# Notches in fibrous materials: micro-mechanisms of deformation and damage

Emrah Sozumert[a], Farukh Farukh[b], Baris Sabuncuoglu[c], Emrah Demirci[a], Memis Acar[a], Behnam Pourdeyhimi[d], Vadim V. Silberschmidt[a] *

[a]*Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University,Leicester, LE11 3TU, UK*
[b]*School of Engineering and Sustainable Development, De Montfort University, Leicester, LE2 7DP, UK*
[c]*Mechatronics Engineering, University of Turkish Aeronautical Association, Ankara, 06790, Turkey*
[d]*The Nonwovens Institute, Textile Engineering, North Carolina State University, Raleigh, NC 27606, USA*

---

**Abstract**

Fibrous networks are ubiquitous structures for many natural materials, such as bones and bacterial cellulose, and artificial ones (e.g. polymer-based nonwovens). Mechanical behaviour of these networks are of interest to researchers since it deviates significantly from that of traditional materials treated usually within the framework of continuum mechanics. The main reason for this difference is a discontinuous character of networks with randomly distributed fibres (that can be also curved) resulting in complex scenarios of fibre-to-fibre interactions in the process of their deformation. This also affects a character of load transfer, characterised by spatial non-uniformity and localisation.
A discontinuous nature of fibrous networks results in their non-trivial failure character and, more specifically, evolution of failure caused by notches. In order to investigate these mechanisms, various notches are introduced both into real-life specimens used in experimentation and discontinuous finite-element (FE) models specially developed (Farukh et al., 2014a; Hou et al., 2009, 2011a; Sabuncuoglu et al, 2013) to mimic the microstructure of fibrous networks. The specimens were tested under tensile loading in one of the principal directions, with FE-based simulations emulating this regime. The effect of notch shape on damage mechanisms, effective material toughness and damage patterns was investigated using the obtained experimental and numerical methods. The developed discontinuous model with direct introduction of microstructural features of fibrous networks allowed assessment of strain distribution over selected paths in them in order to obtain strain profiles in the vicinity of notch tips. Additionally, evolution of damage calculated in advanced numerical simulations demonstrated a good agreement with images from experiments.

*Keywords:* Fibre materials; fibrous networks; deformation; damage; finite-element analysis; notch

## 1. Introduction

Fibrous networks are omnipresent in many natural materials such as biological tissues, cellulose wood, collagen tissues as well as artificial materials such as nonwovens. Their complex microstructures and interactions between their constituent fibres and/or surrounding matrix complicates characterization and assessment of leading deformation and damage mechanisms. Some existing numerical and analytical models along with experimental results are discussed below.

In our experiments, nonwoven samples were used as one of the types of fibrous networks. In general, nonwoven materials have certain anisotropy in their microstructure due to their manufacture, influencing their mechanical performance in three orthogonal directions: machine direction (MD), cross direction (CD) and thickness direction (MD) (Farukh et al., 2014a). Usually, they exhibit higher stiffness in MD compared to that in CD, and TD. Damage begins with fracture of interfibre bonds in bundles, and this results in a rearrangement of fibres, affecting their orientation distribution in fibre-glass nonwoven materials (Jubera et al., 2014; Ridruejo et al., 2010). Yang et al. (2015) investigated tearing resistance of rabbit skin (another example of fibrous material) and found that four mechanisms decreased the possibility of any tearing in presence of a notch: (i) fibril straightening, (ii) fibre reorientation towards a loading direction, (iii) elastic stretching, and (iv) interfibre sliding.

A research of the effect of fibre orientation distribution on effective elastic properties and strength of fibre networks was conducted, and it was established that elastic behaviour of any kind of fibre distributions could be represented by four set of parallel fibres in various ratios (Cox, 1951). Another theory was presented to predict tensile response of spun-bonded nonwovens in respect to fibre orientation distribution function, elastic modulus - assuming that fibres demonstrate behaviour similar to that of laminate composites (Bais-Singh & Goswami, 1995). A computational model based on an incremental deformation principle – updating a strain level and an effective elastic stiffness tensor due changes in orientation of each fibre with regard to a loading direction – was proposed to predict tensile performance of thermally point-bonded nonwovens (Kim & Pourdeyhimi, 2001). Hägglund and Isaksson (2008) coupled macroscopic material degradation and interfibre bond fracture with a model of a randomly-distributed fibre network, where macroscopic degradation was explained in terms of a fracture parameter, which is linearly related to the inverse of bond density above a certain percolation threshold.

