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Numerical modelling of flax short fibre reinforced and flax fibre fabric reinforced polymer composites

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ABSTRACT

The ever-increasing demand of flax short fibre-reinforced and flax fibre fabric-reinforced polymer composites in various engineering applications calls for accurate predictions of their mechanical behaviors. In this study, numerical methods to generate and simulate mechanical properties of flax short fibre-reinforced and flax fibre fabric-reinforced polymer composites are proposed. The microstructures of short flax fibres with different fibre length-to-diameter ratios are generated by algorithm taking fiber defects (e.g. kink band) and fiber bundles into account. Bidirectional flax fabric is generated and discretized by tetrahedron 4-node finite elements. A brittle material law for fibre defects and interfacial zones of fibre bundles is proposed. Flax short fibre/polypropylene and flax fabric/epoxy composites are modeled by a non-linear plasticity model considering an isotropic hardening law and non-local continuum damage mechanics. The numerical modelling results are compared with the experimental results of these composites. This study shows that the simulation can capture the main damage mechanisms of the composites such as fibre breakage initiated at the fiber defects, damage of polymer matrix and the fibre debonding at fibre/matrix interface accurately. In addition, the simulation results exhibit good agreements with the experimental results in the aspects of elastic properties and nonlinear tensile stress-strain behavior of the short fibre and fibre fabric reinforced polymer composites.

1. Introduction

Because of an increasing environmental concern, it is urgent for the development of light-weight, cost-effective and sustainable materials as alternatives to conventional materials. In recent years, the use of bio-fibres to replace glass fibres as reinforcement materials in polymer composites has gained popularity for various engineering applications [1–8]. Natural fibres are widely available in most countries and are cost-effective with low density. They are biodegradable, renewable, non-hazardous and non-abrasive. In addition, their specific mechanical properties are comparable to those of synthetic glass fibres used as reinforcement materials [9–12]. Among all the natural fibres, flax fibre offers the best potential combination of low cost, light weight, and high strength and stiffness for structural application [3,11,13,14], which is a promising alternative to glass fibre in engineering applications, such as civil [8,15–21] and automotive [22–25]. Most recently, flax fibres are also used with other fibres in hybrid structures for different engineering applications. The studies on hybridization of flax fibres with basalt [46], carbon [47] and glass fibres [48–51] show promising structural performance of flax fibre reinforced polymer composites in the aspects of durability, mechanical properties and fire performance. To better utilize natural fibre reinforced polymer composites (i.e. flax) in engineering fields, a full understanding the knowledge of the mechanical properties of their composites will be necessity, which can be achieved with a help of computer simulation [26]. The use of numerical simulation can create different components using such materials in shorter time and less expensive, if appropriate numerical models can be created. Since the natural fibres (i.e. flax) are embedded in the polymer matrix in their composites, it is quite difficult to measure the crack initiation and propagation, damage development and failure mechanisms by experimental studies on a micro-scale level, thus,

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the use of simulation tool will be helpful to determine the progressive failure of the composites [27].

Flax short fibre is one of the most commonly used configurations in polymer composites. Flax short fibre reinforced polymer composites made by extrusion, resin transfer and injection molding techniques have become popular in automotive industry for different components mainly because of their light-weight, excellent energy absorbing properties, sustainability and low costs [13,14]. For example, flax fibre reinforced polypropylene (PP) composites were produced by injection molding using short flax fibers with length up to 25 mm and average diameter about 30 μm [13]. Tensile tests show that the failure mechanisms of short flax/PP composites on micro-scale are fiber breakage, fibre debonding, matrix cracking and split of fiber bundles [28–30]. Semi-analytical approach with orientation averaging technique has been used to numerically model the mechanical properties flax fibers and their short fibre reinforced composites [31]. In this method, it was necessary to create a unit-cell single fiber finite element model. Then, the result of single fiber model was used to obtain the mechanical behavior of multi-fiber model by orientation averaging technique. This technique did not include the effects such as split of fiber bundles, fibre interlocking, fibre defects and multi-axial stress state in the modeling program. To have a more accurate modelling result, indeed, it is important to take the randomness in microstructure and the actual geometry with defects of the fibres into account. In the work done by Mattrand et al. [32], the randomness of flax fibre cross section was modeled by randomized version of the Fourier expansion of its complex coordinate function. In addition, two fibre interface models were developed by using cohesive zone elements. However, the model [33] was very computationally intensive and worked fine only on few fibre models, which cannot represent the actual stochastic microstructure of flax fibre reinforced polymer composite. Moreover, for short flax fibre reinforced polymer composites produced injection molding, the fibre orientation is governed by flow direction, which does not form a periodic microstructure. Thus, appropriate constitutive models for flax fibre, interface zones, fibre bundles and matrix were not well documented in the literature.

