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Finite Element Simulation of Low-Density Thermally Bonded Nonwoven Materials: Effects of Orientation Distribution Function and Arrangement of Bond Points

Xiaonan Hou, Memiş Acar and Vadim V. Silberschmidt

Wolfson School of Mechanical and Manufacturing Engineering

Loughborough University, Leicestershire, LE11 3TU, UK

Abstract

A random and discontinuous microstructure is one of the most characteristic features of a low-density thermally bonded nonwoven material, and it affects the mechanical properties of the nonwoven material significantly. To understand the effect of the microstructure on the overall mechanical properties of the nonwoven material, discontinuous models are developed with random discontinuous structures representing microstructures of real nonwoven material. Measured elastic material properties of polypropylene fibres is introduced into the models to simulate the tensile behaviour of the material for both principle directions: machine direction (MD) and cross direction (CD). Moreover, varying arrangements of bond points and schemes of fibres' orientation distribution are implemented in the models, and the respective effects are analyzed.

PACS: 02.70.Dh; 62.40.+I; 46.65.+g

Keywords: Nonwovens; Finite Element Analysis; Random Microstructure; Anisotropic Behaviour

Introduction

Nonwoven fabric are engineered materials, which are bonded together by random fibres mechanically, thermally or chemically. Within the last 50 years, many efforts have been made to study their material properties. In the literature, the nonwoven fabric is described as an anisotropic, nonhomogeneous, discontinuous and highly nonlinear material [1-4]. From the view point of material's microstructure, the tensile behaviour of nonwovens is determined by the properties of fibres (their mechanical properties and orientation distribution function) and bond areas (their mechanical properties, shape, spacing and frequency). The present theories used to describe the tensile behaviour of thermally bonded nonwoven material are mostly based on a "cell theory", with the nonwoven material divided into cells and each cells containing the features of material's microstructure [5-10]. However, those methods do not allow researches to reveal the real deformation mechanisms of thermally bonded nonwoven materials due to the use of periodic boundary conditions; the models are not capable to describe properly nonuniformity of the nonwoven materials. Therefore, a discontinuous finite element (FE) model with a random fibre assembly was introduced in our earlier paper to describe the mechanical performance of the low-density thermally bonded nonwoven material [11]. In further stages of developing the model, the efforts are made on exploring the capability of the method and the range of problems, to which it can be applied. In this paper, to improve the suggested model, the developed programme, which generates the random fibrous web, is modified to avoid unconnected areas. Then the initial modulus of representative fibres, which form the random fibrous web of the discontinuous models, is determined according to the real material properties of polypropylene fibres. The obtained modulus is introduced into the discontinuous model. Finally, to investigate the effects of fibre's

orientation distribution function (ODF) and arrangement of bond points on overall material properties of the nonwoven material, two different fibres orientation distributions and four different arrangements of bond points are implemented into the discontinuous model and the obtained results are analysed.

Development of discontinuous FE model

The main approach for developing the discontinuous FE model is discussed in our previous paper [11], where the geometry part of the model was generated by assuming the fibres to be straight and arranged according to their orientation distribution function. Due to the large number of fibres, forming the real nonwoven material, it is not practical and efficient to introduce the exact number of fibres into the discontinuous model. The trusses within its geometry part of the FA model are representative fibres, which represent a certain number of fibres having close directions. To introduce real material properties of single fibres into the discontinuous model, it is essential to determine how many fibres correspond to one representative fibre in the model. Therefore, to generate the geometry part with proper numbers of representative fibres, the fibre density of the real nonwoven material have to be determined first. For the real nonwoven material, the average number of fibres n within a certain area A_{fabric} is calculated according to equation 1:

$$n = \frac{\rho_{\text{fabric}} \times A_{\text{fabric}}}{\bar{l} \times \bar{a}_{\text{fibre}} \times \rho_{\text{fibre}}} , \quad (1)$$

where ρ_{fabric} is the density of the nonwoven material, its specific unit is gram per square meters (gsm), \bar{a}_{fibre} is the average cross area of the fibres, ρ_{fibre} is the density of polypropylene fibres, \bar{l} is the average length of the fibres within the area A_{fabric} .

To determine the value of \bar{l} , the Python programme [11] is modified and used to simulate the result of manufacturing process, when the staple fibres are assembled on the transfer belt to form a random fibrous web (Fig.1). During the process, the arrangement of fibres, specifically, the fibres' orientation distribution is determined [4,12]. In the simulation, the arrangement of fibres is according to the measured orientation distribution function of the material. The programme defines a web (Fig. 1) with area $25 \text{ mm} \times 20 \text{ mm}$ and includes 245 trusses. The length of each truss within the web is calculated according to their coordinates, and the average magnitudes are determined for each realisation. The results in Table 1 demonstrate that the average lengths do not deviates much from the global average of 20.42 mm that is used in Eq. 1.

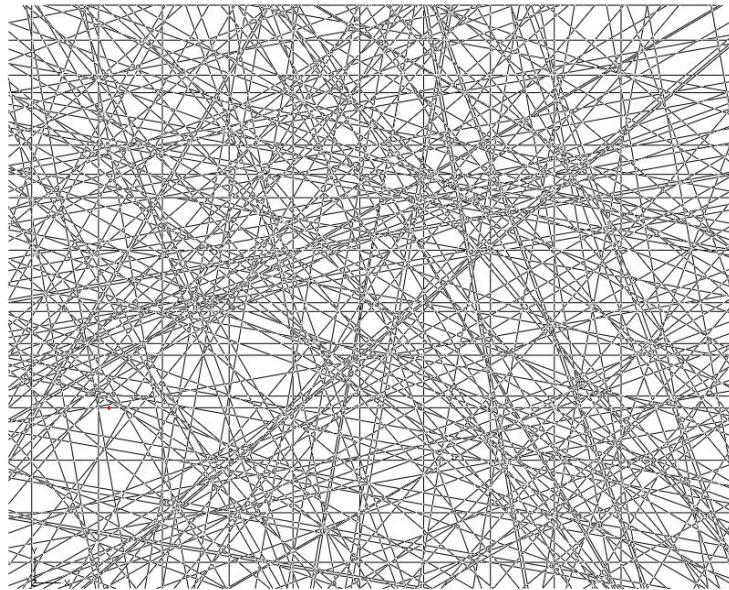


Figure 1: Random fibrous web with $25 \text{ mm} \times 20 \text{ mm}$ area

Table 1: Average length of fibres for different statistical realizations of random fibrous web

Sample	1	2	3	4	5	6	Average value
Average length of fibres (mm)	20.18	20.09	19.98	21.16	20.69	20.40	20.42

The ratio γ of the number of the trusses n' within the discontinuous model to the number of fibres within the real material n can be introduced in the following way:

$$\gamma = \frac{n'}{n}, \quad (2)$$

where n' is measured for the same A_{fabric} . Therefore, the input effective modulus of the lines within the discontinuous model is calculated for the elastic stage as

$$E_{\text{effective}} = \frac{1}{\gamma} E_{\text{fibre}}. \quad (3)$$

The loading conditions used in the discontinuous FEA model are to simulate a tensile test with a constant test speed. But due to the microstructure of the nonwoven material, which is formed by fibres along different orientations, the loading conditions of the fibres differ according to their relative orientations and locations. Figure 2 presents the extension mechanism of a fibre within the nonwoven material, which has original length L and oriented at angle θ to the cross direction. When the fibre is stretched by the external loading force along the machine direction (MD), it demonstrates two types of behaviour: first, it is extended along its own axis. Second, it is reoriented towards the loading direction. Obviously, since the fibres of the nonwoven are assembled randomly with different original angles θ , even when the overall material is extended uniformly with a constant rate, different fibres are stretched with different extension rates along their own axes.

