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Finite element modelling of fibrous networks: Analysis of strain distribution in fibres under tensile load

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ABSTRACT

Deformation behaviour of networks formed by bonded fibres presents significant challenges to specialists in mechanics of materials. In this paper, distribution of fibre strains in a fibrous network was evaluated for various strain levels using an example of a thermally bonded nonwoven material under a tensile load. The study started with the analysis of a reference model of a network with bond points, which is free of the effect of complex material behaviour and orientation distribution of fibres. At the subsequent stage, changes in various parameters such as material properties of fibres and fibre length were added separately into a parametric finite-element model to study their effect on the distribution of strains. The obtained results elucidate the reasons for non-uniformity of fibre-strain distribution under uniform loading conditions. In addition, it was shown that the type of arrangement of bond points, the length and material behaviour of fibres play a crucial role in the character of distribution of strains. At the end of the study, some suggestions are given on the way to obtain a homogeneous distribution of strains throughout the nonwoven structure.

1. Introduction

Fibrous networks are widely encountered in various areas, engineering and biological systems being obvious examples. Typical engineering materials formed by such networks are rubber, cellulose, paper and nonwoven products. In biological systems, various tissues of animals and humans are made of fibrous networks at different length scales. Tendons, cartilage and eye cornea are typical examples of these [1].

The mechanical response of such materials to external loads at macroscopic scale is governed by the behaviour of fibres in the network, which is distinguished at a smaller spatial scale. Due to their random structure and discontinuous character, analysing the mechanical behaviour of these networks has been a very challenging task for specialists in mechanics of solids. Demirci et al. [2] suggested a methodology to determine the anisotropic parameters of a fibrous network, which governs the mechanical response of the global structure. They later used these properties to simulate the tensile behaviour of nonwoven materials with a very good accuracy compared to tests for different material directions [3]. Barbier et al. [4] studied the mechanics of entangled semi-flexible fibres by discretizing each fibre by a small number of segments. It was claimed that the friction plays a minor role in the mechanical response of fibrous networks. Lee et al. [5] developed a computational model to simulate the damage evolution in random fibre composites. The crack-growth phase of the model provided accurate predictions whereas its crack-nucleation phase resulted in some differences with the real behaviour.

Thermally calendar-bonded nonwovens are a type of fibrous network encountered as various types of consumer and industrial products; their purposes are mainly for hygiene and filtration [6]. These materials are manufactured by means of feeding the formed web of fibres to the calendar, where it is condensed in the roller gap between two driven and heated rollers and melted at the contact points within a very short period of time [7]. In order to simulate the mechanical behaviour of low-density nonwoven materials that are characterised by a high effect of discontinuities and randomness in distribution of fibres, a computational procedure was developed in [8]. Using this procedure, finite element models of thermally bonded nonwovens can be generated according to various manufacturing parameters. Parametric studies with the model showed its efficiency to simulate the tensile behaviour of nonwovens and analyse the effect of manufacturing parameters on it [9].

One of general requirements for fibrous networks is a homogeneous distribution of strains and stresses over individual fibres in order to improve structural integrity of the global network. However, one of the conclusions resulting from the previous studies is a wide range of strain distributions observed in fibres even

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under macroscopically uniform external loading conditions. While some fibres were exposed to low strains, others had a strain value even higher than the global strain applied to the entire fabric. This can lead to early fracture of fibres, and progressive fracture can cause the failure of the entire fibrous network much earlier than expected.

In this study, the mechanisms affecting strain distributions in fibrous networks under tensile load were discussed by using the discontinuous nonwoven model developed in [8]. The study starts with the analysis of a reference model, employing a simplified material behaviour, constant orientation of fibres and rigid bond points. This reference model was introduced to understand the contribution of each individual parameter to the distribution of strains avoiding coupling effects. At the next stage, changes in parameters such as material properties, length of fibres and dimensions of bond point were introduced individually into the reference model in order to analyse the effect of each on the strain distribution of fibres. Finally, a nonwoven material with a random fibrous network was analysed, and its mechanical behaviour was compared with that of the reference model.

