Application of layered composite theory for predicting the mechanical properties of geotextiles

Umit Halis Erdogan & Nilüfer Erdem
Dokuz Eylul University, Department of Textile Engineering, Turkey

ABSTRACT: Geotextiles, which are the members of geosynthetics, are gaining more importance in complex applications such as construction sites and agricultural areas by virtue of their various advantages. Geotextiles are exposed to various loads in their application areas so that the knowledge of their mechanical behavior is a required parameter. In this study, a geometrical model was constructed by using theory of layered composite materials to predict the nonwoven geotextiles mechanical properties. Stress analysis of model was performed in commercial finite element software. Mechanical properties of fibers and constructional parameters of fabrics were used as data in the analysis. The comparison of theoretical and experimental results indicated that, meaningful stress data can be obtained from the stress distribution of computed models. However, it was found that, the difference between computed and measured elongation values was high. Consequently, it can be said that the model can be used as a tool to ease the selection of raw material and product type, and thus it will provide an advantage to the manufacturers in terms of cost and duration of design and production processes.

Keywords: Geotextiles, fibers, layered composite theory, finite element method

1 INTRODUCTION

Geotextiles, which are the members of geosynthetics, are gaining more importance in complex applications such as construction sites and agricultural areas by virtue of their various advantages. Geotextiles are generally used together with other geosynthetics in constructional projects. Various mechanical and hydraulic functions such as reinforcement, separation, protection, drainage and filtration are provided by fabrics in a geosynthetic-soil system (Ingold and Miller, 1988). Therefore, knowledge of geotextile mechanical behavior is a required parameter in designing with them. Several parameters of geotextiles such as polymer, fiber and fabric type and their properties have influence on the mechanical behavior of geotextile fabrics (Rawal and Anandjiwala, 2006).

Nonwoven fabrics are the most widely used geotextile materials. These types of geotextiles can be defined as complex sheets or web structures formed by the arrangement of fibers or filaments by mechanical, thermal or solvent methods (Lieberenz, 2003). They are felt like in appearance and are relatively thick. Therefore, method of bonding and orientation of fibers should be considered in mechanical characterization of nonwoven geotextiles. Interactions of several mechanisms in the deformation of fabrics such as breakage, elongation, shear, and bending make more complex the mechanical characterization geotextiles.

Several attempts have been made to predict the mechanical behavior of nonwovens under various types of loads. As a result of these studies, a number of theoretical models were developed. In 1960s Backer and Peterson, reported a fiber network theory for nonwoven fabrics based on fiber tensile properties and orientation of fibers. The elastic theory of orthotropic materials was used in prediction of material constants of a nonwoven. Hearle et al. expanded the fiber network theory and reported a series of papers about mechanical properties of nonwoven fabrics (Hearle and Stevenson 1963, 1964; Hearle and Newton 1967; Hearle and Sultan, 1968). The following theories generally considered the fiber network theory and improved it by using different and/or new experimental and theoretical methods such as image analysis methods and theory of composite materials. In consideration of these studies, several theoretical models have been developed to predict the behavior of nonwovens based on previous general methods known for years (Britton et.al, 1983; Bais-Singh and Goswami, 1995; Pourdeyhimi and Ramanathan, 1996; Kim, 2004, Rawal et. al, 2010, 2011).

In this paper, it is aimed to predict the mechanical behavior of needle punched-heat set heavy nonwoven geotextiles. For this purpose at first, fiber and fabric properties of geotextile specimens were analyzed with standard test methods. Then a theoretical model, which considers wide-width tensile test of nonwoven fabrics, was constructed based on theory of layered composite materials, finite element method and the previous studies (Liao et. al, 1997; Bais-Singh et. al, 1998; Erdogan, 2008). In our previous publications, we considered the properties of a reference fabric to predict the mechanical properties of geotextiles (Erdogan and Erdem, 2011a, 2011b). In this study, single fiber properties and orientation of fibers along the fabrics were used for the prediction of geotextile mechanical behavior. Stress analyses of fabrics were performed with commercially available finite element computer software by using experimental data and constructed model. Theoretical and experimental results were analyzed and discussed.

