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Evaluation of Bending Modulus of Needle-Punched Fabrics Using Two Simply Supported Beam Method

Abstract
In this work the effect of needle-punching parameters, such as the punch-density and depth of needle penetration on the bending properties of polypropylene needled fabrics was investigated. Four samples of needled fabrics were produced using conventional Carding/ Cross-lapping machines. The bending stiffness of the samples was evaluated in the machine-direction using the two simply supported beam and simple cantilever methods. The results indicate that the bending modulus of the fabrics are affected by both the amount of the punch density and depth of needle penetration. The results also revealed that the values of bending modulus obtained by the two simply supported beam method are greater than those obtained by the cantilever method, which is due to the nonlinear nature of the moment-curvature relation of the bent fabric.

Key words: *needled non-woven, punch density, needle penetration depth, bending modulus.*

properties of fabric forming components and their arrangement in the structure of the fabric. The properties of the components can be varied and readily controlled during the manufacturing stage. These controls result in an improvement in fabric functional performances. Needled fabrics are engineered according to their end-use and are extensively used in domestic and technical applications, such as the following

a) Floor coverings, including automobile carpets.
b) Filtration - both wet and dry.
c) Civil and geotechnical engineering applications.
d) Wadding.

Goswami [1] studied the effect of fibre geometry on the punching-force characteristics of webs during needling. These studies showed that the arrangement of fibres within the structure of fabric affect the tensile behaviour of needled fabric [2].

Other researchers [3 - 5] have studied the rigidity and stiffness of conventional woven fabrics. The methods and apparatus which are used to measure the stiffness and bending modulus of woven fabrics have been made available. The thickness of needled fabrics is well in excess of that of woven fabrics, making the employment of these well established methods rather difficult and, in some cases, even impractical for the evaluation of the bending properties of needled fabrics.

The main aim of this work was to adopt a tensile tester to determine the bending modulus of needled fabrics. A two simply supported beam system was used that can cause deflection in the middle of the fabric by application of a load. The tensile tester was set in the compressive mode with a deflecting load, and the amount of resulting deflection in the bent fabric was continuously measured. Based on classical theories, the bending modulus of the fabrics was calculated using the slop of the linear part of the load-elongation (deflection) curve.

In this work four types of needled fabrics of different weight per unit area were produced. The samples were manufactured using different punch densities and needle penetration depths. The bending moduli of the samples in the machine-direction were determined. The simple cantilever method was also used to calculate the bending modulus of the fabrics. The results of the two methods were then compared.

■ Theory

In this work, the two simply supported beam system method was used to determine the bending modulus of needled fabrics. Classical theory of bending using the Bernoulli-Euler law states that
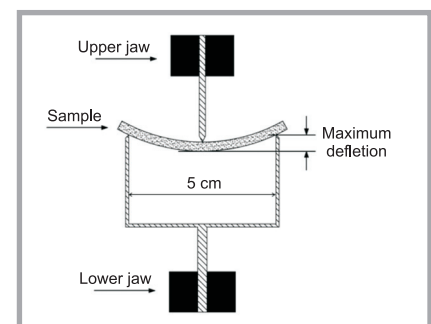

Figure 1. Schematic diagram of the tensile tester adopted for the bending test.

