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***Research Paper***

# Predicting the Mechanical Properties of Thermally Bonded Nonwovens using Theory of Fibre Contacts[#]

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Fibre contacts play a significant role in determining the mechanical properties of nonwoven structures. These structures are subjected to mechanical deformations in various technical and industrial applications. In this paper, an overview of application of theory of fibre contacts to predict the tensile, bending and compressional properties of thermally bonded nonwoven structures has been presented. The theory of fibre contacts has successfully formulated the basis for developing the two dimensional (2D) micromechanical models. A comparison is also made between the theoretical and experimental results.

**Key Words: Fibre Contact; Nonwoven; Thermally Bonded; Fibre Orientation; Bending; Compression; Tensile**

## 1. Introduction

Thermally bonded nonwoven structure consists of fibres oriented randomly or directionally bonded by means of heat energy. There has been an ever-increasing interest in thermally bonded structures as they are amongst the most widely used nonwovens, with applications ranging from baby diapers to high performance geotextiles. The structure of thermally bonded nonwovens is essentially fused fibrous networks consisting of fibres, fused bonds or contacts and pores. In general, fibres and their contacts are significantly important in determining the mechanical behaviour of thermally bonded nonwoven structure. For example, during the application of tensile or compressional load on a typical nonwoven, fibres act as load bearing elements whereas the transfer of stress is being carried out by means of fibre contacts.

van Wyk [1] carried out a pioneering work in computing the distance between the fibres contacts in a random assembly of fibres. Three decades later, Komori & Makashima [2] generalised the concept of calculating the number of contacts for anisotropic fibrous assemblies. Subsequently, the theory was successfully applied to predict the initial tensile response, compressional and shear behaviours of *general* fibrous assemblies [3-6]. Over the years, the theories proposed by Komori and Makashima [2] have been critically analysed as Pan [6, 7] pointed out that the model for calculating the number of contacts was incorrect. Since, the probability of contact changes with successive contacts, i.e. steric hindrance effect. This effect reveals that an existing contact decreases the effective contact length of a fibre, reducing the probability of formation of new contacts. On the other hand, the existing fibre contact will also reduce the free volume of fibrous assembly enhancing the chances of making new contacts. Thus, the effect of steric hinderance is contradictory and complex in nature. Nevertheless, we have successfully modified and combined the theories proposed by Komori and Makashima [2] and Pan [5] for predicting certain mechanical properties of nonwoven structures [8-13].

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Recently, a review of thermally bonded nonwovens has revealed that the maximum level of bonding between the fibres can be obtained in a uniform random structure where the maximum number of fibre-to-fibre contacts is realised [14]. Therefore, this research work presents an overview of development of simple two-dimensional (2D) micromechanical models for predicting the tensile, compressional and bending properties of thermally bonded nonwoven structures using theory of fibre contacts.

## 2. Theory of Fibre Contacts

Considering two fibres, i.e. A and B in three-dimensional space and assuming that the centre of fibre B (θ′, φ′ ) is brought into contact with the surface of fibre A (θ, φ) forming a parallelepiped consisting of two rhombuses of length *l* and height 2*D*, where *D* is the diameter of the fibre, as shown in Fig. 1. Probability of contact (*P*) between the two fibres is the ratio of volume of the parallelepiped to the total volume of fabric [2, 13].

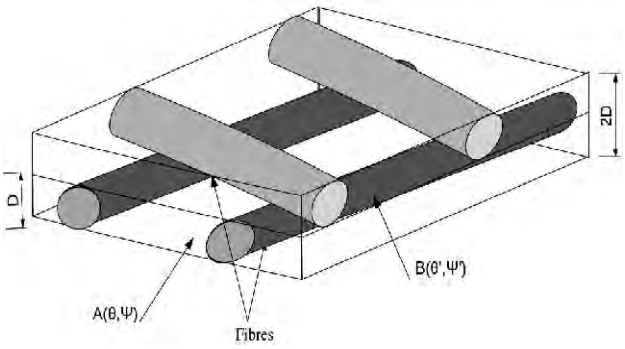


**Fig. 1: Contact of fibre A with fibre B**

Therefore,

$$P = \frac{2Dl^2 \sin\chi}{V} \qquad \text{... (1)}$$

$$\cos\chi = \cos\theta\cos\theta' + \sin\theta\sin\theta'\cos(\varphi - \varphi') \qquad \text{... (2)}$$

where *V* is the total fabric volume and χ is the angle between the two neighbouring axes of fibres A and B. Assuming there are *N* (N>>1) fibres in the fibrous assembly making '*N-1*' contacts with each other, thus the total number of contact places (*m*) can be computed as shown below.

