reducing the weight saving that potentially could be achieved. The aim of the HiPerDuCT programme is to investigate different approaches of introducing more gradual failure or pseudo-ductility into conventional composite materials and thin ply hybridisation is one of the applied methods.
To determine promising hybrid configurations for obtaining optimal pseudo ductile response, it is necessary to not only understand the damage modes of UD hybrid laminates as the constituents of a hybrid composite structure but also to find a simple method to check the effect of different parameters on the final response. In [1], a FE-based method was proposed to understand the details of the damage process in different UD hybrids. The proposed approach was in good agreement with the experimental results of [2]. In this paper, a new analytical method is outlined to make the process of finding new optimised UD hybrids easier and faster. In fact, the previously proposed FE-based approach was good for modelling of specific UD hybrid configurations but expensive for extracting general trends and design guidelines for the UD hybrids. Here, a simple analytical method with an acceptable accuracy is presented to comply with this need.

Any hybrid composite includes at least two different types of fibre. The material which has a lower failure strain (e.g. carbon in a glass/carbon hybrid) will be called the low strain material (LSM) and the one with higher failure strain (e.g. glass in the glass/carbon hybrid) will be called the high strain material (HSM).

2. Damage modes

The possible damage modes of UD hybrid composites are known to be one or a combination of (i) fragmentation (multiple fracture) of the low strain material, (ii) delamination and (iii) failure of the high strain material. The first damage mode in a sandwich hybrid composite under uniform tension is a crack in the low strain material and it happens at the failure strain of the low strain material since there is no stress variation along the length before that. However, the subsequent damage modes depend on the configuration and material properties of the constituents and the interface. Each damage mode requires a certain stress level which can be found based on mechanics of materials and fracture mechanics. The winning damage mode is the one which needs the lowest stress level to occur.

1.1. First fracture in and fragmentation of the low strain material

Before the first failure in the low strain material, there is no strain variation along the specimen so the stress in the laminate at first fracture of the low strain material, $\sigma_{@LF}$, can be related to the strength of the low strain material, S_L as below:

$$\sigma_{@LF} = \frac{E_L}{S_L}\frac{E_H t_H + E_L t_L}{t_H + t_L} \tag{1}$$

where E_H and E_L are the fibre direction modulus of the high and low strain materials. t_H and t_L are also the thickness of the high and low strain material as shown in Figure 1. This figure indicates a hybrid with a crack in the low strain material and the stress variation along the length in each component. Within a $l_c/2$ distance from the crack, the stress in the low strain material is lower than the far field stress and therefore, it is not expected to have a new crack. Since new cracks occur in areas with no stress variation along the length, the fragmentation stress level at which multiple cracks take place within the low strain material can be found using equation 1, provided the strength of the material is uniformly constant along the length.

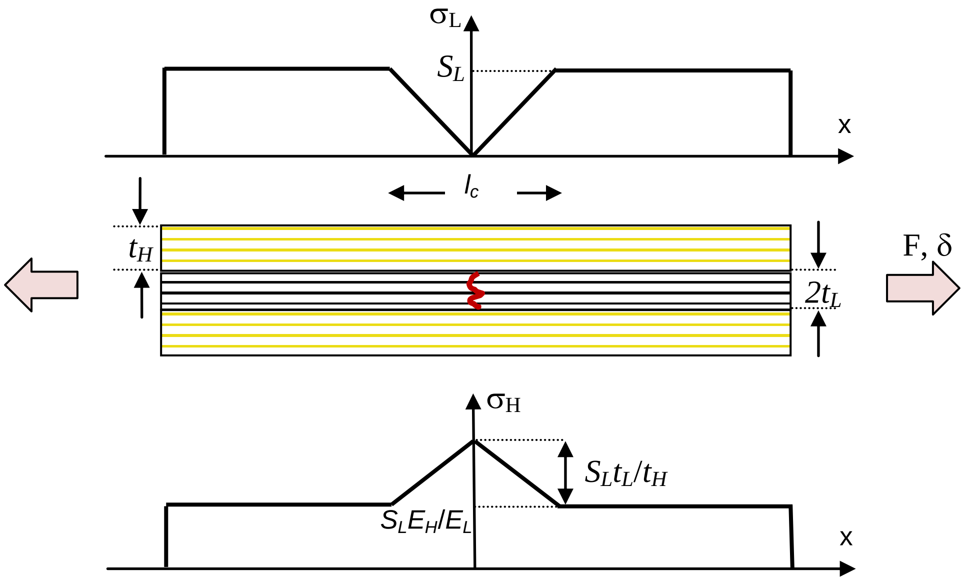

Figure 1- Schematic of low strain material with a crack and stress variation in high and low strain matrials