■ Introduction

Needling parameters such as the punch density, needle penetration depth and the type of needles used can affect the physical and mechanical properties of the fabric. Thus, the functions in the fabric required can be achieved by manipulation of needle punching parameters. Generally the mechanical properties of non-woven fabrics are determined by the
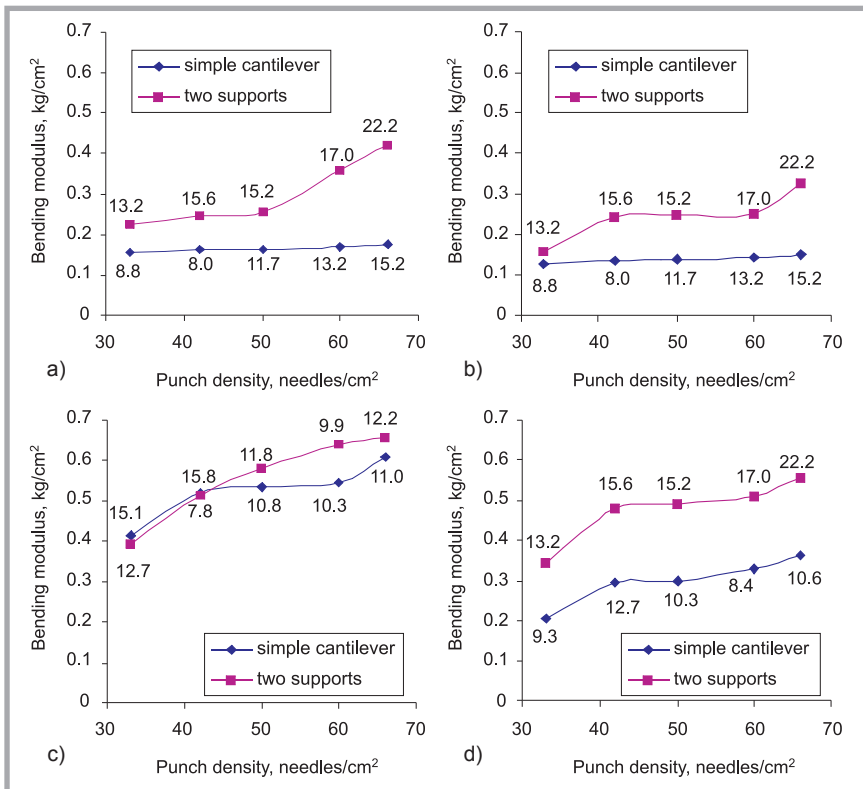
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Figure 2. *Variations in the bending modulus versus the punch density; a) 200 g/cm², b) 300 g/cm², c) 400 g/cm², d) 500 g/cm².*

the curvature "*k*" of the deformed beam at a given point is proportional to the corresponding bending moment [6] i.e.

$$k = \frac{1}{\rho} = \frac{M}{E} \qquad (1)$$

Where:
ρ - Radius of curvature.
M - Bending moment.
E - Elastic modulus.
I - Moment of inertia of the beam cross-section.

In the case of a beam deformed under an applied load, the bending moment varies along the length of the beam. Thus, the curvature along the beam changes with variation in the bending moment. Consider an element (ds) along the deformed beam, it can be shown thatthe deformed shape of the beam is expressed by;

$$\frac{1}{\rho} = \frac{d\theta}{ds} \qquad (2)$$

Where, θ is tangent to the deformed curve at any point [6].

Small deflection analysis

Classical beam theory is valid when the deflection of a beam is small in comparison to its length. Assuming the material

to elastic, with a symmetrical cross-section, then it can be stated that

$dx = ds$ and $\theta = $ dy/dx, *Equation 2* becomes [7]:

$$\frac{d^2y}{dx^2} = \frac{M}{E} \qquad (3)$$

Assuming the boundary condition, the bending moment "*M*" of a spanned elastic beam deflected by the action of an applied load in the middle at any point along the beam can be obtained using *Equation 3* in the form

$$y = \frac{P}{48E}\left(4x^3 - 3L^2x\right) \qquad (4)$$

Where, L and P are the length of the beam and the applied load, respectively [7]. The weight of the fabric can be neglected as it is negligible in comparison to the magnitude of the applied load. The maximum deflection at the middle of the beam" y_{max}" is determined as follows:

$$y_{max} = y_{x=\frac{L}{2}} = \frac{LP^3}{48E} \qquad (5)$$

It is assumed that the cross-section of the beam is a rectangle and remains unchanged during bending. Substituting for the moment of inertia of the rectangle,

the above equation can be written as follows:

$$Y = \frac{LP^3}{4Ebh^3} \qquad (6)$$

Where, b and h are the width and thickness of the rectangular sample, respectively. *Equation 6* can be written as *Equation 7*:

$$P = Y \times \frac{4Ebh^3}{L^3} \qquad (7)$$

This equation shows that the relation between the applied load "*P*" and the deflection of the spanned beam at middle "*Y*" is linear, and the slop of the resulting straight line is equal to $4Ebh^3/L^3$.

