PREDICTION OF TENSILE STIFFNESS AND FAILURE OF CARBON FIBRE COMPOSITE LAMINAE: A MULTI-SCALE NON-DETERMINISTIC APPROACH

F. Malgioglio[1,2*], F. Mesquita[2], C. Breite[2], A. Matveeva[1], L. Farkas[1], W. Desmet[3], S. V. Lomov[2], Y. Swolfs[2]

[1]Siemens Industry Software NV, Interleuvenlaan 68, 3001 Leuven, Belgium
[2]Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44 bus 2450, 3001 Leuven, Belgium
[3]Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300B bus 2420, 3001 Leuven, Belgium
*Corresponding Author: fabio.malgioglio@siemens.com

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Abstract

A non-deterministic multiscale methodology is proposed to predict variability in longitudinal tensile stiffness and strength of unidirectional composite plies. Local composite strength and stiffness are predicted at the microscale and assigned to finite elements models, which represent the material at the scale of a ply. In doing so, fibre volume fraction variations and fibre misalignment are accounted for. The local strength is computed using a fibre break model able to reproduce the onset and accumulation of the fibre breaks at the microscale. A large number of simulations were performed at both scales to study the convergence of the mean values of strength and the variability. It is shown that the local volume fraction variation has a major role in the material failure prediction, while very small misalignment can be considered negligible.

1. Introduction

Fibre-reinforced plastics, due to their advanced mechanical properties, are nowadays the preferred choice in many applications where the mechanical performance and the weight are crucial design requirements, as in the aerospace field and in the automotive industry. Nevertheless, due to their heterogeneous nature, their mechanical behaviour is very complex. Hence, their proper mechanical characterisation requires a high number of experimental tests, while uncertainties enforce the use of large safety factors in the design of composite components. In an industrial context, the ability to virtually characterise the composite material's behaviour is desirable to reduce both cost and time in the design phase.

Failure of brittle materials, such as carbon fibres, is commonly described with the Weibull statistics [1]. However, complex phenomena should be taken into account when many fibres are grouped together in a unidirectional (UD) composite [2]. At first, fibre breaks occur in the weakest fibre locations. The load is then transferred by the matrix to the surrounding fibres and to the broken fibres themselves. Few fibre breaks are usually not sufficient to cause the failure of all the composite, but they introduce stress concentrations that promote new fibre breaks in the neighbour fibres. Eventually, the unstable increase of the number of fibre breaks causes the composite failure. To reproduce and predict the failure mechanism of UD composites in tension, several models were proposed in the literature [3-5]. However, these models neglect the variation in the material in terms of volume fraction V_f and misalignment, while

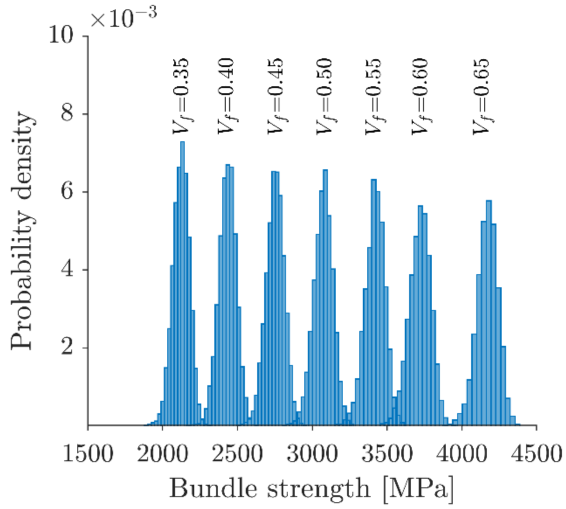

Figure 1 Probability distributions of bundle strengths for different V_f calculated with the fibre break model.