Although a continuous model was not capable of explaining the changes in microstructure (unlike discontinuous models), it was sufficient to analyse the effect of bonding parameters such as bond size and shape. Ridruejo et al. (2010) investigated glass nonwoven felts (employing transversely notched and non-notched samples) using experimental tests and two-dimensional finite-elements models, accounting separately for brittle bond failure and fibre sliding after fracture. Anisotropy coefficients for three orthogonal directions (MD, CD and TD) of fibrous networks might be derived from a fibre orientation distribution (Demirci et al., 2011a), and a tensile response of thermally bonded nonwovens was simulated with a continuous model taking those coefficients into account (Demirci et al., 2011b). Furthermore, for fibres realigned along the loading direction, anisotropy parameters should be updated at every increment of stretching (Raina & Linder, 2014). A lattice-like structure was also used to emulate microstructure of isotropic fibre distributions in nonwoven fibrous mats and constitutive equations were derived to incorporate elastic-plastic response of individual fibres (from RVE in microscale) into a macroscopic model (Silberstein et al., 2012). Discontinuous modelling approach enables to simulate progressive damage evolution by controlling failure of individual fibres (Farukh et al., 2014b).

In this research, the focus is on deformation and fracture mechanisms in presence of various notches in randomly distributed fibre networks. First, virgin samples and samples with various notch shapes were stretched in experiments; second, a feature analysis was conducted to quantify microstructural features such as fibre diameter, fibre orientation distribution, size of bond points. Finally, finite-elements models are generated to quantify changes in microstructure and to obtain strain distribution along notches.

## 2. Material

The material used in this study is 30 g/m$^2$ (or gsm) thermally-bonded nonwoven, composed of mono-component polypropylene fibres (manufactured by FiberVisions, USA). Polypropylene is one of the most commonly used materials for nonwovens thanks to its chemical stability, good mechanical strength and low melting temperature. A calendering process leads to a significant difference in microstructure between bonded and unbounded regions as shown in Fig. 1(a). Apparently, the fabric is composed of staple fibres having diameter of approximately 18 µm with the length of 38.1 mm and linear density around 2.3 denier.

## 3. Experimentation

### *3.1. Assessment of properties*

Mechanical properties of fibres were assessed by performing tensile tests on fibres extracted from the fabric. These single-fibre tests are essential for discrete FE simulation of nonwoven. Details of the single-fibre test are given elsewhere (Sabuncuoglu et al., 2013) . In order to obtain an orientation distribution function (ODF) of fibres, samples were prepared and their images were taken using scanning electron microscopy (SEM). A representative image, which illustrated the clearest view of fibres, was scanned with the algorithm based on the image-analysis techniques and the orientation distribution of fibres was computed.

### *3.2. Notch sensitivity deformation and damage*

Four different types of central notches – square, diamond, circle and slit notches – were introduced in square and rectangular specimens of the nonwoven fabric subjected to a tensile load. Dimensions for rectangular and square coupons were 25 x 25 mm$^2$, 50 x 50 mm$^2$, 25 x 50 mm$^2$ and 50 x 100 mm$^2$. Various notch sizes and shapes – along with different specimen sizes – helped to understand the effects of a specimen size on deformation and damage mechanisms as well as notch-sensitive behaviour of a nonwoven network. In order to take anisotropy of the nonwoven fabric into account, tests were performed along both machine and cross directions of the fabric with Benchtop Tester ® with pneumatic grips.

## 4. Finite-element model development

The models with slits were generated in a finite-element model previously developed to analyse mechanical behavior of thermally bonded nonwovens (Sabuncuoglu et al, 2011). For this purpose, a script was written in Patran Design Language (PCL) to be read by the FE analysis software Patran®. With the script, the fibres were modelled as truss elements that were joined with the shell elements representing the bond points. The code took the dimensional and material parameters as well as orientation distribution of fibres (shown in Fig. 1 (b) as inputs. Then, the FE model of the thermally bonded nonwoven was generated according to those parameters and the random location distribution of fibres.