■ **Material and methods**

The above method ignores the deflection of the beam under its own weight. Therefore, this method in general can be applied to needled non-woven fabrics.

Melt-spun round 90 mm long staple 12 dtex Polypropylene fibres were produced at a crimp frequency of 3 crimp/cm. The fibres were used to manufacture four samples of needled fabrics with a mass per unit area of 200, 300, 400 and 500 g/m². As was stated previously, needled fabrics enjoy a wide range of end-uses. In principle, a carded web is fed to a cross- lapping machine and a batt is formed. The folded fibrous batt must initially be stabilised to such an extent that it can be feed to a proceeding additional finish needling operation. The additional needling operation is designed so that the requirements of a particular end use are realised. Therefore, the initial mechanical properties of the fabrics immediately prior to their presentation for additional finish needling operations are of paramount importance. The most influential parameters that affect the fabric at the initial needling stage are the punch density and needle penetration depth. Thus, realistic needling parameters were chosen throughout the experiments. In order to study the effect of the punch density and needle penetration depth on the bending rigidity and modulus of the needled fabrics, two different sets of experiments were conducted. In the first set of experiments five different punch densities i.e. 33, 42, 51, 60 and 66 punch per cm² were used at a constant needle penetration depth of 13 mm. In the second set of experiments four needle penetration depths i.e. 0.0, 7.0, 13.0 and 20

mm were employed while a constant punch density of 51 needles per cm2 was maintained. GROZ-BECKERT needles, coded G15×18×32×3, were used in the preparation of the test samples.

Simply supported beam

In this work a Zwick 1446-60 tensile tester machine was used to evaluate the bending stiffness of the needled fabrics, for which a U-shaped metallic piece was made. The distance between the two tines of the U-shaped piece was set at 5 cm. The U-shaped piece was fixed on the Zwick's lower jaw. A sharp edge metallic plate, as shown in *Figure 1* (see page 89), was fixed on the upper jaw. 6 × 2.5 cm samples of needled fabrics cut along the machine-direction were prepared. The sample to be tested was then placed on the tines of the U-shape piece. The tensile tester was set to operate in the compressive mode. As the lower jaw moves upwards, the sharp edge of the metallic plate presses downwards on the middle of the sample. The deflecting force is sensed and measured by the load cell of the tensile tester. The amount of upward movement of the lower jaw, labelled as crush in diagrams of the Zwick tester, is a measure of the deflection in the middle of the bent fabric.

Simple cantilever test

The results obtained using the cantilever method were compare with those of other methods. The bending moduli of the fabrics were calculated using a Shirley stiffness tester. The results calculated are shown in *Figures 2* and *3*.

