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An anisotropic non-linear material model for glass fibre reinforced plastics

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ABSTRACT

This paper aims to present a methodology to predict the anisotropic and non-linear behaviour of glass fibre reinforced plastics using finite element methods. A material model is implemented in order to remedy the need of multiple material definitions, and to control the local plastic behaviour as a function of the fibre orientation. Injection moulding simulations traditionally provide second order orientation tensors, which are considered together with a homogenization scheme to compute local material properties. However, in the present study, fourth order tensors are used in combination with traditional methods to provide more accurate material properties. The elastic and plastic response of the material model is optimized to fit experimental test data, until simulations and experiments overlap. The proposed material model can support design engineers in making more informed decisions, allowing them to create smarter products without the need of excessive safety factors, leading to reduced component weight and environmental impact.

1. Introduction

Glass fibre reinforced plastics (GFRP) are widely used in automotive, aerospace and naval industries. High specific strength, corrosion resistance and geometrical freedom due to the injection moulding process allow designers to reduce weight, cost and the environmental impact of load bearing components. The drawback is that fibre reinforced plastics show both non-linear and strong anisotropic material behaviour, which makes the in-use behaviour of components hard to predict. Fibre mass fractions of up to 65% can be found in commercial materials, where the fibres themselves have a high stiffness with linear mechanical response, whilst the polymeric matrix in which they are dispersed is predominantly non-linear.

The mechanical properties due to the combined effect of glass fibres within a polymeric matrix has been studied by several authors [1–4]. By manufacturing and examining samples containing a known alignment of fibres at varying angles relative to the load direction (off-axis tests), the Young's modulus has been shown to vary non-linearly with the fibre orientation. One such example is the U-shaped relationship found by Wang et al. which is illustrated in Fig. 1.

Analytical models for predicting the Young's modulus and ultimate tensile strength as a function of fibre orientation angle has been given by, e.g. [3,4].

However, under normal conditions, the injection moulding process creates a complex flow-induced fibre orientation which is a function of both flow direction, section thickness and velocity profile. Fibres will tend to align in parallel to the flow near mould walls throughout a cross section during filling, but cross-flow at the core and randomly in between [4,5]. During manufacturing, fibres are forced through the runner- and gating systems under high pressure, which can lead to fibre- damage and length reduction [6]. The microstructure of produced parts therefore contains a complex heterogeneous fibre distribution depending on both manufacturing process and part geometry, which results in highly anisotropic and locally varying material behaviour. For, e.g. automotive components, the mechanical response is also influenced by rate effects [7], temperature effects [8] and ageing due to water absorption from the surrounding atmosphere [9].

To predict the behaviour of fibre reinforced components using finite element (FE) methods, advanced constitutive models are required. Such models need to account for the fibre orientation variations due to the injection moulding process as well as the non-linear matrix behaviour in order to produce accurate predictions. These models often rely on complex multi-scale methods, laminate analogy approaches [10], or micromechanics based homogenization methods [11], in order to consider the effective material response due to the underlying and different composite phases. Tucker and Liang reviewed and evaluated a number of the available micromechanical models, and showed that Mori and Tanaka's approach [12] is the most accurate homogenization

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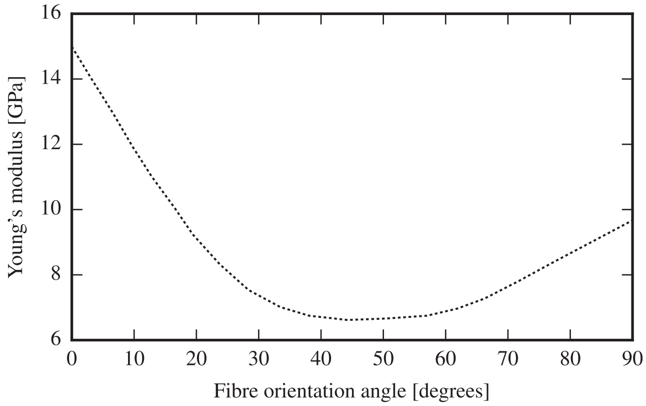

Fig. 1. Young's modulus versus fibre orientation for long glass fibre reinforced polymers with varying fibre alignments (0, 15, 30, 45, 60, 75, 90 degrees) as found experimentally by Wang et al. in [1].