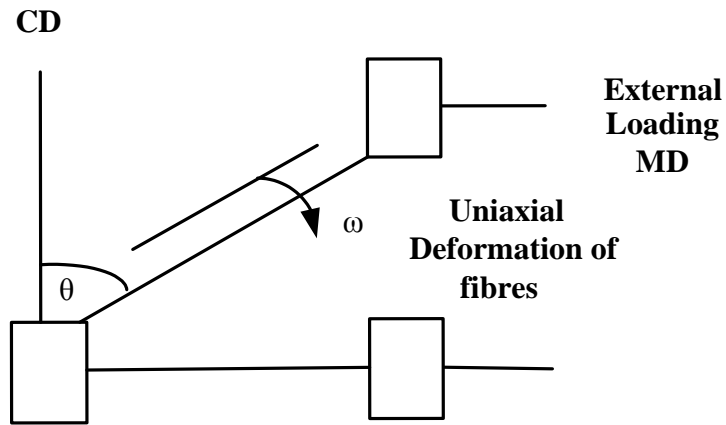


Figure 2: Extension mechanism of fibre within nonwoven fabric

Therefore, the rate-dependent mechanical properties of the polypropylene fibres have to be considered before they are introduced into the discontinuous FE model. Figure 3 shows the tensile behaviour of polypropylene fibres (length: 30 mm) under different testing rates: 50 mm/min, 25mm/min and 12.5 mm/min. It is clear that the mechanical performance of the fibre is highly nonlinear and rate-dependent. However, during the initial stage (I) of the deformation, fibres behave in a similar way and linearly under different testing rates. Moreover, due to the discontinuous microstructure of the material, which is basically formed by loosely arranged fibres, the material's deformation is mainly caused by the rearrangement of fibrous structure. Therefore, the most fibres within the material always have significantly lower levels of strain than the one of the overall material. Hence, the initial modulus of the fibre is used in the discontinuous model to simulate the initial tensile behaviour of the nonwoven material since fibre properties are independent of the extension rate at the initial stage and the fibres are mainly at a low strain level. For the bond points, approximate elastic material properties are employed at this stage because it is hard to measure them experimentally. The chosen modulus is five times higher than that of the fibres.

The Poisson's ratio of polypropylene 0.42 is used in the model for both fibres and bond points.

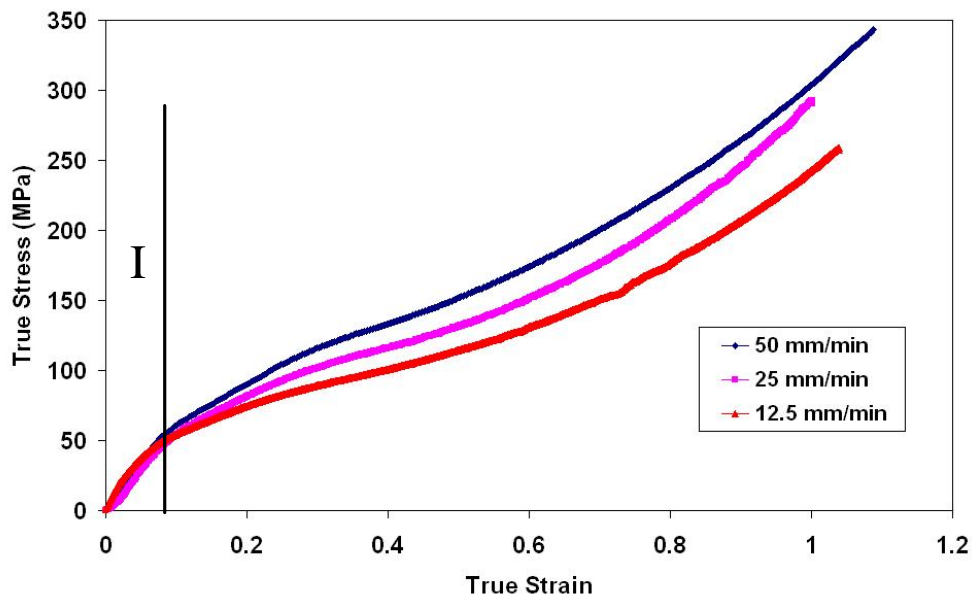


Figure 3: Tensile behaviours of polypropylene fibre at different test speeds

To describe the tensile behaviours of the nonwoven material in its two principle directions - MD and CD -, and analyse the effects of the orientation distribution and arrangement of bond points, eight models with various arrangements of bond points and orientation distributions are developed. Two different fibrous webs are generated according to two different orientation distribution functions as shown in Fig. 4. To ensure that most of the fibres connect to the bond points and avoid unconnected areas, 20 of the 245 lines were generated with designed locations. For OD1 distribution, the highest frequency of fibres occurs for 90° ; a distribution with the largest number of fibres assembled along 0° (loading direction), is denoted OD2. Four different arrangements of bond points – staggered MD, staggered CD, lined MD and lined CD - are suggested for modelling and demonstrated in Fig. 5. The dimensions of bond points for all four arrangements are the same. Within the staggered MD arrangement, the staggered strips of bond points, which are formed by lines of bond points, are

vertical to the loading direction. It is used to simulate the arrangements of bond points for MD specimen of the real nonwoven. The staggered CD simulate the arrangement of bond points for CD specimen of real nonwoven. The arrangement of lined MD and the arrangement lined CD have strips of bond points arranged without staggered. Eight discontinuous models are developed based on two types of fibres orientation distributions and four arrangements of bond points as: (i) OD1/Staggered MD; (ii) OD2/Staggered MD; (iii) OD1/Staggered CD; (iv) OD2/Staggered CD; (v) OD1/Lined MD; (vi) OD2/Lined MD; (vii) OD1/Lined CD and (viii) OD2/Lined CD. The thicknesses of both the fibrous web and the bond points of present models are assumed as constant at 0.02 mm. The elements used in the models are truss element for the fibrous web and shell element for the bond points.

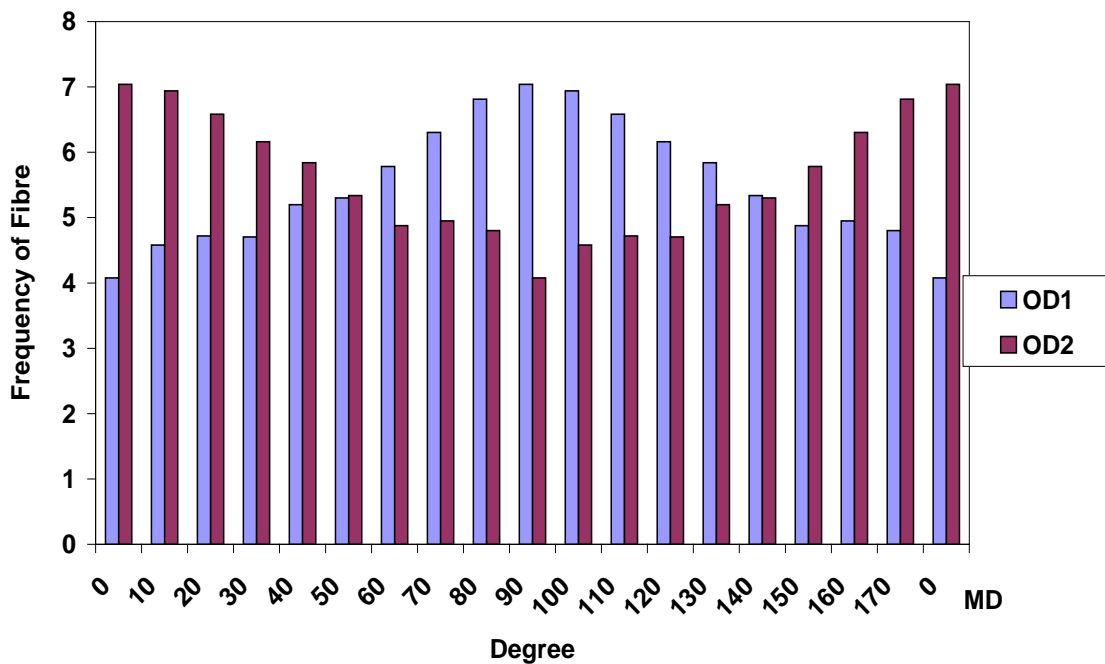
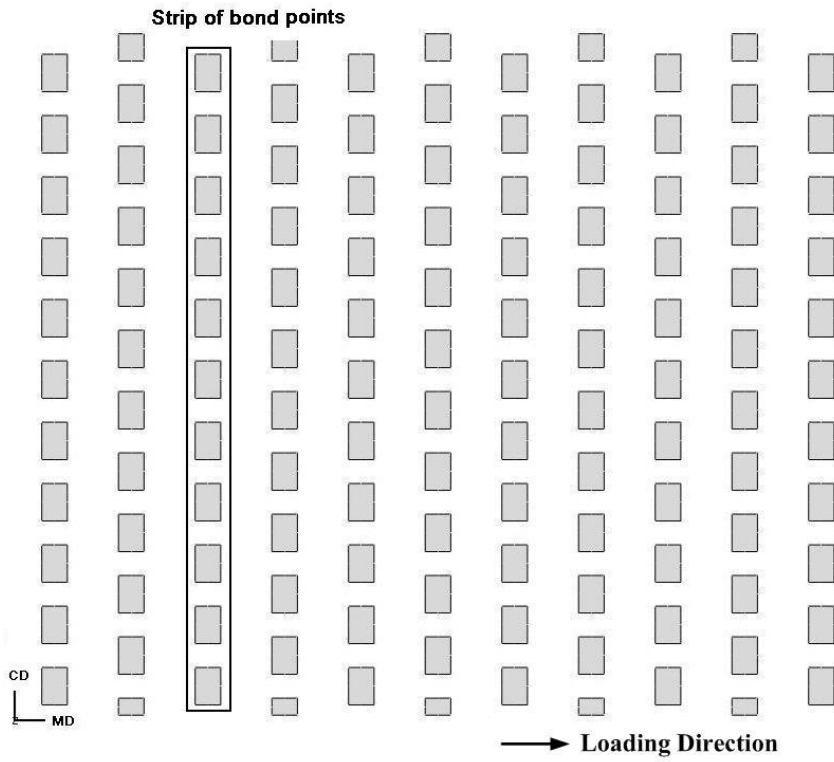
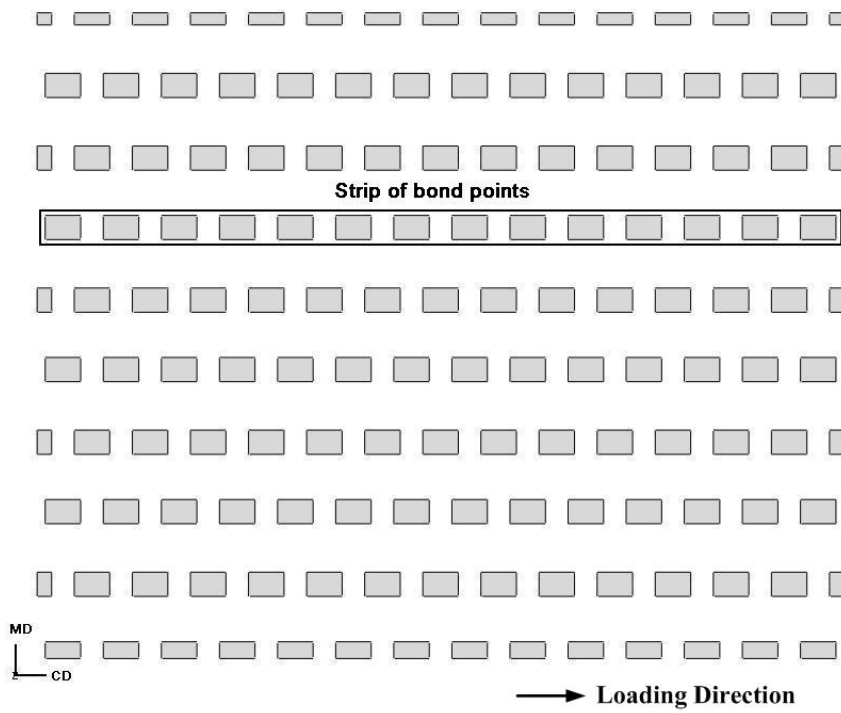


