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# Characterisation and numerical modelling of complex deformation behaviour in thermally bonded nonwovens ☆

Farukh Farukh [a], Emrah Demirci [a,*], Barış Sabuncuoğlu [a], Memiş Acar [a], Behnam Pourdeyhimi [b], Vadim V. Silberschmidt [a]

[a] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, UK
[b] Nonwovens Cooperative Research Center, North Carolina State University, Raleigh, NC, USA

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ABSTRACT

A complex time-dependent deformation and damage behaviour in polymer-based nonwovens are analysed under conditions of multi-stage uniaxial loading. Elastic–plastic and viscous properties of a polypropylene-based fabric are obtained by series of tensile, creep and relaxation tests performed on single fibres extracted from the studied fabric. These properties are implemented in a finite-element (FE) model of nonwoven with direct introduction of fibres according to their actual orientation distribution in order to simulate the rate-dependent deformation up to the onset of damage in thermally bonded nonwovens. The predictions of FE simulations are compared with the experimental data of multi-stage deformation tensile tests and a good agreement is obtained including the mechanisms of deformation. Due to direct modelling of fibres based on their actual orientation distribution and implementation of viscous properties, the model could be extended to other types of polymer-based random fibrous networks.


## 1. Introduction

Nonwovens and their combinations with other materials are used in numerous applications, including geotextiles for soil reinforcement, medical applications, filtration, and aerospace industry [1]. Regardless of the application area of nonwovens, understanding of their deformation and damage behaviour, as well as of relationships between their macroscopic mechanical behaviour, underlying fibre properties and randomness of their microstructure can help to design and optimise the performance of such materials.

Nonwoven fabrics are generally made from continuous or staple fibre webs strengthened by bonding using various techniques such as mechanical bonding, bonding by adhesive or thermal bonding [1]. Compared to other bonding processes, thermal bonding and the products made with this technique offer several advantages such as lower capital investment and manufacturing cost, higher throughput, no hazardous chemical involved and very good recyclability [1,2]. Therefore, it is one the most commonly used technique for the manufacture of nonwovens [3]. In thermally bonded nonwovens, fibrous web is passed through a hot calendar with an embossed pattern. Bonding mainly occurs at raised areas resulting in bonded spots called ‘‘bond points’’. On the other hand, web regions, which are not in contact with the hot engraved pattern, remain unaffected and form the fibre matrix that acts as a link between the bond points. The structure of resulting thermally bonded nonwoven (shown in Fig. 1) is a combination of continuous and discontinuous regions, thanks to which it exhibits a unique and complex mechanical behaviour. The understanding of deformation and damage behaviour of this type of material will help to improve design of products aimed at higher reliability and durability.

A polypropylene-based low-density thermally bonded nonwoven is studied in this work. A deformation and damage behaviour of low-density nonwovens is complicated due to randomness, discontinuity and presence of voids in their microstructure. Moreover, polymer-based constituents exhibit a nonlinear elastic–plastic behaviour including viscous effects, which is the most significant property of polymer materials. Due to these viscous properties, polymer-based materials demonstrate a rate-dependent behaviour such as stress relaxation, creep and damage. Several studies have been conducted to predict the behaviour of such materials by using various numerical modelling techniques. Most of these studies provide a partial solution to the problem of predicting the changes in mechanical behaviour with changes in orientation of constituent fibres [4–6], curliness of fibres [7] and manufacturing conditions [8]. A very few studies were performed to develop a finite element model that can simulate the response of nonwoven materials under mechanical loading [9–17]. All of these studies either focused on initial deformation of the material without considering damage or included only elastic–plastic material properties. To author's

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* Corresponding author. Tel.: +44 1509227621; fax: +44 1509227585.
*E-mail address:* E.Demirci@lboro.ac.uk (E. Demirci).

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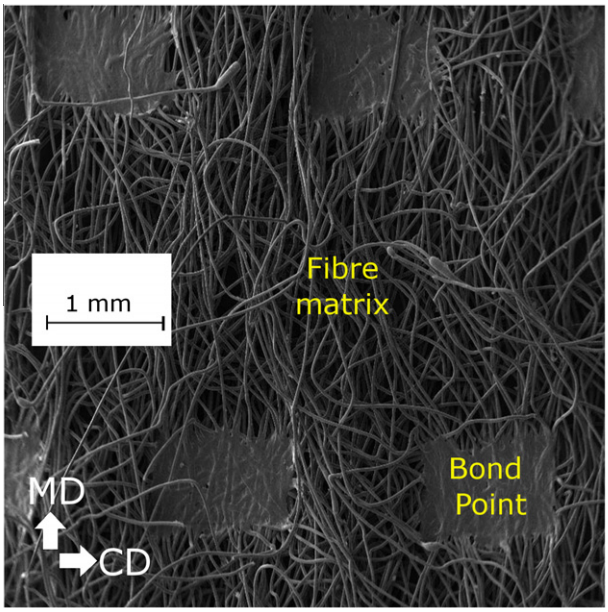


**Fig. 1.** SEM image of nonwoven fabric composed of bond points and fibre matrix.

knowledge, none of these models can predict the damage behaviour of nonwovens while incorporating material's viscous properties. The viscous properties of constituent fibres have a significant effect on the material's behaviour e.g. load-rate sensitivity, stress relaxation and creep-based deformation and damage. Generally, nonwovens in their service life undergo complex loading at various strain rates with or without effects of creep or stress relaxation rather than simple monotonic loading and damage occurs inevitably in the material beyond a certain level of loading. Thus, it is important to understand the damage mechanisms that govern the material behaviour under excessive loading and to develop a finite-element model incorporating the actual orientation distribution and viscous properties of constituent fibres capable to reproduce the response of these materials – including their damage – for complex loading histories.

