THE EFFECT OF RANDOMNESS AT THE MICRO-SCALE ON FAILURE OF COMPOSITES

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ABSTRACT

It is widely accepted that the intrinsic randomness of composite microstructures creates weak regions which may trigger premature failure of the material. This paper uses a virtual testing framework to quantify how failure of aligned discontinuous composites with single or hybrid fibre-types is affected by randomness in three microstructural stochastic variables: fibre-end location, fibre-strength, and fibre-type arrangement. The results show that, by removing randomness at the micro-scale, it should be possible to improve the strength of aligned discontinuous-fibre composites by 20-30%.

1 INTRODUCTION

Composite materials have several intrinsic sources of randomness at the micro-scale, related to the geometry of the microstructure and to the micromechanical properties of the fibres, matrix, and interfaces. It has been widely accepted that these sources of randomness create weak regions in composites which eventually trigger their failure; for instance, longitudinal tensile failure of continuous-fibre composites is governed by the variability of fibre strength and triggered by the presence of weak-fibre clusters. However, there is a striking lack of studies that quantify how large and how weak these clusters need to be, in order to significantly influence the failure process of composites.

As composite microstructures become more complex, new sources of randomness are added to this problem; for instance, the location of fibre-ends in discontinuous composites and the intermingled arrangement of fibre-types in hybrid composites are in general random variables which may influence the failure of these materials. Consequently, this work aims to identify and quantify the sources of randomness which affect the final failure of hybrid and non-hybrid discontinuous composites. To do so, we use our recently-developed virtual testing framework for aligned discontinuous composites with one or more fibre types [1-5].

This paper is organised as follows: Section 2 provides an overview of the virtual testing framework used to predict the response of aligned discontinuous composites. Section 3 analyses the microstructural characteristics of critical weak clusters (which trigger failure of entire virtual specimens), and compares the mechanical response of aligned discontinuous composites with and without significant sources of randomness at the micro-scale. Finally, Section 4 draws the main conclusions.

2 VIRTUAL TESTING FRAMEWORK

2.1 Modelling approach

Our virtual testing framework [1-5] simulates a virtual composite specimen with aligned discontinuous fibres embedded in a polymer matrix. The framework represents individual fibres and matrix explicitly (see Figure 1), and it can simulate composites with a single fibre-type as well as hybrid-fibre composites.

The microstructures simulated in this framework account for randomly-located fibre-ends, and random intermingling of fibre-types in hybrid-fibre composites. The framework uses a shear-lag model to represent the stress-transfer between neighbouring fibres (see Figure 1); this stress-transfer occurs through shearing of the matrix, according to a generic constitutive law which accounts for progressive matrix fracture. Fibres are modelled as linear-elastic up to failure, with stochastic Weibull strength distributions. This framework uses a non-linear fracture mechanics criterion to identify the location, size and shape of the critical weak cluster triggering failure of the entire virtual specimen.