2 MATERIAL AND METHODS

2.1 *Material*

Needle punched-heat set geotextile fabrics, made from polypropylene staple fibers, were supplied by a commercial geotextile producer. Properties of geotextile specimens are summarized in Table-1.

Table 1. Properties of geotextile fabrics

Fabric weight (gr/m^2)	Fabric thickness (mm)	Fiber fineness (denier)	Fiber length (mm)
200	1.48	3	60
400	2.96	3	60
600	4.46	3	60
800	6.09	3	60

2.2 *Experimental*

Tensile tests of polypropylene staple fibers were performed by using Instron 4411 universal tensile tester according to TS EN ISO 5079. An average of 100 tests was recorded .The test length was kept as 20 mm, 0.2-0.4grf pretension was applied and the fibers were strained at a rate of 20 mm/min.

Thickness of the geotextile fabrics was measured using a digital thickness gauge with a certain pressure (2.00 ± 0.2 kPa) according to TS EN ISO 9863-1. An average of 5 thickness readings for each geotextile sample was recorded.

Tensile behavior of geotextile fabrics was examined both in the machine direction (MD) and in the cross machine direction (CD) on a computer controlled Shimadzu Autograph AG-IS Series universal testing machine. The wide-width tensile test, which can be schematically seen in Figure 1, was performed according to TS EN ISO 10319 to minimize the errors which can be caused by edge curling of specimens and to avoid the extreme strains in strip test. Fabrics were strained at a rate of 20 mm/min. An average of ten stress-strain data in the MD and in the CD was obtained for all sample fabrics.

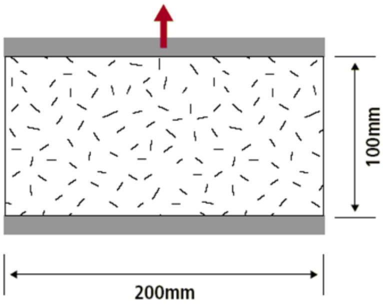


Figure 1. Wide-width tensile test

In the nonwoven production, all fibers in the card web are parallel to each other, but after lapping and punching, fibers in the layers of fabric are oriented at various directions following random or some known statistical distribution. Therefore, the orientation of fibers in a nonwoven fabric is another parameter that needs to be defined as initial data in the theoretical analysis. However, it is very difficult to obtain fiber orientation distribution with experimental methods in heavy nonwovens such as needle punched geotextiles, because they consist of a large number of fiber layers (Pourdeyhimin, 2001). Moreover, after heat setting process, measurement of fiber orientation gets more difficult with both experimental and computational methods. Therefore, in our approach, at first fiber orientation distribution of a light fabric (200gr/m^2) was measured under a projection microscope before heat setting and then the orientation angle of layers in heavy samples was assigned to program considering both the number of web layers in fabrics and the fiber orientation distribution of the light fabric. Fiber orientation distribution of the fabric with 200gr/m^2 unit weight can be seen in Figure 2.

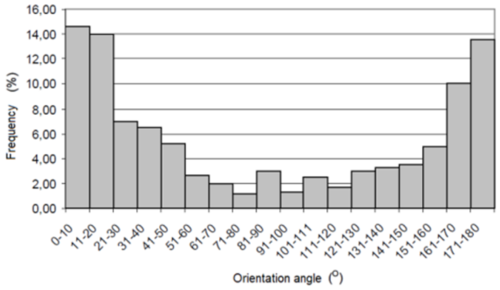


Figure 2. Fiber orientation distribution of the fabric with 200gr/m^2 unit weight

2.3 *Theoretical model*

In this study, a theoretical model was constructed considering the theory of layered composite materials and finite element method to predict the mechanical properties of nonwoven geotextiles. The basic principles of our model are similar to theoretical models of nonwovens proposed in previous publications (Liao et. al, 1997; Bais-Singh et. al, 1998; Erdogan, 2008). We assumed that nonwoven fabrics are made up of fiber layers similar to composite materials. Thus a layered nonwoven can be regarded as a laminate and each layer of fabric can be considered equivalent to a lamina. We also assumed that the nonwoven fabrics are formed by layered finite elements, and fibers (layers) that make up the fabric are bound together at nodal points of the mesh of the finite element. Nonwovens particularly heavy ones consist of a number of fiber layers (placed at an angle) as shown in Figure 3.