■ **Results and discussion**

Flexural experiments were carried out on various needled fabrics. Each test sample, as stated previously, had been prepared at a given punch density and needle penetration depth. It was observed that all samples exhibited a very similar flexural behaviour. The result of a test sample was selected as a typical presentation of flexural behaviour, depicted in *Figure 4*, which shows the load-deflection curves of samples prepared at a given punch density and needle penetration depth. The curves shown were used for calculation of the mean value of the bending modulus. As can be seen, an initial linear region exists, where the applied and induced deflection are linearly related; consequently, *Equation 7* holds true. Thus, the bending modulus of the fabric can be
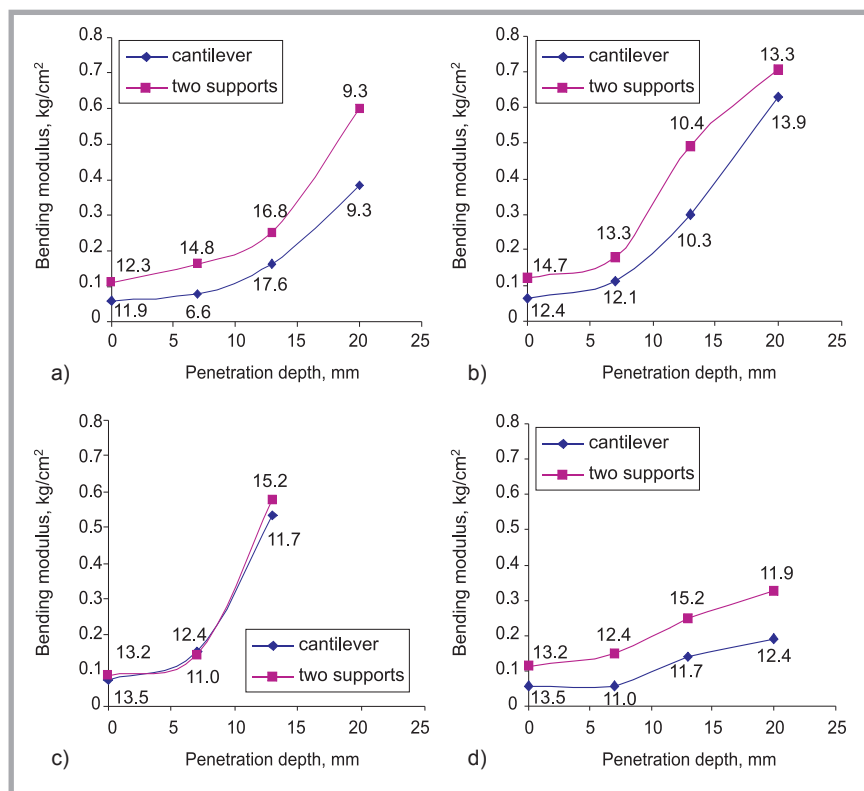
Figure 3. *Variation in the bending modulus versus the penetration depth; a) 200 g/cm2, b) 300 g/cm2, c) 400 g/cm2, d) 500 g/cm2.*
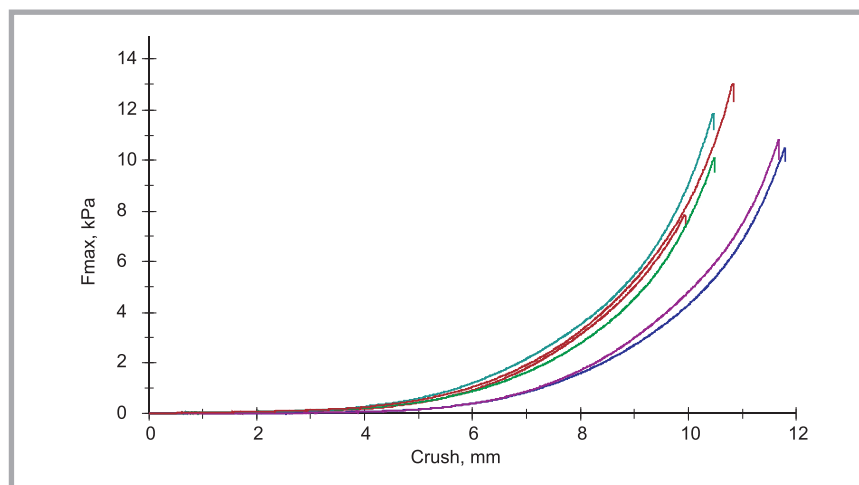
Figure 4. *Typical load-deflection curves at a given needling condition.*

calculated using the slope of the linear region. Beyond this linear region, the linear relationship ceases to exist, which is an indication of the onset of large deformation in the bent fabric. Standard methods were used for calculation of the width and thickness of the samples, the results of which are shown in *Tables 1* to *2*.

