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Stress concentrations in hybrid unidirectional fibre-reinforced composites with random fibre packings

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ABSTRACT

Strength models for fibre-reinforced composites often rely on the calculation of the stress concentrations around a single broken fibre. This paper presents the first results for stress concentrations in unidirectional hybrid composites, more specifically around a broken carbon fibre. The centres of the carbon and hybridisation fibres are randomly placed in a two-dimensional packing. The common assumption that both fibre types have the same fibre radii, is proven to lead to significant errors. The relative ratio of the volume fraction of the two fibre types only has a minor influence on the stress redistribution. A small increase of the stress concentration factors on both fibre types is noted with decreasing carbon fibre content. The ineffective length, which is a measure of the length of the influenced zone, remains unaffected. A stiffer hybridisation fibre reduces the SCFs on the hybridisation fibre, while this influence on the SCFs on carbon fibres is much smaller. The influence of the hybridisation fibre on the ineffective length is again small. The differences with existing literature are explained based on the more realistic packings in this paper. These results should now be implemented in a model to predict the influence on the strength of hybrid composites.

1. Introduction

Hybrid composites are composites in which two different types of fibres are combined. The most brittle fibre in hybrid composites is almost always carbon fibre, while the second fibre, called the hybridisation fibre, typically has a higher failure strain. Popular hybridisation fibres are glass and aramid fibres. By adding hybridisation fibres to carbon fibre composites, several improvements can be achieved [1–5]. If the inner layers of a thick carbon fibre reinforced composite are replaced by glass fibre composite, then the total price of the hybrid composite significantly decreases, while flexural and wear properties can remain unchanged. Other properties, like impact [4] or fatigue resistance [5], can even be improved. However, the most notable improvement is the hybrid effect, which is defined as the apparent failure strain enhancement of the carbon fibre.

Hayashi [6] discovered the hybrid effect in glass/carbon hybrids. This effect was attributed to the difference in thermal contraction of both fibres [1,7]. Later, other authors Zweben [8] proved that the thermal contraction could only account for a hybrid effect of +10%. To explain hybrid effects of up to +50% [1,2], two additional effects were proposed: a statistical effect and a fracture mechanics effect. The statistical effect is caused by the improved dispersion and the decrease of the relative content of the carbon fibre [9]. The fracture mechanics effect is related to the hybridisation fibres bridging the crack tip formed by broken carbon fibres [8,9]. Both effects also illustrate why the hybrid effect is more pronounced at low hybrid volume fractions [2], which is defined as the volume of carbon fibres over the total volume of fibres.

To understand and improve hybrid composites, there is a need for models that can predict this hybrid effect. The first models for fracture propagation in hybrid composites were based on the simple shear lag model developed by Hedgepeth [10]. Hedgepeth assumed that the fibres are the only component in unidirectional composites which carry axial load. The matrix is assumed to carry only shear loads. These assumptions allowed Hedgepeth to obtain an analytical solution for the stress redistribution after a single fibre failure in a 1D packing, which is a single row of parallel fibres [10]. Hedgepeth and Van Dyke later extended his approach to the more realistic, 2D packings, where the parallel fibres are arranged in square or hexagonal packings [11]. The stress redistribution is often simplified to two characteristics: stress concentration factor (SCF) and ineffective length [12,13]. The SCF is the ratio between the stress on an intact fibre and the stress applied at infinity, while the ineffective length is a measure of the length over which the stress in the broken fibre is recovered. The latter is a crucial paraeter as it relates to the extent over which the neighbouring fibres are subjected to stress concentrations.

Zweben [8] calculated both characteristics for hybrid unidirectional fibre-reinforced composites by extending Hedgepeth's shear

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lag model. Zweben assumed a one-dimensional packing of alternating carbon and hybridisation fibres and calculated the corresponding SCFs and ineffective lengths. With some additional assumptions, Zweben identified the three main parameters determining the hybrid effect: (1) the ratio of the failure strains of both fibres, (2) the ratio of the SCF in a composite with only carbon fibres over the SCF of a hybridisation fibre next to a broken carbon fibre, and (3) the ratio of the ineffective length in a composite with only carbon fibres to the ineffective length in a composite with both fibres. Fukuda, Chou and co-workers [9,14–17] further developed this approach. Fukuda [15] made several improvements to Zweben's theories. A consequence is that for the ratio of the SCFs, the SCF of the nearest carbon fibre rather than the nearest hybridisation fibre is considered. Fukuda and Chou [9] demonstrated that the fracture propagation in hybrid composites occurs more gradually than in non-hybrid composites. In a subsequent paper, the same authors also revealed a decrease in the SCF on the carbon fibres, but an increase for the hybridisation fibres [14].