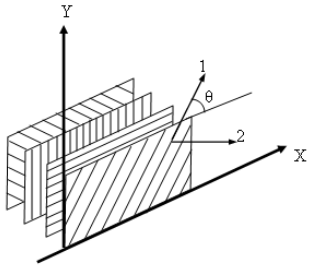


Figure 3. Layered structure of nonwoven fabric

The axes in the X-Y coordinate system represent the global axes, such that the uniaxial loading direction and traverse directions of fabrics coincide with the Y and X axes, respectively. The local axes for an individual layer (lamina) are given by the 1-2 coordinate systems, such that all fibers in the layer are oriented along the 1 direction and the direction 2 is perpendicular to the fibers. A unidirectional layer of fabric falls under orthotropic material category. If the layer is thin and does not carry any out of plane loads, plane stress conditions can be assumed for the layer. The relationship of stress and strain for an orthotropic plane stress problem can be written as (Kaw, 1997);

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} \dfrac{E_1}{1-\upsilon_{12}\upsilon_{21}} & \dfrac{\upsilon_{21}E_1}{1-\upsilon_{12}\upsilon_{21}} & 0 \\ \dfrac{\upsilon_{12}E_2}{1-\upsilon_{12}\upsilon_{21}} & \dfrac{E_2}{1-\upsilon_{12}\upsilon_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \tag{1}$$

Where E1 is the longitudinal Young’s modulus, E2 the traverse Young’s modulus, ν12 and ν21 the major and the minor Poisson’s ratios, G12 the in-plane shear modulus, $\sigma_1, \sigma_2, \tau_{12}$ the layer stresses in the 1-2 coordinate and $\varepsilon_1, \varepsilon_2, \gamma_{12}$ the layer strains in the 1-2 coordinate.

The global and local stresses in a layer are related to each other through the orientation angle of the layer. The relationship of stress and strain between the local and global system can be defined as (Kaw, 1997);

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} Cos^2\theta & Sin^2\theta & -2\,Sin\,\theta Cos\,\theta \\ Sin^2\theta & Cos^2\theta & 2\,Sin\,\theta Cos\,\theta \\ Sin\,\theta Cos\,\theta & -Sin\,\theta Cos\,\theta & Cos^2\theta - Sin^2\theta \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \tag{2}$$

and

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} Cos^2\theta & Sin^2\theta & Sin\,\theta Cos\,\theta \\ Sin^2\theta & Cos^2\theta & -Sin\,\theta Cos\,\theta \\ Sin\,\theta Cos\,\theta & -Sin\,\theta Cos\,\theta & Cos^2\theta - Sin^2\theta \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \tag{3}$$

where, $\sigma_x, \sigma_y, \tau_{xy}$ are the layer stresses in the X-Y coordinate, $\varepsilon_x, \varepsilon_y, \gamma_{xy}$ the layer strains in the X-Y coordinate and θ the orientation angle of the layer.

By substituting Equations (2) and (3) into Equation (1) the stress-strain relationship of each layer in the global coordinate system can be expressed as;

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \frac{E_1}{1-\upsilon_{12}\upsilon_{21}} & \frac{\upsilon_{21}E_1}{1-\upsilon_{12}\upsilon_{21}} & 0 \\ \frac{\upsilon_{12}E_2}{1-\upsilon_{12}\upsilon_{21}} & \frac{E_2}{1-\upsilon_{12}\upsilon_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{bmatrix} Cos^4\theta & Sin^2\theta\,Cos^2\theta & Sin\,\theta\,Cos^3\theta \\ Sin^2\theta\,Cos^2\theta & Sin^4\theta & Sin^3\theta\,Cos\,\theta \\ Sin\,\theta\,Cos^3\theta & Sin^3\theta\,Cos\,\theta & Cos^2\theta\,Sin^2\theta \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{4}$$

If the stress of a material varies with strain uniformly, equation (4) is valid. However in some nonwovens namely needle punched ones, deformation is non-uniform in uniaxial test (Adanur, 1995; Bais-Singh and Goswami, 1995). As it can be seen from stress-stain curve of the fibers, which form the nonwoven geotextiles, are also not uniform (Figure 4). The state of stresses and strains varies in the different regions of curve.