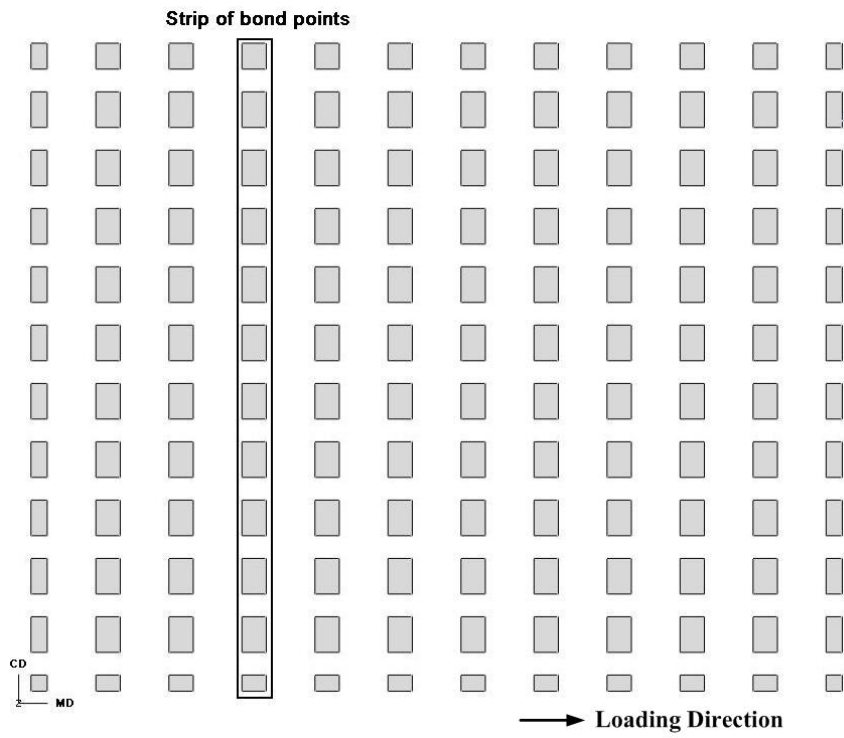
Figure 4: Orientation distribution functions used in discontinuous models



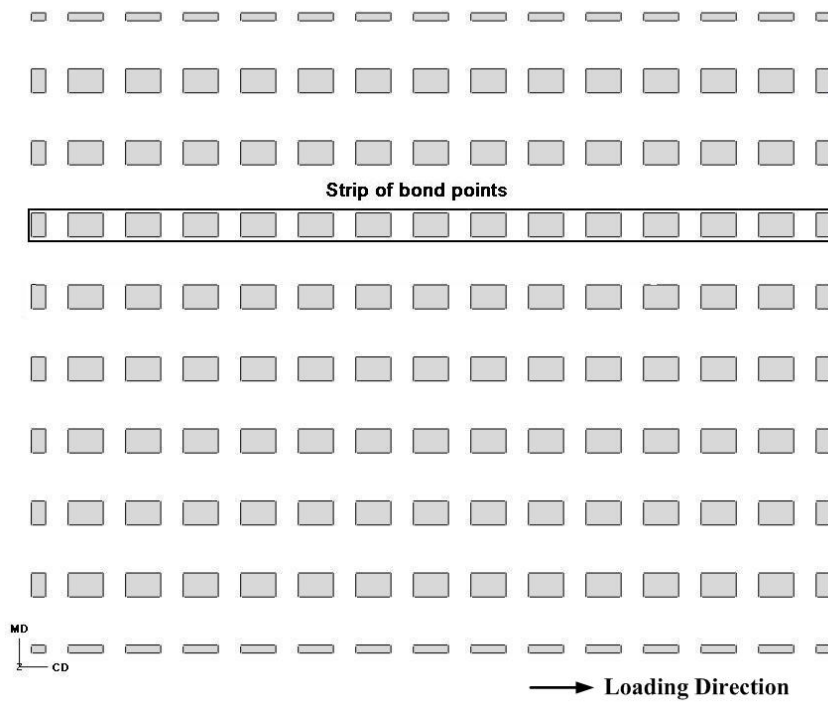
(a)



(b)



(c)



(d)

Figure 5: Arrangement of bond points used in discontinuous model: (a) staggered MD; (b) staggered CD; (c) lined MD; (d) lined CD.