In most of the deformational scenarios presented here, fibres and/or bond points of a real material would be damaged before the maximum level of stretching analysed in simulations would be reached. Obviously, that would change the strain distribution throughout the structure; in addition, the structure itself would change. However, it would be very difficult to elucidate these complex cases of damage-affected strain distributions without understanding the main deformation mechanisms; hence, the numerical analysis of fibrous networks without account for damage was the main focus of analysis at this stage. Therefore, in this study, fibres and bond points were assumed free of damage in order to exclude the complex material behaviour.

2. Methodology

2.1. Reference model

The starting point of the analysis is a reference model that differs from the real nonwoven materials, as discussed above. Such a finite-element model is used to understand the behaviour of ordered fibrous bonded networks with simple mechanical properties of its constituents to serve as a reference point for more adequate models of materials with random distribution of fibres. The reference model has the following features:

- All the fibres were modelled oriented along the so called *machine direction* (MD) of the nonwoven.
- Linear elastic properties were assigned to fibres.
- Bond points were arranged as in the real sample of nonwoven presented in [10].
- Bond points were modelled as rigid bodies in order to avoid their deformation to interact with fibre investigated strains. In order to do this, a very high value of Young's modulus was assigned to the bond-point elements. The effect of bond-point stiffness was also analysed in this study.
- Fibres were modelled as continuous (with infinite length).

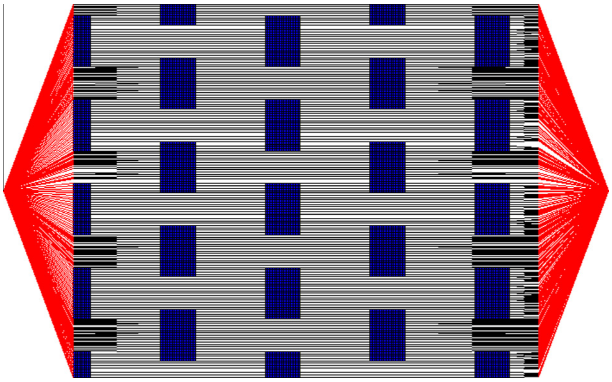

Fig. 1. The finite element implementation of reference nonwoven model.

The finite-element implementation of the reference model is shown in Fig. 1. The model consists of 1759 truss elements representing fibres and 6672 shell elements representing continuous bond-point structures. The other details related the modelling procedure were presented in [8].

2.2. Tensile loading

The distribution of strains in fibres was analysed with respect to intervals of fabric strain. As the true stain and engineering strain differs significantly for large-deformation cases that can be observed in the studied networks, it was aimed to obtain the results for specific intervals of fabric's true strain in order to be able to compare them with fibre strains. Acquiring results in numerical simulations would be convenient if the level of true strain of the fabric was increased with a constant rate. This was achieved by increasing the deformation rate gradually according to relations that take into account the well-known equation that links true strain with engineering one:

$$\varepsilon_{eng} = \exp(\varepsilon_{true}) - 1, \tag{1}$$

$$u = \varepsilon_{eng} gl, \tag{2}$$

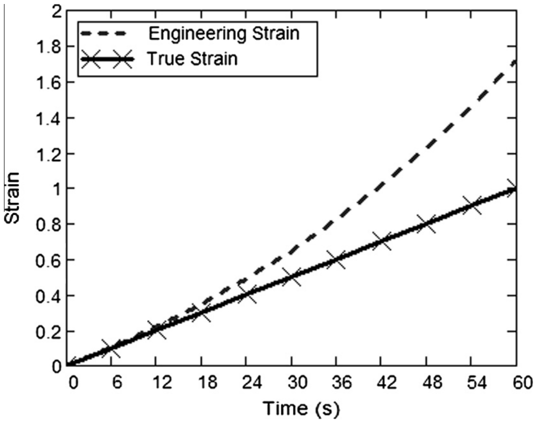

Fig. 2. Evolution of fabric strain with constant true-strain rate.

Table 1
Fibre strain groups for various intervals of true strain.

Strain group	Interval
−1	$\varepsilon_{true} < 0$
0	$0 \leqslant \varepsilon_{true} < 0.025$
1	$0.025 \leqslant \varepsilon_{true} < 0.050$
2	$0.050 \leqslant \varepsilon_{true} < 0.075$
3	$0.075 \leqslant \varepsilon_{true} < 0.1$
...	...
48	$1.200 \leqslant \varepsilon_{true} < 1.475$
49	$1.225 \leqslant \varepsilon_{true}$