1.2. Delamination

Figure 2 indicates a quarter of a *2L* length of the hybrid specimen where the low strain material in the middle has already fragmented and there is also an interlaminar crack. Since the delaminated part of the low strain material does not contribute to load transfer, it is not shown. The length of the delaminated and un-delaminated parts is L_1 and L_2 respectively and t_H and t_L are half of the total thickness of the high and low strain material. In the present paper, a uniform distribution of damage is assumed over the length of the specimen so the shown part of the hybrid in Figure 2 can be treated as a Representative Volume Element (RVE) of the whole specimen.

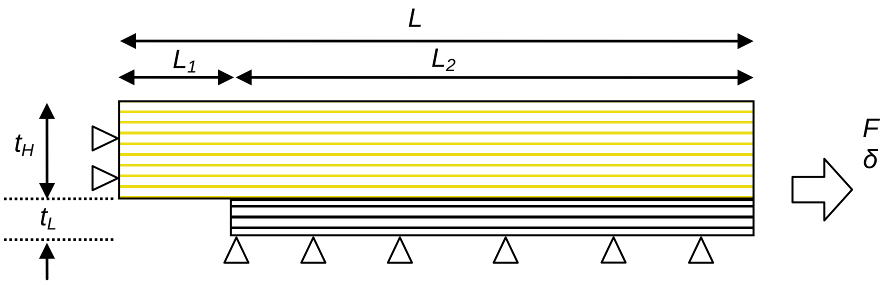

Figure 2- A quarter of a representative volume element of the hybrid with a L_1 length delamination

The stiffness of the RVE, K_{tot}, depends on the length of the delamination and the stiffness of the delaminated and un-delaminated parts. The relationship between the stiffness of these parts and the elastic modulus of the high and low strain material (E_H and E_L) and their thickness (t_H and t_L), can be written as follows:

$$K_{tot} = \frac{D_1 + D_2}{D_1 L_2 + D_2 L_1} \tag{2}$$

Where $D_1 = E_H t_H$ and $D_2 = E_H t_H + E_L t_L$. The total strain energy of the RVE can be found from equation (2) and differentiating with respect to crack length (L_1) gives the energy release rate at the stress level, σ_{del}, where delamination propagates. Delamination propagates when the strain energy release rate is equal to G_{IIc} since the crack propagates due to shear loading. Equation (3) indicates the stress level in the laminate at which delamination propagates.

$$\sigma_{del} = \frac{1}{t_H + t_L} \sqrt{\frac{2G_{IIc} D_1 D_2}{D_2 - D_1}} \tag{3}$$

1.3. Failure of the high strain material

The RVE shown in Figure 2 can also be used for failure analysis of the high strain material. The simplest failure criterion is to check the largest value of stress in the high strain material and compare it with its strength, S_H. Since the low strain material is not contributing to load transfer, the stress in part 1 of the high stress material is higher than in part 2. If a stress concentration factor of K_t is assumed around the crack tip, the maximum/critical value of longitudinal stress in the high strain material, σ_{H_max}, becomes as follows, where σ is the average stress in the laminate.

$$\sigma_{H\_max} = K_t \frac{t_H + t_L}{t_H} \sigma \tag{4}$$

To consider the size effect in the prediction procedure, Weibull random distribution theory, used in [3], can be applied by simply replacing the stress distribution with the right hand side of equation (4). This results in the following equation for predicting high strain material failure

$$\sigma_{@HF} = \frac{S_H}{K_t} \frac{t_H}{\sqrt[m]{V}(t_H + t_L)} \tag{5}$$

where *m* is the Weibull distribution modulus and *V* is the volume of the high strain material.