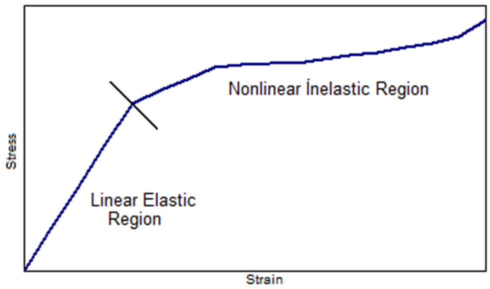


Figure 4. Stress-strain graphs of fibers

Therefore, non-uniform stress-strain behavior was assumed for each layer and the stiffness matrix of layer divided into two parts. In the initial part, stress varies linearly with strain, while it varies nonlinearly in the second part. After reaching the maximum stress, the fibers and/or bonds start to fail and the fabric stress drops to lower values, thus the theoretical calculations were not performed in these regions. The stress-strain relationship of a lamina can thus be given as

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix}=\begin{bmatrix}\frac{E_1}{1-\upsilon_{12}\upsilon_{21}} & \frac{\upsilon_{21}E_1}{1-\upsilon_{12}\upsilon_{21}} & 0\\ \frac{\upsilon_{12}E_2}{1-\upsilon_{12}\upsilon_{21}} & \frac{E_2}{1-\upsilon_{12}\upsilon_{21}} & 0\\ 0 & 0 & G_{12}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix}+\begin{bmatrix}c'_{11} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix} \tag{5}$$

The components of linear part of stiffness matrix are material constants which are denoted by equation (1). The nonlinear part of the stiffness matrix contains only one stiffness term (c'_{11}), which relates the stress and strain components in the layer direction. If the strains are known at any point along the thickness of the laminate (fabric), the global stresses can be calculated for each layer by incorporating equations (4) and (5). Then stresses in all layers can be integrated using the theory of composite materials to give the overall mechanical behavior of the layered nonwoven. Thus, fabric stresses in the X-Y direction for each finite element in the symbolic matrix form can be given by;

$$[\sigma]^e=[D]^e[\varepsilon]^e+[D]^{e'}[\varepsilon]^e \tag{6}$$

where $[D]^e$ and $[D]^{e'}$ are the material constitutive matrices of the element in the linear part and nonlinear part, respectively. $[\sigma]^e=[\sigma_x\sigma_y\tau_{xy}]^T$ and $[\varepsilon]^e=[\varepsilon_x\varepsilon_y\gamma_{xy}]^T$

We incorporated the above finite element constitution relations into a commercial finite element program ANSYS to carry out stress analysis. Experimental data on the fiber tensile properties and web structure parameters are also supplied to software as input data. In the linear part, where the moduli are constant, we considered the orthotropic theory. We considered multi-linear stress-strain assumption in the nonlinear part of stress-strain curve of the fiber. In the multi-linear region, fifteen respective stress-strain values of fiber and in the linear region material constants of fiber, was used as initial data.

Needle punched nonwoven geotextiles were modeled considering the wide-width tensile test. Initial geometry of fabric and the boundary conditions applied to the model are shown in Figure 5. Side AB and CD are constrained within the jaws. All translations and rotations are constrained on side AB. However, side CD is allowed to move only vertically. Both sides AD and BC are allowed to move freely in the traverse direction.

