PLY FRAGMENTATION IN INTERLAYER HYBRID COMPOSITES MODELLED DIRECTLY FROM THE FIBRE BREAK STATISTICS

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Abstract
A fibre break model is developed to investigate fragmentation of carbon plies in unidirectional hybrid carbon/glass composites under tension. With this model, we investigate the influence of the hybrid stacking sequence and glass fibre strength distribution on the failure behaviour of the composite. The decrease of the Weibull scale parameter of glass fibre is shown to reduce the probability of achieving carbon ply fragmentation. When thinner carbon plies are used, carbon ply fragmentation is more likely to occur. A hybrid composite with the most dispersed plies of the two fibre types is found to fail gradually through ply fragmentation. On the other hand, a composite with the same carbon fibre content but blocked plies shows no ply fragmentation and fails simultaneously with the first carbon ply fracture. Our results show that ply fragmentation depends not only on the deterministic features of the laminate design, but also on the stochasticity of the fibre strength.

1. Introduction

The low failure strain of traditional carbon fibre composites and their sudden failure can be mitigated through fibre-hybridisation. By adding a second, high elongation (HE), fibre type to the composite, the ultimate failure strain can be increased relative to the low elongation (LE) fibre composite. Additionally, interlayer hybrid composites exhibit a variety of failure modes depending on the laminate design, including constituent properties and ply thicknesses [1].

Considering carbon/glass laminates made from the same constituent materials, the failure modes are influenced by the ply thicknesses [1]. If the carbon/glass ply thickness ratio is high, the glass plies fail simultaneously with the first fracture in the carbon ply. On the other hand, multiple fractures in the carbon ply are possible without triggering delamination if both the carbon/glass ply thickness ratio and the carbon ply’s thickness are small. When the thickness of the carbon ply increases, its fracture will cause delamination between the two ply types. This general rule was demonstrated for simple configurations where one carbon fibre ply is sandwiched between two glass fibre plies [1]. An understanding the failure behaviour of more complex configurations is needed.

The current study takes a base model [2-4] and further develops it to account for ply fracture. With the developed model, we investigate the parameters controlling carbon ply fragmentation in unidirectional (UD) carbon/glass interlayer hybrid composites. Ply fragmentation is not pre-determined by the constituent properties and stacking sequence but depends on the fibre break development. Three different stacking sequences are modelled: a baseline case with a thin carbon fibre ply sandwiched between glass plies, and two thicker laminates with dispersed and blocked stacking sequences. All stacking sequences were designed in such a way that delamination between plies does not occur. This assumption is reasonable considering the low thickness of the carbon plies. The glass fibre strength distribution is varied to show dependence of the failure behaviour on this parameter.

2. Modelling approach

2.1. General two scale approach

In interlayer hybrid composites with LE and HE fibres, the LE fibre ply fractures first but it does not always determine the ultimate failure of the composite. Instead the ultimate failure of the hybrid composite is controlled by the failure of the HE fibre plies, which may or may not fracture at the same time as the LE fibre ply. The ply fracture under longitudinal tension depends on the stochastic process of breaking individual fibres. More specifically, unidirectional plies fail due to an unstable growth of a cluster of fibre breaks.

The failure of a UD bundle or ply under longitudinal tension using fibre break statistics was previously modelled in [2-4]. The model developed here introduces a new mechanism, namely ply fracture, and its effect on the failure of individual fibres. Thus, the current model encompasses two scales: fibres and plies. The model evaluates the stress state in the vicinity of a ply fracture to determine the failure mode of the hybrid composite. Two case scenarios are possible in the current version of the model: 1) the LE ply fracture may cause the neighbouring HE ply to fracture, leading to a sudden failure of the composite or 2) the LE ply fractures multiple times, known as ply fragmentation, leading to a more gradual failure of the composite.

