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# Damage mechanisms of random fibrous networks

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**Abstract.** Fibrous networks are ubiquitous: they can be found in various engineering applications as well as in biological tissues. Due to complexity of their random microstructure, anisotropic properties and large deformation, their modelling is challenging. Though, there are numerous studies in literature focusing either on numerical simulations of fibrous networks or explaining their damage mechanisms at micro or meso-scale, the respective models usually do not include actual random microstructure and failure mechanisms. The microstructure of fibrous networks, together with highly non-linear mechanical behaviour of their fibres, is a key to initiation of damage, its spatial localization and ultimate failure [1]. Numerical models available in literature are not capable of elucidating actual microstructure of the material and, hence, its influence on damage processes in fibrous networks. To emulate a real-life microstructure in a developed finite-element model, an orientation distribution function for fibres obtained from X-ray micro computed-tomography images was considered to provide actual alignment of fibres. To validate the suggested model, notched and unnotched rectangular specimens were experimentally tested. A good correlation between the experimental data and simulation results was observed. This study revealed a significant effect of a notch on damage evolution.

## 1. Introduction

Fibrous materials are commonly found around us . Despite their extensive use in many products including automotive, hygiene, health applications, understanding of their mechanical properties and performance is not simple due to complexity of their microstructure. This complexity stems from manufacturing processes, non-trivial mechanical behaviour of constituent fibres and their random distribution in the microstructure of the material.

Although some of those networks are man-made, such as, cellulose, papers and most of nonwovens, some are natural. Some of these materials are composed of fibrous network layers as in elastomeric fibrous scaffolds used in engineered soft tissues [2-3]. A main source of constituent fibres is natural or synthetic polymers [3]. As a result, these fibres might show time-dependent and/or non-linear mechanical behaviour, i.e. elasto-plasticity or visco-plasticity [3].

The first attempt to model microstructured nonwoven materials was made by Liao *et al*[4] with the model based on discontinous modelling approach. The model was composed of many discrete cell elements, each representing a number of fibres. The orientation distribution of fibres in real fabrics was partially reflected in the model. Also, fibre-to-fibre interactions (friction or contacts between fibres) in the model were not included, and a partial account of fibre orientation, the model did not reproduce the actual deformation mechanisms and fracture. Similarly, other researchers simulated the mechanical behaviour of fibrous systems (paper, biomaterials, nonwovens)[5-7]. Even though a continuous modelling approach provides a relatively easy way to generate a macroscopic (global) material's structure, it is incapable of representing real microstructure and, hence, deformation and failure mechanisms.

Another type of model was developed by Kim and Pourdeyhimi in 2001 [8] and introduced to predict the behaviour of thermally point bonded nonwovens. This numerical model was based on a principle of incremental deformation with contribution of deformation of each individual fibre calculated. Then, these contributions were summed up to obtain an overall mechanical response. This model had an advantage of incorporation of an fibre orientation distribution function (ODF) to give an account for anisotropy of fibres due to different alignments. Still, it could not reflect properly important deformation and fracture mechanisms of thermally point bonded nonwovens, such as, rearrangement of bond points and changing orientation of fibres.

A model for thermally point bonded low density nonwovens was proposed by Hou *et al* [9]. It was capable of representing an anisotropic nature of that type of nonwoven materials since bond points and the fibre orientation function were introduced directly, allowing to include the actual alignment of fibres. The investigation with this model pointed out that fibre alignment was one of the major factors affecting the mechanical behaviour of nonwoven material.

Subsequently, Somuncuoglu *et al* [10] presented a new model with parametric capabilities to investigate tensile performance of thermally point-bonded nonwoven materials. This new development (its superiority compared to previous finite-element models introduced in the literature), it allows the users to study conveniently the effect of changing manufacturing parameters such as base density (number of fibres on unit area), fibre orientation, pattern and shape of bond points(and their dimensions). This parametric finite-element model has demonstrated its success and reliability in a variety of investigations of thermally point-bonded nonwovens [1, 11-14]. The model is used in this paper to model experimentally observed damage processes.

## 2. Experimental Studies

Properties of constituent fibres and the entire fabric play important role in damage and deformation mechanisms of fibrous materials. In fact, each fibre contributes to the overall mechanical response of the materials. For this reason, characterization of physical and mechanical properties of single fibres is vital. In experimental studies, material parameters and damage (fracture) properties of fibres were obtained by means of single-fibre tests. As for the tests on fabrics, a set of notched and virginal (un-notched) specimen was subjected to tensile loading.