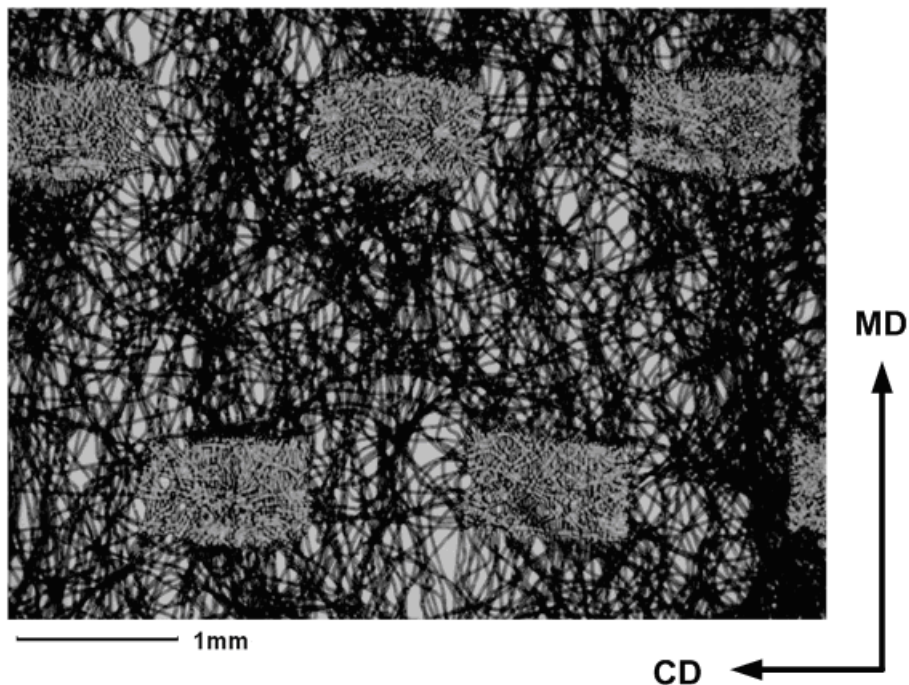
The model OD2/Staggered MD was developed to simulate the tensile behaviour of the real nonwoven material in machine direction. To describe the tensile behaviour in cross direction, the model OD1/Staggered CD was used. Other models are used to investigate the effects of the fibre's orientation and arrangement of bond points by comparing with two models representing the studied real nonwoven. To simulate the tensile behaviours of the nonwoven fabric in two principle directions, the boundary conditions of the models were applied as following: one edge, perpendicular to the loading direction, was fixed as "ENCASTRE". All the degrees of freedom of the nodes located at this boundary are constrained. A uniform displacement (15 mm) in x direction was applied to the opposite boundary of the models to simulate the static tensile deformation.

Analysis of discontinuous FEA models

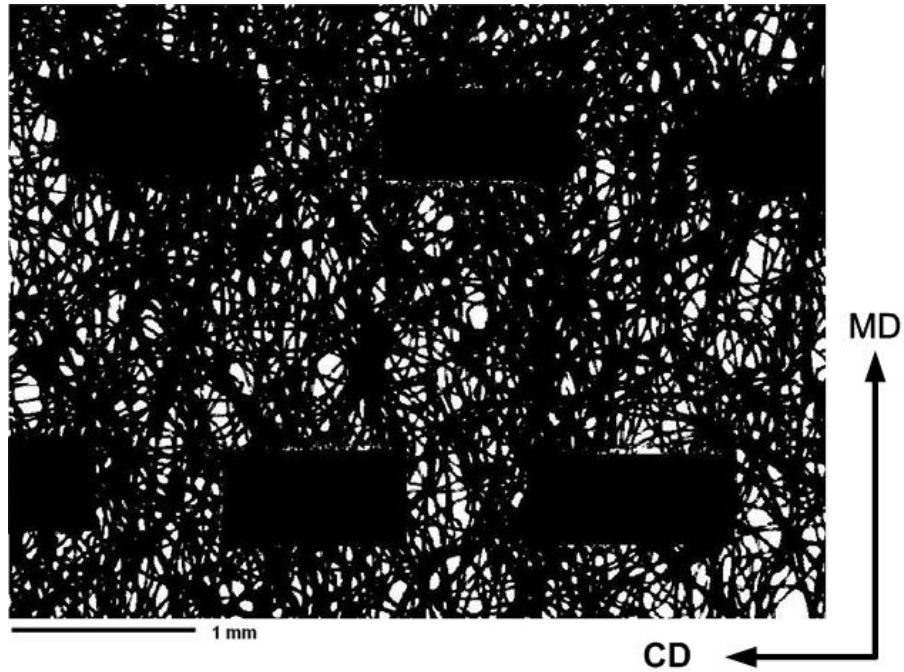
The stress/strain relationships are usually used to quantitatively analyse the results obtained in finite-element simulations. In the area of nonwovens, the traditional unite for stress (or, rather, a distributed load) is Newton per millimetre of the fabric's length with the assumption of the constant thickness of the material, ignoring local thickness fluctuations. However, this method is unsuitable for the low-density nonwovens similar to the one used in present research.

Figure 6a displays the spatially non-uniform microstructure of the low-density nonwoven material. The black colour represents the fibrous web; the white colour represents voids. Voids are randomly located through the material, resulting in its volume changes during the deformation. In axial tension, lateral contraction of the specimen reduces the voids areas due to low compression stiffness of the fibrous

network. This phenomenon results in large overestimation with the traditional strain/stress calculation method. To estimate the effects of voids in the material, the proportion of effective areas (fibrous web and bond points), which could carry out load during the deformation, is calculated with the developed Matlab programme. To improve the assessment method, the picture is converted into a black-and-white one using the gray level threshold of 100 (Fig. 6b). Then the percentage of black pixels as a part of the overall area is calculated; it is equal to 88.01% for the specimen in Fig. 7b. Six images were captured for different areas of the studied material, and the results are shown in Table 2; the average value is 81.68 %. Hence, it is cumbersome to determine the traditionally used strain/stress relationship for this kind of low density nonwoven material. Therefore, all the experimental and numerical results in our research will be presented as the relationship between the force and elongation.



(a)



(b)

Figure 6: Microscopic image of nonwoven material: (a) original picture; (b) black-and-white picture converted with grey level threshold of 100

Table 2: Results of density analysis of nonwoven material

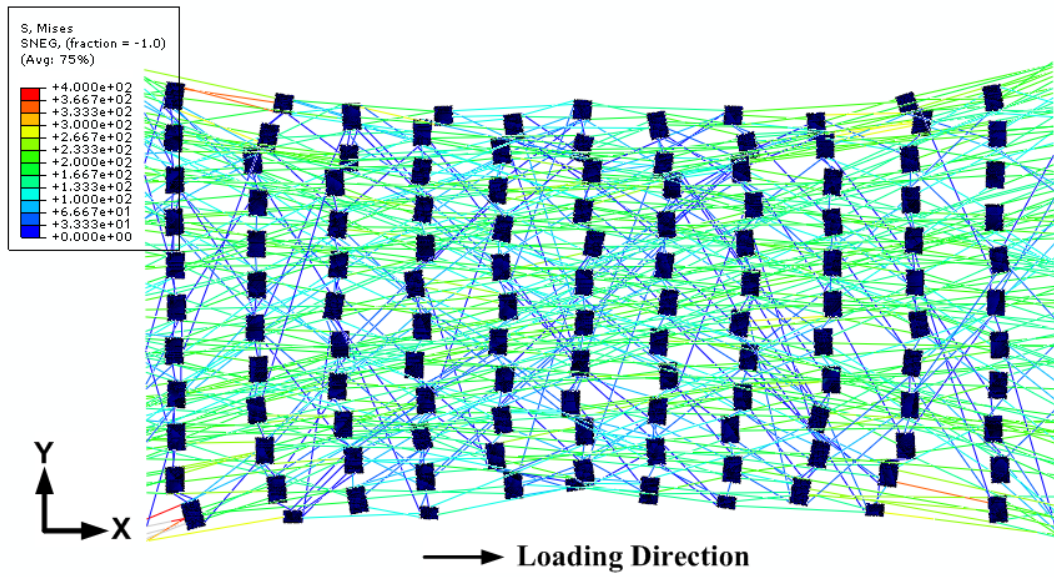
Sample	1	2	3	4	5	6	average	Standard deviation
Percentage (%)	88.01	83.62	78.20	82.61	86.24	71.40	81.68	6.05