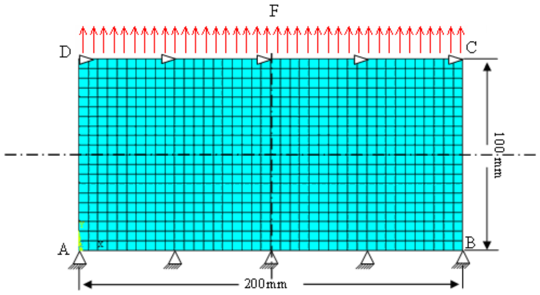


Figure 5. Initial geometry of fabric model

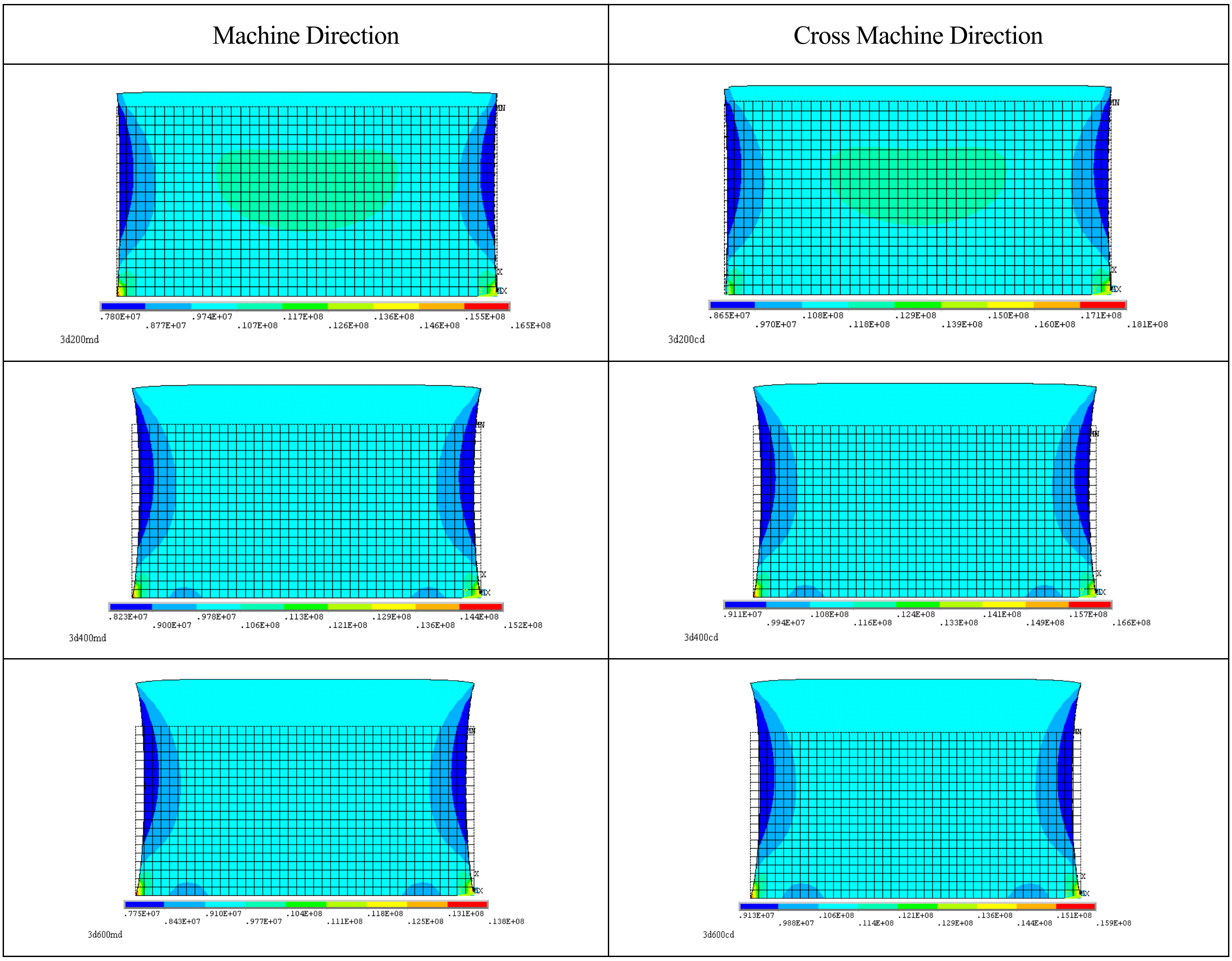
“Structural Layered Composite” element was chosen to mesh the initial fabric model. This element type is suitable for the calculation of the behavior of laminated structures with anisotropic nonlinearities. Uniformly distributed tensile load (negative pressure) was applied to side CD. The magnitudes of applied loads are different for the nonwoven fabric samples and are slightly less than their failure initiation loads. The real constants for layers and elements are given in Table 2. Fabric thickness values are used to assign thickness value for each element.