3. Damage mode map

As described in section 2, the first damage in a sandwich hybrid is a crack in the low strain material, regardless of the material properties and configurations. However, the following damage modes are different. Since the first damage is essentially similar in all of the hybrids and can be found via equation (1), the difference between the various damage processes is related to the following damage modes and the first damage mode is not discussed hereafter.

For any hybrid configuration, it is possible to calculate the values of stress for fragmentation in the low strain material ($\sigma_{@LF}$), delamination (σ_{del}) and also failure in the high strain material ($\sigma_{@HF}$) as presented earlier. The six possible permutations of the damage process are listed in the first column of Table 1. Based on the order of the damage modes, it is possible to predict the expected damage process.

The obtained values and associated order of damage modes rely on the assumed constraints shown in Figure 2. If failure in the HSM occurs at any stage, the calculated values of stress for the other types of damage are not valid afterwards and the damage process cannot progress to other types of damage. Furthermore, if the delamination stress is lower than the LSM fragmentation stress, there is no chance for fragmentation to develop, but the predicted failure stress for the HSM stays valid. The expected damage process for each of the permutations is also shown in Table 1. If delamination happens after fragmentation of the LSM, interlaminar cracks initiate from the tips of the cracks in the LSM in a dispersed manner. This kind of delamination is called dispersed delamination.

No.	Order of required stress for damage modes	Expected damage process after the initial crack in the LSM		
1	$\sigma_{@LF} < \sigma_{del} < \sigma_{@HF}$	Fragmentation in LSM	Dispersed delamination	Failure of HSM
2	$\sigma_{@LF} < \sigma_{@HF} < \sigma_{del}$	Fragmentation of LSM	Failure in HSM	
3a	$\sigma_{del} < \sigma_{@LF} < \sigma_{@HF}$	Single delamination	Failure in HSM	
3b	$\sigma_{del} < \sigma_{@HF} < \sigma_{@LF}$	Single delamination	Failure in HSM	
4a	$\sigma_{@HF} < \sigma_{@LF} < \sigma_{del}$	Failure in HSM		
4b	$\sigma_{@HF} < \sigma_{del} < \sigma_{@LF}$	Failure in HSM		

Table 1- Summary of the expected damage modes for different stress conditions after the initial crack in the LSM

The expected damage processes in Table 1 can be categorised into four groups: (1) fragmentation in the LSM, dispersed delamination and failure in the HSM, (2) fragmentation in the LSM and failure of the HSM, (3) single delamination and failure of the HSM, and (4) premature failure of the HSM. Plotting these four regions for different configurations produces a damage-mode map. This map will be drawn in the example below.

3.1 Damage mode map of SkyFlex carbon/E-glass hybrid

To demonstrate the application of the proposed analytical approach, the combination of ultra-thin SkyFlex carbon/E-glass is selected as a case study. This UD hybrid has been extensively studied experimentally and numerically in [1], [2]. The material properties of the carbon and glass layers as well as the interface are given in Table 2. The value of stress concentration factor, K_t, was assumed equal to one for the following results. The length of the specimen was taken as L=160mm.

Hexcel 913/E-Glass[4]				SkyFlex USN020A Carbon[5]			Interface
E_H (GPa)	S_H (MPa)	Layer thickness (mm)	Weibull Modulus	E_L (GPa)	S_L (MPa)	Layer thickness (mm)	G_{IIC} (N/mm)
38.7*	1350	0.144	29.3	101.7	1962	0.03	1.0

* modified value for the measured thickness of glass layer

Table 2- Elastic material properties of Hexcel 913/E-glass and SkyFlex USN020A carbon prepreg

For any hybrid configuration, it is possible to find the required stress for each damage mode using equations (1), (3) and (5). When the values of required stress for all possible damage modes are found, the expected damage process of the configuration can easily be seen according to Table 1.

Grouping all of the configurations with the same damage process leads to the damage mode map. For given values of relative and absolute carbon thickness, it is possible to uniquely determine any hybrid configuration. Figure 3 shows the six cases summarised in Table 1 on the damage mode map with the relative and absolute carbon thickness as the horizontal and vertical axes. The expected damage processes are schematically shown and numbered on each region of the map.