Analysis of results of simulations

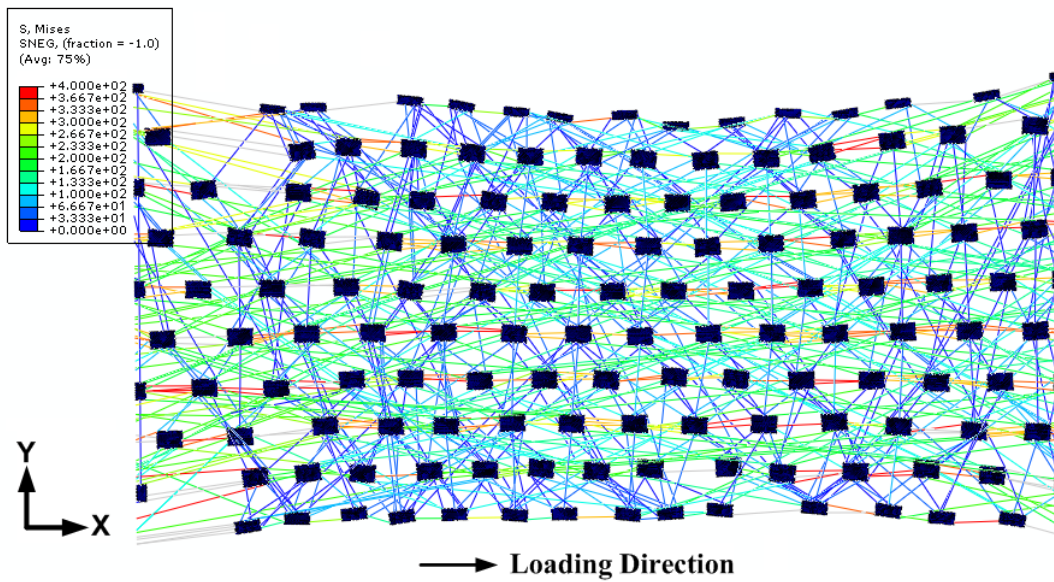
The obtained results of discontinuous FE models are presented in Fig. 7. However, due to the complex structures of the models and relatively high deformation level in the simulations, the elements within the models were distorted and rotated to large degree, especially for the shell elements connected with truss elements. It makes the convergence of the developed models very difficult, and simulations terminate at different strain levels at present stage of our research. As is obvious from Figure 7, all

the models accounting for the random and discontinuous microstructure of the nonwoven material demonstrate the non-uniform stress/strain distributions.

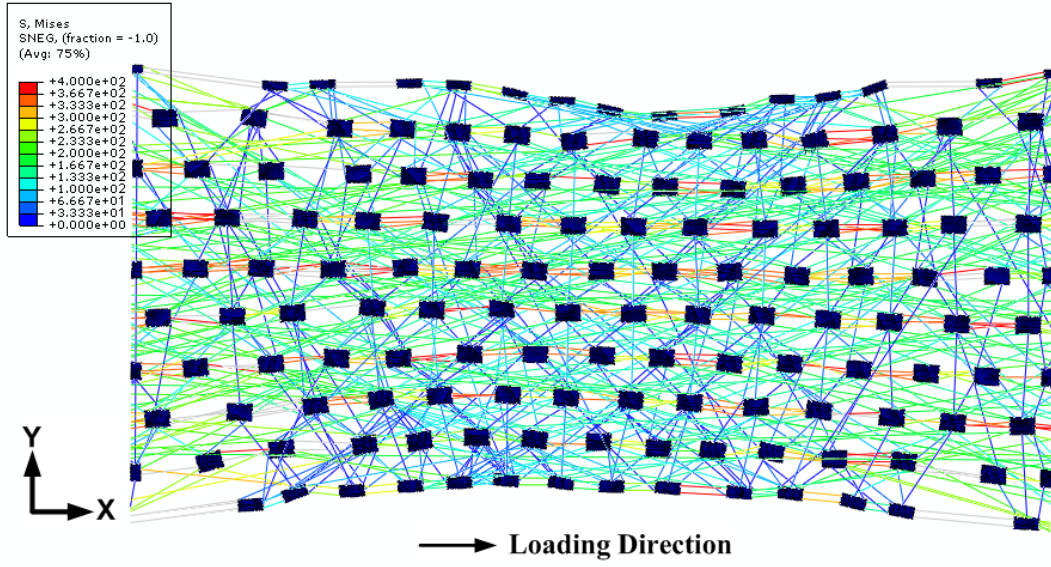
The effect of arrangement of bond points on the deformation mechanism of the material is apparent. The models with the staggered MD and Lined MD arrangements of bond points deform as a stripped system formed by lines of bond points with intermediate layers of fibrous web. The fibres assembled at the corners of the models, which are the ends of the necking curvature, have a higher stress concentration due to the type of boundary conditions. But most of the fibres participate in the load transfer, and the stress distribution is relatively uniform for different fibres. For the models with the staggered CD arrangements of bond points the deformation behaviour is based on a generation of the diamond patterns, which is formed by four neighbouring bond points. Apart of the fibres, located at the corners of the specimens, fibres connecting two neighbouring bond points along the loading direction carry higher stresses even at relatively low strain level, due to their shorter initial length and orientation. It is therefore can be anticipated that these fibres tend to rupture at early stages of the deformation process in the real test. This makes the diamond patterns the basic load carrier, with the load transferred by the boundaries of diamond-shaped cells. The models with lined CD bond points tend to deform as a strip system. However, the bond points can not properly form the strips due to relatively large spaces between two neighbouring bond points along the y direction.



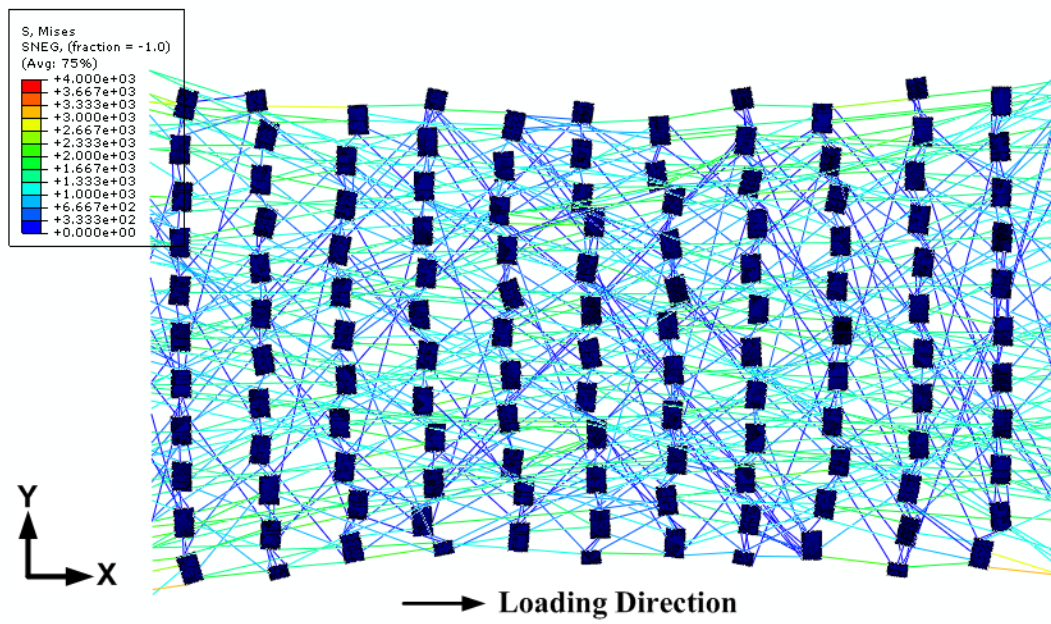
(a)



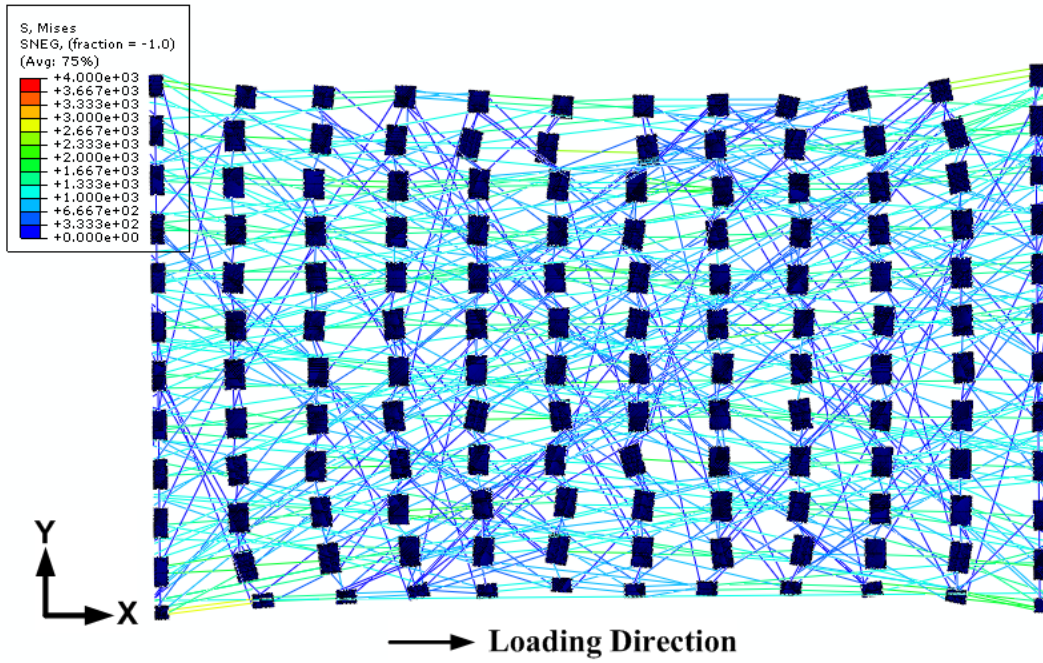
(b)