### *2.1. Material*

The material in this study is a thermally bonded nonwoven with a density of $30 g/m^2$, made of polypropylene fibres. The manufacturing process of this material is as follow: polypropylene fibers were extruded and then stretched to increase their crystallinity, resulting in fibers of up to 40-60 $\mu$-m in diameter. The continuous spun fibres were then laid down randomly on a flat surface, producing an isotropic fiber web sheet (before bonding) which was then bonded by a simultaneous application of pressure and heat. The fibres typically appear as isolated, although it is not infrequent that they form bundles of 2, 3 or even 4 fibres. Partial fusion between fibres at the entanglement points is normally observed. The overall view of the nonwoven fabric at a larger scale demonstrates its isotropic microstructure. The main physical properties of a typical polypropylene fibre are shown in Tab. 1.

**Table 1.** Physical properties of typical polypropylene fibre.

| Linear density (dtex) | Tenacity (N/tex) | Ultimate tensile strength (MPa) | Initial modulus (GPa) |
|---|---|---|---|
| 6.6 | 0.415 | 548 | 1.3 |

### *2.2. Material microstructure*

In this study, the main focus is on microstructure of fibrous networks that affects their deformation and damage behaviour. Its main feature is a presence of two distinct domains: bond points and fibrous matrix, see Fig. 1. Due to spatial distribution of those regions, the nonwoven fabric exhibits its anisotropic mechanical characteristics. Though bond points are formed by large numbers of randomly oriented fibres, they can be assumed as a solid and continuous structure, i.e. isotropic material, as a result of the melting and compaction during their manufacture. Unlike bond points, the fibrous web demonstrates a high level of porosity and, hence, compressibility as well as randomness of the orientation distribution of fibres. A fibre diameter, variations in diameter and length of fibres, frequency of a crimp wave are some of other factors defining anisotropy of the web structure [15].

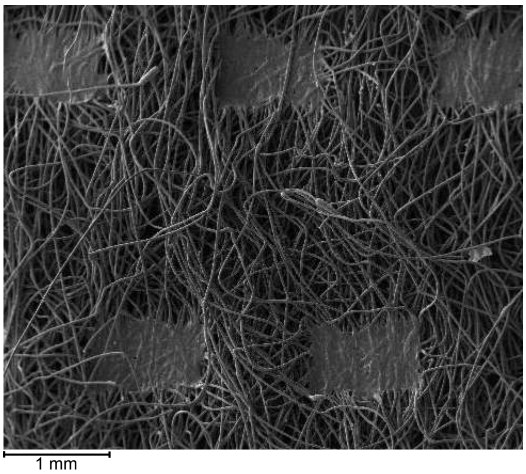


**Figure 1.** SEM image of studied thermally point-bonded nonwoven

### *2.3. Single fibre tests*

As reported, since fibres originate from different raw materials and manufacturing processes, they have different physical properties. It was also revealed [16-19] that fibres even made of the same material demonstrate distinct deformation and failure behaviours before and after their manufacturing process. Thus, individual fibres were extracted from the fabric and tested to assess their material properties. A detailed explanation of this extraction and testing processes can be found elsewhere [18].

### *2.4. Tensile tests on nonwoven specimens*

The experiments focused on rectangular samples with dimensions of 10 mm x 16.5 mm. Additionally, notched samples of nonwovens were produced with a square hole in their centre,

**Table 2.** Parameters of tensile test settings

| Load range (N) | Speed (mm/min) | Max. extension | Preload (N) |
|---|---|---|---|
| 100.0 | 300.0 | 200.0 | 0.5 |

see Fig. 3. Thus, un-notched (virginal) and notched specimens were prepared for tensile tests, with five specimens tested for each combination of parameters (see Tab. 2). The specimens were tested in their machine and cross-machine directions using AMTM D4595 (2011) [20].