The model allows the prediction of the entire stress-strain behaviour of interlayer hybrid composites. The growth of the critical fibre break cluster and the stress state around the ply fracture posed the biggest challenges in the fibre break model development. The two challenges are discussed in the following sections.

2.2. Fibre break model

To predict failure of a UD ply, the base model in [2-4] devides each fibre into small elements and assigns a strength value based on a Weibull probability distribution. Upon deformation, the stress in some of the elements exceeds a critical value leading to a fibre break. The fibre breaks change stresses in both broken and intact neighbouring fibres. The stress redistribution in the presence of fibre breaks is a key element in the model. Eventually, a critical cluster of fibre breaks forms and grows unstably, serving as a stopping criterion for the model.

The stopping criterion allows for the detection of a critical cluster of fibre breaks while it is growing unstably. This definition leads to a situation where not all the fibre break positions in a ply fracture are defined. As the update of the stress field around single fibre breaks is a computationally expensive process, the position of the fibre breaks involved in the ply fracture is found according to the following approach.

Let z_{min} and z_{max}, be the extreme axial locations (see length direction in Figure 1) of the unstable fibre breaks cluster. For each fibre element, the failure index is defined by: $I_f = \frac{\sigma}{\sigma_{max}}$, where σ and σ_{max} are the stress and strength for each individual fibre element, respectively. For each fibre, the broken element's location is defined by the maximum failure index between z_{min} and z_{max}.

When all the fibre break locations at the ply fracture site are defined, the stress is updated both in the fractured ply and nearest intact plies (see section 2.2). If the fibres in the intact plies are strong enough, the composite will continue carrying load. The model continues increasing strain and detecting fibre breaks until each ply fractures at least once.

2.3. Stress redistribution due to ply fracture

Finite elements (FE) models have been developed in the past to investigate the stress field around a single fibre break [5,6]. Analogously, an FE model was created to calculate the stress field around a single ply fracture using commercially available software ABAQUS 2016 (see Figure 1). The basic concept is the same: the cracked surface is normal to the fibre direction. The cracked surface's nodal displacement is released and the non-cracked surface nodes are applied symmetry in the fibre direction. In the ply facture model, the cracked surface covers all the fibres and matrix at the ply fracture.

The cracked surface is extended across the broken ply towards the interlaminar region. The crack front is assumed to lie in the matrix between the carbon and glass fibres (see Figure 1). This option is consistent with the fibre break model's assumption of perfect bonding between fibres and matrix.

The model's dimensions are defined by a compromise between the computational resources available and accuracy of the stress field. The width and length of the FE model used for the calculations was 50 µm and 2 mm, respectively. The thickness depends on the stacking sequence modelled. The boundary conditions applied to the opposing faces in the width direction are periodic. Symmetry was applied in the thickness direction to the hidden face on the right side of Figure 1. A displacement in the fibre direction was applied to the faces opposite to the crack surface. The displacement applied was such that the strain far away from the cracked surface was 2%.