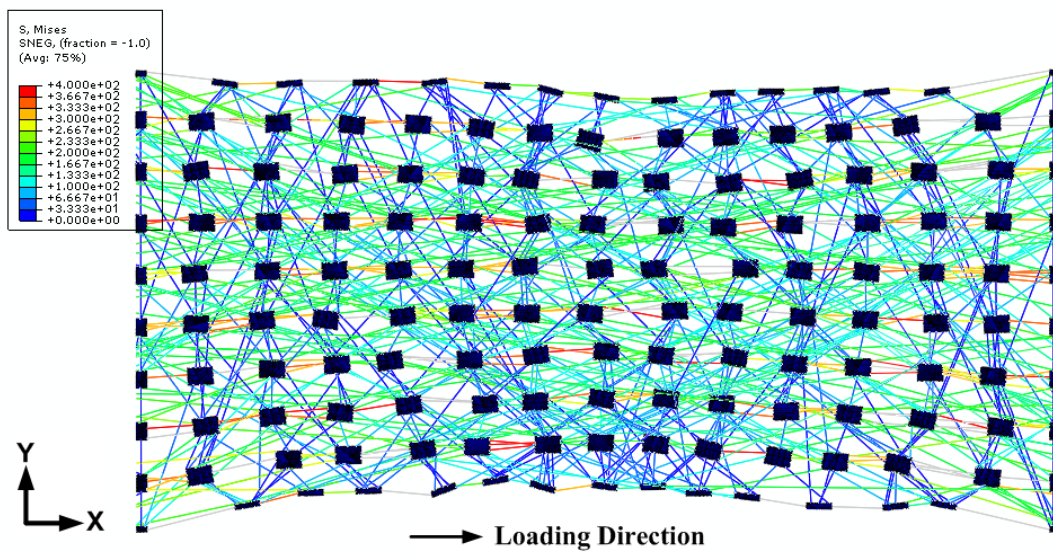
(c)



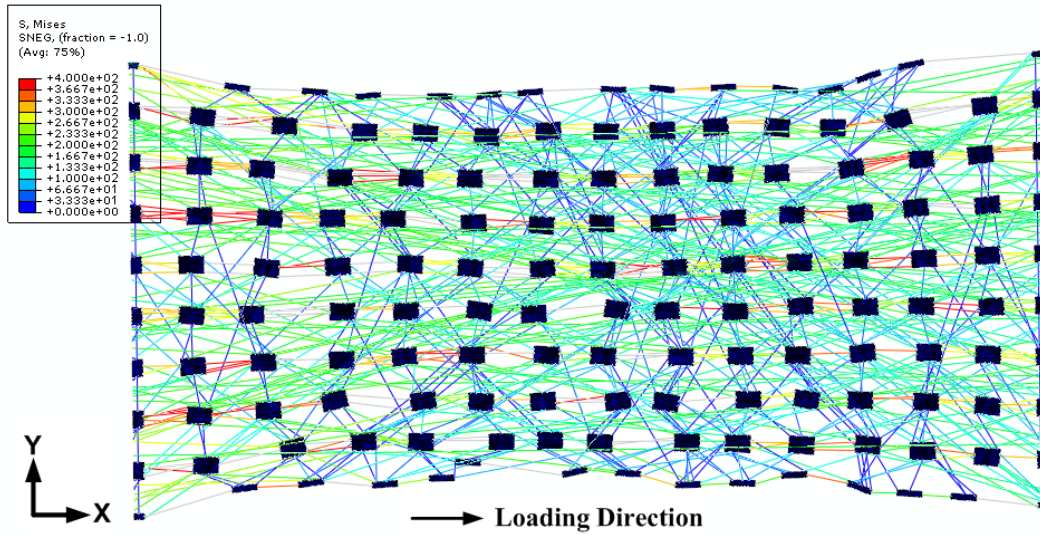
(d)



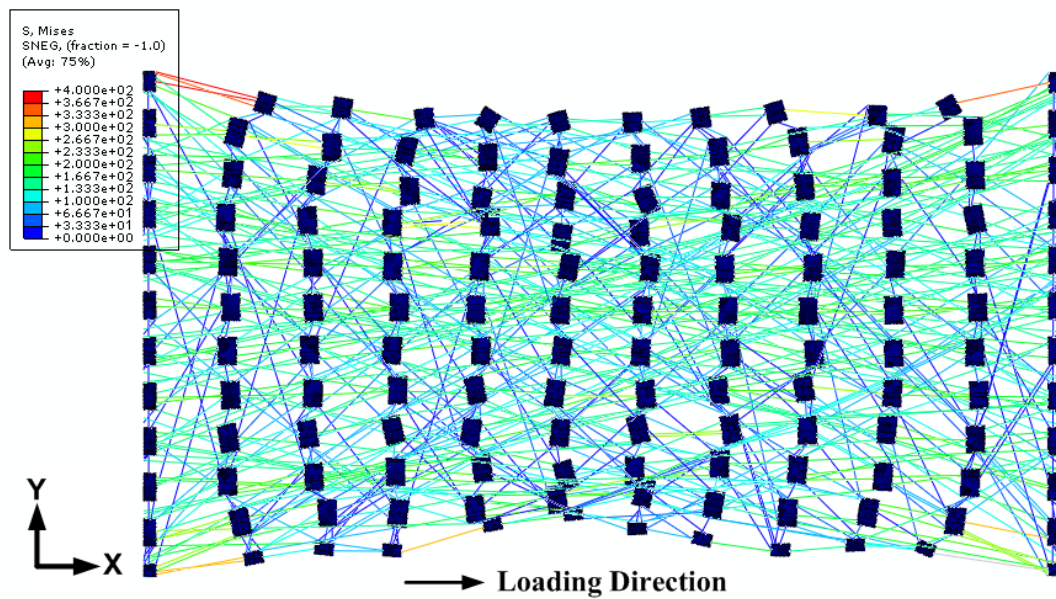
(e)



(f)



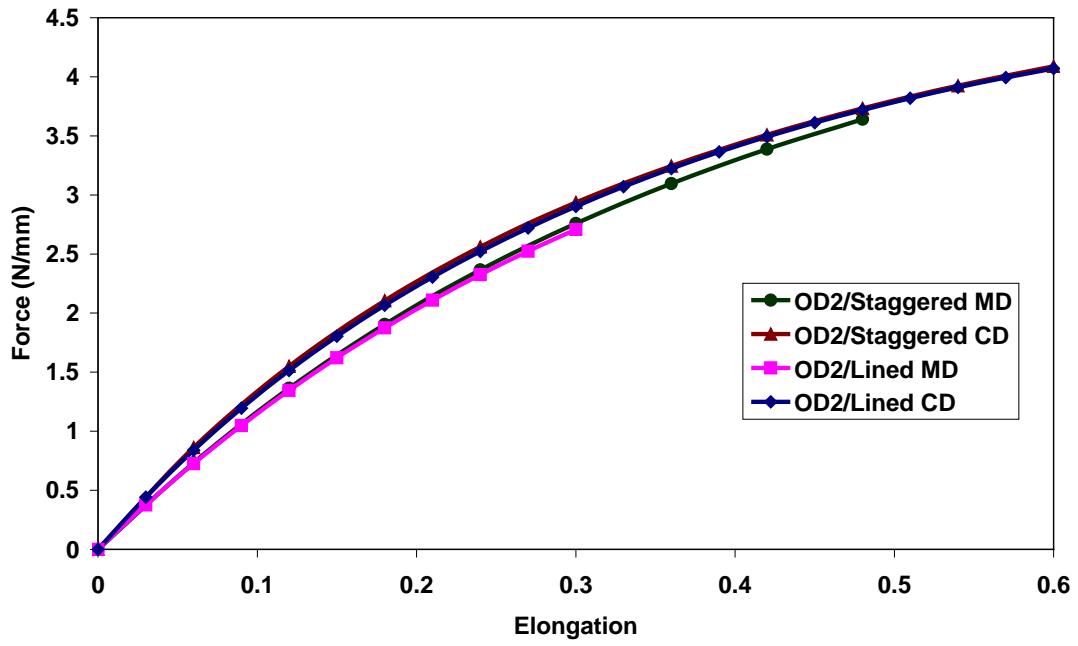
(g)