## 3. Numerical Studies

The experimental studies were complemented by development of a new finite-element model emulating microstructure of the fibrous material to understand its fracture mechanisms under tension. The modelling approaches for fibrous networks in the literature can be divided into two basic groups: discontinuous and continuous. Apparently, the former consider a continuum formulation for the modelled material without any account for porosity inside it. They do not introduce individual fibres into the model, whereas the discontinuous numerical modelling approach aims to incorporate the real microstructure of the material [21]. To have a realistic microstructure, this modelling approach requires modelling single fibres, resulting in a natural introduction of voids and gaps observed in the network as well as another domain - bond points. To model the discontinuous microstructure of fibrous networks, several techniques can be utilized. The first technique is based on building up the microstructure with single fibres to form a complete fibrous network (macrostructure). This scheme allows researchers to perform investigations according to the purpose of their research. In the second technique, SEM or micro CT data are used for direct replication of the microstructure of the fibrous network is replicated based on direct processing of images). Despite being capable to produce similar microstructural models, this technique is cumbersome with regard to account for intersecting or overlapping regions of fibres. Also, to make any change related to other manufacturing parameters, new samples should be scanned for those parameters, so that a new microstructural model could be constructed. Considering advantages and drawbacks of these schemes, the discontinuous modelling approach was employed in this research. In the case of the studied thermally point-bonded nonwoven materials, fibres in the matrix are randomly distributed, and this randomness is affected by the manufacturing process. The fibres are aligned mostly in the direction parallel to that of the production line. This causes a dierence in the strength of fabric in the machine direction (MD) parallel to manufacturing line-and cross direction (CD) - perpendicular to MD. As a result, the fabric is stier and stronger in MD than in CD [22]. Thus, a precise assessment of fibre distribution is of great importance for elucidating of the effect of the microstructure. To express this randomness and orientation characteristics of fibrous materials, a distribution function was introduced by Cox in 1952 [23]. It is known as an *orientation distribution function* (ODF). The ODF was employed in this study to introduce a heterogeneous microstructure; it was determined with an Hugh-transform-based image-processing software developed at Loughborough University (for further information, see [24-25]).

### *3.1. FE modelling of specimens*

A finite-element software package MSC Marc as solver and its Mentat module as pre/post-processor were used in our numerical investigations. The software provides a good support for