Flexural tests were carried out at different punch densities. The mean and% coefficient of variations in the bending modulus were calculated. Variations in the bending modulus versus the punch

density are depicted in *Figure 2*, in which the % coefficients of the variation are shown next to the data points.

As shown in *Figures 2.a* to *2.d*, an increase in the amount of punch density causes a rise in the bending modules of the samples. Furthermore, the mass per unit area significantly affects the rigidity of needled fabrics. Additionally an increase in the rate of the bending modulus is more profound as the mass per unit area of the sample is increased, which is due to the fact that an increase in the

Fabric mass, g/cm²	Punch density, needles/cm²	Fabric thickness, mm
500	33	8.10
	42	7.50
	50	7.20
	60	6.70
	66	6.40
400	33	6.70
	42	6.40
	50	6.05
	60	5.75
	66	5.67
300	33	5.70
	42	5.30
	50	4.75
	60	4.65
	66	4.60
200	33	5.40
	42	5.20
	50	4.60
	60	4.37
	66	4.30

amount of punch density or mass per unit area provides the needle with a larger number of fibres that can be engaged by the barbs. This results in a higher degree of fibre entanglement within the fabric and hence in a visible improvement in the bending properties of the fabrics.

Flexural tests were also carried out at different needle penetration depths. The mean and % coefficient of variations in the bending modulus were calculated. Variations in the mean bending modulus versus the needle penetration depth are depicted in *Figure 3*, in which the% coefficients of variation are shown next to the data points.

The results show that at small needle penetration depths, provided all other factors are equal, fabric rigidity generally remains unaffected. However, at a certain needle penetration depth, fabric rigidity begins to increase rapidly with increases in the needle penetration depth. Again, as in the case of the punch density, the mass per unit area significantly affects the rigidity of the needled fabrics. The effect of the depth of needle penetration on the rigidity of the needled fabrics is greater for heavier fabrics.

The effect of the needle penetration depth on the rigidity of fabrics can be attributed to the fact that as the penetration depth is increased, a higher number of barbs located on the needle shank can participate

in the transfer of fibres within the fibrous web. Once more, as the punch density is increased, the ratio of fibres directly held by the barbs to those that are not gripped directly by the barbs, but are rather in contact with the directly held fibres, is increased. In addition to this, a higher depth of needle penetration causes the transferred fibres to move a longer distance along the thickness of the fabric. The increased fibre displacement results in more compact and rigid fabrics.

It must be pointed out that some difficulties were encountered in the case of the heaviest fabric i.e. 500 g/cm², which can be associated with the discrepancies observed in *Figures 2.d* and *3.d*. The 500 g/cm² specimen produced at a 20 mm needle penetration depth was not stable on the supports. Consequently, it was excluded from the calculations, as can be seen in *Figure 3.d*.

The results also reveal that the values of the moduli obtained by the two simply supported methods are greater in comparison to those obtained by the simple cantilever method. In order to explain the reason behind this difference, the magnitude of the curvature of the beam in the two methods should be considered. In a simply supported beam, the curvature varies from zero at the supports to the maximum in the middle of the beam. The maximum curvature in the case of small deformations can be calculated from the following equation;

$$k_{max} = \frac{12 y_{max}}{L^2} \qquad (8)$$

Where;

y_{max} - maximum deflection.

L - length of the beam.

k_{max} - maximum curvature at middle of the bent beam.

The maximum deflection "y_{max}", of the bent fabric can be obtained using the linear region of the load-deflection curves (*Figure 4*). Substituting the values of the maximum deflection in *Equation 8*, the values of the maximum curvature can then be calculated. For all samples tested in this research, the values of maximum curvature, k_{max}, in the linear region are found to be less than 0.5 cm⁻¹.

