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Numerical analysis of dynamic out-of-plane loading of nonwovens

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Abstract. This paper presents finite element (FE) modelling of deformation behaviour of thermally bonded bicomponent fibre nonwovens under out-of-plane dynamic loading. Nonwoven fabric was treated as an assembly of two regions with distinct mechanical properties. Bond points were treated as composite material having a matrix of the sheath material reinforced with fibres of the core material. Elastic-plastic and viscous properties of the constituent fibres, obtained with tensile and relaxation tests were implemented into the FE model. The mechanical behaviour of the material under out-of-plane dynamic loading was observed with visual techniques. The deformation behaviour of nonwoven under out-of-plane dynamic loading computed with the numerical model was compared with that observed in the tests.

1. Introduction

Nonwovens are used in wide range of consumer and industrial products and applications ranging from disposable items such as wipes and diapers to durable products, such as, geotextiles [1]. Being engineered fabrics, properties of nonwovens can be tailored to serve specific purposes. Regardless of the application areas, structural integrity of nonwovens is the most basic requirement so that they can perform their intended functions under service conditions.

This study focuses on thermally bonded nonwoven materials with polymer-based bicomponent fibres. These bicomponent fibres have a core/sheath structure, with the core material having higher melting point than that of the sheath. During thermal bonding of such fibres, the temperature of the hot calender is adjusted in such a way that only the sheath material melts and forms the bond spots whereas core part of fibres remains intact. On the other hand, the regions where the fibres are not in contact with the calendar remain unaffected and form the fibrous matrix [2]. The structure of resulting thermally bonded nonwoven obtained with scanning electron microscopy (SEM) is shown in Fig. 1. The two regions — bond points and fibre matrix — have distinct characteristics which define unique but complex deformation behaviour of nonwovens. Additionally, this complex behaviour is affected by a specific orientation distribution of fibres and their visco-elasticplastic properties of constituent fibres. Several studies were performed to study the response of the material under mechanical loading [2-10]. The developed finite-element models predicted the deformation behaviour of the fabric

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effectively. Still, these studies focused only on in-plane quasi-static loading neglecting dynamic effects related to time-dependent deformation mechanisms. None of these studies deal with the deformation behaviour of the fabric under dynamic out-of-plane loading.

The susceptibility to deform under out-of-plane dynamic loading is one of the major concerns for various applications of nonwovens such as filters and scaffolds. This paper's aim is to introduce a practical way to simulate a 3D behaviour of thermally bonded nonwoven fabrics under dynamic out-of-plane loading in order to reduce costly and time-consuming trial-and-error stages in product development.

2. Assessment of properties

2.1. Network structure

A thermally bonded nonwoven with planar density of 50 g/m^2 manufactured with PP/PE 75/25 bicomponent fibres is the object of our case study. Information about the bond point size, shape and pattern was obtained from SEM images (Fig. 1).

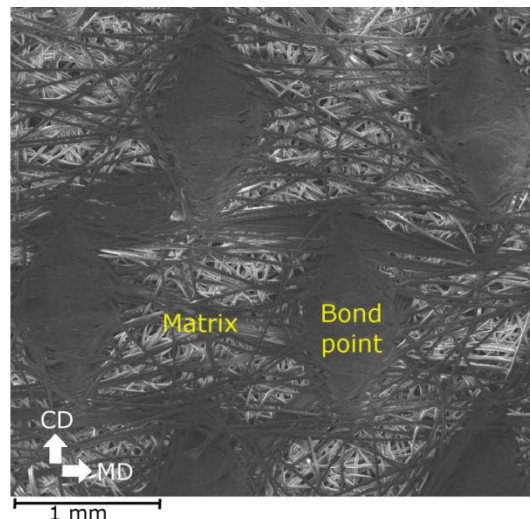


Figure 1. SEM image of 50 g/m^2 thermally bonded nonwoven fabric (PP/PE 75/25)

The fabric was composed of two regions — bond points and fibre matrix— that have different microstructures. Bond points were solid and continuous whereas the fibre matrix was porous (Fig. 1). Due to such microstructure, mechanical properties of these two regions were different. Moreover, it was observed from SEM images that fibres were not fully randomly oriented but preferentially aligned along the machine direction (MD) (Fig. 1), making the mechanical behaviour of bond points and fibre matrix anisotropic. In order to assess the level of anisotropy in mechanical properties of the nonwoven regions, quantification of non-uniformity in orientation distribution of fibres was performed with the use of in-house software — Nonwoven Anisotropy V1— described in [5]. The orientation distribution function (ODF) of fibres obtained from the software is given in Fig. 2.