Table 2 Real constants for elements and layers

Fabric Weight (gr/m^2)	Total Number of Layers	Orientation Angle of Layers (°)	Layer Thickness (mm)	Element Total Thickness (mm)
200	4	0, 10, 170, 180	0.37	1.48
400	12	0, 10, 20, 30, 60, 75, 105, 120, 150, 160, 170, 180	0.25	2.96
600	16	0, 5, 10, 20, 30, 45, 60, 85, 95, 120, 135, 150, 160, 170, 175, 180	0.29	4.46
800	20	0, 5, 10, 15, 20, 30, 45, 50, 60, 85, 95, 120, 130, 135, 150, 160, 165, 170, 175, 180	0.30	6.09

3 RESULTS AND DISCUSSIONS

The constructed theoretical model was used for stress analysis of needle punched-heat set heavy geotextiles. Mechanical properties of fibers and constructional parameters of geotextile fabrics were used as data in the analysis. The distribution of computed stresses of sample fabrics in MD and CD can be seen in Figure 6.



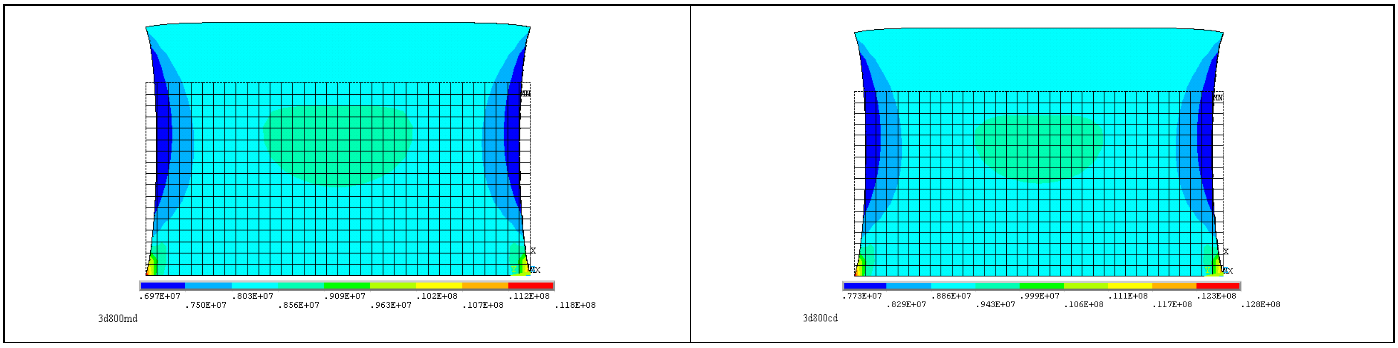


Figure 6. Distributions of computed stresses in simulated sample fabrics

As seen in the plotted contours, the state of stresses is not the same throughout the models because of constraints, imperfectly symmetric distribution of fibers within the fabrics and transverse contraction during tensile deformation. Particularly, stresses are much higher in the corners. Maximum stresses were calculated next to the jaws as a result of constraints. Minimum stresses were obtained near by the free edges. Critical stress distributions and concentrations were calculated around the center of the models. Consequently meaningful stress data can be obtained from the stress distribution of computed models of needle punched heat set nonwoven geotextile samples. The typical shape of the deformed fabric samples in the tensile tests can be seen in Figure 7.

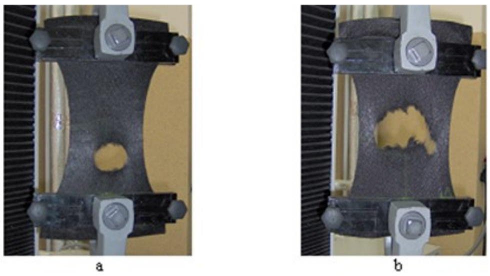


Figure 7. Deformation of fabric (800gr/m^2) in uniaxial tensile tests (a) MD, (b) CD

The comparisons of Figure 6 and Figure 7 shows that experimentally obtained and theoretically computed configurations of geotextile samples are similar in uniaxial tensile tests. There is not any lateral contraction at the jaws of computed figures; however contraction gradually increases to its maximum value at the center of the models. As given in Figure 7, very similar behaviors were observed during experiments due to the geometry of test. The inconstant lateral contraction of nonwoven fabrics in uniaxial tests was successfully simulated in the models. In the computed figures, critical stress concentrations were calculated around the center of models. Similarly, as seen in Figure 7, the experimental breaks usually occur around the center of specimens in uniaxial tensile tests. Considering these test results, element stresses in the center of theoretical solutions were chosen for comparison. Theoretically and experimentally calculated stresses of geotextile samples in the MD and CD are given in Table 3.