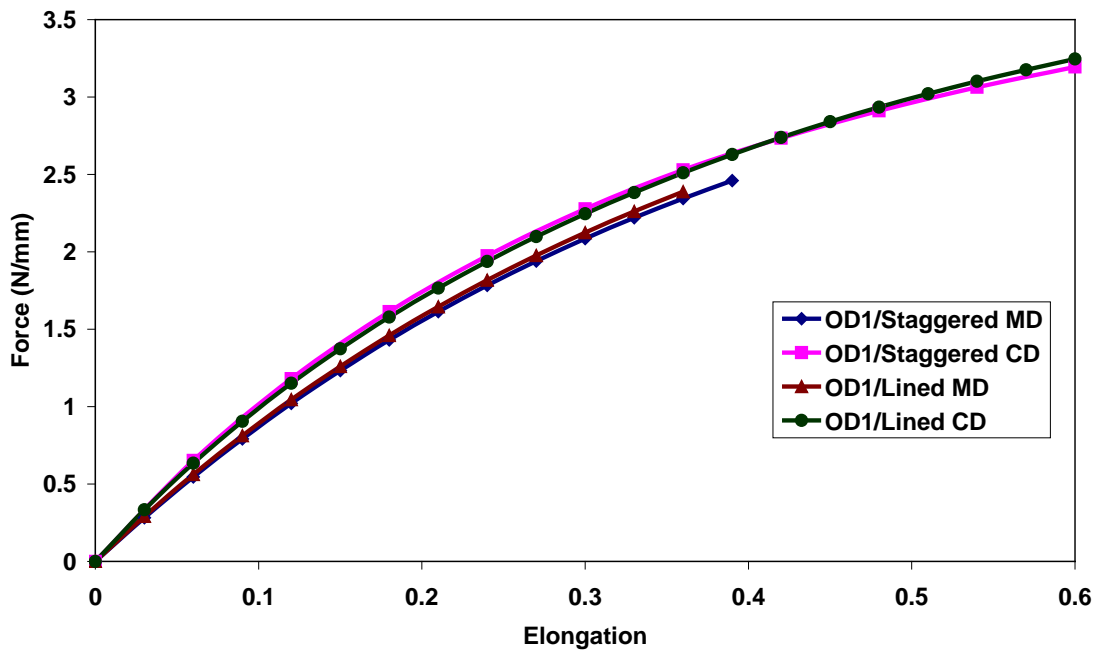
(h)

Figure 7: Deformation of discontinuous FEA models of nonwoven material: (a) OD2/Staggered MD (Strain: 48%); (b) OD1/Staggered CD (Strain: 60%); (c) OD2/Staggered CD (Strain: 60%); (d) OD1/Staggered MD (Strain: 39%); (e) OD2/Lined MD (Strain: 30%); (f) OD1/Lined CD (Strain: 60%); (g) OD2/Lined CD (Strain: 60%); (h) OD1/Lined MD (Strain: 36%).

To analyse the effect of the arrangement of bond points and ODF, models with the same orientation distribution and four different arrangements of bond points are used to compare with each others in order to study the discussed effects. For four models OD2/Staggered MD, OD2/Staggered CD, OD2/Lined MD and OD2/Lined CD, which have the same fibre orientation distribution OD2, the models have a similar material performance (Fig. 8a). And similar results are obtained for four other models OD1/Staggered MD, OD1/Staggered CD, OD1/Lined MD and OD1/Lined CD as shown in Fig. 8b. Although the differences are small, there is still a noticeable trend: the models with Staggered/Lined CD arrangements of bond points have a higher response force than the ones with Staggered/Lined MD arrangements, when the models have the same ODF. Let's note that all the different arrangements of bond points, have the same proportions of bonded areas determined by the spacing between of bond points. It results in similar numbers of fibres connected to bond points and carrying the load. Therefore, the arrangement of bond points does not affect the mechanical response of the nonwoven material significantly during their initial stage. But this effect will become more significant when the fibres within the material achieve their plastic/breaking stage. As demonstrated in simulation results, the different arrangements of bond points result in different deformation mechanisms in the nonwoven material. And the different deformation mechanisms will lead to different stress/strain distributions for the material. In the local area of the material, the fibres, which are basic load carriers, will have different mechanical behaviours depending on their length and orientation. Therefore, when the overall material achieves a higher strain level, the different levels of the overall mechanical response will be obtained.



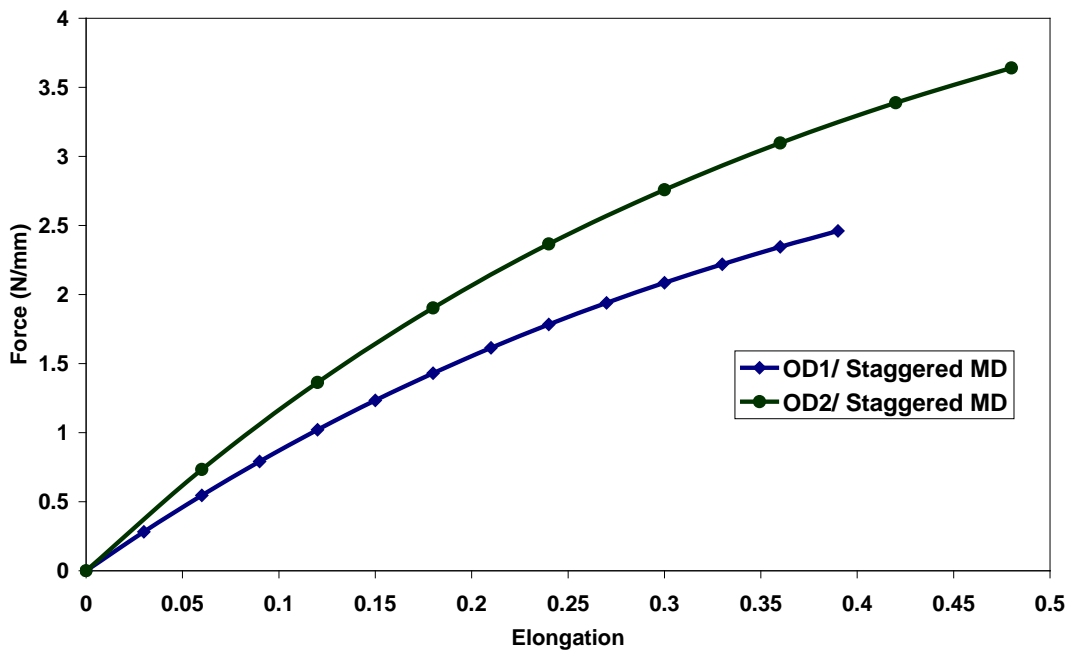
(a)



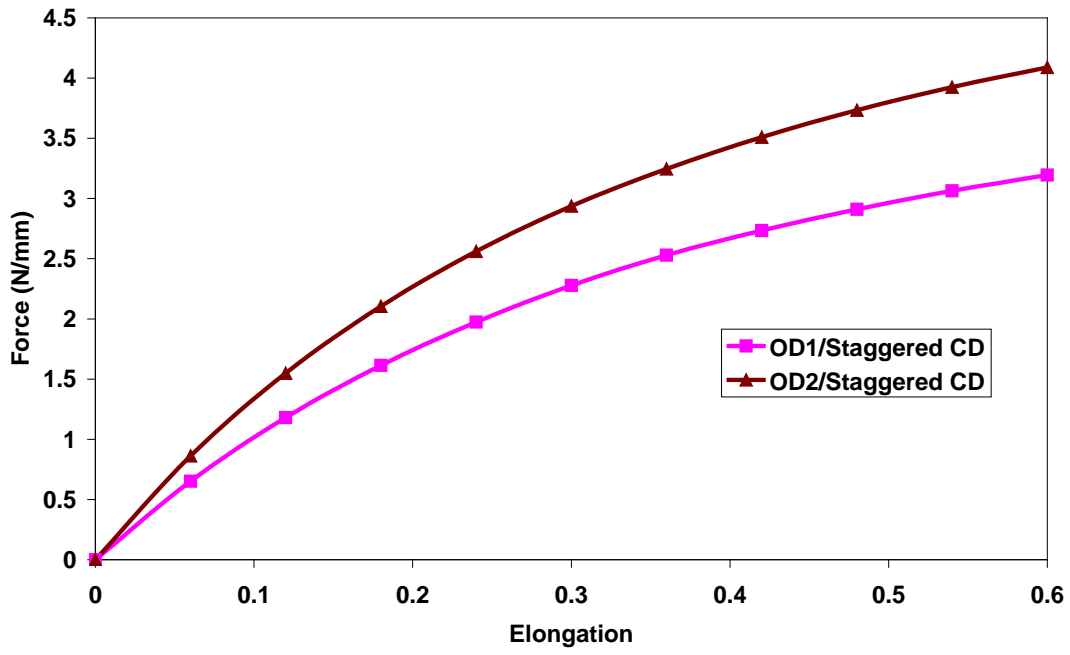
(b)

