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Maximising the hybrid effect in unidirectional hybrid composites

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ABSTRACT

The failure strain of fibre-reinforced composites can be increased by fibre hybridisation. A recently developed model for unidirectional composites was extended to hybrid composites to analyse this synergetic effect, called the hybrid effect. The model predicts individual fibre breaks and interactions among clusters of fibre breaks. Three key parameters were studied to understand how they can maximise the hybrid effect, namely low elongation fibre strength scatter and hybridisation fibre stiffness and failure strain. Larger strength scatter of the low elongation fibres leads to larger hybrid effects, as the scatter spreads out the cluster development over a larger strain interval. The failure strain ratio of the two fibre types should be above 2 for the properties used here, but a higher ratio did not yield any additional benefits. Increasing the stiffness of the hybridisation fibre reduces the stress concentrations on the low elongation fibre and may also enlarge the hybrid effect. These conclusions provide guidelines for designing optimal hybrid composites.

1. Introduction

Fibre-hybridisation is one of the few strategies that can apparently increase the failure strain of carbon fibre composites, while still exploiting the excellent mechanical properties of carbon fibres. In fibre-hybridisation, a hybridisation fibre is added to the low elongation fibres, often with the aim of achieving a better balance in performance. Carbon fibres are typically hybridised with glass [1–9] and aramid [10–13] fibres, but other fibres have also been used: flax [14], polyethylene [15] and polypropylene [16] fibres.

Hayashi [6] was the first to report an apparent failure strain increase of carbon fibres. Hayashi found that when carbon fibre layers were sandwiched in between glass fibre layers, the failure strain of the carbon fibre layers was 40% higher than for a composite consisting of only carbon fibre layers. This increase is called the ‘hybrid effect’. It is often termed an apparent increase, as the intrinsic failure strain or strength of the carbon fibres does not change. Other authors have later reported similar increases [3,13,17,18].

A recent review paper [19] summarised the three hypotheses for the hybrid effect that have been coined so far: (a) residual thermal stresses [8,17], (b) dynamic stress concentrations [20], and (c) failure development [13,21]. The first two hypotheses certainly play a role in the hybrid effect, but can only account for a small part [8,13,17,20]. The third hypothesis, namely failure development, requires an understanding of the failure of unidirectional (UD) non-hybrid composites. Failure of these composites begins with individual fibre breaks. Those fibres locally stop carrying load and shed their load to the adjacent fibres, which causes stress concentrations on the adjacent fibres [22–27]. The broken fibre recovers its load due to shear stress transfer in the matrix. This effect decreases the stress concentrations on the adjacent fibres as a function of the axial distance from the break. Nevertheless, the stress concentrations increase the failure probability of the adjacent fibres, which causes the tendency to develop clusters of fibre breaks [28–32]. These clusters further intensify the stress concentrations. Finally, a critical cluster develops which propagates in an unstable manner and causes final failure of the composite. Adding a hybridisation fibre can significantly alter the failure development and thereby increase the apparent failure strain of the low elongation fibres in the hybrid composite [3,13,18,19,21,33,34].

Many parameters exist that can help to increase the hybrid effect, but most of them are relatively poorly understood in literature. These include the fibre dispersion, the relative volume fraction of both fibres, the low elongation fibre strength scatter, the failure strain ratio and the fibre stiffness ratio. Well dispersed fibres and small low elongation fibre fractions are known to maximise the hybrid effect. This has been extensively demonstrated in experiments [3,19], and now also recently in models [21]. The importance of the other three parameters however has not been quantified yet. Firstly, the importance of the low elongation fibre strength scatter has been identified by several researchers [13,33,35]. A larger strength scatter or lower Weibull modulus is thought to yield a higher hybrid effect, but quantitative predictions are lacking.

Secondly, Zweben's model indicated that the failure strain ratio of both fibre types is crucial for the hybrid effect [13]. As proven by Fukuda [33], this was caused by Zweben's approximate definition of the hybrid

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effect. Fukuda's model improved this definition and found no influence of the failure strain ratio. Zweben and Fukuda laid the ground work for modelling of hybrid composites. Unfortunately, both authors used simple 1D packings, consisting of a single row of fibres, and did not model the entire failure development. Consequently, their models can only give indications of certain trends, but cannot be used to draw strong conclusions. More refined models are needed to establish the importance of the failure strain ratio for maximising the hybrid effect.

Finally, it is well recognised that the stiffness of both fibre types affects the stress concentrations around a fibre break in hybrid composites [13,33,34]. Its importance for the hybrid effect however, has not been quantified yet.

This study extends an existing strength model for UD composites to UD hybrid composites. The focus lies on carbon/glass hybrid composites, but these fibres will be referred to as low elongation (LE) and high elongation (HE) fibres respectively to keep the descriptions generic. The model for hybrid composites in Swolfs et al. [21] ignored the difference in fibre radiuses and used a simplified stress redistribution around the fibre breaks based on very local load sharing. Nevertheless, it was successful in predicting experimentally measured hybrid effects [36]. The model used here is the very first study to include the difference in fibre radiuses and uses randomly dispersed fibres in a random fibre packing. This is essential as regular packings would cause the larger fibres to be closer to the broken fibre than the smaller fibres. In a carbon/glass hybrid composite, this would lead to a too pronounced shielding effect and hence to overestimations of the hybrid effect. Additionally, geometrical limitations would restrict the overall fibre volume fraction in regular packings.