2.2. Mechanical properties

The mechanical properties of regions of nonwoven were obtained in terms of orthotropic parameters defining direction-dependency of their behaviour. These orthotropic parameters, having three symmetry planes, were sufficient to define the level of anisotropy for thermally bonded nonwovens having three principal directions, named *machine direction* (MD), *cross direction* (CD) and *thickness direction* (TD). Orthogonal parameters for MD and CD were calculated based on ODF using the following equations:

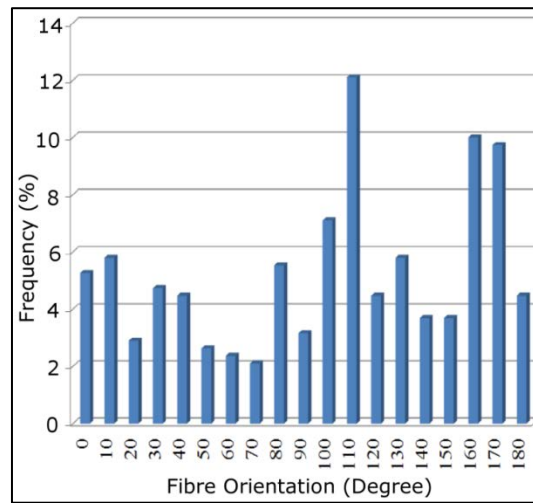


Figure 2. ODF of 50 g/m² thermally bonded nonwoven fabric (PP/PE 75/25)

$$C_{MD} = \frac{\sum_{i=1}^N |\sin \alpha_i|}{\sum_{i=1}^N |\sin \alpha_i| + \sum_{i=1}^N |\cos \alpha_i|}, \quad (1)$$

$$C_{CD} = \frac{\sum_{i=1}^N |\cos \alpha_i|}{\sum_{i=1}^N |\sin \alpha_i| + \sum_{i=1}^N |\cos \alpha_i|}, \quad (2)$$

where C_{MD} and C_{CD} are the parameters defining the level of orthotropy in MD and CD; α_i is the angle between the axis of the i th fibre and CD; N is the total number of fibres accounted by the ODF algorithm. After computing the orthotropic constants, elastic, plastic and viscous properties of bond points and matrix were assessed using mechanical properties of constituent fibres, obtained experimentally, and manufacturing parameters of nonwoven fabric obtained from manufacturer's datasheet [11]. Elastic-plastic properties of bond points and fibre matrix were computed using the Rule of Mixture (RoM) for MD and CD whereas the Halpin-Tsai equations were employed to calculate the mechanical properties along TD. Dynamic properties were determined by normalization of time-dependent behaviour of single fibre used to manufacture the fabric. The details of single-fibre tests and computation of mechanical properties are given elsewhere [2]. The computed flow curves and relaxation moduli of the constituting regions of nonwovens obtained from the algorithm are shown in Fig. 3.

3. Fabric's behaviour

The nonwoven fabric under study, being composed of polymer fibres with viscous properties, demonstrated a time-dependent behaviour. In order to assess the dynamic effects related to its time-dependent deformation behaviour under out-of-plane dynamic loading, drop-weight testing was performed (Fig. 4). The metal sphere ball with a mass of 43.4 g and diameter 22 mm was released from a 100 mm height to fall freely under gravitational acceleration onto the fabric. The ball was consecutively bounced back several times with a gradual decrease in the bouncing height after each impact due to energy-dissipation mechanisms related to viscous properties of the nonwoven. As a

result of the impact of ball, the nonwoven material was exposed to dynamic out-of-plane loading. The maximum heights of the ball after each bounce with respective times are shown as experimental data in Fig. 6. These data for each bounce was recorded with a camera and observed visually.

