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A parametric finite element analysis method for low-density thermally bonded nonwovens

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Abstract

In this study, a new method for the finite element analysis of low-density thermally bonded nonwoven materials is proposed and compared with tensile tests. By using advantages of parametric modelling, the model with a large number of fibres is developed. It has also the advantage to implement easily any changes in its parameters such as dimensions and material properties easily. In the suggested model, bond points in a nonwoven are connected by fibres according to criteria in the input file to prevent cross- ing over bond points and unrealistic long-distance connections. Orientation distribution of fibres is deter- mined by an image analysis technique based on the Hough transform and implemented into the model with the variation of cross-sectional areas of fibres. Creep tests are performed with single fibres to deter- mine a time-dependent response under constant load due to their visco-elastic behaviour. A case of uni- form tension is simulated with various elastic, elasto-plastic and creep material properties. The results for various formulations are compared with each other as well as with the data from tensile tests. The obtained results are discussed and suggestions for further development of the model are presented.

1. Introduction

Computational and analytical modelling of nonwovens has been a challenging task for years and various models have been developed taking into account their orthotropic behaviour in the structure. However, there are a few studies in the literature related to finite element modelling of nonwovens. In a work by Demirci et al. [1] the fibres and bond points were modelled using shell elements with orthotropic material properties assigned to the structure. The model was confirmed by tensile test results. Still it has the limitation that the structure should have a large number of fibres (i.e. relatively high density). In case of voids between the fibres (i.e. low density), the modelling method is not valid. Besides, that method requires sophisticated material models for the shell structure to represent the properties of fibres as well as their orientation distribution. It is also difficult to develop the model for nonlinear material behaviour such as creep and implementation of damage. In the previous works by Mueller and Kochmann [2] and Limem and Warner [3] and Hou et al. [4], orthotropic structure is implemented by modelling the fibres with truss elements leaving only bond points as shell structure. That kind of modelling is appropriate for low density nonwovens as individual fibres are modelled directly and the behaviour should not account for the presence of the voids since they are introduced explicitly. It makes material property's implementation easier compared to the modelling technique with shell structures as the trusses in the model better represent the mechanical behaviour of the fibres. This is because such elements do not carry bending loads just like the real life fibres. Such type of modelling also allows the implementation of advanced material properties and damage mechanisms better compared to the shell-based modelling technique, which would require a complex effective material property to take into account the orthotropic behaviour. Apparently the problem with that kind of modelling is the process of building the finite element model while taking into account the orientation distribution of fibres. It would require a certain amount of fibres to be modelled and connected to the bond points, which is time consuming. Also it was observed that convergence of the analyses could be a significant problem and needs special care [5].

In this study, fibres are modelled as trusses as in the second type of models mentioned above. However, the problem of spending significant effort to formulate the model is solved with a parametric modelling technique, which allows simulating various types of complicated structures once a proper code is generated.

2. Modelled material

In the present case, a 20 gsm nonwoven, composed of mono component polypropylene fibres, is modelled. Its discontinuous fibre arrangement consists of fibres having a length between 20 and 30 mm. More details on dimensions of its pattern of bond points are given in [4].

2.1. Orientation distribution

The material properties of nonwovens are highly anisotropic and the extent of anisotropy is defined by the character of distribution of fibres in the structure along the machine and cross directions. In order to determine the orientation distribution function, small fabric samples are prepared and scanned using an X-ray micro computed tomography system. It is known that orientation distribution results could not be obtained accurately enough in the vicinity of bond points. Thus, it is decided to focus on regions of fibrous network where the effect of bond points is minimum as possible.

After multiple trials, optimal parameters of the system were found providing a proper image. By using image processing operations and changing the view point, an image that shows the fibres in a closer view is obtained (Fig. 1).

The orientation distribution was obtained using the program developed in [6]. The obtained distribution is shown in Fig. 2. In the figure, the fibre angles are given from the horizontal axis in Fig. 1, coinciding with the cross direction. It is observed that most of the fibres are aligned along the angles close to the machine direction, as expected.

