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Computational Modeling of Mechanical Performance in Thermally Point Bonded Nonwovens

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ABSTRACT

Several theoretical models have been proposed in the past for predicting the basic mechanical properties of thermally point bonded nonwovens from structural features of the constituents. However, the role of bond geometry, distribution and related fiber properties were not taken into account. We have developed a mechanics based model to help understand the behavior of point bonded materials as a function of various structural and process variables.

KEYWORDS: Image Analysis, Orientation Distribution Function (ODF), Bond Geometry, Image Simulation, Computational Modeling

Introduction

Several theoretical models have been proposed in the past in an attempt to predict basic performance. The focus of these research efforts has been mainly directed towards the understanding of the mechanical behavior of the structures. Some of these efforts are summarized below.

Backer and Patterson pioneered a fiber web theory to accommodate the broad mechanical design requirements of nonwovens [1]. This model assumes that the fibers are straight and oriented in the machine direction, and that the fiber properties and orientation are uniform from point to point in the fabric. Hearle et al, extended the model to account for local fiber curvature [2]. In this model, fiber orientation distribution, fiber curl distribution, fiber stress-strain relationships and fabric Poisson ratio must be determined before tensile properties may be accurately predicted. It is interesting to note that Hearle et al., measured fiber orientation by means of a projection microscope where the path of the fiber was manually traced on transparency. In a more recent study, Komori and Makishima [3] estimated fiber orientation and length by means of integral analysis. They hypothesized that the anisotropies frequently observed in the fiber assemblies are caused by the particular bias in distribution and orientation of constituent fibers. It was assumed that the fibers were straight-line segments of the same length

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and were uniformly suspended in a unit volume of an assembly. It was found that the density function of orientation could be estimated by solving an integral that relates it to the average numbers of fiber crossovers formed on the unit areas of randomly positioned and variously oriented secant planes. No experimental work was carried out to verify this model. In the early of 1980's, Britton et al. [4-6] demonstrated the feasibility of computer simulation of the behavior of a network generated mathematically. The model is not based on any real fabric; rather it is designed for mathematical convenience in setting up the input data. Grindstaff and Hansen [7] on the other hand developed a computer simulation for stress-strain curve of point-bonded fabrics, but fabric strength mechanism and even fiber orientation distribution (ODF) were not included.

Mi and Batra [8] recently proposed a model to predict the stress-strain behavior for certain point-bonded geometries by incorporating fiber stress-strain properties and the bond geometry into the model. This model however, needs to be refined in terms of its underlying assumptions and developed further to make it applicable to various bond geometries. Our paper discusses the extension of the Mi-Batra model to help understand the behavior of point bonded nonwovens as a function of various structural variables.

The input parameters required for our model are: 1) fiber stress-strain property, 2) network orientation distribution function (ODF) and 3) the details of the bond geometry including bond shape, spacing and frequency. The ODF may be obtained from a real fabric through image analysis techniques previously discussed. We typically use a two-dimensional fast Fourier transform (FFT) method to obtain the ODF from an image. An image of a nonwoven structure is composed of spatial details in the form of brightness transitions cycling from light to dark and from dark to light. Spatial frequencies in a nonwoven image are related to the orientation of the fibers. A full description of the Fourier transform of a continuous function was given previously [9]. Similarly, the details of the bond geometry can be obtained by image analysis methods. However, if these details are not available, we employ a simulation method to specify the structural details.

Image Simulation

Our simulation scheme is based on similar methods previously described. The new simulation scheme takes into account the bond details as well. A simulated image can be designed with the following variables: web density; fiber properties (fiber denier, crimp and thickness with allowed distribution); unit cell size; as well as various bond properties (bond size, shape and pattern).

Figure 1 shows the user interface for the image simulation for preparing the input parameters. The image simulation algorithm and user interface has been programmed in C++. The most import component of the simulation is the way in which lines or

