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Numerical analysis of progressive damage in nonwoven fibrous networks under tension

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ABSTRACT

Understanding a mechanical behaviour of polymer-based nonwoven materials that include large-strain deformation and damage can help to evaluate a response of nonwoven fibrous networks to various loading conditions. Here, a nonwoven felt made by thermal bonding of polypropylene fibres was used as a model system. Its deformation and damage behaviour was analysed by means of experimental assessment of damage evolution based on single-fibre failure and finite-element simulations. Tensile tests of nonwoven fabrics were carried out to characterise their damage behaviour under in-plane mechanical loading. It was found that progressive failure of fibres led to localization of damage initiation and propagation, ultimately resulting in failure of the nonwoven felt. To obtain the criteria that control the onset and propagation of damage in these materials, tensile tests on single fibres, extracted from the felt with bond points attached to their ends, were performed. A finite-element model was developed to study damage initiation and propagation in nonwovens. In the model, structural randomness of a nonwoven fibrous network was implemented by means of direct introduction of fibres according to the orientation distribution function. The evolution of damage in the network was controlled by a single-fibre failure criterion obtained experimentally. The proposed numerical model not only captured the macroscopic response of the felt successfully but also reproduced the underlying mechanisms involved in deformation and damage of nonwovens.

1. Introduction

Nonwoven fibrous networks demonstrate complex deformation and damage behaviour linked to randomness of their microstructure and properties of constituent fibres. In thermally bonded calendered nonwovens, a fabric's structure is composed of continuous and discontinuous regions. These continuous regions called *bond points* are connected by a network of randomly oriented fibres forming a discontinuous region with voids and gaps in it. This combination of two regions with different microstructures, with continuous domains embedded into discontinuous medium, makes it difficult to predict the deformation and damage behaviour of thermally bonded fibrous networks. Experimental characterisation is not always viable and sufficient for a comprehensive understanding of complex phenomena involved in deformation and damage of nonwoven fibrous mats. The challenges involved in experimentation are linked to the need for specialised experimental devices as well as to significant efforts required for experimentation, especially for this type of materials, in which mechanical properties are defined by their non-trivial microstructure and constituent fibres' properties. To tailor and optimise properties of these materials, an understanding of the relationship between their macroscopic behaviour and microstructure along with manufacturing-defined single-fibre properties is essential. Therefore, the aim of this work is to develop a numerical model incorporating the fabric's microstructure, properties of constituent fibres and main deformation and damage mechanisms.

The behaviour of woven fibrous networks that are mostly used in composites for various multi-functional applications, is better understood than that of nonwoven fibrous networks (either as standalone fabrics or in combination with epoxies in the form of composites) (Li et al., 2010; Blacklock et al., 2012; Rinaldi et al., 2012; Parsons et al., 2013). Still, several studies were performed to model and predict the mechanical response of nonwoven fibrous networks. Most of the work in this field is related to paper, which is a very special type of nonwoven (Schulgasser, 1981; Ostoja-Starzewski and Stahl, 2000; Isaksson et al., 2004; Isaksson