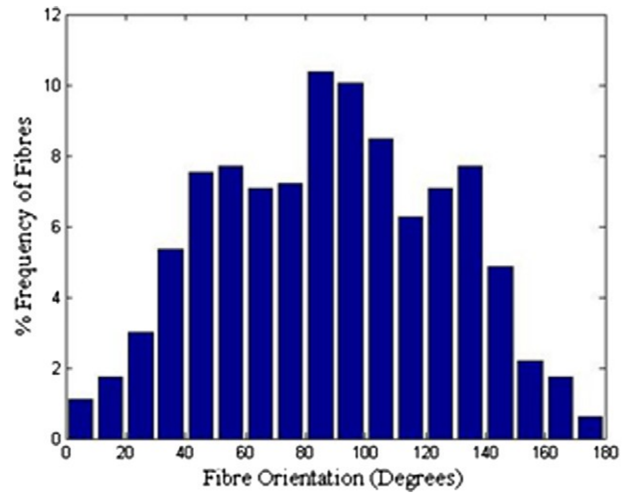

Fig. 2. Orientation distribution obtained for present nonwoven.

2.2. Material properties

The material of the fibres used in this study is polypropylene that has passed through some stages during manufacturing. First, the fibres are drawn through a nozzle to increase their stiffness. Then they are given some crimp so that they can entangle during bonding process. Hence, it is not possible to use the conventional properties of polypropylene obtained from standard specimens or from literature. Also, it is known that polypropylene shows complex inelastic mechanical behaviour including, e.g. creep. Hence, before modelling this advanced behaviour, the tensile stress strain behaviour is determined at various loading rates.

2.3. Tensile tests

Single fibre test are performed with a 5 N load cell to determine the stress–strain behaviour of polypropylene fibres which have a diameter approximately 0.02 mm [5]. In general, stress–strain behaviour of materials is obtained for a constant speed of cross head movement. This gives the stress–strain behaviour for a constant engineering strain rate. Still, it is known that at high deformations, values of engineering strain and true strain values give different results. Hence an expression is developed that relates the cross head displacement to the constant true strain rate:

$$u = L_0 + L_0 \exp(e_{true} t); \quad (1)$$

where e_{true}, L_0 and u are the true strain rate, gage length and cross head displacement, respectively. As it can be seen from Eq. (1), the displacement is a nonlinear function of time for constant true strain rate. So the test speed should be increased gradually by applying acceleration to the cross head to achieve a constant true strain rate. This regime is not available for the tensile test machine so it was decided to increase the speed incrementally until the end of the test in order to compensate the decrease in the true strain rate that would occur in the test with a constant cross-head speed.

The test input is calculated for different gauge-length values and test speeds. The average of stress, strain curves according to constant true strain rate values are shown in Fig. 3. The constant true stress values are implemented into the model according to true strain and true strain rate values. The yield point is determined as a point where a sudden slope change occurs in engineering stress vs. engineering strain plots. For the elastic properties,

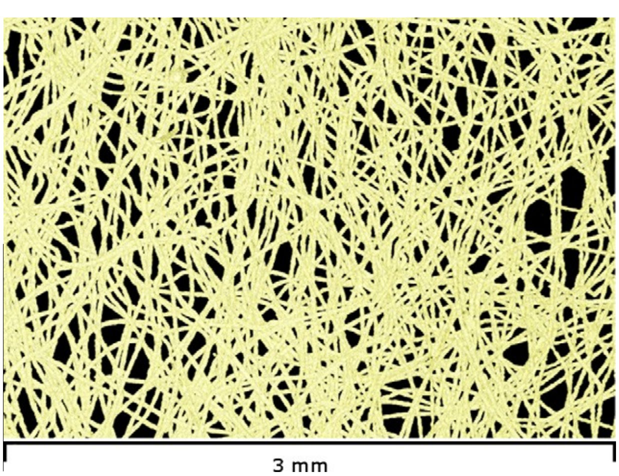

Fig. 1. Image obtained for studied nonwoven.