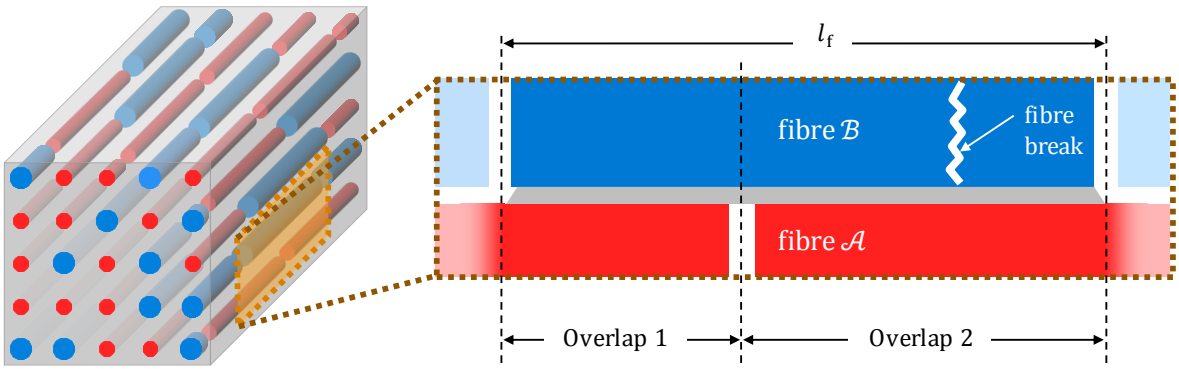
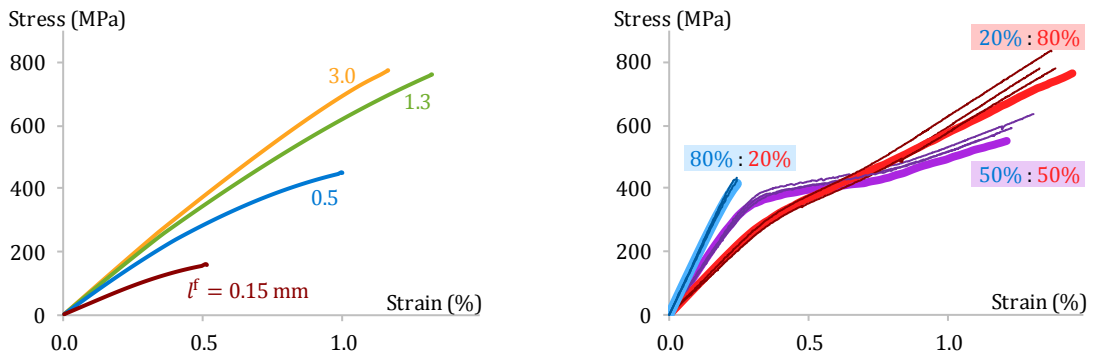


Figure 1: Overview of the virtual testing framework [1-5].

2.2 Overview of modelling results

Figure 2a shows the stress-strain curves predicted by the virtual testing framework for aligned discontinuous carbon/epoxy composites, considering different fibre-lengths. Discontinuous composites with short fibres ($l^f \leq 0.5$ mm for the case considered in Figure 2a) have a non-linear response, with low strength and failure governed by matrix (or fibre-matrix interface) failure and fibre pull-out. Above a threshold fibre length ($l^f \approx 1.3$ mm), failure of the composite becomes governed by fibre failure, and the non-linearity of the stress-strain response is progressively reduced for further increases in fibre length.

Figure 2b shows the stress-strain curves predicted by the virtual testing framework and validated against experiments [6] for hybrid aligned discontinuous composites; these materials are composed by High-Modulus Carbon (HMC, low elongation) and High Strength Carbon (HSC, high elongation) 3 mm long fibres embedded in an epoxy matrix. For 50:50 or 20:80 HMC:HSC volume ratios, the hybrid discontinuous composite exhibits a characteristic pseudo-ductile stress-strain response [6], with progressive fragmentation of the low-elongation HMC fibres; in these cases, ultimate failure of the hybrid composite is governed by failure of the high-elongation HSC fibres. For a 80:20 HMC:HSC volume ratio, the response of the composite is brittle, as failure of the low-elongation HMC fibres triggers failure of the entire specimen.



a) Non-hybrid carbon/epoxy composites, considering four different fibre lengths [1].

b) HMC:HSC hybrids with three fibre-type ratios. Model predictions [2-3] are shown by thick lines, and experimental data [6] is shown by thin lines.

Figure 2: Stress vs. strain curves predicted by the virtual testing framework.

3 ANALYSIS OF STOCHASTIC VARIABLES IN CRITICAL WEAK CLUSTERS

3.1 Averaging the characteristics of weak clusters triggering failure

Our virtual testing framework [1-5] is a suitable tool to analyse how the intrinsic variability of the microstructure affects final failure in aligned discontinuous composites due to two features:

- The fracture mechanics-based criterion used by the framework to calculate the point of final specimen failure also identifies the critical weak cluster from which failure is triggered. This allows us to study the characteristics of those critical weak clusters in a systematic way;
- The framework represents the microstructure of the composite explicitly, allowing us to realise spatial distributions of stochastic variables such as overlap length between neighbouring fibres, fibre strength, and fibre-type arrangement in hybrids.