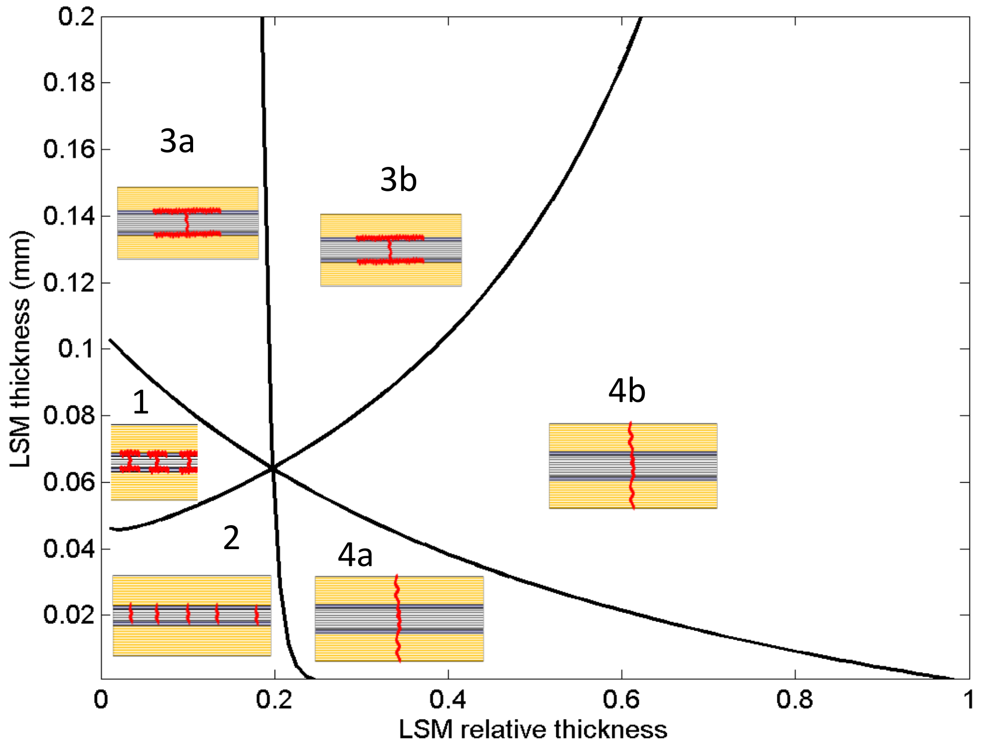

Figure 3- Damage mode map for SkyFlex/E-glass hybrid

To avoid brittle failure, it is necessary to have the UD hybrid configuration away from either region 3 or 4. In region 4, the high strain material will fail straightaway after the first crack in the low strain material and in region 3, the integrity of the whole laminate is lost due to the long interlaminar cracks. However, the damage process in region 1 and 2 is gradual and pseudo-ductile. If the hybrid configuration is located in region 2, fragmentation in the low strain material occurs before HSM final failure. The hybrid configurations within region 1 have another extra damage mode, dispersed delamination, before HSM final failure which adds to the produced pseudo-ductility. Figure 4 indicates the distribution of the required stress level for each of the fragmentation, delamination and HSM final failure modes in regions 1 and 2. The value of required stress for LSM fragmentation in these two regions is lower than the other two damage modes and therefore, it is the first damage mode. The required stress level for delamination is also lower than HSM failure in region 2 so it occurs before HSM failure.