$$m = \frac{2DN(N-1)l^2 I}{V} \approx \frac{2DN^2 l^2 I}{V} \qquad \text{... (3)}$$

$$I = \int_0^{\pi} d\theta \int_0^{\pi} J(\theta,\varphi)\sin\theta\,\Omega(\theta,\varphi)d\varphi \qquad \text{... (4)}$$

$$J(\theta,\varphi) = \int_0^{\pi} d\theta' \int_0^{\pi} \sin\chi(\theta,\varphi,\theta',\varphi')\,\Omega(\theta',\varphi')\sin\theta' d\varphi' \qquad \text{... (5)}$$

However, in order to avoid double counting of contacts, the real number of contacts (*n*) in the fibrous assembly as:

$$n = \frac{m}{2} = \frac{DN^2 l^2 I}{V} = \frac{DL^2 I}{V} \qquad \text{... (6)}$$

where *L* is the total length of the fibres in a given fabric volume (*L* = *N.l*)

Now consider a fibre of average length $\bar{b}$ between the two contacts whose direction with respect to spherical coordinate system is defined by out of plane ($\theta$) and in-plane ($\varphi$) fibre orientation angles, as shown in Fig. 2. Assuming, the fibre orientation distribution function, Ω, describing the probability of finding a fibre in the infinitesimal range of angle $\theta$ and $\theta + d\theta$ and $\varphi$ and $\varphi + d\varphi$, is defined by $\Omega(\theta, \psi)\ \sin\theta \mathrm{d}\theta \mathrm{d}\psi$. However, the following normalisation condition must be satisfied:

$$\int_{\theta=0}^{\pi} \int_{\varphi=-\pi/2}^{\pi/2} \Omega(\theta,\varphi)\sin\theta d\theta d\varphi = 1 \qquad \text{... (7)}$$

According to Komori and Makashima [2] the mean length of the fibre between the centre of two neighbouring contacts projected on the planar

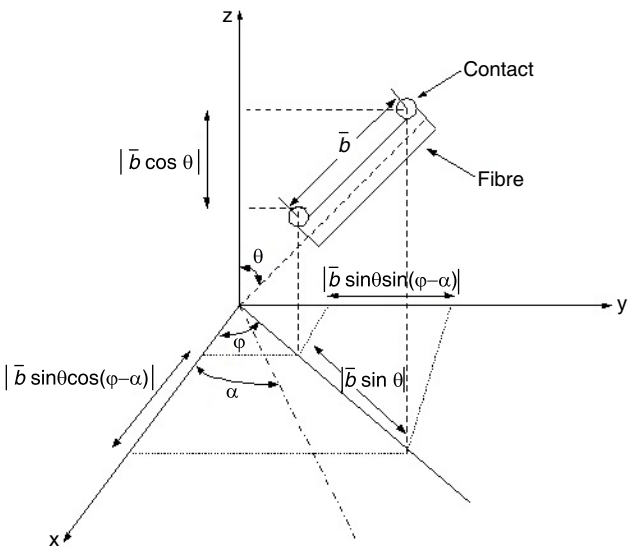


**Fig. 2: Projection of a fibre between two contacts on XY and XZ planes**

direction, $\bar{b}_j$ (here the subscript *j* represents a planar direction and α is the test direction), can be expressed as follows:

$$\bar{b}_{j(\alpha)} = \bar{b}K_{j(\alpha)} = \frac{V}{2DLI}K_{j(\alpha)} = \frac{\pi D}{8V_f I}K_{j(\alpha)} \quad \text{... (8)}$$

where *D* is the fibre diameter and *L* is the total length of the fibres in a volume *V* , $V_f$ is the fibre volume fraction, *I* is an integral defining the orientation distribution function of the fibres and $K_j$ or $K_\alpha$ is the directional parameter or geometric coefficient when $\bar{b}$ is projected on the planar direction i.e. *j* or test direction ($\alpha$), respectively.