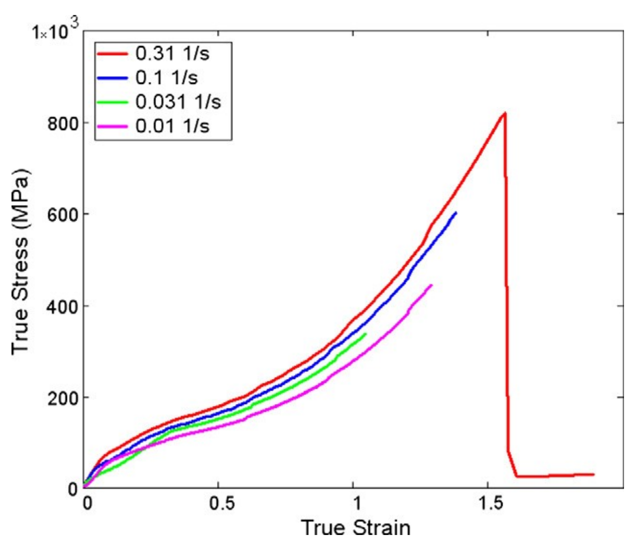

Fig. 3. Average true strain–true stress curves according to different true strain rate.

Young's modulus of 680 MPa value is assigned to the model, determined by calculating the average slope of the stress–strain curve below the yield point obtained in the tensile tests. The value of 0.35 is used as the Poisson's ratio [7].

According to Fig. 3, fibres of the studied nonwoven demonstrate rate dependent deformation behaviour. Thus, it was decided to determine creep behaviour of polypropylene fibres and implement into the finite element model.

2.4. Creep tests

In order to implement creep behaviour, various tests are performed at constant true stress values which are below the yield point. Generally, creep tests are applied for several hours because it was shown that after a significant amount of time, logarithmic values of creep strain show linear behaviour with respect to time [8]. However, the simulated tensile test time is about 2–3 min so all the tests are conducted for 300 s which is low enough to be comparable with the simulated tensile test and high enough considering the future studies. According to the test results, it was observed that the structure undergoes a significant creep deformation which should not be discarded especially in cases of loading with low speeds. The software allows the application of creep behaviour as creep strain rate input according to time, temperature and equivalent stress. After various curve fitting operations, creep strain rate is implemented with respect to time and stress data as the effect of temperature is not within the scope of the study.

3. Parametric finite element modelling

3.1. Model creation

In order to be able to model different types of nonwovens in the future, the finite element model is created by employing parametric modelling techniques. This requires the model to be constructed by using subroutines that the software could read and operate instead of using its graphical user interface.

In order to develop the model, firstly, bond points, introduced according to their pattern in a real nonwoven, are connected to each other by fibres from equally spaced locations around the perimeter without taking into account the orientation distribution. The lines connecting the bond points, which represent the fibres, are drawn by the routine one by one (Fig. 4). The prescribed conditions to draw the fibre lines are, avoiding the connections in the same bond point, avoiding unrealistic connections between very far bond points and the prevention of crossing of bond points with fibres. The first two cases are handled by analyzing the location of the bond points and fibre connections. The last case is handled with the technique described in [9].

Fig. 5 shows the modelled fabric with dimensions of 25 mm gage length and 20 mm height used simulate tensile tests. The total number of fibre lines drawn in this model is 15636, which would be impossible to model with conventional modelling method that uses graphical user interface of the software. If the actual cross-sectional area of fibres were assigned to the fibres in the model, it would give nearly the same amount of nonwoven weight density in the real structure. The nodes in the border of tensile test direction are connected to a single node by multi point constraint (MPC) elements in order to apply and acquire the force and displacement data easily (Fig. 6). The bond points are modelled with plane stress elements with 0.02 mm thickness which was measured in [5]. The mesh seed of the elements of bond points are rather large because of the convergence problems that have been experienced during the solution. The fibres are all truss elements which has no bending stiffness. The nodes of truss elements behave as hinges in finite element modelling and make the analysis diverge. In order to prevent this, each fibre is assigned by only one element which has common nodes with the plane stress element nodes of bond points. During loading, one of the MPC nodes is held fixed and the other is given a displacement profile with a constant test speed of 25 mm/min.

