Computational Materials Science 151 (2018) 14–24

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Numerical modelling of entangled carbon fibre material under compression

Fadhel Chatti[a], Dominique Poquillon[b], Christophe Bouvet[a,*], Guilhem Michon[a]

[a] Institut Clément Ader, CNRS UMR 5312, Université de Toulouse, ISAE-SUPAERO, 3 Rue Caroline Aigle, 31400 Toulouse, France
[b] CIRIMAT, Université de Toulouse, INP-ENSIACET, 4, allée Emile Monso, BP 44362, 31432 Toulouse Cedex 4, France

ARTICLE INFO

Keywords:
Entangled fibres
Core material
RVE
Finite element model
Compression

ABSTRACT

A new entangled cross-linked material was recently developed in order to present a new core material that can resolve the drawbacks of the honeycomb. The optimization of entangled carbon fibres requires a deep understanding of the influence of the parameters of a fibre network on its macroscopic behaviour. This paper presents a 3D finite element model to investigate the compressive behaviour of this fibrous material. The current work focuses on a representative volume element (RVE) with appropriate boundary conditions and initial fibre distribution close to that of the experimental test. The morphology of the RVE is examined before loading. The simulation results show a good correlation with the experimental data in terms of stress–strain curves. The descriptors of the morphology such as the distance between contacts and fibre orientation are studied under compression loading.

1. Introduction

Sandwich structures are of great interest due to their attractive benefits, which include high stiffness to weight ratios [1,2]. As a result of these advantages, the use of composites has improved greatly in structural applications, first of all in the aerospace field.

Honeycomb is widely used as a core material in sandwich structures due to its good cost–benefit ratio and its high stiffness for bending solicitations. Although this cellular material presents attractive properties, its implementation in complex structures and its quality control process are often difficult. Other drawbacks of this material are the low vibration damping and the closed porosity, which can induce condensation in operating conditions.

Recently, Mezeix [3,4] developed a new material in which carbon fibres were first entangled (Fig. 1) and then cross-linked (Fig. 2) with epoxy resin to increase the stiffness for compression solicitations. Although this material offers many advantages that provide solutions to the drawbacks of the honeycomb, such as open porosity, adaptability to complex structures, and good vibration damping [5], it cannot substitute for honeycomb in the aerospace field due to its low stiffness for compression solicitations. In order to understand and optimize the behaviour of this material, a numerical study seems necessary and this current work presents the first step in its modelling. Unlike honeycomb, which has been significantly studied [6,7], limited researches [8,9] have been conducted to study and understand fibrous materials because of their complex tangled geometry.

The manufacturing process that will be presented later in Section 2 does not allow blocking of all the fibre–fibre contacts by the epoxy junctions (cf. Fig. 2). That is why we can find two types of interactions between fibres in the entangled cross-linked material. The first is the interaction through the cross-links and the second is the friction between fibre surfaces. Piollet [5] has concluded that this second type of interaction is responsible for the promising vibration damping of such material. Frequent fibre–fibre contacts without cross-links exist initially in the material and their number can grow significantly under loading. This growth is mainly due to the deformation of the fibres, which induces new fibre-to-fibre contact, but also, at larger strain, due to the breaking of some epoxy junctions. This allows some fibres to move more freely and then to touch others fibres. These fibre–fibre interactions have a noticeable effect on the macroscopic behaviour. A numerical study of fibre networks without cross-links can have considerable importance and can bring a first idea about the influence of fibre–fibre contacts without junctions on the behaviour of the cross-linked material.

This investigation is based on a representative volume element (RVE) because macroscopic stresses and strains can be determined by the microscopic stresses and strains over a representative cell unit. Hill [10] concluded that the complex computation can be reduced by the use of RVE as a full-scale model.

The first model of the uniaxial compression of 3D randomly oriented fibre assembly was developed by van Wyk [11]. It is based on the bending of fibres between contacts but does not take into account the fibre friction, the slippage, or the fibre twisting. Van Wyk does not include the frictional forces between fibres and he considered the

* Corresponding author.
E-mail address: christophe.bouvet@isae.fr (C. Bouvet).

https://doi.org/10.1016/j.commatsci.2018.04.045
Received 24 February 2018; Received in revised form 17 April 2018; Accepted 19 April 2018
0927-0256/

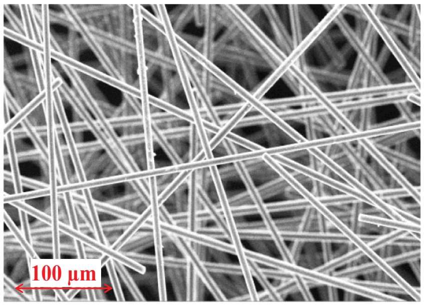

Fig. 1. Scanning electron microscope observation of entangled carbon fibres before packing operation.