Furthermore, the total fibre length in the volume *V* is, $L = N(V)\cdot l_f$, where $l_f$ is the average fibre length, and *N*(*V*) is the total number of fibres in the volume *V*:

$$N(V) = \frac{V \cdot V_f}{l_f \dfrac{\pi D^2}{4}} \quad \text{... (9)}$$

Consider a mesodomain consisting of a fibre connected with the contacts at its ends and having a length of $\bar{b}_{j(\alpha)}$. Without losing generality, the mesodomain is a constituent of a macroscopic volume, *V*, such that it has a unit cross-sectional area and volume, *dV* or $\bar{b}_{j(\alpha)}$. According to Pan *et al.* [5], the number of contacts is proportional to the volume of the domain. Following the principle of continuum mechanics, the number of contacts ($n_{dV_{j(\alpha)}}$) inside the volume $dV_{j(\alpha)}$ having a unit cross-sectional area can be calculated, as shown below:

$$n_{dV_{j(\alpha)}} = n\frac{\bar{b}_{j(\alpha)}A_j}{V} \quad \text{... (10)}$$

Combining equations (6), (8)-(10)

$$n_{dV_{j(\alpha)}} = \frac{2V_f}{\pi D^2}K_{j(\alpha)} \quad \text{... (11)}$$

## 3. Tensile Model of Thermally Bonded Nonwoven Structures

Consider a mesodomain consisting of a fibre connected with the contacts at its ends in a volume, *dV*. Therefore, the stress of the sample can be calculated as the sum of the tensile forces, applied by the fibres to all the $n_{dV}$ contacts (assuming each contact comprises of two fibres) in the given volume [5]. Assuming the fibres are orientated in the in-plane direction, φ, and the tensile force is applied at an angle, α, as shown in Fig. 2. Thus, the stress in the nonwoven, $T(\alpha)$, can be calculated as follows [8].

$$T(\alpha) = \sum_{k=1}^{n} 2\sigma_f \cos\beta_{ik} n_{dV}\chi(\beta_{ik}) \quad \text{... (12)}$$

where $\sigma_f \cos\beta_{ik}$ is the projection of the tension of the fibre on the test direction.

Combining equations (11) and (12) to obtain the following expression of fabric stress, .

$$T(\alpha) = \frac{4V_f}{\pi D^2}K_\alpha \sum_{k=1}^{n}\sigma^f \cos\beta_{ik}\chi(\beta_{ik}); \beta_i = \varphi_i - \alpha \quad \text{... (13)}$$

and

$$K_\alpha = \int_{-\pi/2-\alpha}^{\pi/2-\alpha} \left|\cos(\varphi-\alpha)\right| \Omega(\varphi-\alpha) d\varphi \quad \text{... (14)}$$

where $\bar{\varepsilon}$ is the average strain on the fabric, $m$ is the mass per unit area, $\chi(\beta_{ik})$ be a frequency of $k$-th bin of a histogram, representing the distribution as a function of the initial fibre orientation angle ( $\beta_i$ ).

It must be noted that the nonwoven consisting of two types of fibres having different diameters should have probabilistic mean diameter [5] in equations (11) and (13).

Using the approach of Hearle and Stevenson [15], the tension of a fibre oriented at an angle β with respect to the fabric test direction can be computed from the following equation.

$$\sigma^f = f(\varepsilon_f) =$$

$$f\left[\left(\cos^2\beta(1+\bar{\varepsilon})^2 + (1-\bar{\varepsilon}\nu)^2 \sin^2\beta\right)^{1/2} - 1\right] \quad \text{... (15)}$$

where ν is the Poisson's ratio of the fabric in various test directions.

It is important to consider fibre reorientation during the application of tensile load as the fibre aligns in the loading direction. Thus, equation (13) can be modified by incorporating the effect of fibre reorientation, as shown in Fig. 3, here fibre OB is aligned at an initial orientation angle, $\beta_i$, with respect to the loading or test direction. During uniaxial tensile loading, the upper end of the fibre moved from B to C and the orientation angle is changed to $\beta_f$, with respect to the loading or test direction. The reorientation of the fibre can be related with the fabric strain, Poisson's ratio and initial fibre orientation angle by the following expression. The detailed mathematical treatment is presented in the reference [9].

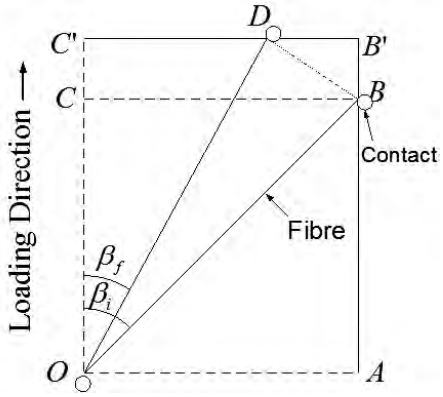


**Fig. 3: Relationship between fibre and fabric strains**

$$\beta_f = \cos^{-1}\left[\frac{(1+\bar{\varepsilon})}{\sqrt{(1+\bar{\varepsilon})^2 + \tan^2\beta_i(1-\nu\bar{\varepsilon})^2}}\right] \quad \text{... (16)}$$

where $\bar{\varepsilon}$ is the applied tensile strain to the nonwoven structure.