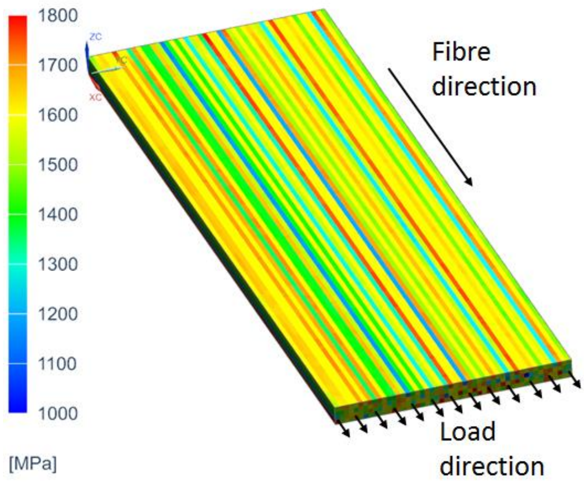

Figure 2 Longitudinal stress results of the ply model for a virtual coupon. The higher local stresses correspond to higher V_f.

they are experimentally observed in these materials [6-8]. The results of the experimental tests show a non-deterministic response, i.e. scatter, partially due to the intrinsic material variability. The purpose of this paper is to reproduce such non-deterministic behaviour by including the variation of V_f and misalignment.

In this paper, the effect of material variability at different scales on the mechanical response of UD laminae loaded in longitudinal tension is studied numerically. The input data considered here can be measured experimentally and are consistently extracted from references in the literature for carbon/epoxy preimpregnated laminae.

2. Multiscale model

A classical homogenisation approach based on Representative Volume Elements (RVEs) allows to predict the mechanical properties of a material. However, the variability of the mechanical properties cannot be reproduced accurately. This is because the local variabilities of the material, e.g. stiffness, occurring at different scales, are averaged in the RVE. Instead, an approach based on smaller volume elements (with different properties) can be successfully used to capture local variations of mechanical properties happening at different scales [6]. Two scales of interest are considered here: the *microscale* and *ply scale*. A scale transition is necessary to link the different scales. In this work, the scales are treated sequentially, meaning that the properties at the microscale are precalculated. Finite elements models representing composite plies are generated. Every element of the ply model represent a portion of material, whose properties are calculated at the microscale. Every element, assumed to be locally homogeneous and orthotropic, differs in local material orientation and elastic properties, which are calculated with Chamis' homogenization rules [9]. The distributions generated with the fibre break model (by means of Monte Carlo analysis) are used to assign strength to each element. Monte Carlo method is also used to assess the variability of the mechanical properties of the ply at a higher scale.

2.1. Microscale model

The fibre break model used in this work was previously described in [2,5] and recently compared with other fibre break models for UD composite bundles of fibres [10]. The model considers composite bundles of fibers loaded in longitudinal tension. Fibres in the bundles are considered parallel and randomly distributed in the transverse direction [11,12]. The model predicts the accumulation of fiber breaks up to the final failure, accounting for stress recovery in the broken fibres and stress redistribution in the intact fibres close to fibre breaks. In this work, a volume of 70 by 70 µm in the transverse direction and 2000 µm in the longitudinal direction is considered, where 70 µm correspond to the minimum length for which V_f is uncorrelated in the transverse direction [6] and 2000 µm, which was chosen long enough to capture the stress recovery along broken fibres. The material system chosen for this work is IM7/8552 carbon epoxy prepreg. The inputs of the model are the Weibull parameters of single fibre strength [13], the elastic and failure properties of the matrix [14] and different values of V_f (from 0.35 to 0.65). It is assumed that the matrix has a plastic behaviour as in [15]. Fibres are assumed parallel at this scale, so misalignment is not modeled in the microscale model.

The distributions of composite bundle strength (Figure 1) were obtained with Monte Carlo analyses of the fibre break model with different V_f. The aim of including the V_f variation and computing different distributions of composite strength is to capture the behaviour of the local material, whose V_f may differ from the average one. It is assumed that the composite bundle strength can be described with Weibull statistics, which allows the scaling of the distributions from the length of the fibre break model (2000 µm) to the length of one finite element at the ply scale (70 µm), described in the next section.

2.2. Ply model

At the mesoscale, UD plies are built with 3D solid elements. To each element, V_f and local orientation are assigned by sampling statistical distributions from experimental data in the literature, assuming that the virtual material has the same variability. The cross section of the elements is chosen equal to the one of the unit cell used at the microscale (70 µm). The same value is used for the element length to ensure a good aspect ratio.