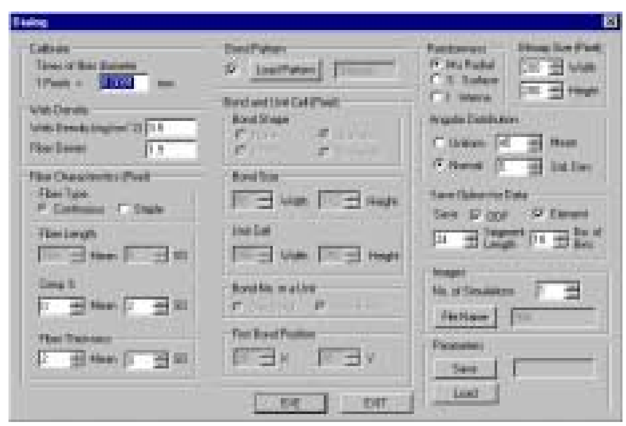

Figure 1. Input parameters for image simulation

curves are generated. For continuous fiber simulations, we use the procedure known as μ-randomness. μ-randomness is defined by the perpendicular distance from a fixed reference point (preferably located in the center of the image) and angular position of the perpendicular. Distance is sampled from random distribution and the slope is sampled from an appropriate distribution. For staple fiber simulations we use a procedure known as I-randomness. Under this procedure a point is chosen at random by its x and y coordinates such that it lies in a plane larger than the image by fiber length. This ensures that the edges of the image plane are intersected by appropriate fibers of a length having their center of mass outside the image plan. A slope is selected from an appropriate distribution. A full description of methods for generating a network of lines was given previously [10].

Figure 2 shows one example of the input model. The images were generated with different number of lines, but basically following the same randomness with a specific bond pattern.

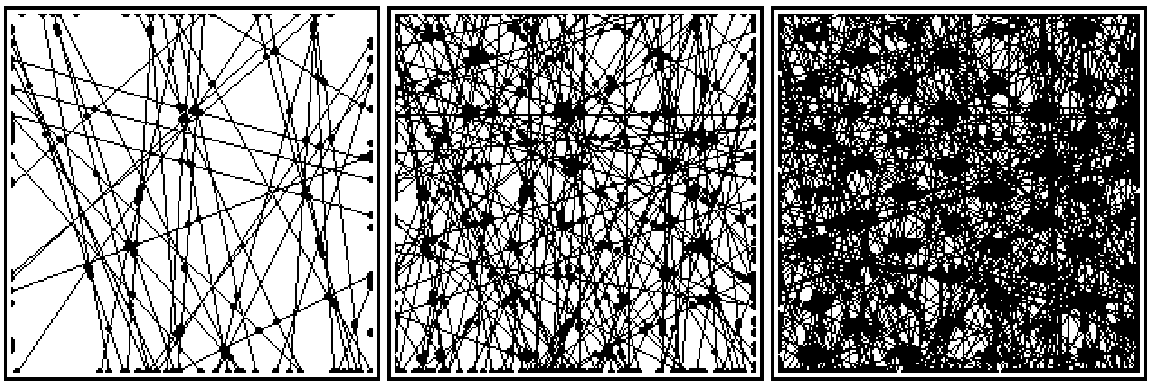

Figure 2. Image simulation and data acquisition; total number of simulated lines (left) 50 lines, (middle) 150 lines and (right) 350 lines

Theoretical Background

The model is based on the incremental deformation principle. Consider a fiber segment of original length, l_0, oriented at an angle θ relative to the machine direction (MD), see Figure 3.

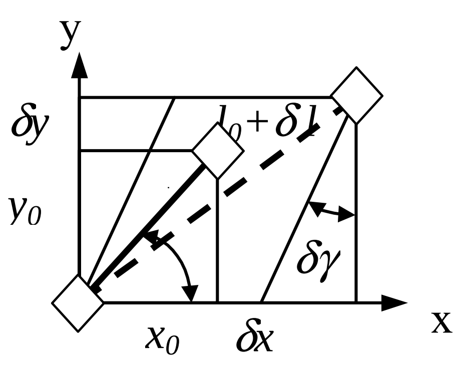

Figure 3. Incremental deformation of web

Both ends of this fiber segment are anchored at two different bond sites. As the web is deformed, the fiber segment is extended to a length ($l_0+\delta l$) such that:

$$(l_0+\Delta l)^2 = (y_0+\Delta y)^2 + (x_0+\Delta x+ \tan\delta\gamma\cdot((y_0+\Delta y)))^2$$

where, Δl is the elongation of the fiber, Δx and Δy are the elongation components in machine direction (MD) and cross direction (CD), respectively, and $\delta\gamma$ is the shear strain of the web.