3.2. Implementation of orientation distribution

It was decided to implement orientation distribution into the model by assigning cross-sectional areas to fibres in the structure based on the orientation distribution. The total fibre mass is obtained from the following relation:

$$\rho \sum_{i=1}^{NF} CA(i) \, length(i) = m_{total\_fibre}; \qquad (2)$$

where ρ is the material's density, CA(i) and NF represent the cross-sectional area of the ith fibre and the total number of fibres in the model, respectively. length(i) is the fibre's length and m_{total_fibre} is the total mass of fibres in the fibrous matrix of nonwoven. The cross-sectional area of fibres aligned along angles within a given interval is assumed to be directly proportional to the respective band of ODF and inversely proportional to the number of fibres in that interval. This assumption states that the contribution of stress or strain equations is linear with respect to the cross-sectional area. The fibres are modelled as truss elements in the model. Truss elements can only sustain axial loading. The stress and strain distribu-

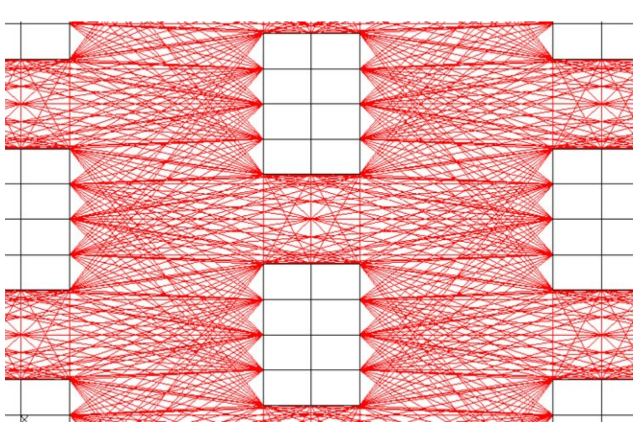

Fig. 4. Fibre connections between bond points.

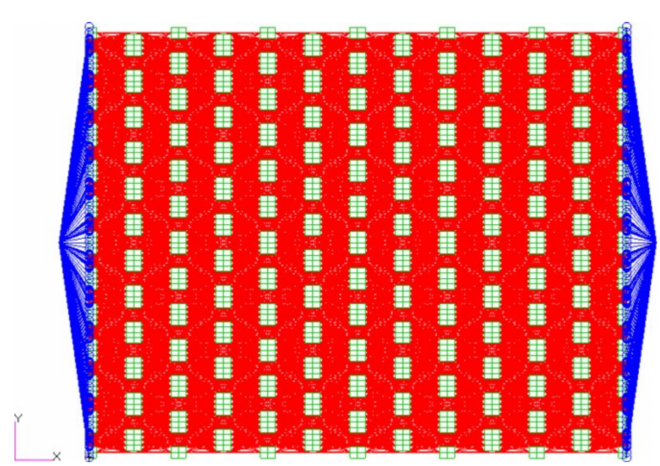

Fig. 5. Modelled fabric.