Misalignment of fibres and its spatial correlation (both in the plane of the lamina and out of plane) were measured experimentally for a prepreg material in [7]. The misalignment standard deviations measured are 1.12˚and 0.70˚for in-plane and out-of-plane misalignment respectively. The correlation lengths for in-plane and out-of-plane misalignment are 3.7 mm and 2.4 mm. The correlation widths for in-plane and out-of-plane are equal to 0.73 mm. Here, it is assumed that the virtual material has the same standard deviation and correlation of misalignment as in [7]. It is assumed that V_f has a very small variation in the longitudinal direction. Local material orientation is assigned to each element using the algorithm proposed in [16]. The length and width of the ply model are 10.5 and 3.5 mm respectively. These are chosen greater than 3 times the correlation length for fibre misalignment in the longitudinal and transverse directions, provided in [7]. The thickness is chosen equal to 0.28 mm, which is in the order of magnitude of the thickness of a UD ply. Strength can be assigned to each element by sampling the probability distribution correspondent to the specific V_f of each element and element size. To do so, the distributions obtained with the microscale model in the previous section must be scaled to the element size according to the Weibull formulation and interpolated to the exact value of V_f. The generated virtual coupons are loaded in tension by applying displacement (Figure 2). Boundary conditions are applied in such a way that Poisson's contraction is allowed. In this work, it is assumed that the first ply failure, corresponding to the failure of the first element, causes the catastrophic failure of all the structure. Under this assumption, it is not necessary to simulate the failure process with a non-linear analysis at the ply scale, instead a linear analysis is performed. A global strain of 1% is applied to the structure and the

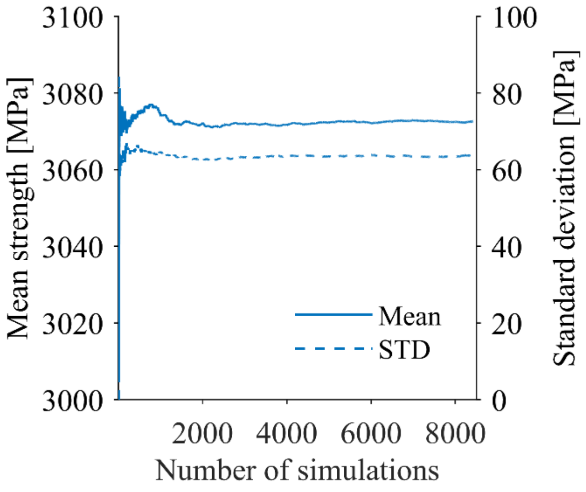

Figure 4 Convergence of the mean and standard deviation of fibre break model results for $V_f = 0.5$.

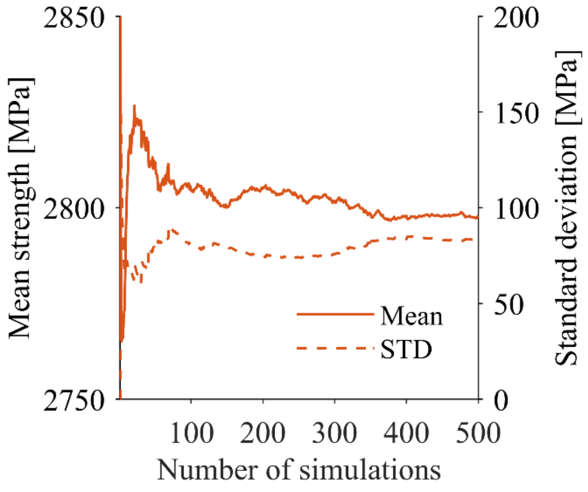

Figure 3 Convergence of themean and standard deviation of virtual testing results with the ply model.

stress field of each coupon is extracted. The failing element is identified as the one with the highest failure index. The global failure strain and stress are extrapolated with a linear proportion. For each virtual coupon generated, two simulations were performed with and without misalignment.