For these reasons, we ran Monte-Carlo simulations of aligned discontinuous composites to determine the average characteristics of these critical weak clusters, using the method shown in Figure 3 and summarised hereafter. For a given composite specification (i.e. with a given set of microstructural parameters), we predicted the stress-strain curves and the critical cluster of 1000 Representative Volume Elements (RVEs) which were nominally identical but had different stochastic realisations of fibre-end locations, fibre strengths, and fibre-type arrangements (in hybrids); subsequently, we staggered the cross-section of the RVEs so that their critical clusters were centred on top of each other, as illustrated in Figure 3. Then, at each point of the staggered RVEs, we averaged a selected stochastic variable characterising the material locally (e.g. initial fibre-overlapping lengths, fibre strengths, fibre-type ratios in hybrids); any deviation of the local averages in the centre of the staggered RVEs from the expected value in the entire RVE (e.g. shorter overlaps, weaker fibres, or higher concentration of low-elongation fibres) identifies a statistically significant source of weakness in the microstructure of the material.

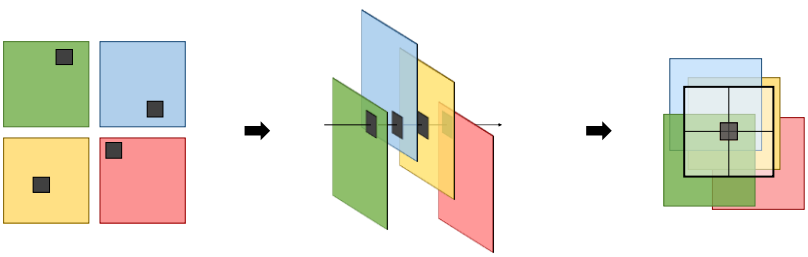
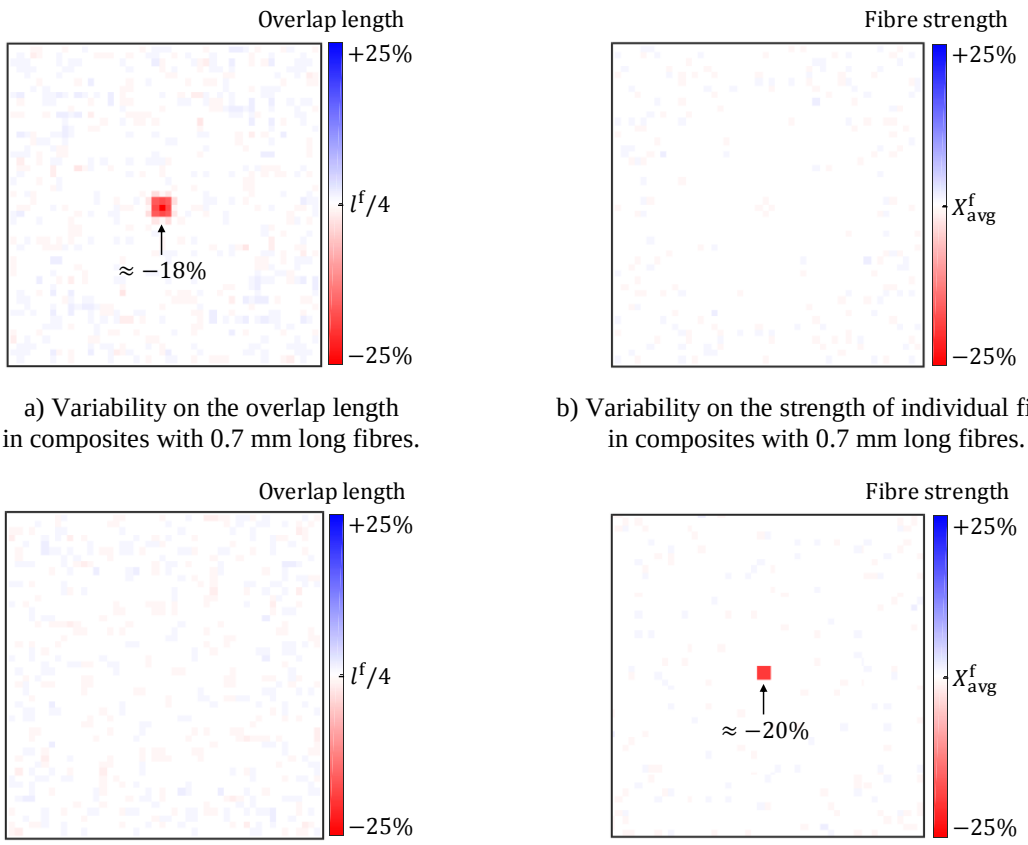


Figure 3: Method used to average the characteristics of the critical weak clusters (shown in dark grey) triggering failure of a RVE [1,7].

