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Numerical modelling of shear hysteresis of entangled cross-linked carbon fibres intended for core material

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ABSTRACT

The analysis of an entangled cross-linked fibrous material at low deformation is explored as way of predicting the shear behaviour, especially the shear hysteresis. This paper presents a 3D finite element model to characterize the carbon fibre network rigidified by epoxy cross-links. The morphology of the representative volume element (RVE) is studied to guarantee that it is representative of the actual material that was characterized experimentally. Two steps are simulated, namely the initial compression during the shaping and before the polymerization of the epoxy resin and the cyclic shear testing of the material with its rigidified network of fibres. A numerical simulation of an RVE is used to present a description of the measured hysteresis loop that is decomposed of linear and nonlinear parts. A comparison between the numerical prediction and the experiment data is discussed. Even if the 3D numerical model under-predict the average shear stiffness of the material, it can capture the complex shapes of the measured hysteresis loops at different strain amplitudes.

1. Introduction

Composite materials have become increasingly used in numerous sectors, including automotive, aerospace and marine, due to their technical advantages, such as their desirable stiffness to weight ratio [1]. Sandwich structures are lightweight composite structures that have become indispensable in many industrial applications. They are composed of two thin and rigid skins separated by a thick and light core material in order to offer high stiffness for bending applications. Many theories and analysis methodologies have been presented to understand these structures [2–5]. Studies have been conducted to develop and design different configurations of core materials in order to enhance the performance of the whole sandwich structure [6–8]. Until recently, the honeycomb was the most used core material in sandwich structures because it offered the best stiffness to weight ratio. However, it has limitations with regards to the implementation in complex structures, process control and, most notably, vibration damping. Thus, different methods have been tested to enhance the damping of sandwich structures [9–11].

Based on the investigation of Poquillon et al. [12], Mezeix et al. [13,14] proposed a new fibrous material that can be used as a core material to enhance the vibration damping of the sandwich structure. This structure provides a high energy dissipation through friction between the fibres [15]. It is based on entangled cross-linked fibres that can be manufactured from aramid, glass, carbon fibres or from a mixture of them.

In this study, a 3D numerical modelling method was developed to better understand the intrinsic behaviour of the entangled cross-linked material and to model its vibration behaviour. Dunlop [16] is among the first researchers to present an analytical model to exhibit mechanical hysteresis. He produced the hysteresis loops during the compression-release cycling of the fibre assembly by a combination of frictional-slippage effects and van Wyk's [17] theory of compression of fibre assemblies.

In 1989, Carnaby and Pan [18] presented a theory for the compression hysteresis of fibre assemblies. They developed an iterative algorithm, in which the system geometry is updated on successive increments, to cope with large and nonlinear deformations. A comparison between the theoretical prediction and the experimental data showed a reasonable agreement. They concluded that the effects of slipping fibres are among the main causes that led to differences in the mechanical hysteresis behaviour. They also stated that the model could be improved by taking the fibre viscoelasticity in the total hysteresis into account. Beil and Roberts [19] examined the phenomenon of compression hysteresis through an analysis of the energy of the fibre network. Their mathematical model can predict the dissipation of energy

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due to dry friction. However, the stabilization of the mechanical behaviour during the loading cycle and the residual deformation were not properly modelled. According to the authors, this may be because the viscoelastic effects were neglected. Barbier et al. [20] used a discrete element simulation adapted from molecular dynamics in order to predict the hysteresis between the compression and release of entangled semi-flexible fibres. They concluded that hysteresis is related to the friction of contact on normal forces [21]. However, because of the limitations of the computing resources available, they were not able to simulate a sufficient number of fibres to get a realistic initial configuration compared to the experimental data.

Thus far, studies on an entangled cross-linked material have focused on the vibration behaviour [22]. An original method combining existing hysteresis models was introduced. Al Majid and Dufour Generalized Dahl's Model [23,24], along with other hysteresis models, have been used to model the hysteresis loops. The three nonlinear parts of the behaviour were combined after modelling them separately.

This paper presents a numerical model that characterizes the hysteresis loop of an entangled cross-linked material during shear cycling. It comprehends of the origin of the different parts of the behaviour through the study of morphological parameters.

2. Material and experimental data

2.1. Material fabrication

The manufacturing of an entangled cross-linked material was done manually at the laboratory scale. Fig. 1(a) shows scanning electron microscope (SEM) images of an entangled cross-linked material made with carbon fibres. The fibres have a diameter of several micrometres and are randomly bonded by the resin junctions.

The manufacturing process of the entangled cross-linked material was devolved by Mezeix et al. [6,13] and it was described as consisting of four main steps.