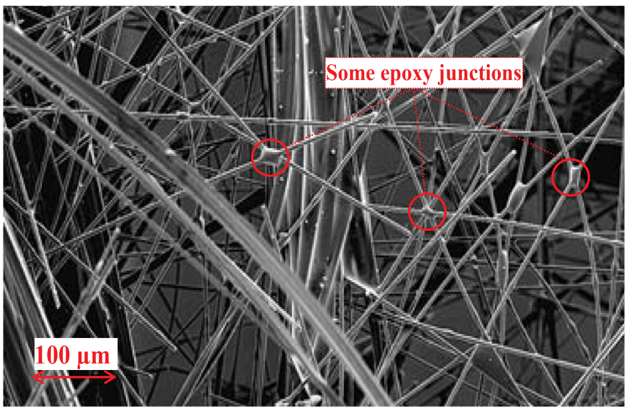

Fig. 2. Scanning electron microscope observation of entangled cross-linked carbon fibres.

distance between contacts to be proportional to the fibre volume fraction. He proposed the following equation, which presents the relationship between pressure and volume:

$$P = kE_{fibre}(f^3 - f_0^3) \tag{1}$$

where k an empirical constant, E_{fibre} is the fibre elastic modulus, f is the fibre volume fraction, and f_0 is the initial fibre volume fraction, that is to say the fibre volume fraction without any forces at the maximum unforced packing. Van Wyk concluded that his theory is valid only for a moderate fibre volume fraction lower than 10%.

Komori and Makishima [12] developed a theory that takes into account the fibre direction in different configurations in order to predict the number of fibre-to-fibre contacts in fibre assemblies. However, they do not predict the mechanical properties of the fibre network. The applicability of this theory is limited because it assumes affine deformation of the contact points between the fibres and it is only available for axial compression loading. Ning Pan [13] reported that the prediction of the number of contacts is too high in Komori and Makishima's theory. He proposed a modified approach to provide predictions of microstructural characteristics of fibre assemblies. He studied three different fibrous systems: ideal twist yarn, 2D random structure, and 3D random assembly, which can be a great basis for investigations of the properties of practical fibre assemblies. Lee, Carnaby, and Tandon [14] analysed the compression of a random fibre assembly using the bending energy while neglecting the crimp. Their model shows that if only fibre crimp is increased for a generated initial geometry, the tangent compression modulus actually decreases. A micromechanical theory based on a statistical investigation of the distribution of contacts was developed by Toll [15]. He assumes that there is no statistical correlation between the height of particle and the distribution of the incremental forces. This assumption is a limitation of his approach because it can break down if the individual particles differ greatly in stiffness or size. Toll proposed an approach to calculate the number of contacts per fibre for slender fibres:

$$N_c = \frac{8}{\pi} frg \tag{2}$$

where f is the fibre volume fraction, g is a constant depending on the fibre orientation distribution, and r is the fibre aspect ratio. Beil and Roberts [22] carried out a numerical simulation of the uniaxial compression of a fibre assembly. In their model, the frictional and repulsion forces are used to model the fibre contact points. Their results show that the number of contacts in the assembly increases at a higher rate than that predicted by van Wyk. Their numerical model is limited to modelling a low volume fraction of $f = 0.8\%$ and its computational cost is very high. Barbier et al. [16,17] used discrete element simulations for a larger volume fraction of up to 35% but for assemblies of only 250 fibres with a small aspect ratio (20) because of the computational cost. Durville [18] proposed a finite element approach that discretizes the contact–friction interactions from intermediate geometries to simulate the mechanical behaviour of beam assemblies. The application of this approach to the simulation of knot tightening proves that it is able to model the mechanical behaviour of fibrous materials. Recently, Abd El-Rahman and Tucker [19] presented a numerical model of a fibre network which advanced the understanding of the evolution of microstructure under deformation. Although this model can be used for a high volume fraction of $f = 25\%$, it was not compared with experimental data. Their numerical results are affected by fibres coming out of the simulation box. This loss of fibres can have an impact on the stress, fibre distribution, and number of contacts.

2. Material and methods

2.1. Manufacturing process

In the present work, the entangled material is made with carbon fibres which provide high mechanical performance. The filament diameter is 7 µm and the elastic modulus is 240 GPa. A Mettler balance (± 0.1 g) is used to weigh the samples. Microscopic observations of entangled material are carried out using an FEI Quanta 450 scanning electron microscope operating at 15 kV.

Mezeix [3] introduced the process of manufacturing. First of all, carbon yarns are cut to a fixed length of 12 mm. Many fibre lengths were tested before choosing the size of 12 mm which guarantees the best separation and entanglement of the fibres [3,4]. Then, carbon fibres are simultaneously separated from the received yarns and entangled in a 64 L blower room by manual application of compressed air. The air flow pressure is 6 bar. Fig. 1 shows a scanning electron microscopic observation of the separated entangled fibres. The contacts between fibres are not glued and so the fibres are free to move. We will focus just on the entangled material without cross-links in this current work, which will be considered as a first investigation of the influence of microstructural properties in the global behaviour of the assembly. This first step is necessary before blocking (see Fig. 2) some points of contact with epoxy junctions as this gluing is done on an assembly of fibres that has been submitted to prepacking during a first compression step.

2.2. Experimental set-up

The entangled fibres are placed in a cylindrical cell to be tested as shown in Fig. 3a. The two pistons are made of PVC (polyvinyl chloride), while the cylinder is made of PMMA (polymethyl methacrylate). The inner diameter of the cylinder is equal to 60 mm, which is five times larger than the fibre length. The entangled fibre sample can be compressed within the cell to different volume fractions by means of a movable piston. Initially, a mass of 9 g of entangled fibres is packed manually in the cylinder. The upper piston is moved down until a volume fraction equal to 6% is obtained. This process induces a