3. Convergence study

The Monte Carlo method is a well known and popular approach to face non-deterministic problems. Nevertheless, establishing a proper convergence criterion is not trivial and may require a very high number of simulations. In this work, convergence is studied by increasing the number of simulations (both at the microscale and at the ply scale) until a plateau of the mean and standard deviation is reached (Figure 3 and Figure 4). Then, convergence is considered achieved when the change in the mean and standard deviation lies within ±1 MPa range compared with the whole population. At the microscale, ~8500 simulations were performed for 7 different volume fractions. Convergence was reached at a value of ~2000 simulations. At the mesoscale, 500 simulations were performed and convergence was reached after ~400 simulations for the mean and ~420 for the standard deviation.

4. Results and discussion

The results of the microscale model, in terms of strength probability distributions for different V_f, are shown in Figure 1. The strength of composite bundles increases with V_f, which is a consequence of the higher number of fibres able to share the load in the same composite volume. It can be noted that the height of the peaks of the distributions decreases with V_f. Considering that the area under PDF (probability density functions) equals to 1 for each curve, the decrease in the height of the peaks leads to the increase of the distribution width, indicating the increase of variability. On the other hand, it is expected that the variability decreases with the number of fibres, because closer fibres cause higher stress concentrations and, therefore, fibre breaks are more likely to propagate. If the variability is

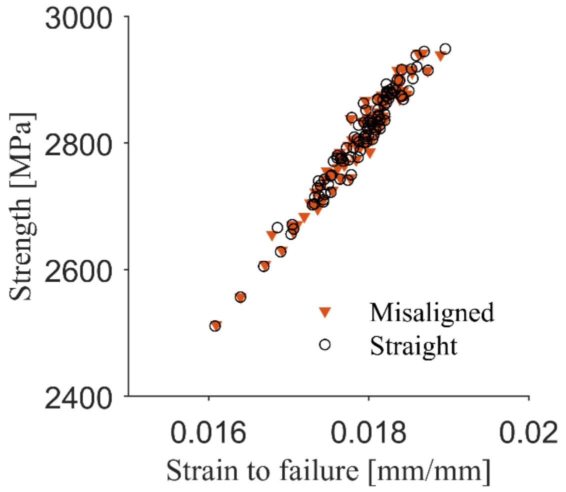

Figure 5 Failure stress and strain of 100 virtual coupons with and without misalignment.

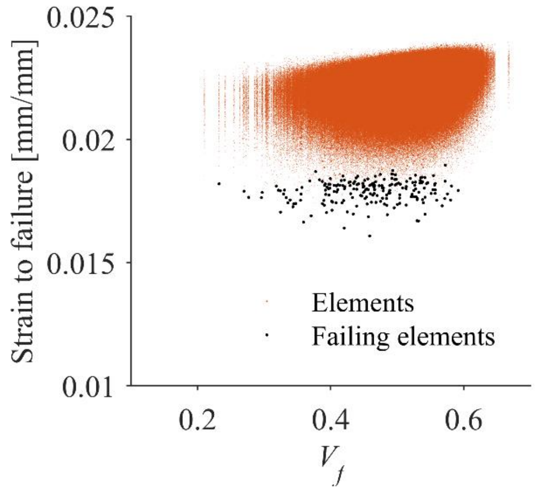

Figure 6 Strain to failure and V_f map. Each point represents a single finite element. In black only the failing elements for each coupon are represented.

expressed in terms of coefficient of variation (and of Weibull modulus) instead of the width of the distributions, it is found that the variability decreases with V_f, as expected.

The results obtained with several simulations of the ply model are shown in Figure 5. The low level of misalignment considered is shown to have a minor effect on the stiffness and strength in this approach (Figure 5). Instead, it is important to consider V_f , since it affects local strength of the material, as shown in Figure 1. For the considered loading case and in the assumption that the final composite failure coincides with the first ply failure, the elements with the lowest strain to failure govern the global failure. Figure 6 shows a map of all the elements in all the simulations on the ply scale in terms of strain to failure assigned to each element and V_f . The weakest element of every virtual coupon are indicated in black. The V_f of the failing elements is less then the nominal V_f (i.e. the mean of the distribution of V_f considered) in ~80% of the cases. This result depends on the shape of the cloud in Figure 6, which is a consequence of the fibre break model and the input data used.