- The yarn is cut to a fixed length because the appropriate length for better entanglement depends on the kind of fibre.
- After placing the cut fibres in a 64 L blower room, compressed air at a pressure of 6 bars is used to separate the yarns and entangle the fibres simultaneously.
- Resin droplets are sprayed to block the contacts between fibres, where the pressure of paint spray gun is set at 2 bars.
- The moulding and polymerization process starts by placing the entangled cross-linked fibres in the mould. Epoxy polymerization is achieved in an oven at 70 °C during 8 h.

Table 1
Properties of carbon fibres and epoxy resin according to the supplier data.

	Diameter (µm)	Length (mm)	Young's Modulus (MPa)	Density (kg/m^3)	Poisson ratio
Carbon fibre	7	31	240	1770	0.3
Epoxy resin			5	1800	0.3

Experimental data are available for materials made from carbon fibres, glass fibres and aramid fibres for different fibre volume fractions (from 6 to 12%). In the present work that is devoted to numerical simulation, the most studied configuration involves an 8.5% volume fraction of the carbon fibre. This fibre was chosen because of its high performance compared to other types of fibres. The numerical simulations will be compared to the experimental data. These carbon fibres (Toho Tenax, HTS 5631, 800tex F1200) were cross-linked after their entanglement by a resin epoxy (Sicomin, SR1710). Epoxy resins are widely associated with carbon fibres in the manufacture of aerospace composites. Table 1 presents the characteristics of the carbon fibres and epoxy resin.

2.2. Experimental data

In a sandwich structure, the core material is used mainly in shear, so the investigation of the shear behaviour of an entangled cross-linked material would be of great interest [25]. This investigation was carried out experimentally by Piollet et al. [22]. The dimensions of the tested samples were 60 × 40 × 20 mm^3 and the cut fibres had a length of 31 mm. The fibre volume fraction was 8.5%, which corresponds to 7.2 g of carbon. This also corresponds to more than 100 km of total fibre length and more than 3 million fibres. For this work, 1.44 g of epoxy was sprayed on each sample to join the carbon fibres after the entanglement. It is important to note that not all contacts became stuck and the fibre separation was not perfect. There were still small strands. The numerical simulation was made with fibres of the same diameter of at least 7 µm. This parameter may be adjusted during the simulation to take into account the dispersion observed experimentally but for which no quantitative data is available.

The shear tests were carried out on a BOSE ElectroForce® 3330 machine. During each test, as detailed in [22], two samples were loaded simultaneously in a double lap configuration in order to guarantee shearing only, as illustrated in Fig. 2. Experimental testing was carried out for frequencies varying from 1 to 80 Hz and for shear strain amplitudes ranging from 0.05% to 1%. No noticeable effect of the test

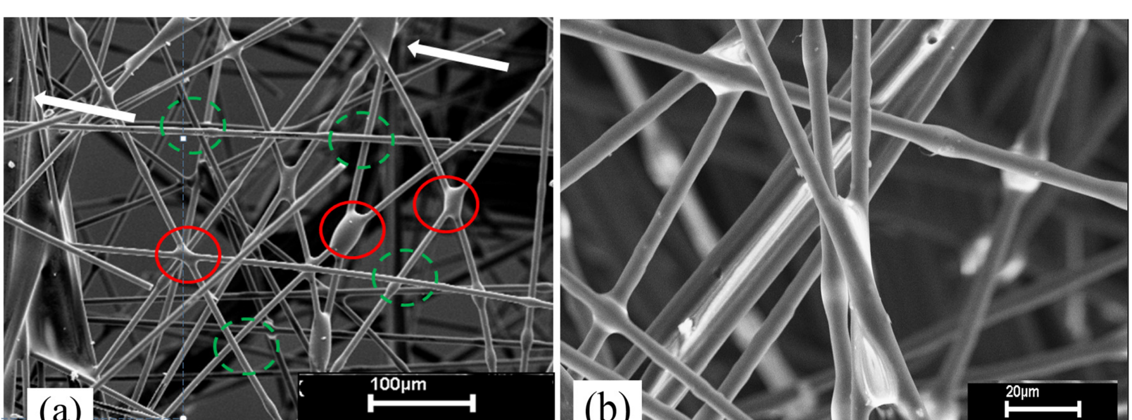

Fig. 1. SEM observation of entangled cross-linked carbon fibres with a volume fraction, f, of 8.5%. (a) The red circles indicate cross-linked fibres due to the epoxy resin, the green dashed circles indicate non-cross-linked contacts and the white arrows indicate that some yarn are not perfectly separated such that some fibres were grouped by two or more. b) Magnified view of a tiny yarn with four fibres in the background. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)