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Global load-sharing model for unidirectional hybrid fibre-reinforced composites

Yentl Swolfs [a,*], R.M. McMeeking [b,c,d], V.P. Rajan [c], F.W. Zok [c], Ignaas Verpoest [a], Larissa Gorbatikh [a]

[a] Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44 bus 2450, Belgium
[b] Department of Mechanical Engineering, University of California, Santa Barbara, CA 93106, USA
[c] Materials Department, University of California, Santa Barbara, CA 93106, USA
[d] School of Engineering, University of Aberdeen, King's College, Aberdeen AB24 3UE, Scotland, UK

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ABSTRACT

A promising strategy to increase the tensile failure strain of carbon fibre-reinforced composites is to hybridise carbon fibres with other, higher-elongation fibres. The resulting increase in failure strain is known as the hybrid effect. In the present article, a global load-sharing model for hybrid composites is developed and used to carry out a parametric study for carbon/glass hybrids. Hybrid effects of up to 15% increase in failure strain are predicted, corresponding reasonably well to literature data. Scatter in the carbon fibre strength is shown to be crucial for the hybrid effect, while the scatter in glass fibre strength is much less important. In contrast to reports in earlier literature, the ratio of failure strains of the two fibres has only a small influence on the hybrid effect. The results provide guidelines for designing optimal hybrid composites.

1. Introduction

Carbon fibre-reinforced polymer matrix composites combine excellent mechanical properties with low density, making them a popular choice for lightweight, high-performance applications (Verpoest et al., 2014). Among their main limitations are their low tensile failure strain (only about 2%) and their high cost. Higher failure strains can be obtained with the use of polymer fibres (Swolfs et al., 2013a, 2014c, 2014d) or metal fibres (Callens et al., 2014), but these changes are accompanied by reductions in stiffness and strength and/or an increase in density.

An alternative solution is to employ hybridisation, wherein two fibre types are combined in a single composite. By hybridising, the drawbacks of one fibre can be balanced out by the virtues of the other (Hine et al., 2014; Swolfs et al., 2014a). The most common combination is carbon and glass: carbon being the low-elongation fibre (LE) and glass the high-elongation (HE) fibre. This hybrid composite maintains good mechanical performance but dramatically reduces the cost compared to an all-carbon fibre-reinforced composite. Furthermore, some hybrid composites are known to exhibit synergistic effects whereby their properties exceed those expected based on considerations of rules-of-mixtures (Czél and

Abbreviations: ; GLS, global load-sharing; CF, carbon fibre; GF, glass fibre; HE, high elongation; LE, low elongation

* Corresponding author.
E-mail addresses: yentl.swolfs@mtm.kuleuven.be (Y. Swolfs), rmcm@engineering.ucsb.edu (R.M. McMeeking), varun.p.rajan@gmail.com (V.P. Rajan), zok@engineering.ucsb.edu (F.W. Zok), ignaas.verpoest@mtm.kuleuven.be (I. Verpoest), larissa.gorbatikh@mtm.kuleuven.be (L. Gorbatikh).

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Wisnom, 2013; Diao et al., 2012; Kretsis, 1987; Manders and Bader, 1981; Peijs et al., 1990; Perry and Adams, 1975; Swolfs et al., 2014b; Taketa et al., 2010; You et al., 2007). This is referred to as the hybrid effect.

Hayashi (1972) is credited with the discovery of the hybrid effect. Hayashi found that the failure strain of an all-carbon fibre composite could be increased by 40% by sandwiching the carbon fibre layers between glass fibre layers. Despite some confusion among early researchers, as documented by Phillips (1976), the hybrid effect in regard to initial failure strain is now well established. Three main causes quoted for the hybrid effect are (1) residual thermal stresses, (2) fracture propagation effects, and (3) dynamic stress concentrations (Swolfs et al., 2014b).

Residual stresses are caused by differences in thermal expansion coefficients of the two fibre types. They arise upon cooling following curing of a thermosetting resin or solidification of a thermoplastic resin. They lead to residual axial compressive stresses in the carbon fibres, which counteract the applied stresses and lead to an apparent failure strain enhancement (Manders and Bader, 1981). Using representative thermal expansion coefficients and longitudinal Young's moduli, the magnitude of this hybrid effect can be shown to be small for carbon/glass hybrid composites.