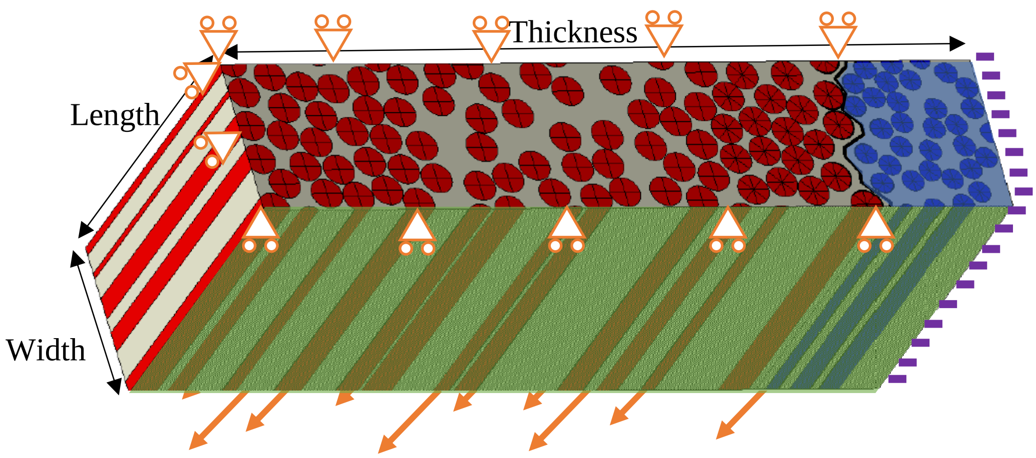

Figure 1 – FE model design and applied boundary conditions. The blue surface is the cracked surface and the green face is subjected to periodical conditions to the opposite side. Thickness symmetry is represented by the purple lines.

2.4. Model parameters

Three different carbon/glass stacking sequences were simulated in this work: a baseline case with $(G/C/G)$ stacking sequence and two thicker stacking sequences defined by $(G/G/C/C/C/G/G)$ and $(G/C/G/C/G/C/G)$ where C and G stand for carbon and glass plies, respectively. Each carbon ply had a thickness of 30 µm and the glass plies 100 µm. The fibre break model's width and length of the composite were 0.5 and 5 mm, respectively. The constituent material properties are presented in Table 1. The glass fibre strength distribution scale parameter was varied throughout the simulations.

Table 1 – Constituent material properties.

	Carbon fibre	**S-glass fibre**	**Epoxy matrix**
Fibre diameter [μm]	7	10 [7]	-
Axial Stiffness [GPa]	230	86.9 [7]	3
Weibull scale parameter [GPa]	3.5	Variable	-
Weibull modulus	6	4.52 [8]	-
Reference gage length [mm]	10	25.4 [8]	-
Ply fibre volume fraction [%]	50	60	-

The material model for the epoxy matrix was chosen as plastic. This is especially important in the FE model, as the local yielding of the matrix strongly influences the stress field around a fibre break or ply fracture. The plasticity law of the matrix is given by Equation 1:

$$\sigma_p = \sigma_Y \cdot (1 + \frac{\varepsilon_p}{\alpha})^{\beta}, \tag{1}$$

where σ_p and ε_p are the matrix plastic stress and strain respectively. σ_Y, α and β were 46 MPa, 0.0008 mm/mm and 0.2 respectively [9].

Variation in the strength scale parameter of the glass fibres, $\sigma_{0,GF}$, changes the failure behaviour. The glass fibres either sustain the stress concentrations imposed by the carbon ply fractures or fail simultaneously with the first carbon fibre ply fracture depending on $\sigma_{0,GF}$. The $\sigma_{0,GF}$ variation was performed coarsely as a first approach (2.5, 2, 1.5 and 1 GPa) and then in a refined way (1.9, 1.8, 1.7 and 1.6 GPa). The strength probability distribution for each fibre type is given by Equation 2:

$$P = 1 - \exp[-\left(\frac{L}{L_0}\right) \cdot \left(\frac{\sigma}{\sigma_0}\right)^m], \tag{2}$$

where P is the probability that a segment of fibre of length L will fail when an axial stress σ is applied to it, L_0 is the reference gauge length, σ_0 is the Weibull strength scale parameter and m is the Weibull shape parameter. A total of 100 simulations was performed for each stacking sequence and each $\sigma_{0,GF}$.

3. Results and discussion

By changing the $\sigma_{0,GF}$, the failure mode transitions from the carbon ply fully saturated with cracks, depicted in Figure 2, to an immediate failure of glass upon the first carbon ply fracture. The saturation state is reached if the maximum stress in the ply is lower than the far field stress, $\sigma_{nominal}$. A partially broken ply is defined if the carbon ply fractures at least once but it does not reach the saturation state and the glass ply does not fracture immediately. Finally, for the $(G/C/G/C/G/C/G)$ stacking sequence, where each carbon ply can saturate independently, partial saturation is defined as the state where at least one of the carbon plies saturated but not all of them did.

