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Review

A review of input data and modelling assumptions in longitudinal strength models for unidirectional fibre-reinforced composites

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A B S T R A C T

Fibre-reinforced composites are rapidly increasing their market share in structural applications. Nevertheless, this increase would be much stronger if reliable failure predictions were available. These predictions are not only insufficiently reliable for complex loading of multidirectional composites, but even for longitudinal tensile failure of unidirectional (UD) composites. Since composite failure usually coincides with longitudinal failure of a 0° ply, the reliability often hinges on longitudinal failure predictions of UD composites. Despite great progress in the state-of-the-art models, significant obstacles remain in collecting the necessary input data and understanding the influence of the modelling assumptions. This review therefore surveys the mechanics, chemistry and physics involved in tensile failure of UD composites and highlights potential areas for improvement. Specific proposals are made to advance the state-of-the-art strength models, which could catalyse the use of composites in structural applications.

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1. Introduction

Predictive models for mechanical properties are crucial for designing composite applications in an optimal manner. Even though some stiffness variations are unavoidable in real parts [1], predictions of composite stiffness are often used with confidence in industrial applications. Predictions of strength and damage development, however, remain highly challenging. The World Wide Failure Exercise I, II and III therefore attempted to predict failure of multidirectional composites under complex loading conditions [2–4]. A large spread on the modelling predictions was found, indicating the reason for the lack of confidence of industry in models. The large spread was attributed to the complex internal structure of fibre-reinforced composites and complex interactions between fibre and matrix.

The longitudinal tensile failure and damage development in 0° unidirectional (UD) composites is better understood. It is also crucial in the failure of multidirectional composites, as final failure usually coincides with failure of the 0° plies. A key concept in longitudinal tensile failure of UD composites is that the fibres in a bundle do not all possess exactly the same strength. Instead, the strength of these fibres typically follows a Weibull distribution [5]. This fibre strength variation is crucial in the longitudinal tensile failure development of UD composites. Upon increasing the applied strain, the weakest fibres fail first. Each broken fibre locally stops carrying load and sheds that load to the nearby fibres. The matrix surrounding the fibre break is loaded in shear and transfers stress back onto the broken fibre [6–10]. Therefore, the nearby fibres will locally carry stress concentrations, but the magnitude decreases with increasing distance from the fibre break [11–16].

A vital consequence of these stress concentrations is that they increase the failure probability of the nearby fibres. Eventually, this increased failure probability will lead to the development of fibre break clusters [17–20], which further intensify the stress concentrations. One of these clusters will reach a certain critical size, after which this cluster propagate unstably. This unstable propagation will rapidly cover the entire cross-section of the composite and hence cause final composite failure. Apart from fibre strength, the stress redistribution around fibre breaks is also a crucial parameter in the failure development of UD composites. For a given fibre type, this redistribution is governed by properties of the matrix and the fibre–matrix interface. The magnitude of the stress concentrations and the length over which they are significant is crucial in determining failure of a UD composite. Correctly capturing the fibre strength statistics and stress redistribution around a broken fibre is therefore crucial to the success of strength models for UD composites. If this is combined with the appropriate input data, then a good correlation with experiments should be achievable. There are however significant experimental and theoretical difficulties in obtaining reliable input data for both aspects. This review aims to provide guidelines on how these input parameters should be measured and in which cases they are important. It will also propose strategies to overcome these difficulties in the future.

Even in the ideal scenario that the fibre, matrix and interfacial properties are measured accurately, deviations from experimental measurements may still occur. Every state-of-the-art strength model inevitably requires a set of assumptions that limit its accuracy. The Section 3 hence provides an overview of the most important and common assumptions in strength models for UD composites. Guidelines are provided on the importance of the various assumptions whenever the literature offers sufficient information to do so.

The focus of this review is on the input data and the modelling assumptions. The goal is to describe both aspects in a generic way that is largely independent of the chosen modelling approach. Describing the models themselves is therefore outside the scope of this review, as doing this in a comprehensive manner would be nearly impossible.

Depending on the nature of the model, many different outputs can be obtained. The literature has focused mainly on the tensile strength of the composite. Recently however, the availability of synchrotron radiation computed tomography has sparked the interest in tracking individual fibre breaks and clusters of fibre breaks [17–25]. Whenever this review mentions the word predictions, it refers either to tensile strength predictions or to a combination of tensile strength and fibre break predictions. Specific references to fibre break predictions will always be explicitly indicated.

The majority of the cited studies deal with carbon fibres in a thermoset matrix. This was not a deliberate choice, but occurred nonetheless for two reasons. Firstly, there is a large body of knowledge on carbon fibres and its composites. Secondly, the higher performance of thermoset carbon fibre composites has sparked a larger interest in predictive models than for thermoset composites with other fibres. Metal and ceramic matrix composites can also reach high performance levels, but they are not used in tensile loading as often as thermoset carbon fibre composites. Consequently, the majority of the literature on input data measurements and models focused on carbon fibre and its composites. Nevertheless, there are important aspects to be learned from other fibres as well as from other research fields. This review therefore also looks at studies on other fibre types and from other fields. This is especially true for Section 2.1, as there is a great body of knowledge on the strength of ceramic fibres such as SiC fibres.

2. Input data

Predictions of any model depend strongly on the input data. This is even more so in strength models for UD composites, which are often dominated by the fibre strength parameters. The matrix and interfacial properties also play an important role, as they will determine the magnitude and extent of the stress concentrations. Many different types of properties can be plugged into strength models, making it crucial to understand the importance of each of them. This section reviews the most recent insights into the two most crucial input data: fibre strength and the matrix/interfacial properties.