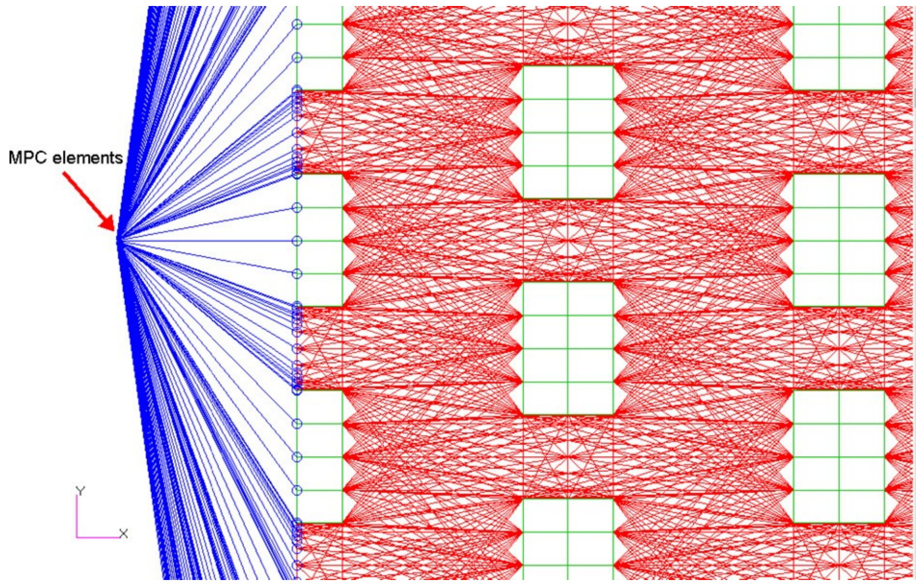

Fig. 6. Closer view of FE model showing MPC elements.