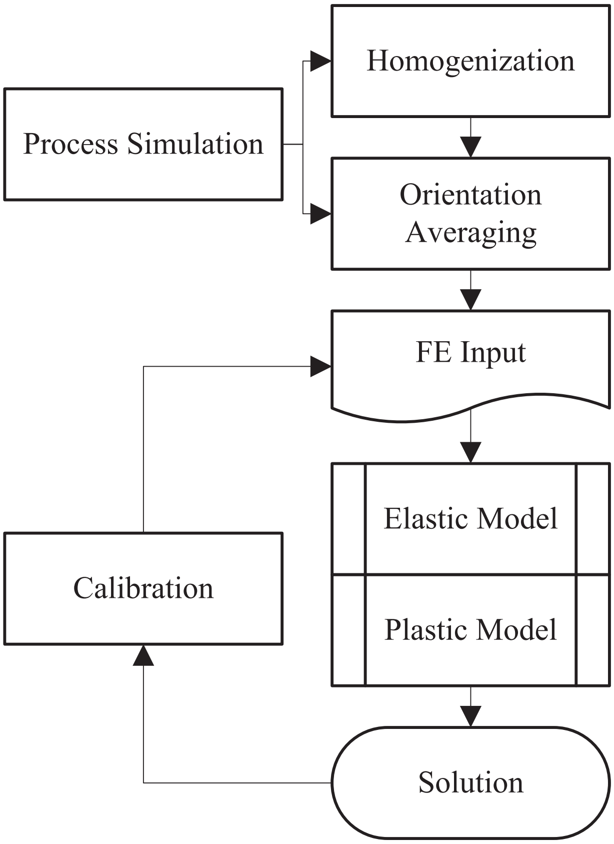

Fig. 2. Implementation flowchart. Process simulations are used as input for homogenization and orientation averaging. LS-DYNA™ subroutine-specific FE input is generated, and simulations are iterated until the response overlaps experimental results for off-axis tests. When optimization has been performed, the calibration step is removed from the process.

method when predicting the effective stiffness of short fibre reinforced polymers [13] with a fibre volume fraction of less than 30%. Several authors have since then applied homogenization schemes together with Advani and Tucker's orientation averaging method [14] to predict the anisotropic behaviour of composite materials [15,16] coupled with injection moulding simulations [17–21]. Due to the complex mechanisms behind the mechanical behaviour of fibre reinforced polymers, parameters governing plasticity and damage of such models are commonly found by optimizing the simulation response towards experimental stress–strain curves for known geometries and fibre orientations

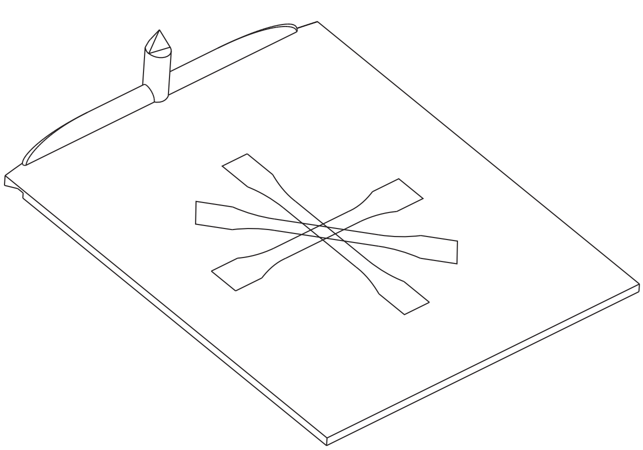

Fig. 3. Plate geometry optimized for extraction of tensile bars with aligned fibre direction, suitable for off-axis tensile tests.

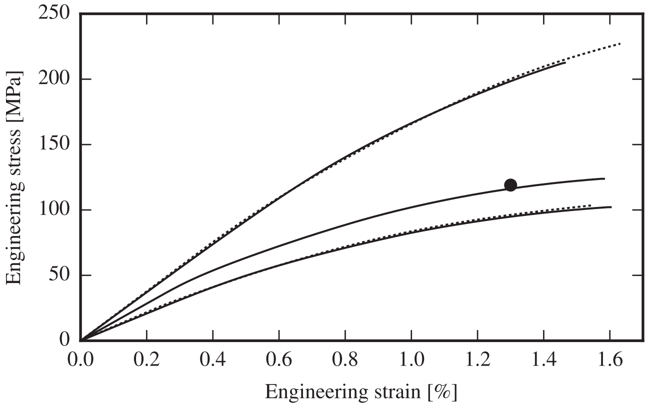

Fig. 4. Simulation model response (solid lines) for 0 (upper), 45 (middle) and 90 (lower) degrees fibre alignment with respect to the load direction, compared to experimental results (dotted lines) for 0 (upper) and 90 (lower) degrees fibre alignment. Simulation response target for 45 degrees was found by interpolation using Fig. 3 in [2] and is indicated with a dot.

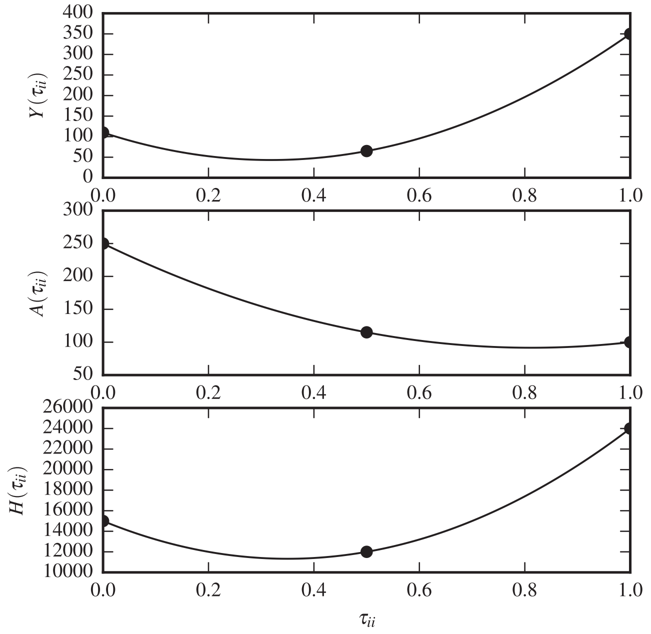

Fig. 5. Polynomials on Lagrangian form for fibre-orientation governed hardening behaviour, optimized for a material reinforced with 50% glass fibres, defined by three data points and experiments each.