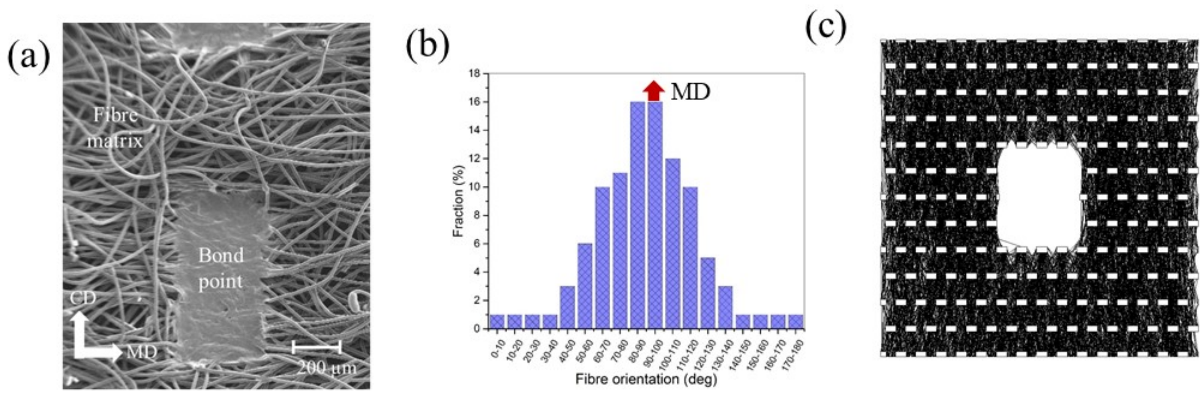


Fig. 1. (a) SEM image of 30 g/m$^2$ thermally bonded calendared nonwoven; (b) ODF calculated from SEM images; (c) FE model for square notch specimen

The longitudinal slit and the square notch were generated symmetrically with regard to the centre of the fabric according to dimensions of 6.35 mm for 25 x 25 $mm^2$. The model with a square notch of 6.35 mm is shown in Fig. 1(c).

## 5. Results

### *5.1. Tensile tests, deformation and damage of networks*

The samples were stretched in MD and force-extension data were recorded during the experiments. The force data was normalized by the effective width (equal to the difference between the specimen width and the notch width) to assess deformation and damage behaviours by a corresponding part exposed to external loading. Different levels of sensitivity to various shapes and aspect ratios of the notches were observed. Toughness of the tested samples were calculated from the normalized force-extension data in Table 1 and maximum normalized strengths were obtained from the curves in Table 2.

Table 1: Toughness (normalized by cross-section carrying load) (N) for virgin samples and various notch samples

| Sample Size/Damage | Virgin | Longitudinal Slit | Square |
|---|---|---|---|
| 25 x 25 $mm^2$ | 41.5 | 36.9 | 41.3 |
| 25 x 50 $mm^2$ | 71.4 | 88.9 | 72.1 |
| 50 x 50 $mm^2$ | 52.5 | 62.1 | 42.8 |
| 50 x 100 $mm^2$ | 178.1 | 167.4 | 132.5 |

Table 2: Maximum strength (normalized by the cross-section carrying load) (N/mm) for virgin samples and various notch samples

| Sample Size/Damage | Virgin | Longitudinal Slit | Square |
|---|---|---|---|
| 25 x 25 $mm^2$ | 1.66 | 1.67 | 1.71 |
| 25 x 50 $mm^2$ | 1.48 | 1.43 | 1.53 |
| 50 x 50 $mm^2$ | 1.52 | 1.53 | 1.44 |
| 50 x 100 $mm^2$ | 1.53 | 1.47 | 1.56 |

The levels of tensile strength of virgin specimens and specimens with longitudinal slit are the same. The main factor of this behaviour is fibre orientation distribution of fibrous specimens, and the longitudinal cut did not damage many of fibres carrying the axial load. On the other hand, the circular cut decreased toughness of the fibrous networks substantially. As for the maximum normalized strengths, the aspect ratio of specimens did not affect it much, but the notch shape did.

Fibres in specimens were straightened in the tensile tests, and, then, they started to participate in a load transfer; meanwhile, they were re-aligned continuously towards the loading direction. When the samples were stretched along the MD, weak areas (with a lower spatial density of fibres) occurred at random locations, and fibres were bundled around bond points. Introduced damage areas in the samples grew in both MD and CD, and the rate of damage growth was bigger in MD than that in CD. The sharp edges of the introduced damage were blunted as a result of such processes. Bond points in the specimens were rotated by different amounts due to non-uniformity in fibre orientation distribution and complex interaction between them and attached fibres.

### *5.2. Finite-element simulations and strain-distribution analysis*

Images of the specimens with the slit and the square notch were obtained in experiments and FE simulations, and their comparisons are presented in Fig. 2. It is clear that deformation and damage features (such as necking) of the specimens were reproduced by the FE models. Blunting of sharp edges of the introduced damages in experiments were also captured in the simulations. From the macroscopic point of view, it was found the longitudinal slit and the central square notch became an elliptical and a rectangle damage zones, respectively in specimens in both the experiments and the numerical simulations.