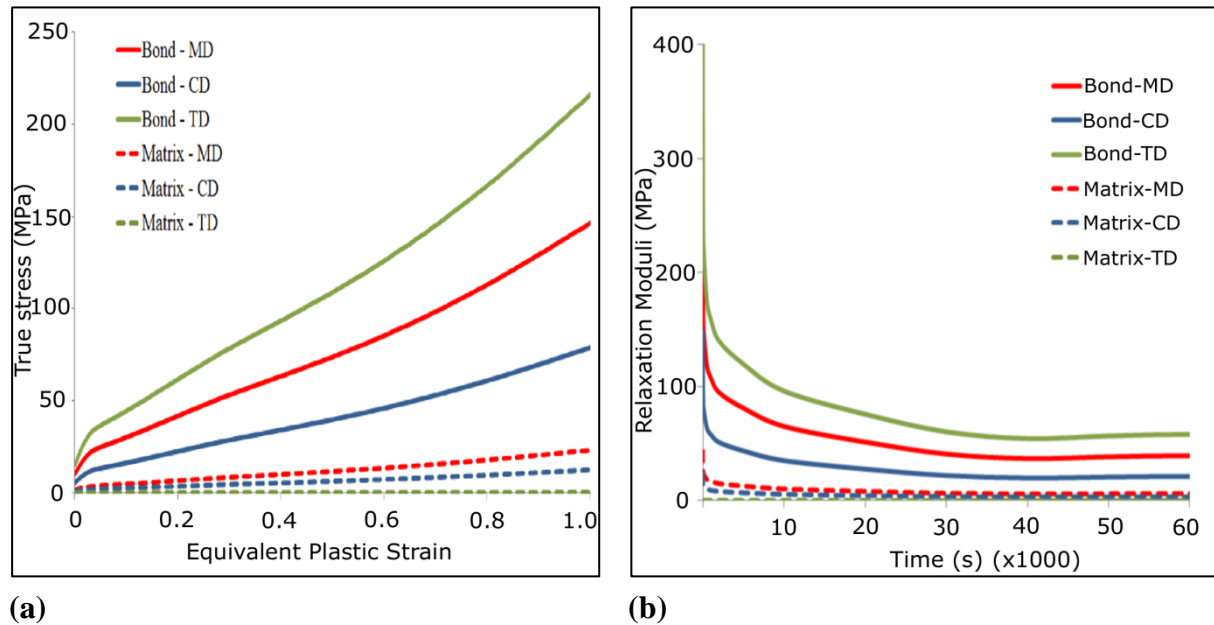


Figure 3. Flow curves and relaxation moduli of 50 g/m² (PP/PE 75/25) nonwoven regions

4. Finite-element model

The FE model for the nonwoven under study was composed of two distinct regions—bond points and matrix. The material properties of these regions obtained with the discussed algorithm were used to characterise their orthotropic viscoelastic-plastic behaviour in the FE model. The simulations were carried out using commercial software MSC.Marc[®]. The model with dimensions 200 mm × 200 mm, equal to that of the fabric in our experiments, was prepared (Fig. 5) using 88500 bi-linear four-node thin shell elements. The bond-point shape, size and pattern of the model were similar to that of the fabric. Since the stiffness of the metallic sphere was much higher than that of the fabric, it was modelled as a rigid body with weight. To allow comparability of simulation results with experimental ones, the boundary conditions implemented in the FE model were similar to those used in experiments. The size and dropping distance of the rigid sphere were the same as in the experiments. A constant gravitational acceleration of 9.812 m/s² was applied to the rigid-body sphere, which was released from its initial steady-state position. The edges of the modelled fabric were fully constrained as in our tests (Fig. 4).

5. Results and discussions

A drop-weight simulation was performed with exact specimen size, dimensions, and boundary conditions to replicate the experiments. Stress distributions in the fabric's model as a result of four successive impacts obtained for the moments of maximum deformation are given in Fig. 6.