3.2 Results for non-hybrid discontinuous composites

Figure 4 shows the results of the analysis of stochastic variables in carbon/epoxy aligned discontinuous composites with a single fibre-type (with average strength $X_{\mathrm{avg}}^{\mathrm{f}}$), for two fibre lengths (0.7 mm or 6.0 mm). Failure of composites with short fibres is triggered by clusters of fibres with shorter overlaps than average (see Fig. 4a), with no influence of fibre strength (Fig. 4b). On the contrary, failure of composites with long fibres (see Fig. 4c-d) is triggered by clusters of weaker fibres, which fragment before catastrophic fracture propagation. Fig. 4 also shows that the size of the critical cluster decreases with fibre length (from approximatively 9 fibres at 0.7 mm long fibres to 4 fibres at 6.0 mm long fibres), because the composite becomes more brittle with increasing fibre length.



a) Variability on the overlap length in composites with 0.7 mm long fibres.

b) Variability on the strength of individual fibres in composites with 0.7 mm long fibres.

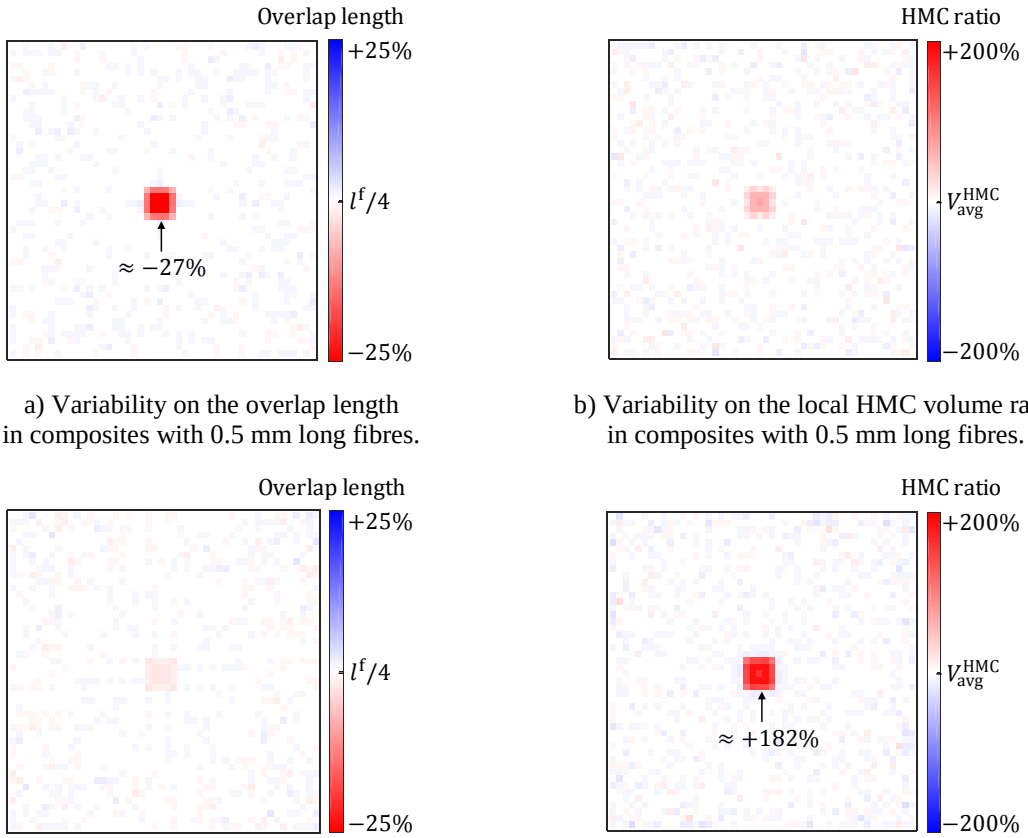
c) Variability on the overlap length in composites with 6.0 mm long fibres.

d) Variability on the strength of individual fibres in composites with 6.0 mm long fibres.