Flax fabric is another configuration which is widely used in polymer composites because the woven fabric allows the control of fibre orientation and quality control, good reproducibility and high productivity [34]. For flax fabric reinforced polymer composites, several numerical modeling studies can be found in the literature, e.g. Refs. [35,36]. Liang et al. [35] modelled the tensile properties of unidirectional flax fabric reinforced laminates. Poilâne et al. [36] modelled the viscoelastic behavior of unidirectional flax fabric polymer composite successfully. In addition, the simulation of vibration damping of multi-layer flax-carbon composite in the frame of plate theory was also documented by Assarar et al. [37]. Flax fibres and PP or epoxy matrix have highly nonlinear material behavior. Even for small strains the experimental results show a nonlinear stress-strain curve [30]. In despite of many attempts to

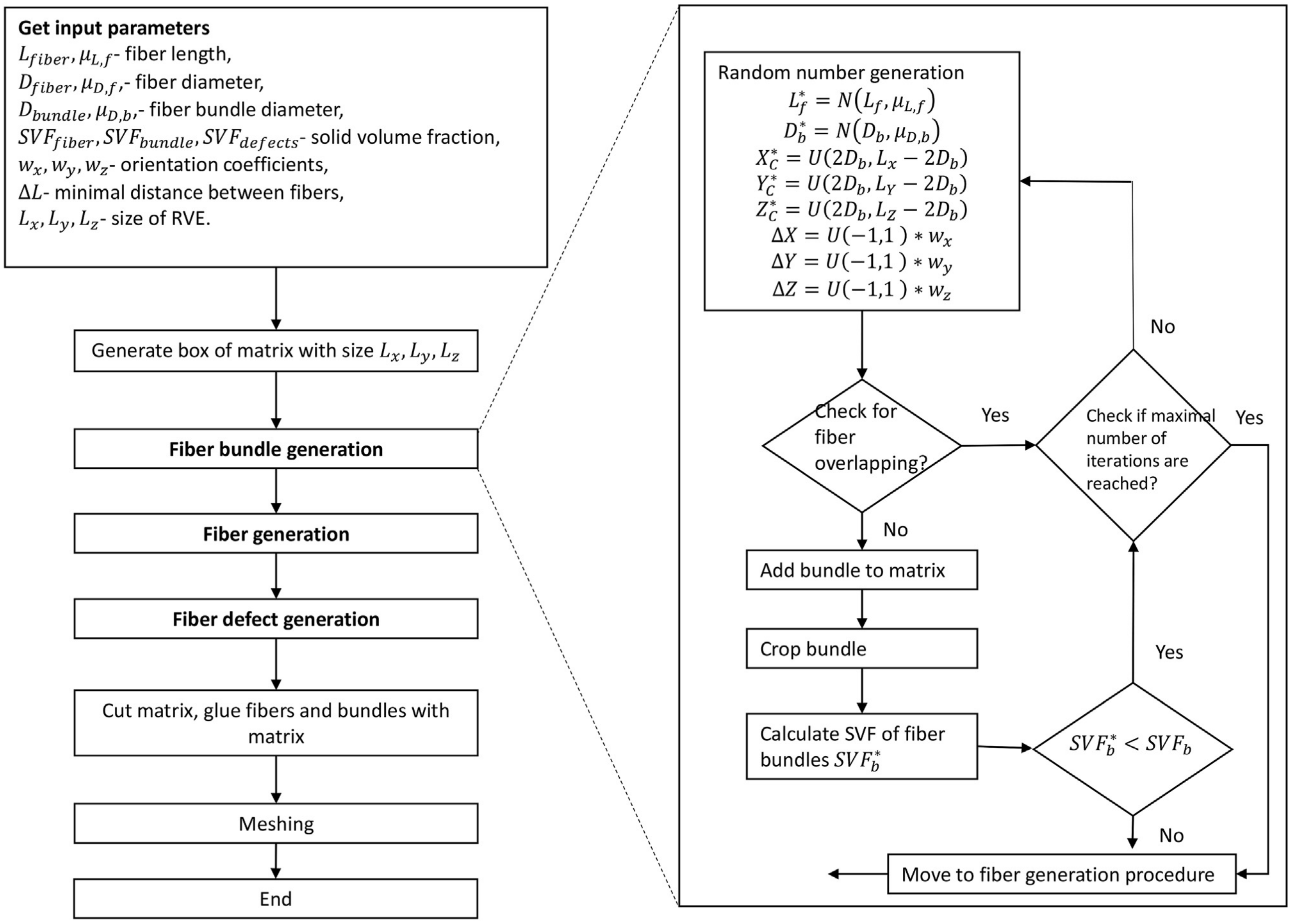

Fig. 1. Flow chart of representative volume element (RVE) generation for short flax fiber reinforced polymer composite, where $N(x,y)$– random number according to normal distribution with mean value x and standard deviation y, $U(x,y)$– random number according to uniform distribution in interval [x,y]. Only fiber bundle generation algorithm is shown explicitly. However fiber and fiber defect generation algorithm is analogical.