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and Hagglund, 2007; Isaksson and Hagglund, 2009; Harrysson and Ristinmaa, 2008; Bronkhorst, 2003). In the context of nonwoven networks, several techniques were used to simulate a mechanical behaviour of these materials. A continuum model incorporating an orientation distribution of fibres by considering orthotropic symmetric planes was developed (Demirci et al., 2011, 2012). This model was used successfully to predict the stress–strain behaviour of high-density nonwovens but it was incapable to account for changes in the network's topology with localization of damage. Ridruejo et al. (2010, 2012) introduced a continuum model to predict a meso-level response of the fabric without explicit introduction of fibres into the model, and thus, it was unable to reproduce the effect of the actual microstructure; mechanisms of fabric's deformation and damage were implemented in a phenomenological way. In order to resolve the issues with continuum models, another technique based on a composite laminate model, incorporating the effect of non-uniform orientation distribution of fibres, was used (Bais-Singh et al., 1998). In that model, fibre layers were stacked on top of each other in a way that the fibres in each new layer were at an angle relative to that in the preceding one. This model was unable to capture all the aspects of the real fabric's behaviour such as re-orientation of fibres since they were fixed within the layer and could not slide on top of each other. In an effort to incorporate a realistic non-uniform microstructure of nonwovens into the model, an approach based on homogenisation was developed using a representative volume element (RVE). Petterson (1959) introduced the model to predict a macroscopic response of the fabric by homogenising the behaviour of a unit cell incorporating a random distribution of fibres' orientation. More recently, Silberstein et al. (2012) suggested an approach of employing a similar RVE-based technique to predict a macroscopic behaviour of the fabric. The model consists of a multilayer triangular network and uses a homogenisation technique to predict a response to monotonic and cyclic loading. Such models based on the homogenisation technique do not predict localization of damage and changes in material's microstructure caused by this damage. In order to overcome these shortcomings, microstructure-based models employing direct introduction of individual fibres according to their orientation distribution were developed (Hou et al., 2009, 2011a, 2011b; Sabuncuoglu et al., 2012; Farukh et al., 2012a). Though this modelling technique is computationally not as efficient as a continuum one, however, it can account explicitly for all the main mechanisms involved in deformation and fracture of nonwovens. Moreover, a model based on this technique naturally introduces voids and gaps into consideration that are a distinctive feature of fibrous networks especially in case of low-density nonwovens. Such models can simulate the deformation behaviour of the fabric very accurately but up to a certain level of deformation; none of these models can predict the damage initiation and propagation in nonwovens. A model, based on the same approach to introduction of discontinuous microstructure, was presented by Ridruejo et al. (2011) who employed bundles of random fibres, without using their actual orientation in the real fabric, in the model. With that approach, a glass-fibre nonwoven felt, in which damage of the fabric occurred as failure of bonds rather than fibre bundles, was studied. In addition to these, models have been proposed by Isaksson et al. (2012) and Wilbrink et al. (2013) focussed on a crack-growth direction and bond failure in fibrous networks, respectively. Thus, it can be concluded that despite of the benefits of different reviewed models for analysis of various aspects of mechanical behaviour and mechanisms involved in deformation and failure of nonwoven fibrous networks, they present only partial solutions. None of the models can predict evolution of deformation and damage of the fabric up to its failure in terms of progressive failure of fibres while incorporating explicitly the realistic material's microstructure by introducing fibres and constituent fibre properties into the model.

In this paper, a thermally bonded nonwoven fibrous network with its actual microstructure was modelled in finite-element environment using a parametric modelling technique based on a specially developed user subroutine. A random anisotropic nature of the fabric was captured by introducing the fibres directly into the model according to their orientation distribution in the fabric. The variability of elastic–plastic mechanical properties of constituent fibres and a single-fibre failure criterion were introduced into the model. Damage initiation and evolution in the model were controlled by this criterion as progressive failure of fibres resulted in damage initiation and propagation in nonwovens.

2. Experimentation

The model developed in this paper is based on experiments with single fibres and a nonwoven fabric reported in Farukh et al. (2012b). These experiments provided information necessary for development of a finite-element model, such as a number of fibres and their orientation distribution function, dimensions of bond points, their shape, and a pattern obtained from morphological characterisation of the fabric as well as material properties obtained in single-fibre experiments. Moreover, tensile tests performed on specimens of the fabric provided a basis for physical interpretations of the results obtained with the model not only in terms of material's constitutive behaviour but also the mechanisms involved in its deformation and damage. Therefore, single-fibre and fabric experiments crucial for this study are briefly recalled here.

2.1. Material

The materials used in this study were low-density (<50 g/m^2) thermally bonded calendered nonwovens based on polypropylene (PP) fibres, manufactured by FibreVisions®, USA. Polypropylene fibres of 18 μm diameter were used to manufacture a fabric. The staple fibre with length of 38.1 mm were laid randomly on a conveyor belt resulting in an anisotropic web, in which more fibres were oriented along the direction of the belt, called *machine direction* (MD) as compared to that in the direction perpendicular to MD on the plane of the web, called *cross direction* (CD). The web was then bonded with a hot calendering technique at a temperature of 156 °C, which lies within the optimal temperature window for PP. Different basis weights of material, i.e. 20, 30 and 40 g/m^2 were used in this study. The overall microstructure of the fabric is shown at different scales in Fig. 1.

2.2. Assessment of properties

2.2.1. Single-fibre behaviour

The material properties, especially related to failure, of single fibres extracted from the studied thermally bonded fabric are different from those of the virgin fibres due to the pressure and temperature involved in the bonding process (Chidambaram et al., 2000; Wang and Michielsen, 2001; Michielsen and Wang, 2002; Wang and Michielsen, 2002; Bhat et al., 2004; Farukh et al., 2012b). Therefore, individual fibres extracted from the fabric were used to obtain their material properties as these are its basic constituent. A complete detail on fibre extraction and preparation of the specimen is given in (Farukh et al., 2012b). Tensile tests were carried out on those extracted fibres at various levels of constant engineering strain rates – 0.5, 0.1 and 0.01 1/s – using Instron® Micro Tester 5848 with a high-precision ±5 N load cell. Due to difficulties to control the fibre's length, a constant engineering strain rate was achieved by modifying the velocity of the cross-head with