The distribution of longitudinal stiffness obtained with the ply model (with misalignment) is presented in Figure 7. The predicted stiffness with the rule of mixtures (~156 GPa) is within the distribution. The difference in stiffness between the experiments and the predictions is due to the different V_f of the tested material and of the virtual material, therefore the results are normilized by the nominal V_f used in the simulations.

In Figure 8, the strength results obtained with the fibre break model and with the ply model are compared with the datasheet of the material [17]. The fibre break model results were obtained by scaling the Weibull distribution correspondent to the nominal V_f to the length of the ply model. Compared with the fibre break model, the predictions with the ply model are lower and with a larger scatter, due to V_f variability in the ply model. The results of the ply model and the experiments appear in a good agreement. However, some caution is still required in stating that the prediction is fully correct. The results of the ply scale model depend on the results at the microscale, in particular on the choice of input data, e.g. the fibre strength parameters. For this reason, experimental validation for this model is necessary in the future. It is also important to mention that testing errors, unavoidable in real experiments, are diffcult to assess. Reproducing them was not the purpose of this study.

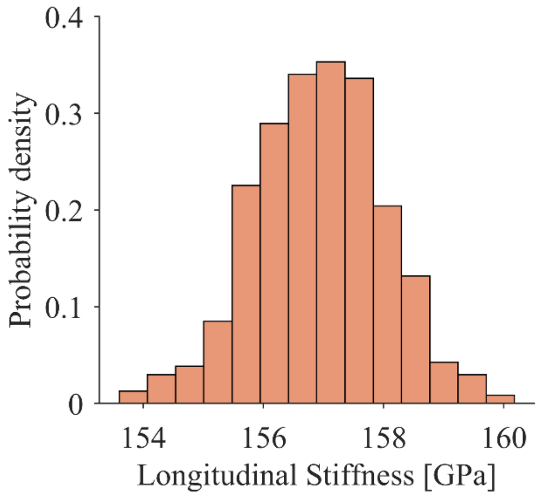

Figure 7 Probability distribution of longitudinal stiffness obtained with the ply model.

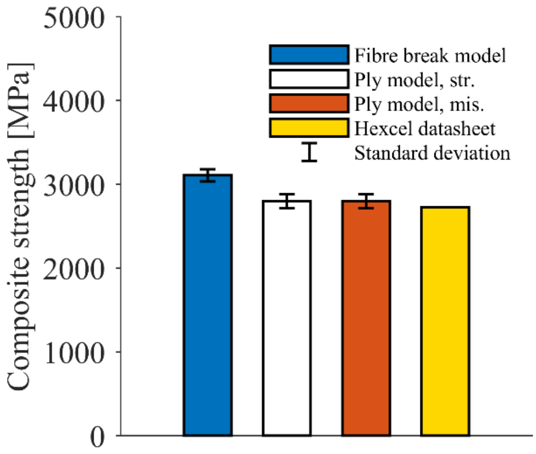

Figure 8 Comparison between the results obtained with the fibre break model, the ply model with straight fibres, with misalignment and the strength from the datasheet [17].

5. Conclusions

A multiscale approach is proposed to predict longitudinal stiffness and strength of UD composites, accounting for the material variability. The required inputs are the mechanical properties of the constituents, the distribution of fibre volume fraction and misalignment and their correlation length. The inputs used in this work, which can be measured experimentally, were taken from the literature. It is shown that the strength overpredictions obtained with the microscale model can be decreased by considering the material variability at the ply scale. It is shown that the variability of V_f influences the results of the simulations, since in general failure occurs in an area where V_f is different from the average one. The influence of misalignment, instead, was shown to be negligible for the small level of misalignment considered. Further studies will be addressed to extend the current procedure to different failure modes and progressive damage.

Acknowledgments

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