Figure 4: Average characteristics of the critical weak clusters triggering failure of aligned discontinuous composites with one single fibre-type.

3.3 Results for hybrid discontinuous composites

Figure 5 shows the results of the analysis of stochastic variables in aligned discontinuous composites with hybrid (HMC:HSC, with a HMC volume ratio of $V_{\mathrm{avg}}^{\mathrm{HMC}}$ =20%) fibre types, for two fibre lengths (0.5 mm or 6.0 mm). As observed for non-hybrids, failure of hybrid composites with short fibres is also triggered by clusters of fibres with shorter overlaps than average (see Fig. 5a-b), as previously observed for non-hybrids. Failure of hybrid composites with long fibres (see Fig. 5c-d) is triggered by clusters of low-elongation (i.e. HMC) fibres, which fragment and therefore lose their load-carrying capability before the high-elongation (i.e. HSC) fibres.



a) Variability on the overlap length in composites with 0.5 mm long fibres.

b) Variability on the local HMC volume ratio in composites with 0.5 mm long fibres.

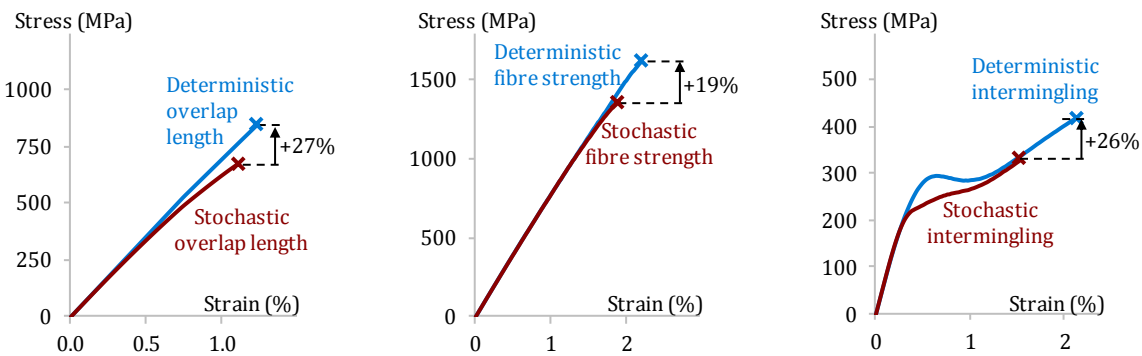
c) Variability on the overlap length in composites with 6.0 mm long fibres.

d) Variability on the local HMC volume ratio in composites with 6.0 mm long fibres.

Figure 5: Average characteristics of the critical weak clusters triggering failure of aligned discontinuous composites with hybrid (HMC/HSC) fibre-types.

3.4 Effect of removing the randomness at the micro-scale

Figure 6 compares the stress-strain curves predicted by the virtual testing framework for composites with and without variability on selected stochastic variables. The results show that, by removing randomness at the micro-scale, it would possible to increase the strength of aligned discontinuous-fibre composites by 20-30%.



a) Single-type short fibres.

b) Single-type long fibres.

c) Hybrid long fibres [4].

Figure 6: Stress-strain curves predicted for composites with ('stochastic') and without ('deterministic') randomness of a selected stochastic variable (identified in the graphs). The same average for the selected property is used in both 'deterministic' and 'stochastic' cases.

4 CONCLUSIONS

We proposed a virtual testing framework to quantify the effect of randomness at the micro-scale on failure of aligned discontinuous composites. For the cases analysed, the following conclusions can be drawn:

- Aligned discontinuous composites with short fibres (which fail predominantly by fibre debond and pull-out) are weakened by regions with short overlaps between neighbouring fibres. Removing the variability in overlap lengths increases the strength of the composite by approximately 27%;

- Aligned discontinuous composites with long fibres (which fail predominantly by fibre fracture) are weakened by regions with weaker fibres, with negligible influence of the variability in fibre overlapping length. Removing the variability in fibre strength increases the strength of the composite by approximately 19%;

- Failure of hybrid composites with sufficiently long fibres may be triggered by clusters of low-elongation fibres, which fragment at low applied strains. Removing the variability of the local levels of intermingling between the two fibre-types increases the strength of the composite by approximately 26%.

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