A finite-element model based on nonwoven's microstructure and properties of constituent fibres (including viscous ones) will provide insights in, and better exploration of, the design space of products containing nonwoven parts, which is the aim of this study. A parametric finite-element modelling technique is used to incorporate the orientation distribution of fibres, with the number of fibres exactly equal to that in the actual fabric. Using this parametric technique, randomness of the fabric's structure is captured by direct modelling of fibres and thus explicitly accounts for the main mechanisms of deformation (affected by time-dependent parameters of constituent fibres) of thermally bonded nonwoven material up to the onset of damage. Elastic–plastic and viscous material properties, considered significant in case of polymer-based nonwovens and obtained by performing a series of experiments on constituent fibres, are implemented in the model. The results obtained with the model were compared with those of multi-stage tensile loading tests on nonwovens in two principal directions: machine direction (MD) and cross direction (CD) up to the onset of damage.

## 2. Experimentation

### 2.1. Material

A polypropylene (PP) based mono-component thermally bonded low-density nonwoven was used in this study. Its basis weight was 20 g/m$^2$ and it was manufactured at an optimal bonding temperature between 150 °C and 160 °C. Randomly oriented fibres were thermally bonded with square-shaped bond points (Fig. 1). Approximately 14% of the fabric area was bonded with bond density of 23.68 spots/cm$^2$.

### 2.2. Single-fibre behaviour

Nonwoven fabric used in this study was composed of PP fibres having a length, diameter and linear density of 38.1 mm, 18 μm and 2.3 denier, respectively. Fibres were extracted from a free edge of the fabric, and a series of experiments were performed to obtain the required material properties. Both edges of extracted fibres were attached to the sticky strips of paper to prevent slippage, dislocation and damage, and to provide a firm grip and convenient mounting on Instron® Micro Tester having ±5 N load cell. A high-speed camera (Photron Fastcam SA3®) was used to make sure that fibres were not stretched during preparation and mounting of single-fibre specimens. Tensile, creep and relaxation tests were performed on such specimens at various loading rates, levels of engineering stress and strain. All the parameters necessary to model the elastic–plastic behaviour of a fibre such as its modulus of elasticity and flow curve were obtained with the uniaxial tensile tests whereas its viscous properties were quantified through the creep and relaxation tests. The details of single-fibre tensile test are given elsewhere [17]. The viscous properties obtained with single-fibre creep tests were implemented into the FE model based on a creep strain rate as a function of time and stress level (Fig. 2). Curve-fitting procedures were carried out to obtain smooth curves for a creep strain rate as a function of time and stress level [13]. Generally, creep tests of ordinary materials are performed at stress levels below the yield stress of the material; however, the model in this study was developed to simulate deformation up to the onset of damage. At this stage most fibres bear stresses significantly higher than yield stress; therefore, single-fibre creep tests were performed at various stresses including those exceeding yield stress (75 MPa in this case). Since creep in material can cause deformation ultimately leading to material damage, all three stages of creep – primary, secondary and tertiary – were

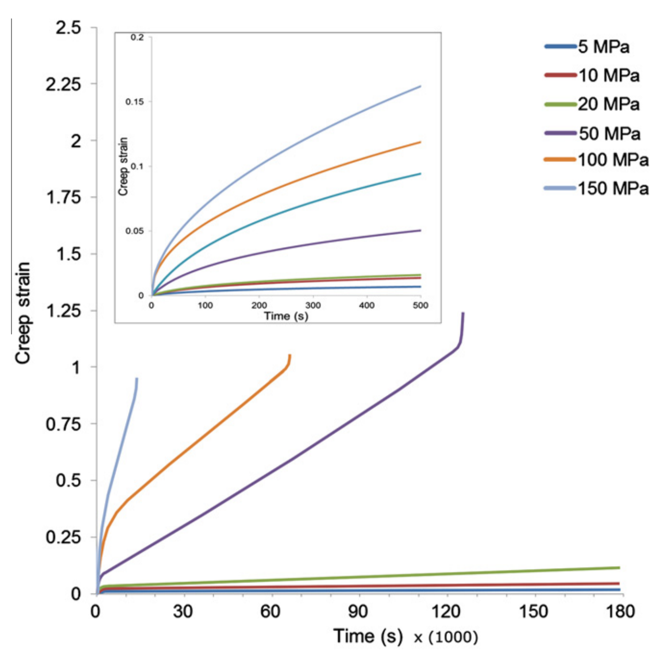


**Fig. 2.** Single-fibre creep tests for various stress levels.