Table 3. Experimental and Calculated Stresses

Fabric Weight (gr/m^2)	**Stresses (Pa)**			
	Experimental		**Theoretical**	
	MD	**CD**	**MD**	**CD**
200	1.03 10^{7}	1.14 10^{7}	1.08 10^{7}	1.19 10^{7}
400	1.01 10^{7}	1.11 10^{7}	1.05 10^{7}	1.15 10^{7}
600	9.36 10^{6}	1.09 10^{7}	9.69 10^{6}	1.13 10^{7}
800	8.32 10^{6}	9.16 10^{6}	8.59 10^{6}	9.45 10^{6}

As seen in the Table 3, predicted stresses in the center of plotted models are compatible with experimental ones and close to measured maximum stresses. Experimentally measured maximum stresses are predicted with almost 8-9 % average margin of error in the center of the models. Computed and tested stress-strain curve of the fabric having 400 gr/m^2 unit weights can be seen in Figure 8.

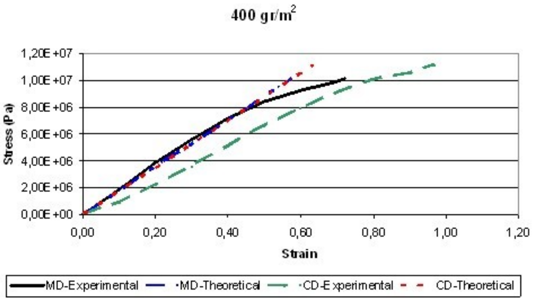


Figure 8. Comparison between theoretical and experimental results of 400 g/m^2 fabric

The comparison of all samples shows that, reasonable agreement is obtained between the theoretical and experimental stresses. However, in the case of elongations, the model could not predict the strains of heavy geotextiles in uniaxial tensile test accurately. As the fabric weight increases and fabrics become thicker, higher displacements were predicted with respect to experimental measurements.

4 CONCLUSION

Geotextiles are exposed to various loads in their application areas so that the knowledge of their mechanical behaviors is a required parameter in designing geosynthetic-soil systems. In this study, a theoretical approach is proposed to predict the mechanical properties of heavy needle punched heat set nonwoven geotextiles using layered composite theory and finite element method. Stress analyses of geotextile fabrics were performed with commercially available finite element computer software by using experimental data and the constructed model. Mechanical properties of fibers and constructional parameters of fabrics were used as data in the analysis. Theoretical and experimental results were analyzed and discussed. Comparison of theoretical and experimental results indicated that, meaningful stress data can be obtained from the stress distribution of computed models. Calculated stresses in the center of the model, where the experimental breaks are usually observed, are close to measured maximum stress. Moreover, similar fabric configurations were observed in the experimental and computed results. However, in the case of elongations, predicted values are not very close to the experimental ones. This is most probably due to the reorientation of staple fibers in the beginning of tensile tests. Moreover in fabrics bonded areas are not as homogeneous as in constructed model and thickness of fabric are not uniform as assumed in the model. As a nature of bonding process, weak bonded zones can also occur in real fabrics.

Consequently, constructed model makes it possible to predict the stress distribution in heavy needle punched geotextiles. However, the elongation of heavy fabrics cannot be predicted with adequate accuracy. Therefore further work, which may consider the reorientation of fibers during deformation of heavy nonwovens, is needed. It should be concluded that the model can be used as a tool to ease the selection of raw material and product type, and thus it will provide an advantage to the manufacturers in terms of cost and duration of design and production processes.

ACKNOWLEDGMENTS

This research was a part of a project supported by The Scientific Research Department of Dokuz Eylul University (Project No: 2005.KB.FEN.004). Their generous financial support of this project is gratefully acknowledged. We also thank Geo-Tipptex Kft. for supplying geotextile fabrics and Hassan Group for their technical supports.