Thus, the fabric stress, $T(\alpha)$ given in the equation (13) can be calculated using modified relation in order to consider the effect of fibre reorientation, as shown below.

$$T(\alpha) = \frac{4V_f}{\pi D^2} K_\alpha \sum_{k=1}^{n} \sigma^f \cos\beta_{fk} \chi(\beta_{fk}) \quad \text{... (17)}$$

$$K_\alpha = \int_{-\pi/2-\alpha}^{\pi/2-\alpha} \left|\cos(\beta_f)\right| \chi(\beta_f) d\beta_f \quad \text{... (18)}$$

In addition, there is relative change in the fabric volume during the application of uniaxial loading and hence, the fibre volume fraction needs to be updated [16].

$$V_f(\bar{\varepsilon}) = \frac{V_f}{(1+\bar{\varepsilon})(1-\nu\bar{\varepsilon})^2} \quad \text{... (19)}$$

where ν is the Poisson's ratio of the fabric.

Combining equations (17)-(19), the fabric stress would be updated as fibre reorientation occurs in the nonwoven structure along with the changes in fibre volume fractions. A Matlab® code was developed to compute the value of tensile stresses in various test directions at different levels of strains.

Furthermore, in case of thermally bonded nonwovens the tensile strength can be determined through the maximum pull-out stress ($P_{max}$) required for breaking the fibre-bond interface [9, 17].

$$P_{\max} = Int\left(\frac{2V_f}{\pi D^2}K_\alpha\right)\frac{\tau_b w_b}{\rho}\tanh\rho\bar{b}_b \quad \text{... (20)}$$

$$\rho = \sqrt{\frac{G_b w_b}{E_f \pi r_f^2 t_b}} \quad \text{... (21)}$$

$$w_b = \sqrt{(\bar{b}_b - D)^2 + D^2} \quad \text{... (22)}$$

$$\bar{b}_b = D\left\{\int_{-\pi/2-\alpha+\beta_f'}^{\pi/2-\alpha+\beta_f''}\frac{1}{\left|\sin(\beta_f)\right|}\chi(\beta_f)d\beta_f\right\} \quad \text{... (23)}$$

Also

$$\beta_f'' > \beta_f > \beta_f' \quad \text{... (24)}$$

where

$$\beta_f'' = \pi - \sin^{-1}\left(\frac{D}{l_f}\right) \quad \text{... (25)}$$

and

$$\beta_f' = \sin^{-1}\left(\frac{D}{l_f}\right) \quad \text{... (26)}$$

where $w_b$ is the mean width of the bond, $r_f$ is the radius of the fibre, $D$ is the diameter of the fibre, $t_b$ ($\approx 0.8r_f$) is the thickness of the bond, $E_f$ is the fibre modulus, $l_f$ is the average fibre length, $V_f$ is the fibre volume fraction and $G_b$, $\tau_b$ are the shear modulus and shear strength of bond formed between the fibres.

## 4. Compressional Model of Thermally Bonded Nonwoven Structures

Thermally bonded nonwoven structure can be simulated as a series of fibre segments bonded by two contact points. In other words, the fibre segment can be treated as a beam with the built-in ends. According to Pan *et al.* [3], the forces acting on each fibre segment can be divided into normal and tangential components. The normal component ($C_n$) tends to bend the fibre midway between the contacts whereas tangential component ($C_p$) stretches the contact and fibre segment along the fibre axis, (see Fig. 4) and the latter component is neglected in our

