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Micromechanics based elasto-visco-plastic response of long fibre composites using functionally graded interphases at quasi-static and moderate strain rates

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ABSTRACT

A unit cell model is developed to capture the elasto-visco-plastic response of a long fibre composite using a 3-dimensional finite element model. Using a glass rubber model, the elasto-visco-plastic response of the matrix is analysed and the fibre is considered to deform elastically. A functionally graded interphase zone is defined in the region surrounding and encompassing a reinforcing fibre. The model subdivides the interphase zone into an infinite number of concentric rings where stress and strain compatibility is preserved. This model aims to improve on the computational efficiency of micromechanics models where the fibre and matrix are modeled as separate materials. The mechanics of the fibre deformation are governed by a transformation tensor for transversely isotropic materials based on Eshelby's method. The model is calibrated using experimental data for the transverse compression of a unidirectional composite; it is then validated using axial compression and shear data for quasi static strain rates. For moderate strain rate the model is also calibrated for one of the transverse strain rates then validated using the other strain rates and axial compression. The proposed unit cell model is capable of predicting the elasto-visco-plastic response of long fibre composites to a very high accuracy.

1. Introduction

For adaptation of composite materials within automotive structures, accurate modelling techniques are required to predict the material response. Sabiston et al. have developed a micromechanics model accounting for the elastic response of long fibre composite materials combining the properties of the fibre and matrix to find the overall elastic material response [1]. In order to accurately model the response of composite automotive structures the strain rate effects must be accounted for in the model. The capabilities of using composite materials in automotive structural components have been shown by Refs. [2–4]. Modelling of composite crush structures have been developed for the specific case of axial crush members [5,6]. A generalized approach to modelling the strain rate dependent response of composite materials is required to accurately model materials for the automotive design process.

The micro-mechanical behaviour of composites has been developed in detail by Aboudi [7] who also performed early work on the development of micro mechanics based failure of composite [8,9]. Recently cohesive models have been used at the micro scale to model debonding of composites resulting in the prediction of the macroscopic stress strain response [10–13]. Using this technique the fibre and matrix are modeled as separate distinct materials with finite element meshes for each material. An interface based approach has been recently used by Krause to model damage evolution in fatigue loading [14]. Using cohesive elements to model the interface between the fibre and matrix and multi element micromechanics models presents several drawbacks; they are computationally expensive and the interface properties are geometry dependant, as shown in Ref. [1]. A surface-based cohesive contact approach has also been used to predict delamination and debonding in a carbon fibre reinforced plastics to create the overall

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material response, the computational inefficiency of using cohesive elements is also discussed [15]. This approach is less computationally expensive than cohesive elements when used at the ply level. However, it remains expensive if used at the micro-level, because separate elements are still required to model the fibre and matrix. The boundary conditions applied to a micromechanics unit cell approach have been shown to have a large effect on the homogenized response of the material, limiting the predictive capabilities of some of these approaches [16–18].

Using an interphase within the region surrounding the fibre is another method of describing the load transfer between the fibre and matrix; this method was developed by Refs. [19–21], and has also been used by Refs. [22–24]. Functionally graded materials (FGMs) have properties such as elastic modulus and Poisson's ratio, which change as a function of position [25,26]. Using the concept of FGMs [27,28], Sabiston et al. developed a new unit cell model for the elastic response of long fibre composites under various loading conditions using a functionally graded interphase (FGI) [1]. Yang and Pitchumani experimentally showed that, a FGI exists in the region surrounding the fibre [29]. This has also been shown by Li et al. [30]; and Karger-Kocsis et al. highlights advancements in interphases and particularly the experimental validation of FGI [31].

The strain rate dependence of polymer matrix composite materials has been shown in Refs. [32–35]. Modelling of the strain rate dependence of composites has been demonstrated by Park et al. but the model is not applicable to all loadings [36]. Karim and Hoo Fatt have proposed a phenomenological model for the strain rate dependence of composites but this model is only applicable to two dimensions [37]. Shokrieh et al. have developed a framework to model the strain rate dependence of unidirectional composites based off micromechanics, however this method does not directly account for the local load transfer and uses empirical approaches to modelling the strain rate dependence [38]. The leading factor to the strain rate dependence of composites are the material response of the polymer matrices [39]. The strain rate dependence of epoxy is shown in Ref. [40]. Modelling the elasto-visco-plastic response of polymers involves complex material models to capture the physical phenomena such as the models developed by Refs. [41–44].