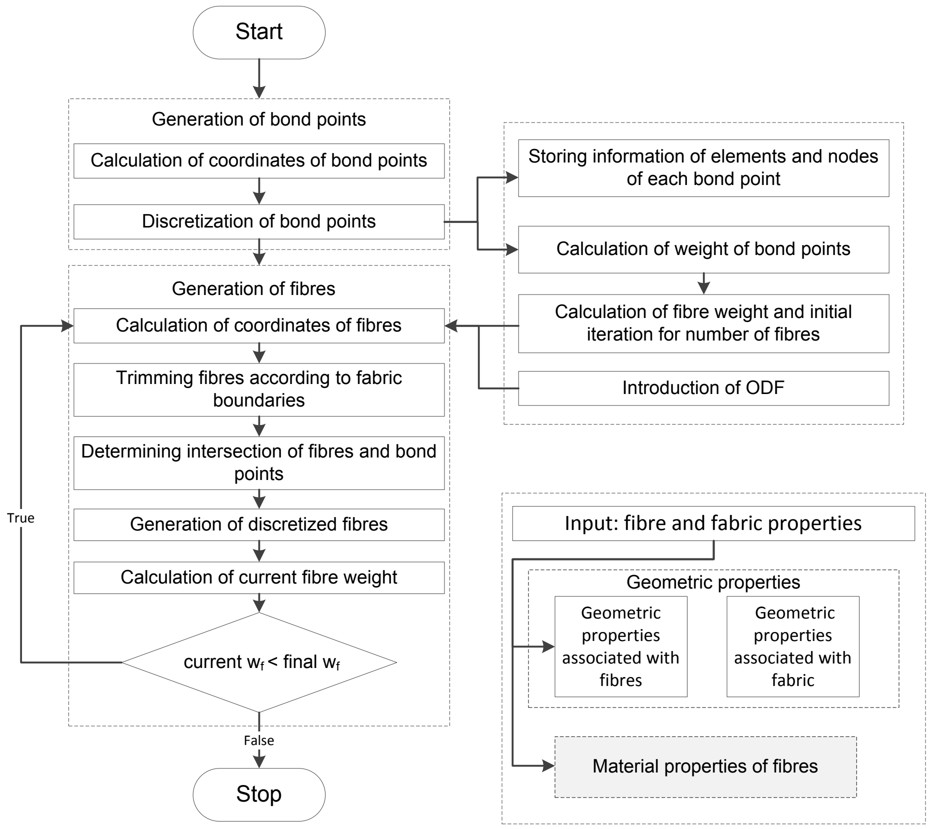


**Figure 2.** Flow chart of generation of nonwoven network

generation of complex geometries using a python scripting language. Figure 2 illustrates a flow chart for generation of the nonwoven network. In the python script, four important parts were considered: (i) input of fibre and fabric properties; (ii) generation of bond points; (iii) generation of fibres; (iv) storing information of nodes and elements of the finite- element model. In the input block, class geometry properties of the fibres and fabric, such as the average fibre length and cross-section and dimensions of the fabric are defined as well as the materials properties of fibres such as their flow curve and elastic modulus, obtained in the single-fibres tests. After reading this information, coordinates of the bond points were calculated depending on their shape and pattern for the modelled fabric. By the end of this calculation, bond points geometry was discretized, and the nodes and element numbers in each individual bond point were stored for the subsequent steps. At this point, according to the weight of bond points and of the total fibrous structure, the weight of fibrous matrix (i.e. without bond points) was calculated, and the coordinates and the angles of fibres with respect to MD of the web were determined based on the measured ODF. Meanwhile, the intersection points of fibres and bond points were computed, and the nearest nodes in the vicinity found with a search algorithm. Together with this, to match nodes of fibres and bond points, fibres were rotated by a small angle, and discretization of the fibre geometries took place. The generation of the fibrous matrix in the model was performed according to the condition that individual fibres were added to the model until the current weight of the web reached the prescribed magnitude. In the developed finite-element model, the microstructure of material was generated using truss elements for fibres and thin shell elements for bond points. The reason for this choice was the low density of the material used in this research. Truss elements were aligned in the same plane. The shell elements could be used to model bond points since their thickness-to-length and thickness-to-width ratios were low for the use of volumetric elements. The generated finite-element web with a square notch is depicted in Fig.3.

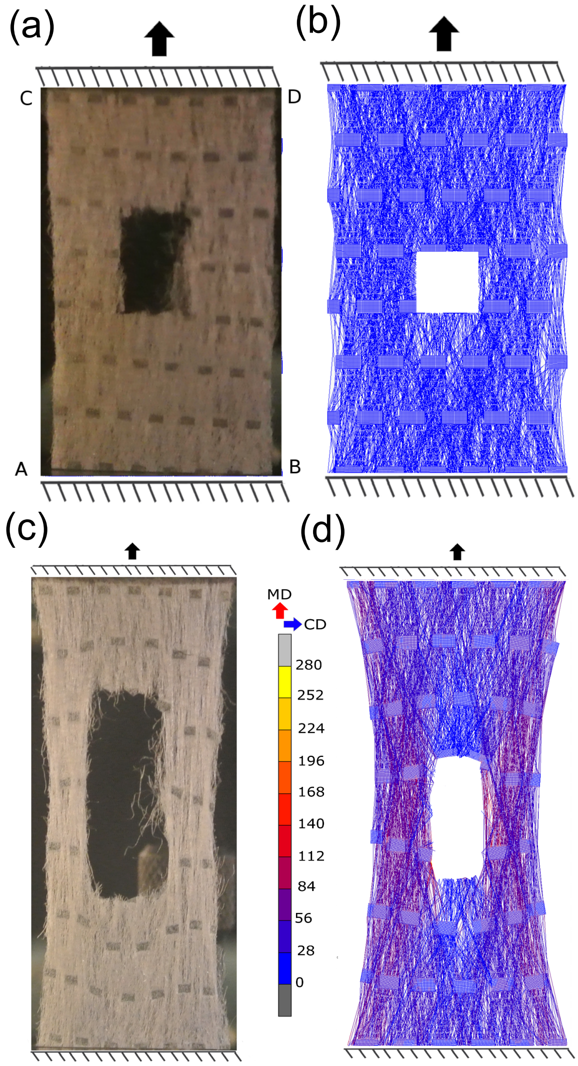


**Figure 3.** Undeformed specimen with square notch (dimensions 10 mm x 16.5 mm) (a) and finite element model(b). Notched specimens stretched by 30 percent demonstrate similar deformed shape in experiments and simulations c and d, showing also von Mises stress).