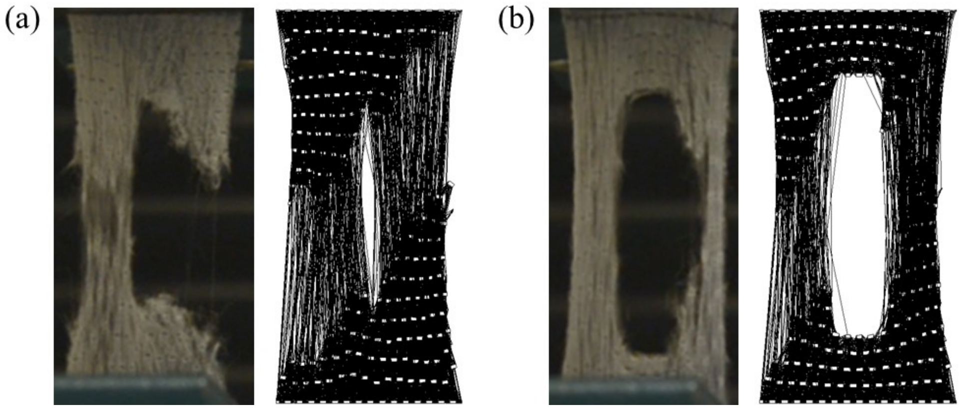


Fig. 2: Comparison of damage patterns for slit (a) and square notch (b) at extension of 100%

In the FE simulations, fibres of specimens with the slit and the square damage were tracked to assess the extent of localization of strain distributions over two parallel paths (shown in in Figs. 3 (a) and (b)); distributions of logarithmic strain for the selected paths at overall fabric extension of 90% are presented in the same figures. The failure strain of individual fibres $\varepsilon_f$ was 1.0. It was observed that, in strain distributions of slit-damage case, no sharp increase at the notch tip was obtained. The main reason is attributed to distinct load-transfer mechanisms, where fibres realigned along the longitudinal (loading) direction might not transfer their high deformation to the neighborhood fibres. In contrast to the specimen with the slit, the one with the square notch demonstrated behavior close to that of continuous materials, with the load easily transferred in the longitudinal and transverse directions. Therefore, a presence of notch in specimens can intensify stress distribution at the notch tip. Additionally, strain localisations affected by the number of fibres at notch tips can be controlled by the notch shape.

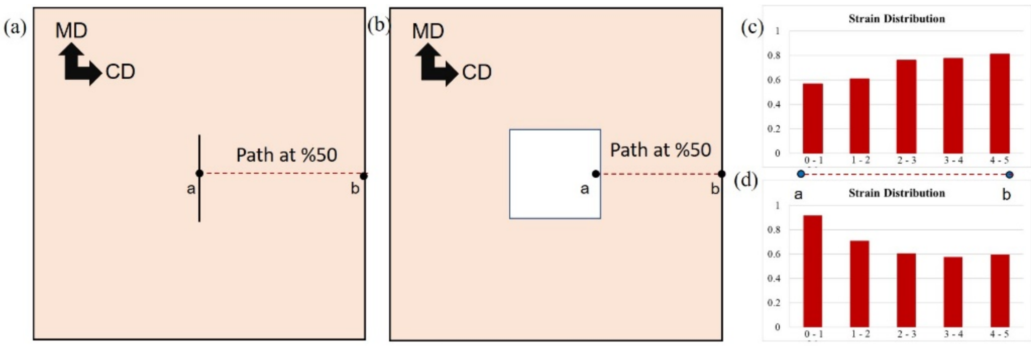


Fig. 3: Two paths selected in specimens with slit (a) and square notch (b). (c) Strain distributions along paths a-b for slit (c) and square notch (d) calculated at global extension of 90%

## 6. Conclusions

The micromechanisms of falure evolution in the nonwoven specimens with introduced notches and without them were investigated. Fibrous networks were tested experimentally with axial loading on a set of samples with various notch shapes and various specimen's aspect ratios. Additionally, stretching of specimens with two notch shapes (square notch and longitudinal slit) were analyzed in FE simulations to perform a strain-distribution analysis. Some conclusions can be drawn from these studies:

- While the notch shape had a significant effect on toughness of the fibrous network,s the sample size had no significant effect on their maximum strength.
- The deformation and damage performances of the samples with the longitudinal slit were found similar to those of the samples without any notch.
- Material toughness and the maximum strength of fibrous specimens were decreased by the highest extent in the case of the circular notch.
- The damage growth, strain localizations and failure patterns in the experiments and the FE simulations showed a good agreement.

## Acknowledgements

We greatly acknowledge the support by the Nonwoven Institute at North Carolina State University, Raleigh, USA, and the EU Framework Programme for Research and Innovation: Horizon 2020 (MSCA RISE-2014 grant No 644175 MATRIXASSAY).