In order to compare the response of the model with experiments alone, evolution of height of the sphere obtained in the simulation and its maximum height, recorded at each bounce in the experiments, were compared (Fig. 5). The heights in the experiment and simulation correspond to the distances between the initial fabric plane and the metal sphere. The results obtained with the FE model were in good agreement with the experimental ones confirming the success of the model to predict the time-dependent behaviour of the fabric under dynamic out-of-plane loading. The average difference in heights obtained from simulation was less than 20% as compared to experimental data. This time-

dependent behaviour is manifested by the changing bouncing height of the metal sphere after each successive impact. An interesting observation here is that the stress distributions in the fabric under loading extended more along MD than CD due to fabric's microstructure. Besides, the stress magnitudes decreased with each successive bounce showing energy dissipation by the fabric due to its time-dependent properties. The values of energy dissipation by the fabric obtained from experiment and simulation as a percentage of initial energy are given in Table 1.

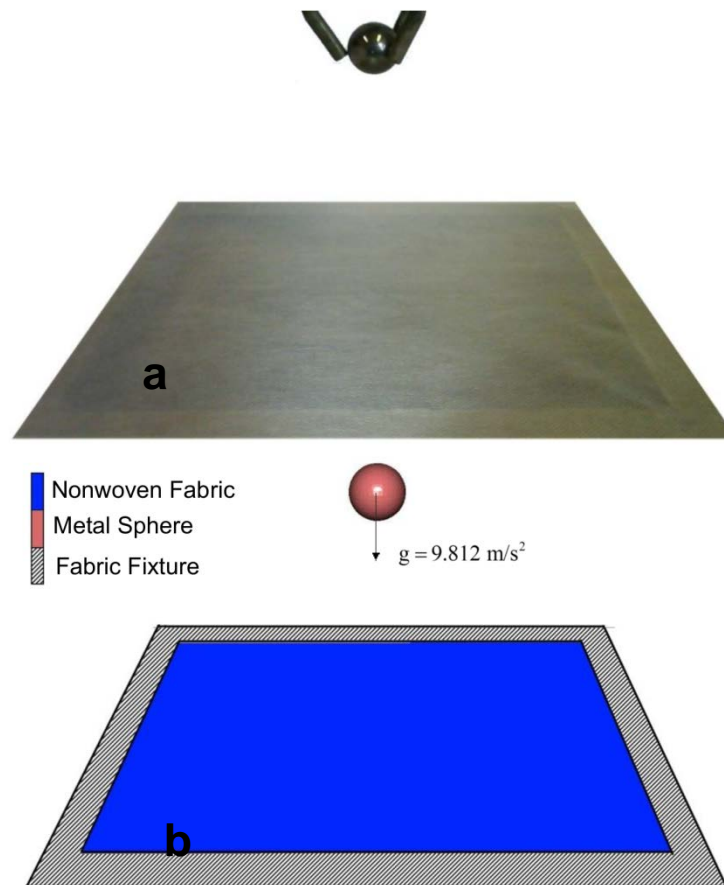


Figure 4. (a) Test setup; (b) corresponding FE model

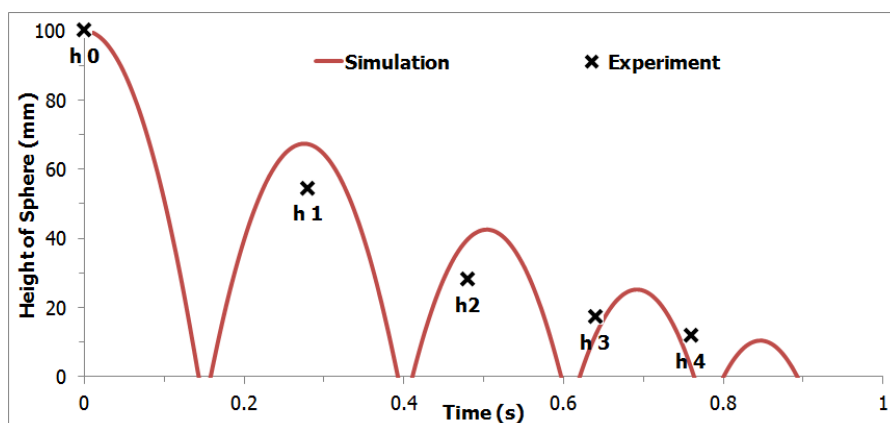


Figure 5. Height of sphere in experiment and FE simulations after each impact

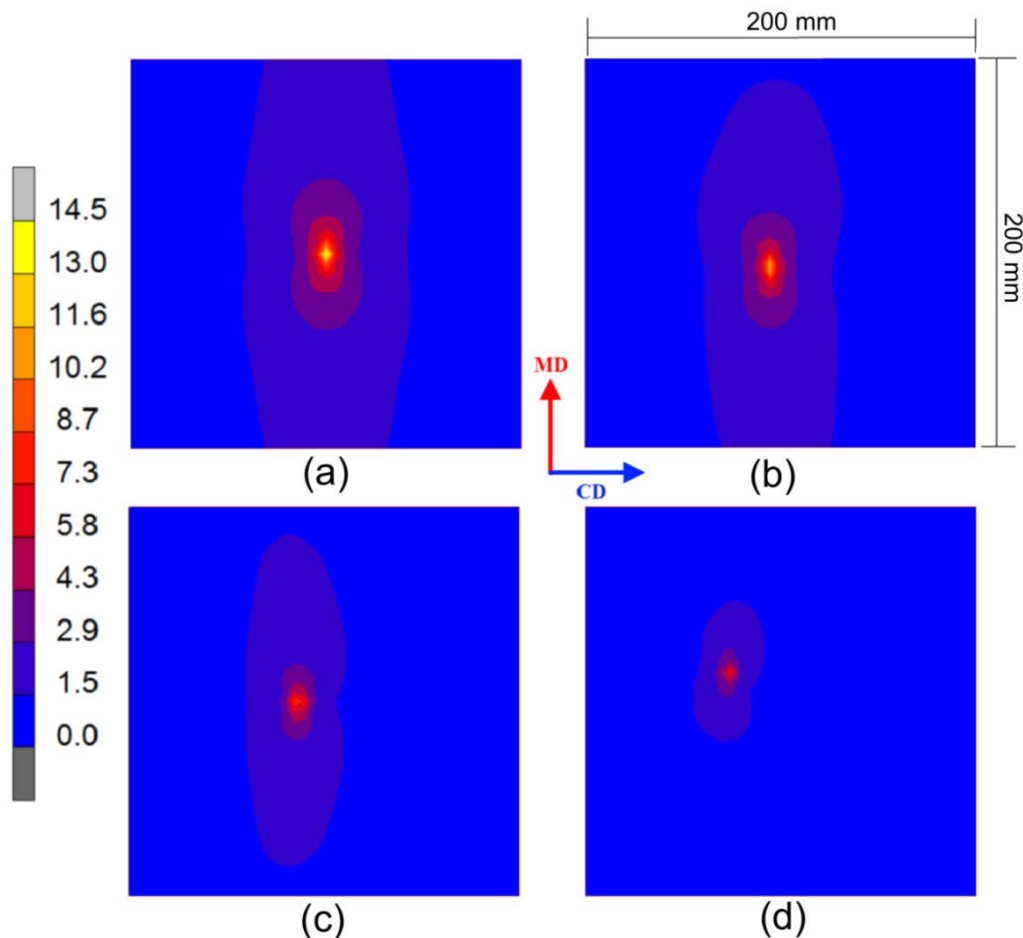


Figure 6. Distribution of equivalent von Mises stress (in MPa) of deformed nonwoven in model at first (a), second (b), third (c) and fourth (d) impacts

Table 1. Percentage of initial energy dissipated in each bounce

	1 st bounce	2 nd bounce	3 rd bounce	4 th bounce
Experiment	45.63	26.32	10.79	5.24
Simulation	32.67	24.53	17.2	15.8

6. Conclusions

In this paper, a practical way of simulating the real-life behaviour of a thermally bonded bicomponent fibre nonwoven under dynamic loading is introduced. A preferential orientation distribution of fibres and polymer-based constituents led to a complex mechanical behaviour of the fabric, which was modelled by employing two distinct regions with different mechanical properties. A straight-forward method for developing the model of nonwoven was introduced, based on two steps: assessment of fabric's properties and FE modelling. Anisotropic material properties for the bond points and fibre matrix implemented into the model were computed using the developed algorithm. The novel numerical model proposed in this study is effective in predicting the mechanical behaviour of thermally bonded nonwoven fabrics under dynamic out-of-plane loading including time effects, as was verified with experiments. Since the model accounts for anisotropy and constituent material's properties, it is expected that determination and implementation of damage criteria into it can increase its capability to predict damage behaviour of the fabric as well.

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