### *3.2. Numerical results and comparisons*

At micro scale, at the initial stage of deformation, reorientation of fibres defined the respective stress-strain behaviour. Then, stress concentration around the notch began to increase, generating tension in fibres surrounding the notch. Further increases in the load overcame local frictional forces between these fibres, and the size of a damaged area grew significantly, limiting contraction in the lateral direction. The stress transfer was also channelled to other fibres due to the presence of frictional fibre-to-fibre contacts, and when these inter-fibre forces were overcome, the final rupture occurred in the nonwoven material.

From the experimental tests, the shapes of notch-induced damages were found to change significantly at high levels of stain. The square hole became rectangular, stretched along

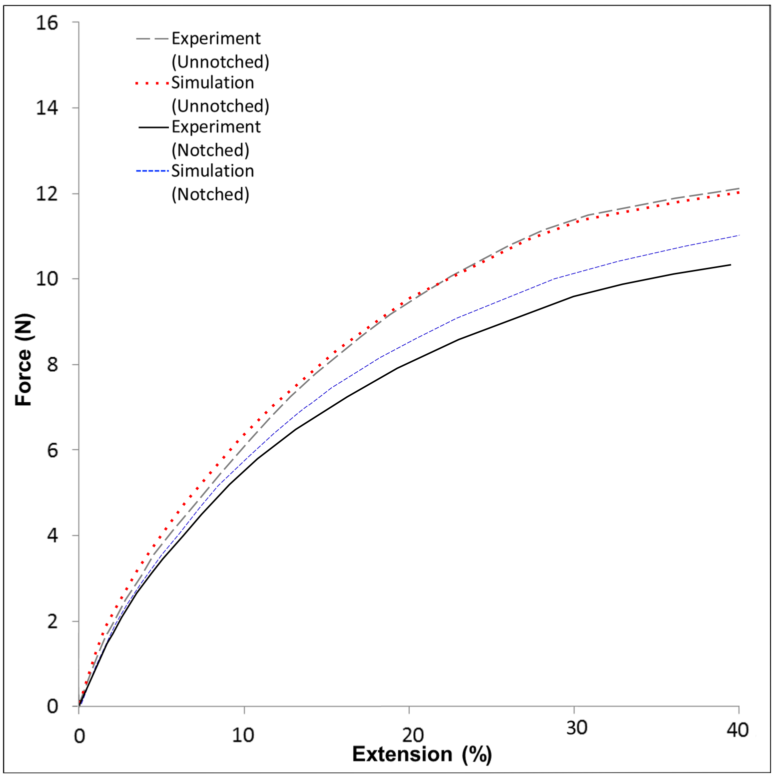


**Figure 4.** Force-displacement curves for notched and un-notched specimens obtained in experiments and simulations

the machine direction. In addition, force-displacement diagrams of notched and un-notched specimens obtained in experiments (mean curves) and simulations were compared, see Fig. 4; these curves show a good correlation. The trend of the curves on un-notched specimens is clearly above square notched specimens.

## 4. Conclusions

In this research, the effect of a central notch on nonwoven fibrous networks was investigated experimentally and numerically. To represent a realistic microstructure of the material in the finite-element model, a random distribution of fibres was introduced employing the measured orientation distribution function of fibres. Using this method, gaps and voids, typical for low-density nonwovens, were successfully represented in the model as well as the distinct character of orientation of fibres. Specimens with a square notch were used in the experiments, and the same geometry was generated in a virtual environment. The growth and final shape of the central notch in simulations are similar to those in the experiments. Similarly, the change in alignment of bond points during the simulations demonstrated behaviour comparable to that in the tests. It is concluded that experiments and simulations are in a good agreement quantitatively and qualitatively. Thus, the current model is capable of reproducing deformation until the onset of damage. Since the damage progress is determined by the fibre scale and the properties of fibres in used in the simulation were obtained from the fibres extracted from fabric rather than unprocessed fibres, the same model can be utilized to simulate fracture of the real material. From the industrial and academic points of view, this continuous modelling approach allows designers and researchers to simulate mechanical behaviour of a wide spectrum of fibrous materials. Factors affecting damage and failure mechanism can be accounted for, and, ultimately, products with optimum manufacturing and material parameters could be designed for their better performance. In the future work, larger experimental specimens will be used to investigate the effect of a notch size on damage progress, though an increase in the size of specimens results in significantly higher computation times. The effect of notch shape on damage mechanism will be also investigated. This investigation can be extended by incorporating fibre-to-fibre interactions.

## 5. Acknowledgements

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