In the case of very small increments of strain at each deformation step, the incremental strain, $\delta\varepsilon_\theta$, and the incremental specific stress, Δf_θ, in the bridging fiber are respectively,

$$\delta\varepsilon_\theta = \frac{l_x}{l_0}\delta\varepsilon_x \cos\theta + \frac{l_y}{l_0}\delta\varepsilon_y \sin\theta + \delta\gamma \sin\theta\cos\theta$$

and

$$\Delta f_\theta = E(\varepsilon)\left(\frac{l_x}{l_0}\delta\varepsilon_x \cos\theta + \frac{l_y}{l_0}\delta\varepsilon_y \sin\theta + \delta\gamma \sin\theta\cos\theta \right)$$

The global coordinates sytem (MD and CD direction) are obtained from the local coordinate system (fiber direction) by a rotation angle of θ at which the fiber is oriented. As the model employs the input generated from the image simulation, the contribution of all fibers to the global coordinates can be obtained by simply summing the contributions of each fiber without the need for considering specific structural parameters of the web such as the web areal density and fiber linear density.

The incremental forces ΔF_x and ΔF_x, in MD and CD, respectively, and the incremental shear force ΔF_{xy} acting on the circumscribed rectangle are given by in the matrix form as

$$\begin{Bmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_{xy} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{bmatrix} \cdot \begin{Bmatrix} \delta\varepsilon_x \\ \delta\varepsilon_y \\ \delta\varepsilon_{xy} \end{Bmatrix}$$

where

$$Q_{11} = \sum_{n=1}^{N} E(\varepsilon_n)\cos^3\theta_n \frac{l_{nx}}{l_{n0}}$$

$$Q_{12} = \sum_{n=1}^{N} E(\varepsilon_n)\sin\theta_n \cos^2\theta_n \frac{l_{ny}}{l_{n0}}$$

$$Q_{13} = \sum_{n=1}^{N} E(\varepsilon_n)\sin\theta_n \cos^3\theta_n$$

$$Q_{21} = \sum_{n=1}^{N} E(\varepsilon_n)\sin^2\theta_n \cos\theta_n \frac{l_{nx}}{l_{n0}}$$

$$Q_{22} = \sum_{n=1}^{N} E(\varepsilon_n)\sin^3\theta_n \frac{l_{ny}}{l_{n0}}$$

$$Q_{23} = \sum_{n=1}^{N} E(\varepsilon_n)\sin^3\theta_n \cos\theta_n$$

$$Q_{31} = \sum_{n=1}^{N} E(\varepsilon_n)\sin\theta_n \cos^2\theta_n \frac{l_{nx}}{l_{n0}}$$

$$Q_{32} = \sum_{n=1}^{N} E(\varepsilon_n)\sin^2\theta_n \cos\theta_n \frac{l_{ny}}{l_{n0}}$$

$$Q_{33} = \sum_{n=1}^{N} E(\varepsilon_n)\sin^2\theta_n \cos^2\theta_n$$

where, l_x and l_y, are the relative distance between these two bond sites in the global MD and CD, respectively; $E(\varepsilon_n)$, is the local modulus of n^{th} fiber, obtained from load-strain curve of the fiber. In general, $E(\varepsilon_n)$ varies with extension if the fiber load-extension behavior is nonlinear; $\delta\varepsilon_x$ and $\delta\varepsilon_y$, are the incremental tensile strains of web in MD and CD, respectively, and $\delta\gamma$ is the shear strain of the web.

Assuming a rectangular area circumscribing the bond site, oriented parallel to the MD and CD, the incremental linear tensile foreces and shear forces are defined as the forces acting on the unit width and height of the rectanglular region.

Computational Algorithm

The main concepts are summarized as follows. The web characteristics and fiber properties form the input to the model. Incremental strain, de-bonding force, computation method and iteration method form the input parameters for computational modeling. The entire program (computational algorithm and user interface) has been programmed in C++ and operates under Microsoft Windows (Figure 4).

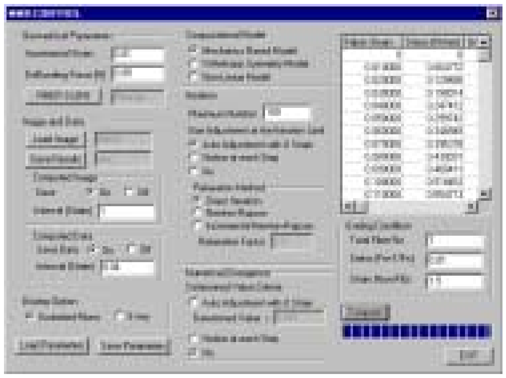

Figure 4. Input options for computational modeling

The program models the stress/strain behavior by incrementally straining the fabric and computing the linear stress components at each strain level. The program calculates the fiber strain from the original fiber length and the elongated fiber length. To form the global constitution equation, the fiber strain component is transformed at the global x-y coordinate using the delta (x), delta (y), shear angle, and their original values. At each incremental strain level, the resulting force components are determined. The model is programmed such to ensure that the force balance is maintained. That is, the summation of all force components must equal zero. If the force balance is not maintained, the force brought about by the changes in strain is re-calculated until convergence is achieved. Once convergence is met, the total force is checked against the amount of force required to fail the fibers. The bonding strength is assumed to exceed the rupture strength of the fibers. If the force required to fail the fibers in the computational model are higher than the corresponding experimental data, those elements are eliminated and the force balance convergence is reevaluated. If the model meets web failure conditions, the resulting data will be automatically saved and displayed for review.

