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Characterisation of random carbon fibre composites from a directed fibre preforming process: The effect of fibre length

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Abstract

The effect of fibre length on the tensile properties of 2D random carbon fibre composites is examined. Mechanical property data from carbon/epoxy plaques produced using a directed fibre preforming process is presented for tow lengths from 3 mm to 115 mm. Shorter lengths improved preform coverage and gave increasingly higher strength whilst modulus was independent of fibre length. Varying degrees of filamentisation were induced to separate 24K tows into smaller bundles. By maximising the level of filamentisation the stiffness and strength were increased by 18.9% and 44.1%, respectively.

Analytical models for predicting stiffness and strength are compared against experimental data and a good correlation is observed for highly filamentised fibres because of scale effects. An expression for critical tow length has been developed for more accurate strength prediction, based upon the number of filaments within the bundle. Experimental results confirm that the critical tow length is proportional to the tow filament count.

Keywords: A. Carbon fibre; A. Discontinuous reinforcement; E. Preform; A. Tow

1. Introduction

Mechanical properties of random carbon composites produced by directed fibre preforming (DFP) are heavily influenced by size and scale effects [1]. Large filament counts (24K+) create high variations in local properties (particularly for thin laminates) and filament end synchronisation causes local weak points. Uniform fibre coverage and smaller bundle sizes are therefore desirable. There is an increased tendency for the tow to filamentise into smaller bundles of filaments for shorter chop lengths. This intrinsic splitting is influenced by the fibre surface treatment [1] and processing conditions [2,3], and inherently reduces the areal density variation associated with high filament count tows.

Primarily, this paper investigates the effect of fibre length on the tensile properties of directed carbon fibre preforms (DCFP). It also aims to determine the relationship between level of filamentisation and mechanical properties and to understand the physical effects. Filamentisation improves coverage for thin laminates, both in terms of areal density and fibre angle variation, potentially enabling inexpensive, high filament count tows to be used. However, there are associated disadvantages: Preform loft can increase by up to 650%, which is problematic for handling and cutting. Smaller tows also reduce preform permeability, which lengthens injection time. This involves controlling filamentisation to ensure that the virgin tow is split in a regular manner to avoid the occurrence of single filaments, which improves fibre packing efficiency and thereby reduces preform loft.

A review of analytical stiffness and strength models is presented and selected models are applied using a multi-level approach to account for the meso-scale fibre architecture.

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The shear-lag model [4] and an adaptation of the inclusion model [5] are compared against experimental stiffness results. A critical tow length model is presented for improving strength predictions which rely on slip-theory and is applied using an analytical model by van Hattum and Bernado [6] and a stochastic model by Wetherhold [7–9] using estimated bundle sizes.

2. Fibre length effects

Random orientations and finite fibre lengths complicate the prediction of discontinuous fibre composite properties. An earlier study considered the simplest of random fibre architectures [1] as a platform for the development of more comprehensive physical models. This paper aims to establish fibre length influences on the mechanical properties.

Fibre length effects were anticipated in two areas; critical fibre length effects and coverage effects. The first category is a universal consideration of discontinuous composites and has been widely discussed [4,10]. Maximum utilisation of the fibre properties only occurs beyond a critical length, at the transition from fibre pull-out to fibre breakage. The second is stochastic, where shorter fibres give greater macroscopic homogeneity of both areal density and fibre orientation distribution for a finite area. Both effects must be considered at the tow level rather than the filament level, as the tow cross-section is on the same scale as the thickness of the laminate.

2.1. Random fibre stiffness prediction

Cox [4] pioneered the prediction of fibre length effects on modulus by realising the significance of the fibre–matrix interface for stress transfer in discontinuous fibre composites. *Shear-lag analysis* assumes that the fibre ends do not carry any load and therefore the reinforcing efficiency of the fibre increases as fibre length increases, since a greater proportion of the fibre length is loaded. This analytical solution is often incorporated as an efficiency factor in a modified Rule of Mixtures (ROM) equation. A critical fibre aspect ratio (length/diameter) of 600 typically exists for a carbon/epoxy system [11], below which the modulus of the composite is reduced. Thus, a critical tow length also exists [11–13] since synchronised filaments within tows are analogous to large, single fibres [14,15]. Short fibres are attractive for DCFP as they inherently reduce the coverage issues associated with processing large filament count tows [1]. However, it is important to ensure that the critical bundle length is exceeded when processing discontinuous fibres.

A limitation of the shear-lag model is the assumption that no tensile load is transferred between the fibres ends. Previous studies suggest strains of up to 0.5% are present at the fibre ends when $E_f/E_m = 16$ [16]. However, when axial loads were introduced into the matrix in [17], it was evident that the end effects were negligible as E_f/E_m tends to 100 (as is the case for carbon/epoxy).

The effect of fibre aspect ratio has been investigated using micro-mechanical approaches in conjunction with classical laminate theory (CLT) [18–21]. The concentric cylinders assemblage (CCA) [22] was introduced in [1] to predict theoretical, unidirectional (UD) ply properties. Although exact [23], the CCA is only applicable to discontinuous fibre materials with high aspect ratios, (i.e. at the filament level). Variants of the Halpin–Tsai [24–26] and Mori–Tanaka [27] methods are the most common micromechanical approaches for discontinuous fibre composites. Based on the dilute particulate method of Eshelby [28], the Mori–Tanaka [27] model not only considers the stress and strain fields around and within each inclusion, but more importantly accounts for changes in these fields due to fibre interactions at higher volume fractions (>5%). Closed-form equations have been derived for the elastic constants of discontinuous UD composites [29,30]. The model is accurate at low ($V_f < 0.3$) and at extremely high volume fractions ($V_f \to 1$), but the values at intermediate V_f are the result of a mathematical fit and are physically unrealistic. This is confirmed by comparisons of the shear modulus for continuous fibres [31], which show that the model diverges from the physical result beyond the dilute case. Despite this, the simple closed form of the Mori–Tanaka method is still applicable to discontinuous fibre composites [23] and comparisons with finite element models [32,33] show that the Mori–Tanaka method is superior to the shear-lag theory and Halpin–Tsai for aligned short fibres. The closed-form expressions have been reformulated by Qiu and Weng [5,34] to include the effects of anisotropic constituents, such as carbon fibre. A comparison is made in the results section of this paper to show the influence of fibre anisotropy and fibre aspect ratio on the mechanical properties for aligned, discontinuous fibre materials.

Variations in fibre length are encountered not only due to processing inconsistencies but also due to a length-dependent critical fibre volume fraction [35]. Increasing fibre-to-fibre contact beyond a critical point causes fibre breakage and consequently a reduction in mechanical properties. Established analytical models have been developed further [19,36] to study the effect of fibre length distributions (FLD) on the tensile stiffness. Comparisons with experimental data and finite element models [33] show that the mean fibre length is sufficient to model length effects, providing the modal length is close to the mean value [37]. The chop length variability for the studied DCFP process follows a normal distribution and hence, the number-average length is representative (for a target length of 38.3 mm the coefficient of variation (COV) was 0.6%).

2.2. Random fibre strength prediction

Unlike stiffness, the strength of a discontinuous fibre will never attain the strength of a continuous fibre because of the stress concentrations introduced at the fibre ends. The length at which a plateau in strength occurs may be up to 5–10 times longer than the corresponding critical length