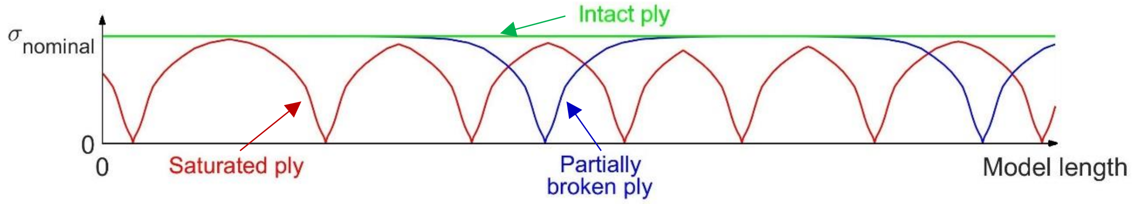

Figure 2 – Stress state of the carbon ply in its intact, partially broken and saturated state.

For all of the stacking sequences, the failure mode transitions from saturation to immediate failure as $\sigma_{0,GF}$ decreases. There are two interesting aspects to analyse from Figure 3. Firstly, even for the same stacking sequence and glass fibre strength distribution, multiple failure modes can occur. For example, the $(G/G/C/C/C/G/G)$ stacking sequence with $\sigma_{0,GF} = 2$ GPa achieved all three failure modes possible for that stacking sequence. This is due to the stochasticity of the fibre strength, which has an influence on the failure of the composite. If the glass fibres elements happen to be weak close to the carbon ply fracture locations, the composite fails for a lower strain. Secondly, even though the $(G/G/C/C/C/G/G)$ and $(G/C/G/C/G/C/G)$ stacking sequences have the same carbon fibre content, their failure mode transition occurs for a different $\sigma_{0,GF}$. The $(G/G/C/C/C/G/G)$ stacking sequence transitions for a higher $\sigma_{0,GF}$, which means it has a lower potential for a gradual failure.

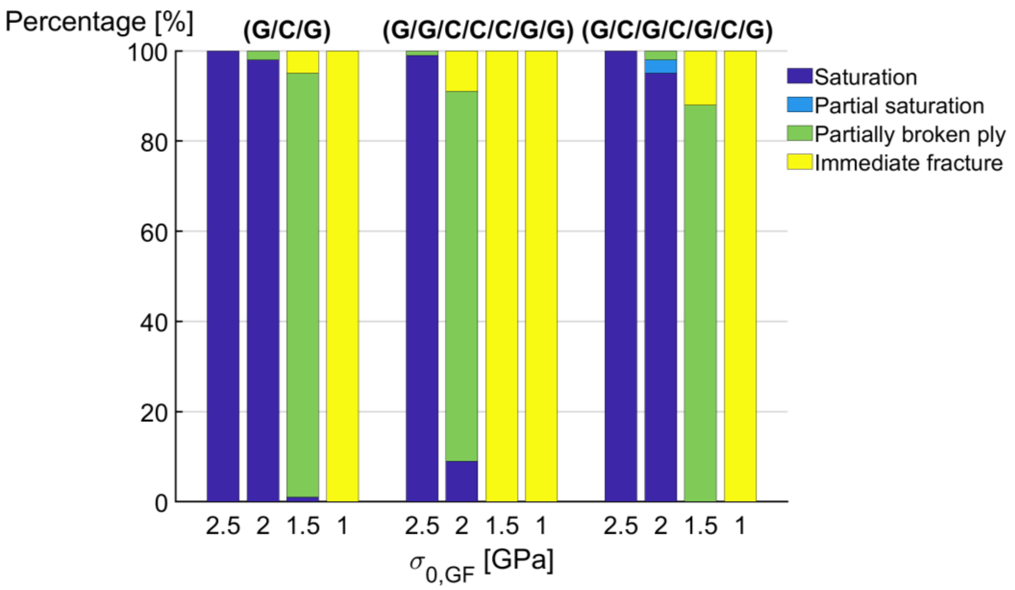

Figure 3 – Failure mode variation with $\sigma_{0,GF}$ for the different stacking sequences tested – coarse variation.