REFERENCES

Adanur, S. 1995. Wellington sears handbook of industrial textiles. Lancaster & Basel: Technomic Pub. Co. Inc.

Backer, S. & Peterson, D.R. 1960. Some principles of nonwoven fabrics. Textile Research Journal, Vol. 30 (9), pp. 704-711.

Bais-Singh S. & Goswami, B.C. 1995. Theoretical determination of the mechanical response of spun-bonded nonwovens. Journal of Textile Institute, Vol. 86 (2), pp. 271-289.

Bais-Singh, S., Biggers, S. & Goswami B.C. 1998. Finite element modeling of the non-uniform deformation of the spun-bonded nonwovens. Textile Research Journal, Vol. 68(5), pp. 327-342.

Britton, P.N., Sampson, A.J. & Gettys, W.E. 1983. Computer simulation of mechanical properties of nonwoven fabrics part I: Method. Textile Research Journal, Vol. 53(6), pp. 363-368.

Erdogan, U.H. 2008. An investigation about in use properties of polypropylene fibers used in geotextiles by different methods, Ph.D. Dissertation, Dokuz Eylül University, İzmir, Turkey.

Erdogan, U.H. & Erdem, N. 2011a. Modeling the tensile behaviour of needle punched nonwoven geotextiles International Journal of Clothing Science and Technology, Vol. 23(4), pp. 258-268.

Erdogan, U.H. & Erdem, N. 2011b. A theoretical approach for predicting the tensile behavior of needle punched-heat set heavy geotextiles. Industria Textila, Vol. 62(5), pp. 227-232.

Hearle, J.W.S & Stevenson, P.J. 1963. Studies in nonwoven fabrics part III: The anisotropy of nonwoven fabrics. Textile Research Journal, Vol. 33(10), pp. 877-888.

Hearle, J.W.S, & Stevenson, P.J. 1964. Studies in nonwoven fabrics part IV: Prediction of tensile properties. Textile Research Journal, Vol. 34(3), pp. 181-191.

Hearle, J.W.S & Newton, A. 1967. Nonwoven fabric studies part XIV: Derivation of generalized mechanics the energy method. Textile Research Journal. Vol. 37(9), pp. 778-797.

Hearle, J.W.S. & Sultan, M.A.I. (1968). A study of needled fabrics, part III: The influence of fiber type and dimensions. Journal of Textile Institute, Vol. 59, pp. 137-147.

Ingold, T.S. & Miller, K.S. 1988. Geotextiles Handbook. Londra: Thomas Telford.

Kaw, K. 1997. Mechanics of composite materials. New-York: CRC Press.

Kim, H.S. 2004. Orthotropic theory for the prediction of mechanical performance in thermally point-bonded nonwovens. Fibers and Polymers, Vol. 5(2), pp. 139-144.

Liao, T., Adanur, S. & Drean, J.Y. 1997. Predicting the mechanical properties of nonwoven geotextiles with the finite element method. Textile Research Journal, Vol. 67(10), pp. 753-760.

Lieberenz, K. 2003. Geononwovens. Albrecht, W., Fuchs, H. ve Kittelman W. (Ed.) In nonwoven fabrics raw materials, manufacture, applications, characteristics, testing processes pp. 576-586. Weinheim: Wiley-VCH Inc.

Pourdeyhimi, B. & Ramanathan R. 1996. Measuring fiber orientation in nonwovens part I: Simulation. Textile Research Journal, Vol. 66(11), pp. 713-722.

Pourdeyhimi, B. 2001. Fiber orientation distribution in heavy nonwovens. NCRC Newsletter, 7.

Rawal, A. & Anandjivala, R. 2006. Relationship between process parameters and properties of multifunctional needlepunched geotextiles. Journal of Industrial Textiles, Vol. 35(4) pp. 271-285.

Rawal, A., Priyadarshi, A., Lomov, S.V., Verpoest, I., Vankerrebrouck, J., 2010. Tensile behavior of thermally bonded nonwoven structures: model description. Journal of Materials Science Vol. 45, pp. 2274-2284.

Rawal, A., Kochhar A., Gupta A.2011. Biaxial tensile behavior of spunbonded nonwoven geotextiles. Geotextiles and Geomembranes. Vol. 29 (2011) pp. 596-599.