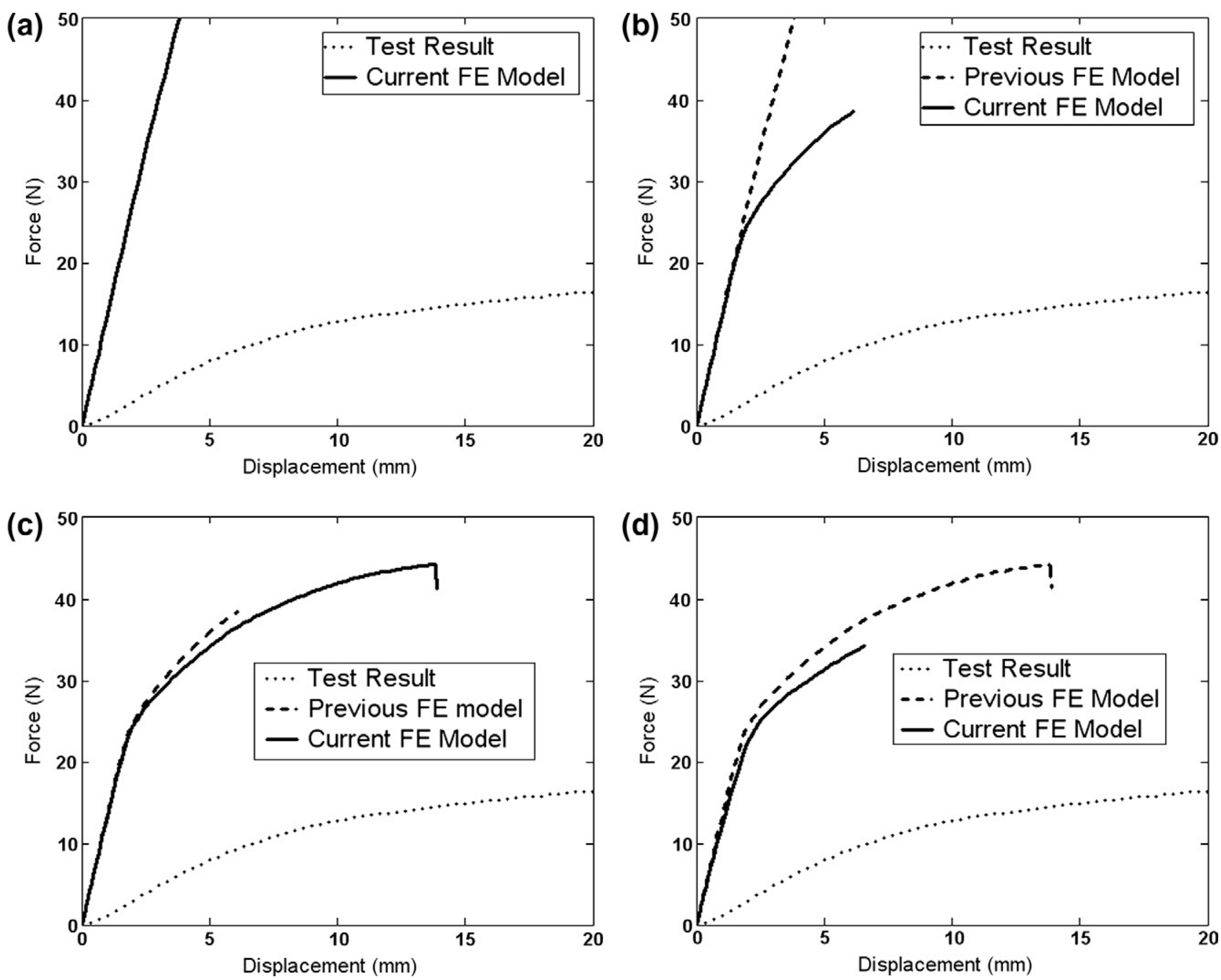

Fig. 7. Force–displacement plots for various material formulations: (a) elastic fibres and BPs; (b) elasto-plastic fibres and elastic BPs; (c) elasto-plastic fibres and BPs; (d) elasto-plastic fibre and BP with creep.

tion along the element' length is uniform. These two properties make the stiffness equations linearly dependent on the cross-sectional area of the truss element. The expression for the fibre's cross-sectional area can be written as follows:

$$CA(i) = k\frac{ODF(i)/100}{NL(i)}; \qquad (3)$$

where NL(i) is the number of lines that have the same orientation as fibre i. ODF(i) is the respective magnitude of the orientation distribution function. The value of k can be found by substituting, Eq. (3) into Eq. (2). The calculated values of cross-sectional area are allocated to each fibre with respect to its orientation with the help of a developed subroutine.

4. Results

4.1. Simulation results for tensile test

As an initial study, the differences in material modelling cases are studied and the effects are analyzed. Fig. 7 shows force vs. displacement curves for various cases studied in comparison with the tensile test results. Dashed curves in Fig. 7b–d show the simulation result of the preceding modelling stage in order to understand the effect of a more complex model. The maximum strain levels attained in simulations differs from that in the actual test and between the models because of convergence problems experienced in all simulations. Shown in Fig. 7a, the case of totally elastic behaviour not only demonstrates very stiff results, but also cannot reproduce the nonlinear displacement behaviour. Introduction of plastic modelling of fibres in Fig. 7b shows still stiff results but the slope of the nonlinear part is closer to the actual behaviour. When bond points are also modelled with plastic behaviour (Fig. 7c), the total fabric's behaviour does not change too much compared with the previous case confirming the expectation that the properties of fibres dominate the model. In Fig. 7d, creep is also implemented showing that it also has a little effect for this case of simulation.

4.2. Material behaviour studies

In order to study the effect of each material parameter, various analyses were performed with respective material property, changing within broad limits. This changes were implemented using multiplication factors applied to Young's modulus and the stress–strain curves beyond yield point. Fig. 8a shows the effect of different multiplication factors for elasto-plastic properties of fibres, demonstrating its large effect on the deformation behaviour. In Fig. 8b, the material properties of bond points are multiplied by