The main transition between failure modes happens when the glass fibre scale parameter changes from 1.5 to 2 GPa. A finer $\sigma_{0,GF}$ variation was performed between these values with a step of 0.1 GPa. The failure mode variation (see Figure 4) is now much more gradual for all the stacking sequences. None of the simulations reached the saturation state for the $(G/G/C/C/C/G/G)$ stacking sequence but this does not apply to the $(G/C/G/C/G/C/G)$ stacking sequence. For this stacking sequence, the carbon plies saturated for the majority of the simulations when the $\sigma_{0,GF}$ was 1.9 and 1.8 GPa. Note that for this stacking sequence, the partial saturation state was also possible. For the $(G/C/G)$ stacking sequence, the carbon ply also saturated for the majority of the simulations, except in the case of $\sigma_{0,GF} = 1.6$ GPa.

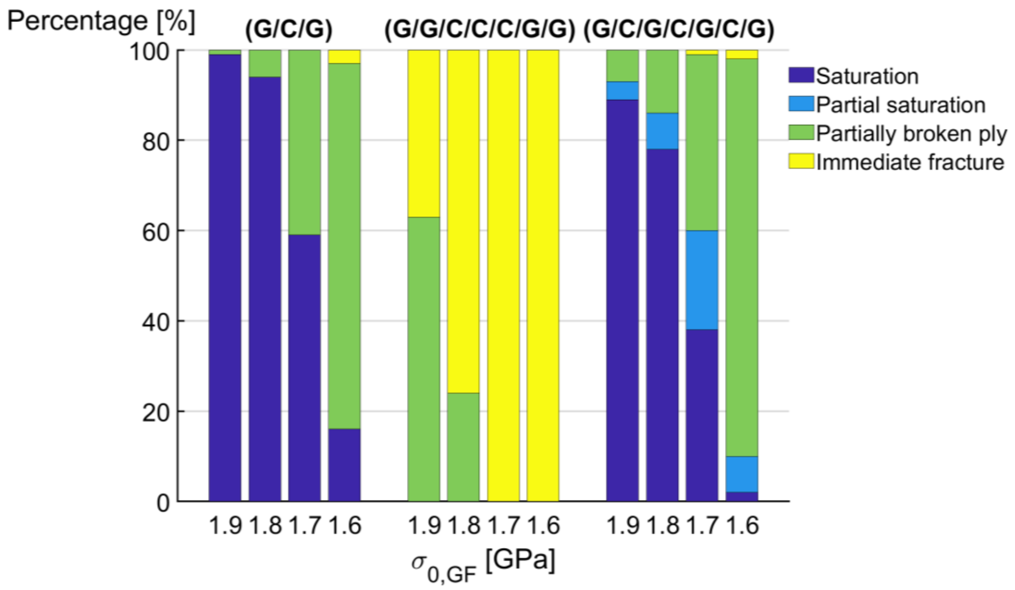

Figure 4 – Failure mode variation with the $\sigma_{0,GF}$ for the different stacking sequences tested – fine variation.

4. Conclusion

A model was developed to predict ply fragmentation based on fibre break statistics. There was a gradual shift in failure mode for each of the studied stacking sequences as the Weibull glass scale parameter, $\sigma_{0,GF}$, varied. Still, for the same stacking sequence and glass ply strength, multiple failure modes were possible due to the stochasticity of the fibre strength. The $(G/G/C/C/C/G/G)$ and $(G/C/G/C/G/C/G)$ stacking sequences, although having the same carbon fibre content, reach a saturation state for different limiting $\sigma_{0,GF}$.

Acknowledgments

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