The failure strains of both fibres are measured experimentally by single fibre tests. The SCF and ineffective length have been measured experimentally using Raman spectroscopy [18–21], but are often calculated using shear lag models. The latter models, however, have some severe disadvantages when applied to hybrid composites. Firstly, they do not allow anisotropic fibres, which results in significant errors [22]. Secondly, they are unable to cope with random distribution of both fibre types. An alternative approach to calculate the SCF and ineffective length is the finite element method. This approach results in a more accurate prediction of the stress redistribution [23]. Unfortunately, it is also computationally intensive. It cannot handle enough fibres to fully describe the statistical nature of composite failure. Therefore, the relevant data should be extracted from the FEM stress fields and put into a separate strength model [13,24]. The results presented here are the first step in this procedure. This paper will describe how the SCF and ineffective length depend on the fibre radii used, the hybrid volume fraction and the type of hybridisation fibre. To allow for a proper comparison with the literature, all materials are assumed to be linearly elastic. A subsequent paper will demonstrate how these results are affected by matrix plasticity and how they can be incorporated into a strength model.

2. Model description

This section describes the finite element model which is used throughout this paper. This consists of a 3D model, with a 2D random fibre packing (see Fig. 1). The fibre in the centre of the cylindrical model is always a carbon fibre, while the other fibres can either be carbon fibre or hybridisation fibre. The hybridisation fibre is either a glass or aramid fibre and is assumed to remain intact, as their failure strain is typically higher than that of carbon fibre. The carbon fibre in the centre of the model is assumed to be the only broken fibre; all the other fibres are assumed to remain intact.

The model consists of three steps: the generation of random fibre packings, the creation of the finite element model and extraction of the data from the stress field. This procedure is based on the approach developed earlier in [22], but uses an adapted random fibre packing generator. The generator, which was developed by Melro et al. [25], was extended to work with different fibre radii.

As in the original generator, a three-step procedure was followed. The first step creates random fibre locations within the square representative volume element (RVE). The type and radius of the fibre are decided based on the hybrid volume fraction. If the current hybrid volume fraction is larger than the required fraction, then a hybridisation fibre is chosen. Otherwise, a carbon fibre is added. The newly generated fibre is added to the RVE, if it does not overlap with the other fibres. In the second step, the generator tries to move each fibre closer to its three nearest neighbours. This is done to create more open space to thereby increase the probability that a new fibre can be added in the first step. This step is explained in great detail in [25]. The third step moves the fibres at the edges of the RVE inward. This again creates more open space for the first step. The second and the third step remained unaltered compared to [25], except for the criterion which checks for overlapping of fibres. The overlapping criterion is used in all three steps and checks whether fibres overlap, taking into account the fibre radii.

These three steps are repeated until the required fibre volume fraction is reached. Since a more efficient packing is possible in packings with two distinct fibre radii [26], higher fibre volume fractions can be achieved. In all models presented in this paper, the overall fibre volume fraction was set to 70%. The hybrid volume fraction was varied between 0% and 100% of carbon fibre (CF): 0%CF, 20%CF, 50%CF, 80%CF and 100%CF.

Based on the two-dimensional packings, three-dimensional finite element models are created. To reduce edge effect, a circular model of 112 μm diameter is cut out of the square RVE of 200 μm by 200 μm. This was chosen large enough for the stresses around the broken fibre to be unaffeced by the size of the model. The total amount of fibres included in each model depends on the hybrid volume fraction and varies between 60 and 180 fibres per model. A 3D view of the model is presented in Fig. 1a and

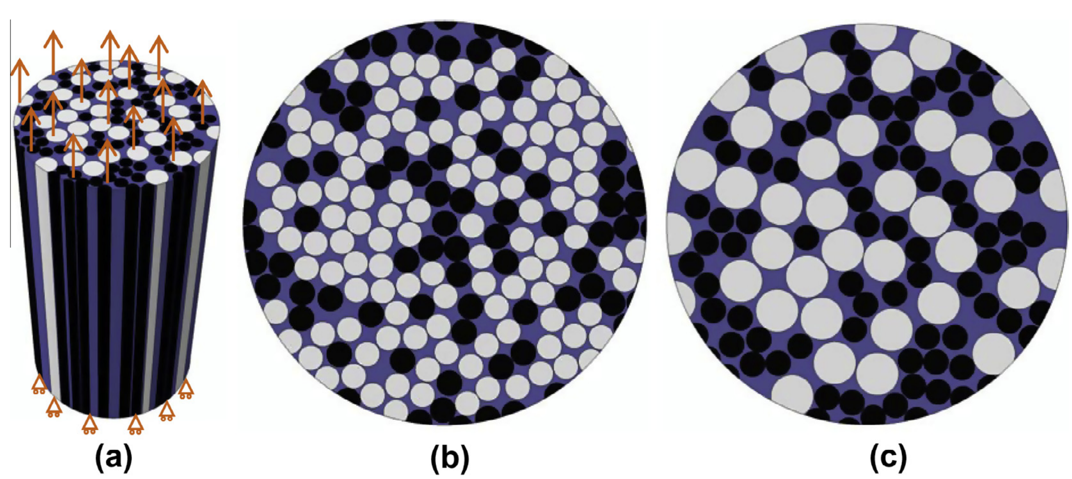

Fig. 1. Illustration of the models with carbon fibres in black, glass fibres in white and matrix in purple: (a) 3D view of the entire model with the applied boundary conditions, (b) top view with the same fibre radii, and (c) with different fibre radii.