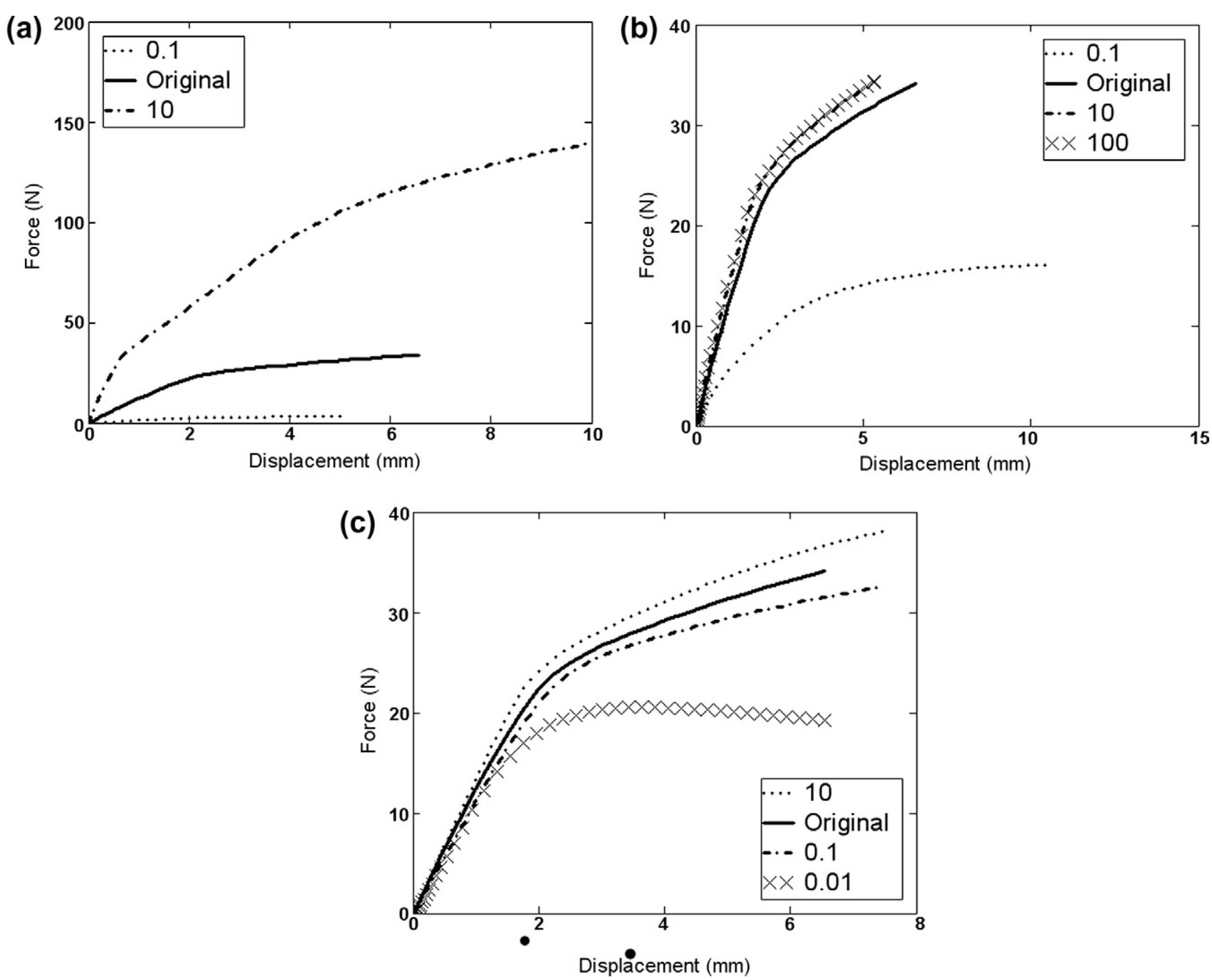

Fig. 8. Force vs. displacement plots: (a) fibres with different elasto-plastic material behaviour multipliers; (b) bond points with different elasto-plastic material behaviour multipliers; (c) effect of different rates of loading.

different factors. Apparently, the deformation behaviours for multiplication factors of 10 and 100 show very similar behaviour. The latter factor means the material of bond points has elastic properties close to those of aluminium which can be treated as rigid, compared to the stiffness of polypropylene. The original deformation behaviour is also very close to the multiplication factors 10 and 100. This implies that it could be possible to model bond points as rigid bodies. Still, this assumption may not be valid for cases of bi-component fibres, damage analysis and different density levels of the nonwoven material.

The effect of creep was studied by performing analyses with the same deformation behaviour but for different rates of loading (Fig. 8c). The original one and the ones obtained with the use of multiplication factor of 0.1 and 10 give similar results implying that creep for this range does not affect significantly the material's behaviour. However, when the factor of 100 is employed, the creep behaviour is very prominent and hence, should not be discarded, especially for large deformation cases.

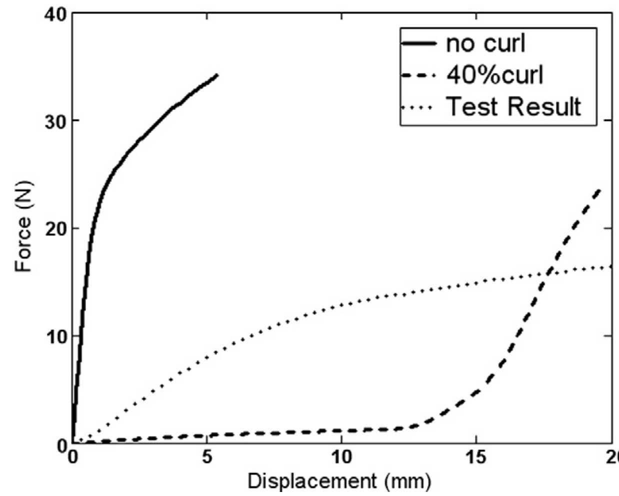

Fig. 10. Simulation with 40% curl factor compared with the original simulation and test data.

