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Effects of defects on the tensile strength of short-fibre composite materials

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ABSTRACT

Heterogeneous materials tend to fail at the weakest cross-section, where the presence of microstructural heterogeneities or defects controls the tensile strength. Short-fibre composites are an example of heterogeneous materials, where unwanted fibre agglomerates are likely to initiate tensile failure. In this study, the dimensions and orientation of fibre agglomerates have been analysed from three-dimensional images obtained by X-ray microtomography. The geometry of the specific agglomerate responsible for failure initiation has been identified and correlated with the strength. At the plane of fracture, a defect in the form of a large fibre agglomerate was almost inevitably found. These new experimental findings highlight a problem of some existing strength criteria, which are principally based on a rule of mixture of the strengths of constituent phases, and not on the weakest link. Only a weak correlation was found between stress concentration induced by the critical agglomerate and the strength. A strong correlation was however found between the stress intensity and the strength, which underlines the importance of the size of largest defects in formulation of improved failure criteria for short-fibre composites. The increased use of three-dimensional imaging will facilitate the quantification of dimensions of the critical flaws.

1. Introduction

The micromechanical models used to predict tensile strength of short-fibre composite materials, e.g. the Fukuda–Chou model (1982) or the Cox model (1952), have been inspired by micromechanical models for elastic properties, where the composite stiffness is determined from stiffness contributions of the constituents and effects of fibre orientation, fibre content and fibre length. These models may have surprisingly good predictive capabilities (Andersons and Joffe, 2011; Andersons et al., 2011; Virk et al., 2012) although mechanism-based criterion would be preferable, relying on the dimensions and properties of the most severe flaw initiating ultimate failure. With the advent and increased use of three-dimensional imaging techniques, most notably microfocus X-ray computed tomography, it is becoming easier to quantify these parameters (Buffière et al., 1999; Molnár and Bojtár, 2012). The present study is an attempt to investigate the correlation between composite strength and the physical features of the failure instigating flaw in an important class of brittle heterogeneous materials, namely short-fibre composites.

Although no previous studies have been found on the effects of critical flaws in the specific form of fibre agglomerates on strength, there are several studies on the relation

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between voids and strength among other mechanical properties of materials (Harper et al., 1987; Huang, 2004; Liu et al., 2006). The general consensus is that it is the most severe flaw or imperfection in the material that gives rise to brittle tensile failure. This is typically evidenced by fractography, where the examination of fracture surfaces by scanning electron microscopy can be traced back to the critical flaw that initiated crack growth leading to final failure (Greenhalgh, 1993; Hull, 1999). X-ray computed tomography (XμCT) provides a useful non-destructive technique to quantify the microstructure of materials, not only on the fracture surface, but also in three-dimensions inside the material. To this end, XμCT has already been used to measure crack growth and pores in concrete material under compressive loading (see e.g. Landis and Keane, 1999; Landis et al., 2003). For fibre composite materials, XμCT has for instance been used to quantify internal damage (Schilling et al., 2005) and to observe crack opening due to tensile loading (Moffat et al., 2008).

In the present study, the samples were scanned before and after mechanical testing, allowing to identify the specific microstructural features that caused the failure. A short-fibre composite was chosen as model for a heterogeneous material, whose microstructure can be characterized by XμCT. Wood fibres were dispersed in a polylactide (PLA) matrix, forming a renewable composite material suitable for packaging applications. The cellulosic fibres tend to agglomerate in the injection-moulding process (Chinga-Carrasco et al., 2012), and thus form natural defects which could be related to the macroscopic strength.

In the following, the modelling approach is presented. Two strength models are outlined: (i) one accounting for the stress concentration factor caused by the largest detected flaw, (ii) one based on a fracture mechanics approach, where the size of the largest flaw is considered. Both of these models account the largest defect, in contrast to rule-of-mixture based criteria. The stress concentration factor approach accounts for the shape of the largest defect, and the stress intensity factor approach accounts also for the size of the largest defect. Thereafter, experimental details are presented, followed by the results and comparison of the correlation between the experimental results and the two models. Finally, some concluding remarks are given concerning developments of mechanism based models for strength predictions of heterogeneous composite materials.

2. Stress analysis

2.1. Assumptions

For the present model material, scanning electron microscopy revealed that the fibres were agglomerated into clusters of roughly ellipsoidal shape. Thus, three-dimensional general ellipsoids were considered versatile enough to describe the shape of the agglomerates for modelling purposes. Although it is a major idealization that the fibre agglomerates take an ellipsoidal shape with regard to the surrounding stress field, some hypothesis has to be made in order to make a quantitative analysis possible. We argue that this assumption is acceptable, since the aim at this stage is only to compare stress concentration effects with size-dependent stress-intensity effects on strength. Furthermore, the mechanical behaviour of the material is assumed to be elastic, since the macroscopic tensile behaviour was observed to be linearly elastic. Furthermore, the material was observed to fail in a brittle manner.

Fractographic studies of the material and other similar wood-fibre composites (Chinga-Carrasco et al., 2010), have shown that fibre agglomerates easily debond from the surrounding thermoplastic matrix. Oksman et al. (2009) noticed that the strength of cellulose fibre composites was unaffected by the type of fibre when the fibre–matrix interface is poor, as is commonly the case for melt-processed cellulose fibre reinforced thermoplastics. Nyström et al. (2007) showed that the aspect ratio, i.e. the shape of the reinforcing units, had a large impact on composite strength, whereas the strength of the reinforcement has negligible influence on the measured strength for cellulose-fibre composites. Again, this was linked to poor adhesion and interfacial stress transfer. No residual resin was found on the fibre surfaces as would be expected in cohesive failure with a stronger interfacial bond. At the instance of failure, it is assumed that the largest agglomerate is completely debonded from the matrix, and that the agglomerate does not carry any load. Even if the fibre agglomerates would be bonded to the matrix, the stiffness of the fibre in the transverse direction is much inferior to typical polymer matrix systems (Bergander and Salmén, 2000; Joffre et al., 2014). If effects of lumen and other voids are taken into account, the transverse stiffness of the fibre agglomerates would be even lower.

Since the agglomerates tend to debond from the matrix and have relatively low transverse stiffness, they are regarded as ellipsoidal cavities. Thus the stiffness of the ellipsoidal inclusions is effectively set to zero. The dimensions, distributions, and orientation of defects inside the material have been characterized by XμCT. Since it is a non-destructive technique, the samples have been scanned before and after tensile testing. The three-dimensional images obtained have been used to identify the specific agglomerate responsible for the failure of the sample during mechanical loading.

The first step is to estimate the stress state around the ellipsoidal cavity surrounded by a resin rich region. Accurate analytical solutions exist for the stress state around an inclusion in an infinite matrix (Mura, 1987). The stress perturbation with regard to the far-field applied stress in the composite is different from the one caused by inclusion in the hypothetical infinite matrix. If we assume that the agglomerate is embedded in a matrix surrounded by the composite material, the strain continuity at the matrix/composite interface gives a relationship between the far-field applied stress in the composite case, σ_{ij}^{∞}, and the fictitious applied stress in the infinite matrix case, σ_{ij}^{0},

$$S_{ijkl}^{c}\sigma_{kl}^{\infty} = S_{ijkl}^{m}\sigma_{kl}^{0} \quad (1)$$

where S_{ijkl}^{c} and S_{ijkl}^{m} are the compliance tensors of the composite and matrix, respectively. By multiplication with the