There are two distinct regions in the moment-curvature relation of a bent fabric. The first region is non-linear, which is related to the corrective couple and internal

Fabric mass, g/cm²	Penetration depths, mm	Fabric thickness, mm
500	0	9.40
	7	9.30
	13	7.20
	20	6.00
400	0	8.10
	7	7.95
	13	6.05
	20	4.60
300	0	7.00
	7	6.80
	13	4.75
	20	4.30
200	0	6.10
	7	6.00
	13	4.60
	20	3.85

friction of the fabric structure. The second region commences beyond a transition curvature, where the M-k relation is almost linear. The slope of the moment-curvature curve in each of the above regions is a measure of the bending rigidity of the fabric. The slope is smaller in the second region (final rigidity) in comparison to the first (initial rigidity). According to Kawabata and Niwa [8], the curvature in the second region lies almost in the range of 0.5 to 1.5 cm⁻¹. Various workers have tried to present a solution to the moment-curvature relation of fabrics. In this respect the bi-linear theory of Haung [9] is based on the assumption of the existence of two linear regions. This is the main reason behind differences in the value of bending rigidity of a fabric when different methods are employed.

As explained previously, the maximum curvature obtained using the simply supported method lies in the first region, with a value of less than 0.5 cm⁻¹. This yields to a greater bending modulus in comparison to that obtained using the simple cantilever method, where the deflection is larger and the maximum curvature lies in the second region.

■ Conclusions

A modified tensile tester was used to measure the bending modulus of needled fabrics. The simple cantilever and two simply supported beam test methods were employed, the results of which were compared. It was found that the latter method yields greater values of the bending modulus for needled fabrics in

comparison to the former method, which is due to the non-linear nature of the moment-curvature relation of the fabrics. The results also revealed that not only the punch density and needle penetration depth but also the mass per unit area of the fabrics significantly affects the rigidity of the needled fabrics.

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Acknowledgment

References

1. *Goswami B., Beak T. and Scardino F.L., Influence of Fibre Geometry on the Punching-Force Characteristics of Web during Needle Felting, Textile Research Journal, vol. 38, 605-612, 1972.*
2. *Adanur S. and Liao T., Fibre Arrangement Characteristics and Their Effects on Non-woven Tensile Behavior, Textile Research Journal, vol. 69, 816-824, 1999.*
3. *Kocik M., Zurek W., Krucinska I., Gersak J., Jakubczyk J., Evaluating the Bending Rigidity of Flat Textiles with the Use of an Instron Tensile Tester, FibreS & TEXTIELS in Eastern Europe, 13, No. 2(50), 31-34, 2005.*
4. *Szablewski, P., Kobza, W., Numerical Analysis of Pierce's Cantilever Test for the Bending Rigidity of Textiles, FibreS & TEXTIELS in Eastern Europe, 11, No. 4(43), 54-57, 2003.*
5. *Zhou, N., Ghosh, T.K., On-line Measurement of Fabric Bending Behavior, part II: Effects of Fabric Nonlinear Bending Behavior, Tex. Res. J., 68, 533-542, 1998.*
6. *Kang, T.J., Joo, K.H., Lee, K.W., Analyzing Fabric Buckling Based on Nonlinear Bending Properties, Tex. Res. J., 74, 172-177, 2004.*
7. *Timoshenko, S., Young, D. H., Elements of Strength of Materials, Van Nostrand, New York, 5th Edition, 1969.*
8. *Kawabata, S., Niwa, M., Modern textile characterization methods, Chapter 10, Objective Measurement of Fabric Hand, The University of Shiga Prefecture, Hikon City, Japan, 329-354, 1995.*
9. *Huang, N.C., Finite Biaxial Extension of Completely Set Plain Woven Fabrics, J. App. Mech., 46, 651-655, 1979.*

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- Modelling and identification of the mechanical properties of textile composite materials
- Optimisation of the mechanical and thermal properties of fibre reinforced composites
- Sensitivity analysis and optimal design of the shape and thermomechanical properties of structural elements
- Identification and computer oriented simulation of defects in structures using thermographic methods and modal analysis

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- Creation of principles for the modelling of textile products subjected to static and dynamic loads
- Computer oriented analysis and synthesis of textile products, composite structures and structural elements subjected to mechanical and thermal loads

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