5. Discussion

A large deformation tensile behaviour of a low density nonwoven is simulated in this study. It is shown that the simulations give stiffer results when compared with those of the tests. This can be attributed mainly to the curliness of fibres in the structure. When the computed tomography image shown in Fig. 1 is analyzed, it was determined that there are fibres that were curled as much as 40%. This means that they begin to carry load only after they are fully straightened under tensile load. In order to show its effect, an analysis was performed by giving 40% curl to all of the fibres. This is accomplished by modifying their stress–strain plots of fibres by introducing some initial low stiffness deformation according to its gage length as shown in Fig. 9. The simulation for this curl factor is compared with the test data and initial simulation (Fig. 10). The simulation with 40% curl gives less stiffer values according to the test results. Here, the same curl factor was assigned to all fibres whereas in reality there should be a distribution of fibre curl. It explains why the actual test result lies somewhere between the simulated two extreme cases. Further studies will be carried out to determine the distribution of curliness in the structure.

At the later stage of deformation, even simulations with fibre curl of 40% gave stiffer results according to tests. This can be due to another mechanism – continuous damage of bond points during the deformation – that has not been incorporated into the developed model at that stage of analysis. Fig. 11 shows a microscopic image of the studied nonwoven under tensile strain of 15%. Even for this relatively low value, which is close to the point of deflection of slope of the tensile force–deformation curve, there were some bond points (marked by a circle in Fig. 11) that lost their integrity as fibres started to be pulled out one by one. The strength of bond points is governed by the temperature and pressure applied during manufacturing which was not accounted in this model.

According to the parametric finite element studies for different material behaviours, it was shown that bond points can be modelled as rigid for the studied nonwoven. The results of analysis also demonstrate that fibre properties are crucial for accurate modelling of the deformation behaviour. Modelling of the elasto-plastic material behaviour makes the slope of deformation behaviour close to the test demonstrating its importance for realistic simulations. The creep properties are not so effective in this type of loading but should be taken into account for lower strain rates.

In this type of modelling, the effect of fibre length cannot be taken into account though it can also affect the deformation behaviour. The suggested parametric modelling technique is still the development stage, and an alternative modelling method will be developed that can handle the orientation distribution function

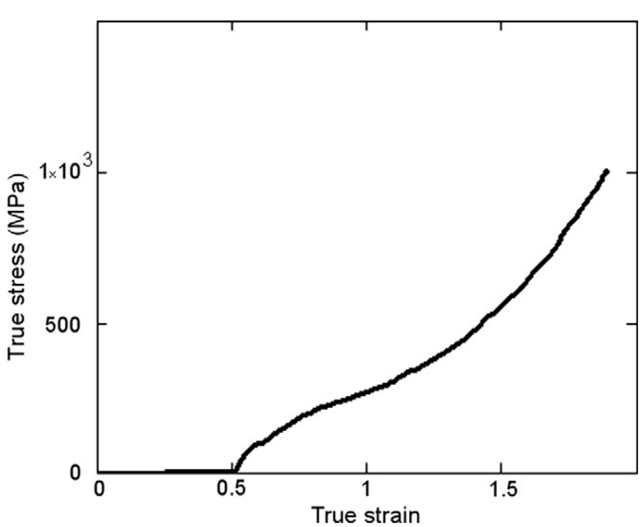

Fig. 9. Stress–strain curve for 0.1 s^{-1} true strain rate test.

Fig. 11. Damage in bond points.

and fibre length more accurately. Still, this model shows the convenience of parametric modelling in the simulation of nonwoven materials since both analysis parameters and modelling details can be altered easily by using it.

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