Three key parameters for maximising the hybrid effect are analysed: the LE fibre strength scatter, the failure strain ratio, and the stiffness of the HE fibre. The influence of hybrid volume fraction and dispersion will not be analysed here, as we have already analysed these parameters in detail earlier [21]. The focus is on the hybrid effect for the initial failure strain, which corresponds to propagation of the first critical cluster. It is not the intention to predict what happens afterwards, as that is often a complicated mix of fragmentation, fibre bundle debonding, delamination growth and more fibre breaks. The stiffness and strength will not be discussed here, but the stiffness can easily be obtained from the linear rule-of-mixtures. The strength would follow directly from the stiffness and failure strain, as all our predictions are linearly elastic.

2. Model description

2.1. General approach

The general approach of the model has been extensively described in literature [21,23,32,37] and is similar to the works of Curtin, Okabe and co-workers [24,38–40]. The model starts off by creating a representative volume element (RVE) consisting of parallel fibres. These fibres are divided into fibre elements, as illustrated in Fig. 1. A strength consistent with a Weibull distribution is assigned to each element. The fibre bundle consists of a random fibre packing of two fibre types, which are randomly dispersed and have a different radius (see Fig. 1).

The model gradually increments the global strain and checks for element failure by comparing element strength to element stress. If no new element fails in this strain increment, then the strain is further incremented. If new elements have failed, then the model recalculates the stress redistribution around these broken elements. The model first searches for clusters of fibre breaks. Two fibre breaks are considered to be part of a cluster if (1) the lateral distance between their fibre centres is less than 4 LE fibre radiuses, and (2) the axial distance between the fibre breaks is less than 10 LE fibre radiuses. Fibre breaks that are further away have a negligible influence on each other [22,34]. The definition of a cluster was the same irrespective of the fibre properties and the applied stress level.

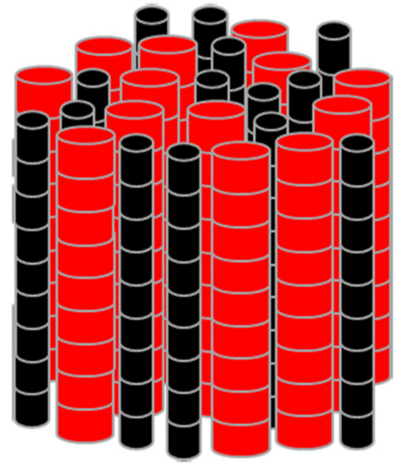

Fig. 1. Illustration of the chain-of-bundles approach for LE/HE hybrid composites. Each fibre is divided into fibre elements. The image is not to scale and the actual model contains more and longer fibres.

The model then updates the stress concentration factors. This update is performed by first assuming that there are no interactions among fibre breaks and then correcting for those interactions. The stress concentration factors (SCFs) without interactions are obtained from the stress fields in finite element (FE) models for hybrid composites with a single fibre break. The FE model takes into account the radius of both fibre types, but assumes a linear elastic and well-bonded matrix. Using an elastic matrix is an approximation that will affect the predicted failure strains. Including plasticity would increase or decrease the failure strains of the reference and hybrid composite in a similar way. The influence on the hybrid effect will therefore be minor, as it is defined as the relative ratio of these two failure strains. Including plasticity would however require the difficult implementation of an ineffective length that changes with applied strain. An alternative approach would be to use the ineffective length at a strain that is close to the failure strain. Given that the hybrid effect will change the failure strain, this may introduce additional and unwanted artefacts. Due to these reasons, the best solution was to use an elastic matrix.

A tiny matrix crack was added to avoid a stress singularity in the broken fibre. An extensive description can be found in Swolfs et al. [23,34]. The SCFs were defined as the relative increase compared to the nominal stress level. The ineffective length was defined as the relative distance from the break at which 90% of the nominal fibre stress is recovered.

The stress profiles from the FE solutions are imported into the strength model using trend line equations for various characteristic points. Interactions among fibre breaks are taken into account through an enhanced superposition principle. This principle has been described and validated in Swolfs et al. [23]. It is based on linear superposition of the individual fibre break solutions with a correction to satisfy force equilibrium.

After updating the SCFs, the model calculates element stresses and checks for element failure again. This entire procedure is repeated until the failure criterion is satisfied, after which the model is interrupted. The failure criterion is satisfied if more than 10% of the fibres are broken within an axial segment of 35 μm, which corresponds to the length of 10 LE fibre elements. This criterion corresponds to a large number of iterations within a single strain increment. This indicates that a critical cluster is growing unstably, and further computation would become slow and meaningless.

The development of clusters as well as global strain ε and average composite stress σ_c are tracked at each strain increment. The composite stress is calculated according to Eq. (1), which is the sum of three components. The first component is the sum of all element stresses σ_{el} divided by the number of elements n_{el} and multiplied by the fibre volume fraction V_f. The second component is calculated by multiplying the