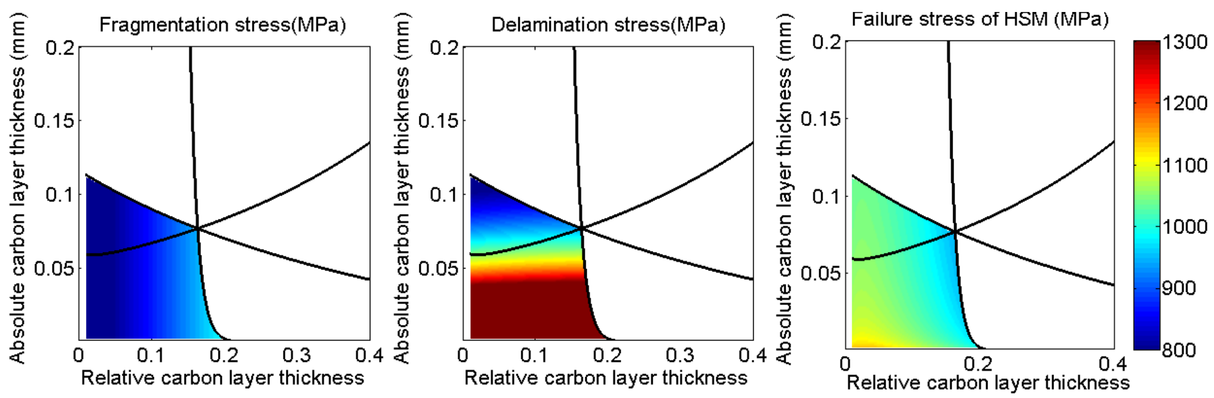

Figure 4- Damage mode map of SkyFlex carbon/E-glass hybrid including the required stress for each damage mode of UD hybrids (fragmentation, delamination and failure of HSM)

Figure 5 is the damage mode map of the same hybrid combination (Figure 3) with the tested specimens from [1], [2]. The specimens with similar damage mode are shown with similar markers defined on the picture. The observed damage modes [1], [2] are in good agreement with the damage mode map.

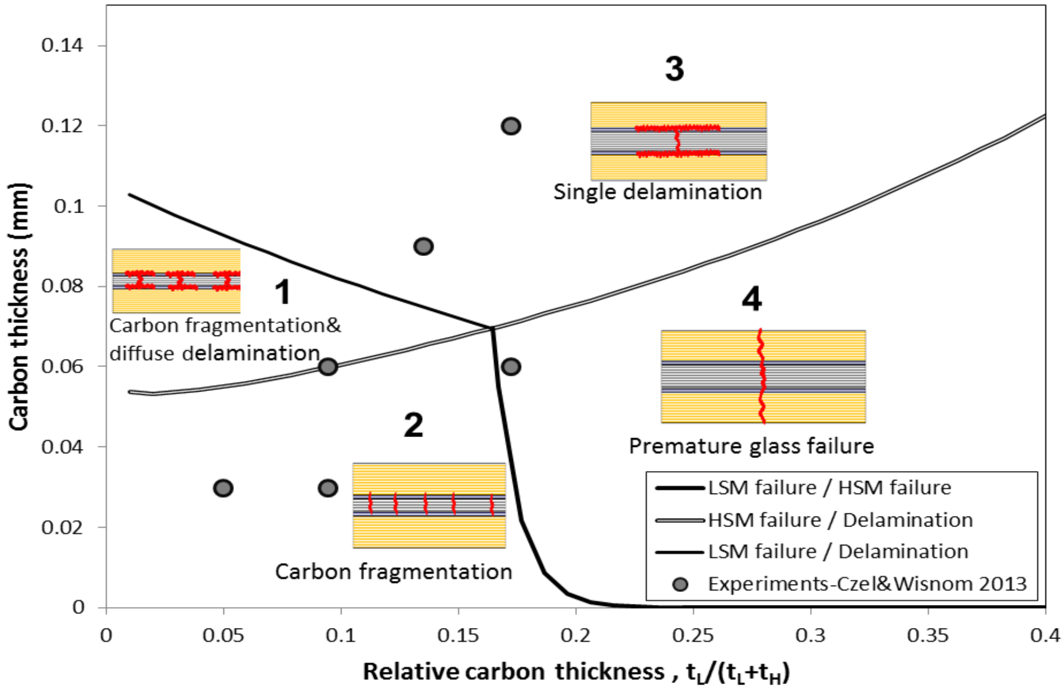

Figure 5- Comparison between the predicted damage modes using the proposed analytical method for SkyFlex carbon/E-glass hybrid and the experimental specimens[1], [2]

4. Conclusion

In this paper, an analytical method for predicting the damage process of UD hybrids was presented. Three stress criteria for the three possible damage modes in hybrids were derived and used for predicting the damage process of the UH hybrid composite. To have an overall picture of the behaviour of a material combination, the required stress for each of the possible damage modes in a hybrid have been plotted. Different regions of damage process have been shown on a damage mode map, which can give a quick overview of the optimum configurations for a certain hybrid material configuration. There was a good agreement between the damage mode map of SkyFlex carbon/E-glass hybrid and the experimental results. Such a method is useful to find the desired damage process of a specific material set quickly and therefore can be used in the design procedure for new hybrid composites.

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