## References

Bais-Singh, S., Goswami, B. C., 1995. Theoretical Determination of the Mechanical Response of Spun-bonded Nonwovens. Journal of Textile Institute, 862, 271–288.

Cox, H. L., 1951. The elasticity and strength of paper and other fibrous materials. British Journal of Applied Physics, 33, 72–79.

Demirci, E., Acar, M., Pourdeyhimi, B., Silberschmidt, V. V., 2011a. Computation of mechanical anisotropy in thermally bonded bicomponent fibre nonwovens. Computational Materials Science, 521, 157–163.

Demirci, E., Acar, M., Pourdeyhimi, B., Silberschmidt, V. V., 2011b. Dynamic Response of Thermally Bonded Bicomponent Fibre Nonwovens. Applied Mechanics and Materials, 70, 405–409.

Demirci, E., Acar, M., Pourdeyhimi, B., Silberschmidt, V. V., 2011c. Finite element modelling of thermally bonded bicomponent fibre nonwovens: Tensile behaviour. Computational Materials Science, 504, 1286–1291.

Farukh, F., Demirci, E., Sabuncuoglu, B., Acar, M., Pourdeyhimi, B., Silberschmidt, V. V., 2014a. Mechanical behaviour of nonwovens: Analysis of effect of manufacturing parameters with parametric computational model. Computational Materials Science.

Farukh, F., Demirci, E., Sabuncuoglu, B., Acar, M., Pourdeyhimi, B., Silberschmidt, V. V., 2014b. Numerical analysis of progressive damage in nonwoven fibrous networks under tension. International Journal of Solids and Structures, 519, 1670–1685.

Hägglund, R., Isaksson, P., 2008. On the coupling between macroscopic material degradation and interfiber bond fracture in an idealized fiber network. International Journal of Solids and Structures, 453–4, 868–878.

Hou, X., Acar, M., Silberschmidt, V. V., 2009. 2D finite element analysis of thermally bonded nonwoven materials: Continuous and discontinuous models. Computational Materials Science, 463, 700–707.

Hou, X., Acar, M., Silberschmidt, V. V., 2011a. Finite element simulation of low-density thermally bonded nonwoven materials: Effects of orientation distribution function and arrangement of bond points. Computational Materials Science, 504, 1292–1298.

Hou, X., Acar, M., Silberschmidt, V. V., 2011b. Non-uniformity of deformation in low-density thermally point bonded non-woven material: Effect of microstructure. Journal of Materials Science, 462, 307–315.

Jubera, R., Ridruejo, A., González, C., LLorca, J., 2014. Mechanical behavior and deformation micromechanisms of polypropylene nonwoven fabrics as a function of temperature and strain rate. Mechanics of Materials, 74, 14–25.

Kim, H. S., Pourdeyhimi, B., 2001. Computational Modeling of Mechanical Performance in Thermally Point Bonded Nonwovens. Image Rochester, N.Y., 14, 1–7.

Raina, A., Linder, C., 2014. A homogenization approach for nonwoven materials based on fiber undulations and reorientation. Journal of the Mechanics and Physics of Solids, 651, 12–34.

Ridruejo, A., Gonzlez, C., Llorca, J., 2010a. Damage micromechanisms and notch sensitivity of glass-fiber non-woven felts: An experimental and numerical study. Journal of the Mechanics and Physics of Solids.

Sabuncuoglu, B., Acar, M., Silberschmidt, V. V., 2011. Analysis of Creep Behavior of Polypropylene Fibers. Applied Mechanics and Materials, 70, 410–415.

Sabuncuoglu, B., Acar, M., Silberschmidt, V. V., 2013. Finite element modelling of fibrous networks: Analysis of strain distribution in fibres under tensile load. Computational Materials Science, 79, 143–158.

Sabuncuoglu, B., Demirci, E., Acar, M., Silberschmidt, V. V., 2013. Analysis of rate-dependent tensile properties of polypropylene fibres used in thermally bonded nonwovens. Journal of the Textile Institute, 1049, 965–971.

Silberstein, M. N., Pai, C.-L., Rutledge, G. C., Boyce, M. C., 2012. Elastic–plastic behavior of non-woven fibrous mats. Journal of the Mechanics and Physics of Solids, 602, 295–318.

Yang, W., Sherman, V. R., Gludovatz, B., Schaible, E., Stewart, P., Ritchie, R. O., Meyers, M. A., 2015. On the tear resistance of skin. Nature Communications, 6, 6649.