The second cause, the fracture propagation effect, is based on the way unidirectional composites fail. Being brittle, fibres do not have a deterministic strength, but rather have strengths that follow weakest link fracture statistics. When a fibre breaks in a composite, the surrounding matrix is loaded in shear. The matrix transfers stress to the intact segment of the broken fibre through shear lag. Simultaneously, the shear in the matrix transfers load shed by the broken fibre onto those surrounding it. The resulting stress concentrations in surrounding fibres increase their failure probability (Behzadi et al., 2009; Nedele and Wisnom, 1994; Swolfs et al., 2013b) and eventually leads to the development of clusters of spatially-correlated broken fibres (Pimenta and Pinho, 2013; Scott et al., 2012; Swolfs et al., 2015b, 2015d). Once a cluster reaches a critical size, additional fibre fracture occurs unstably and the composite ruptures.

Hybridisation can influence the fibre failure process in several ways. Firstly, stress concentrations and stress recovery at a broken fibre are altered by the presence of neighbouring fibres with different stiffness (Swolfs et al., 2013c; Zweben, 1977). Because of the dynamic nature of fibre fracture, changes in the local elastic moduli also alter the propagation of the resulting stress waves (Xing et al., 1981). Secondly, if the two fibre types are dispersed uniformly, the development of a critical cluster of the LE fibres may be delayed by the presence of the neighbouring HE fibres (Harlow, 1983). Finally, a point often overlooked, scaling effects also play a role. For a constant sample size, the number of LE fibres is reduced by hybridisation. A composite with fewer LE fibres has a higher probability of reaching high strengths. The magnitude of this effect is presently not known.

Dynamic stress concentrations (Xing et al., 1981) and thermal stresses (Manders and Bader, 1981) have been judged to be insufficient to rationalise the reported magnitudes of the hybrid effects (typically 10–50%) (Kretsis, 1987). Therefore, it is generally assumed that the fracture propagation effect is the dominant cause.

Many authors have attempted to model hybrid composites (Dai and Mishnaevsky, 2014; Fukuda, 1984; Fukunaga et al., 1984; Swolfs et al., 2015a; Zeng, 1994; Zweben, 1977) Several of the influencing parameters have been analysed, but the conclusions are not always straightforward to interpret. Zweben (1977) indicated that the ratio of the failure strain for the two fibre types is a critical parameter controlling the hybrid effect, while Fukuda (1984) later showed that this does not influence the hybrid effect. This apparent disagreement, however, was based on differing definitions of the hybrid effect.

Fukunaga et al. (1984) demonstrated that the hybrid effect is equal to zero if the LE fibres have a deterministic strength. From a theoretical viewpoint, it can indeed be deduced that in this situation the fracture propagation effect vanishes. However, the converse effect – a potential change in failure strain due to high scatter in the strengths of the HE fibres – has not been proven or demonstrated.

Models of fibre fragmentation and bundle rupture for composites with a single fibre population are well established. A useful baseline of results is obtained by assuming that stress re-distribution around fibre breaks follows global load-sharing (GLS). This approach assumes that the load shed by a broken fibre is distributed uniformly over all unbroken fibres in the plane of the break (Curtin, 1991a, 1991b). Under these conditions, the fibres break independently of one another. Although such models normally neglect the axial stress borne by the matrix, the matrix contribution can be added to the bundle response in a straightforward manner.

Curtin was the first to develop an approximate analysis of the stress–strain response of a fragmenting bundle. Assuming that the fibre strength follows a Weibull distribution and using a Taylor series expansion to approximate the Weibull function, Curtin obtained useful analytic solutions for the stress–strain curve as well as the strength and failure strain. Curtin's model was later extended by Neumeister to account in an approximate way for the overlap of influence zones adjacent to fibre breaks (Neumeister, 1993a, 1993b). Hui et al. (1995) subsequently developed an exact solution to the fibre fragmentation problem.

The principal objective of the present article is to develop a GLS framework for predicting tensile failure of hybrid composites, based on Hui's exact fibre fragmentation solution (Hui et al., 1995). A parametric study is conducted on a family of hybrid composites comprising carbon and glass fibres in an epoxy matrix. The framework presented here could be readily adapted to other fibre combinations. Some of the limitations of the GLS approach are discussed in due course.