Figure 8: Results of FEA simulations for discontinuous models with various orientation distribution: (a) OD2; (b) OD1

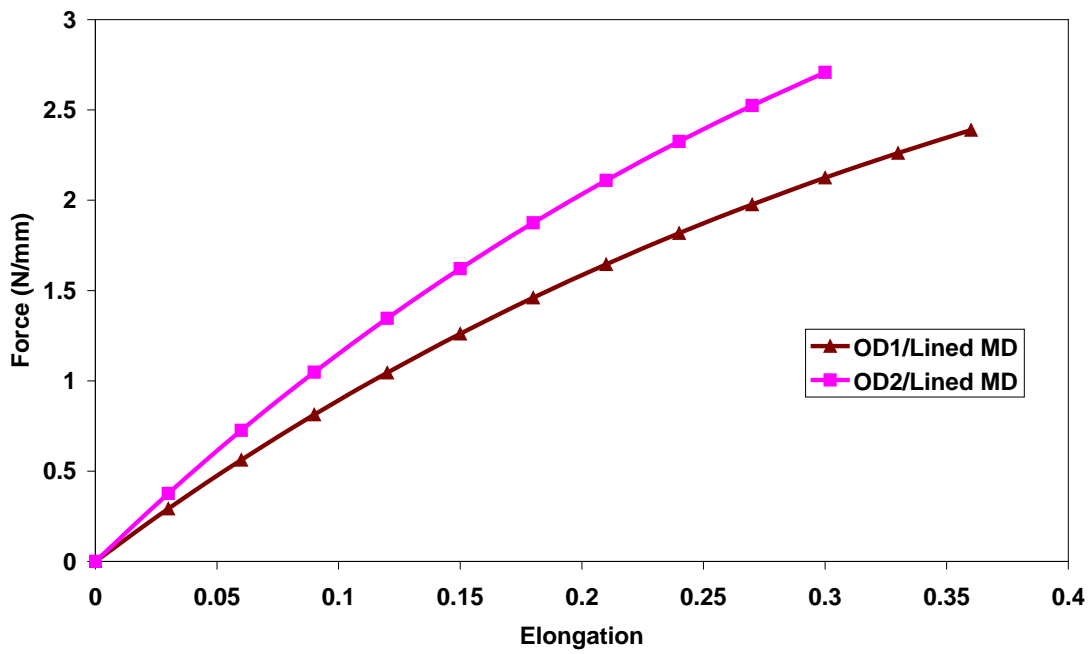
Figure 9 shows the results of the models with the same arrangements of bond points but different orientation distributions of fibres. For the models with the staggered MD arrangement of bond points, an evident difference is demonstrated as displayed in Fig. 9a. The difference is 31.9 % (0.67 N) for the reaction force, when the elongation is 36%. A similar result (Fig. 9b) is obtained for the models with the staggered CD arrangement of bond points, and the considerable difference between their reaction force is 28.2 % (0.89 N) at the elongation 60%. For the models with lined arrangements of bond points, the trends are similar to the models with staggered bond points, which are shown in Fig. 9c and 9d. The models with fibres orientation distribution OD2 have higher stiffness than the models with OD1 orientation distribution. The obtained results demonstrate that the fibres' orientation distribution has a significant effect on the overall mechanical properties of the material. More fibres aligned along the loading direction lead to a better mechanical performance.



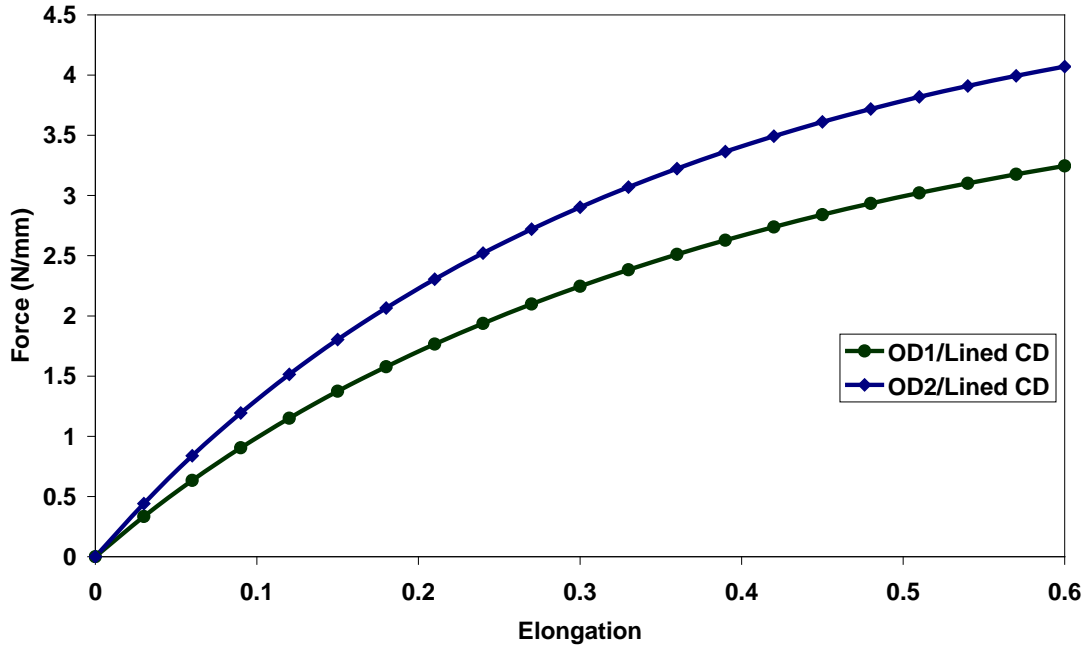
(a)



(b)



(c)



(d)

Figure 9: Results of FEA simulations for discontinuous models with same arrangement of bond points: (a) staggered MD arrangement; (b) staggered CD arrangement; (c) lined MD arrangement; (d) lined CD arrangement

Conclusions

A finite element approach to simulate the low-density thermally bonded nonwoven material was modified by direct introduction of its discontinuous structure. The material's effective modulus was calculated according to the measured material properties of polypropylene fibres forming the nonwoven and implemented into the discontinuous model. Based on the modified finite element approach, eight discontinuous models were developed to investigate the effects of the material's geometry features –the arrangement of bond points and fibres orientation distribution– on the overall performance of the material and the obtained results were analysed with regard to studied features. The detailed results follow:

1. It is possible to use a smaller number of truss elements to represent the mass of fibres of the network in discontinuous FEA models. The discontinuous models could also include the information on the material's microstructure and real properties of the fibres to describe the deformation mechanism of the nonwoven. Moreover, it is also possible to implement the rate-dependent plastic properties of fibres and material properties of bond points into the model to simulate further mechanical performance of the nonwoven material.

2. Eight discontinuous FEA models with different orientation distributions and arrangements of bond points were analysed. The results reveals that the material's discontinuous structure does affect the mechanical properties. The effect of the type of fibres' orientation distribution is due to the changing proportion of fibres along or close to the loading direction. More fibres along or close to the directions lead to a higher mechanical overall response of the specimen in this direction. This result is very important for design of a nonwoven material with certain preferred loading direction.

3. The different arrangements of bond points lead to different stress/strain relationship of the material, which are caused by different mechanisms of deformation of the fibrous network. At the initial stage of the deformation, the effect is not significant, but it is obvious that the arrangement of bond points will play an important role in the material's deformation behaviour at higher elongation levels.

Acknowledgments

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