Applications of the Model

Figure 5 demonstrates the case for different fiber strengths. In this case, it is assumed that the all other conditions remain constant.

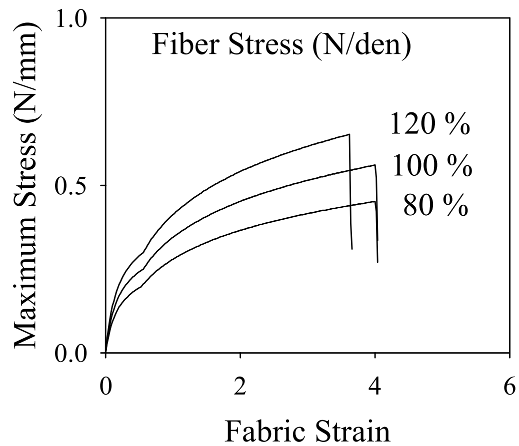

Figure 5. Web Stress-Strain curves as function of fiber strength

When using stronger fiber, the web modulus and failure stress increase but the elongation at the maximum stress decreases. This propensity of the web directly reflects the property of constituent fibers.

The images shown in Figure 6 are used to examine the effect of ODF anisotropy on the tensile behavior. The images are simulated with a normal distribution where the mean orientation as well as all other features is kept constant, but the ODF Standard deviation values are varied from 5 to 50 in increments of 5. The results are shown in Figure 7. It is clear that as the degree of anisotropy decreases (higher ODF Standard deviation), the maximum failure stress of the web decreases also because of the direct contribution of the force components toward the loading direction becoming much smaller.

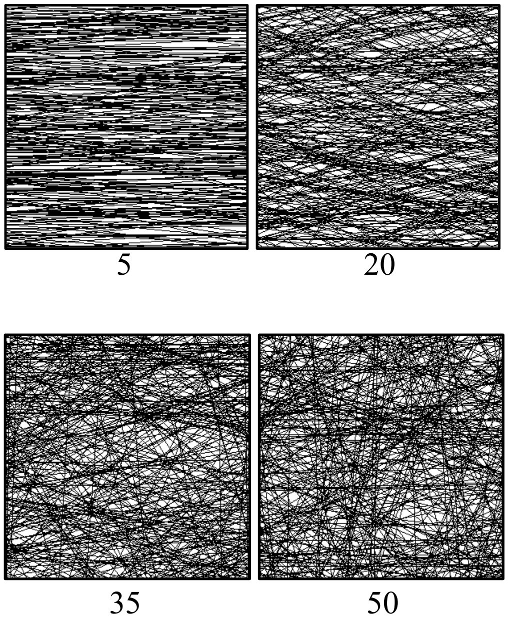

Figure 6. Images with varying degrees of anisotropy

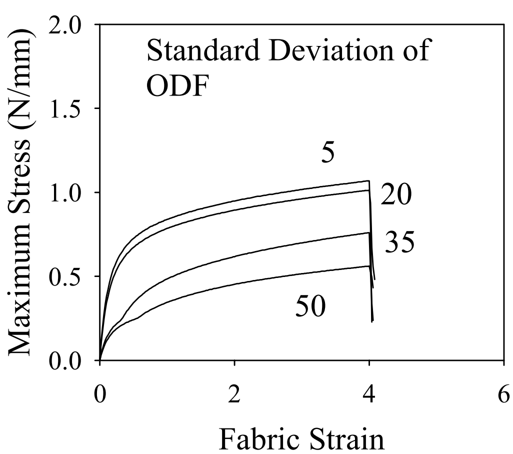

Figure 7. Web Stress-Strain curves as function of Anisotropy.

Conclusions

We have developed a mechanics based model to help understand the behavior of point bonded nonwovens as a function of structural variables. This model appears to have considerable promise in eliminating much of the elaborate experimentation that is currently required in the development of new products or the improvement of current products and processes.

Acknowledgments

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