In the current work, the method presented in Ref. [1] is expanded to capture the response of a long fibre composite in an elasto-visco-plastic regime. It is considered that, the fibre deforms elastically; the elasto-visco-plastic response of the polymer matrix is captured using a glass rubber constitutive model. The stress in the composite changes as a function of position within the interphase zone in a functionally graded manner. This allows the model to capture the non linear response of the constituents. New interphase functions are introduced to better describe the FGI. The new model is compared to experimental results to the point of material failure to validate for accuracy.

2. Functionally graded unit cell and mechanics

The unit cell framework including the FGI proposed by Sabiston et al. [1] is used in a micro scale model. A representative fibre is aligned with the x_1 axis of the unit cell. The faces of the unit cell are at one unit in each direction such that they can be mapped to any hexahedral. A three dimensional representation of the unit cell with the representative fibre is given in Fig. 1.

The interphase zone is a region surrounding the representative fibre and is described in cylindrical coordinates about the axis of the unit cell. The stress changes as a function of position in radial coordinates within the interphase zone. The interphase zone is defined using the material paring constants k and l to give the bounds of the interphase zone as

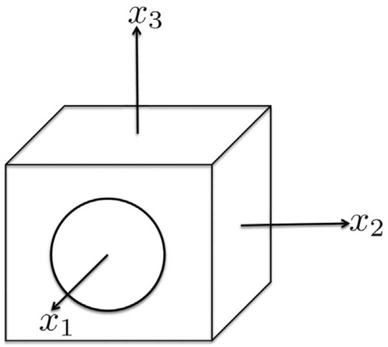

Fig. 1. Unit cell configuration with fibre in x_1 direction.

$$r_{is} = kr_f \; 0 < k < 1 \tag{1}$$

$$r_{if} = lr_f \; l \geq 1 \tag{2}$$

where r_{is} and r_{if} are the interphase start and interphase finish radii respectively. The radius of the representative fibre in the unit cell r_f is a function of the fibre volume fraction given by

$$r_f = \sqrt{\frac{4V_f}{\pi}} \tag{3}$$

where V_f is the volume fraction of fibres in the composite.

The model works by separating the deformation within the unit cell into three domains. The deformation of the fibre determined using Eshelby's approach [45], the deformation of the bulk matrix material and the deformation of the matrix material within the interphase zone. These three deformation fields are input to constitutive laws to determine the average stress of each of these regimes. As the stress within the interphase zone changes as a function of position it is desirable to represent the stress as a step function between the stress in the fibre and the stress in the matrix material within the interphase to define the three regions of deformation. The radius where this step occurs is known as the representative interface radius r_{im}, which falls in between r_{is} and r_{if} in the interphase zone. These radii and how the deformation is segregated within the unit cell is shown in Fig. 2, the different shaded regions represent the three deformation domains. The fibre deformation region is bounded by r_{im}, the matrix portion of the interphase occurs between r_{im} and r_{if} and the bulk matrix

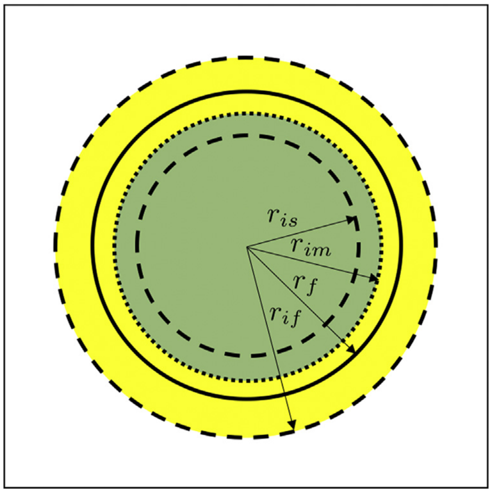

Fig. 2. Unit cell subdivision of the x_2, x_3 plane into the radii and deformation regions.