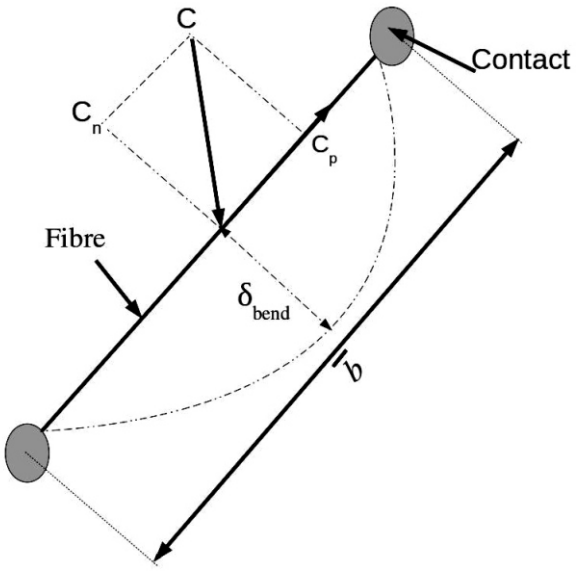


**Fig. 4: Deformation of element of fibre due to applied force**

analysis [11]. The deflection of fibre segment with built-in ends has been considered, as shown below.

$$\delta_{bend} = \frac{C_n(m_l\bar{b})^3}{3E_f I_f} \quad \text{... (27)}$$

where $\delta_{bend}$ is the bending deflection of the fibre segment, $C_n$ is the normal component of the external load, $m_l$ represents the proportion of fibre segment length between the two contacts, $E_f$ and $I_f$ are the elastic modulus and moment of inertia of constituent fibres.

Also,

$$m_l = 1 - \frac{8V_f IR}{\pi} \quad \text{... (28)}$$

where

$$R = \int_0^{\pi} d\theta \int_0^{\pi} \Omega(\theta,\varphi) J'(\theta,\varphi) \sin\theta d\varphi \quad \text{... (29)}$$

and

$$J'(\theta,\varphi) = \int_{\theta_1'}^{\theta_2'} d\theta \int_{\varphi_1'}^{\varphi_2'} \Omega(\theta',\varphi') \sin\theta' \frac{1}{\sin\chi} d\varphi' \quad \text{... (3)}$$

It is assumed that the applied pressure ($P$) is distributed uniformly and transmitted in all the contact points inside the mesodomain. Thus,

$$P = n_{dV} C_{jn} \quad \text{... (31)}$$

Combining the above equations

$$P = \frac{6 E_{fi} I^2 V_f^3 K_j^2 \Delta\varepsilon_j}{\pi^2 m_l^3} \quad \text{... (32)}$$

Also,

$$\Delta\varepsilon_j = \frac{\delta_{bend}^i}{\bar{b}_j} = \frac{T_0 - T}{T_0} \quad \text{... (33)}$$

where $\Delta\varepsilon_j$ is the compressional strain and $T_0$ and $T$ are the initial and final nonwoven thicknesses, respectively.

In a 2D micromechanical model, assuming the fibres lying parallel to the XY plane (sheet-like assembly), i.e. $\theta = \pi/2$ such that Ω can be expressed using Dirac's delta function, i.e. $\Omega(\theta,\varphi) = \Omega_{\varphi}(\varphi) \cdot \delta(\theta - \pi/2)$.

## 5. Bending Model of Thermally Bonded Nonwoven Structures

As mentioned earlier, thermally bonded structure may be assumed as a series of fibre segments bonded by two contact points. In other words, the fibre segment can be treated as a beam with the built-in ends. These built-in ends or contacts are responsible for restricting the motion of the fibre segments in the nonwoven structure. Higher the number of contacts between the fibres more is the resistance to bending of a nonwoven structure. Strictly speaking, the expression of moments of fibres about the axis of bending, given in Freeston and Platt no freedom model [18], should include the number of contacts present in the mesodomain. Thus, the bending moment per unit width of a nonwoven fabric as shown below [12].

$$M = n_{dV} \int_{-t/2}^{t/2} \int_{-b/2}^{b/2} M_f dx dy \quad \text{... (34)}$$

Thus, the bending moment, $M_f$, of a fibre is given by the following expression [18].

$$M_f = (EA)_f y^2 \cos^3\varphi / \rho \quad \text{... (35)}$$

where $y$ is the distance from the neutral axis of the fabric, $\rho$ is the radius of curvature of the bent fabric and $(EA)_f$ is elastic modulus multiplied by cross-sectional area of fibre.

Combining equations (11), (34) and (35),

$$M = \frac{V_f E_f t^3}{24\rho} \int_{-\pi/2}^{\pi/2} \cos^4\varphi \, \Omega(\varphi) d\varphi \quad \text{... (36)}$$

Thus, bending rigidity per unit width in a defined test direction ($\alpha$) can be calculated as follows.

$$D = \frac{V_f E_f t^3}{24} \int_{-\pi/2-\alpha}^{\pi/2-\alpha} \cos^4(\varphi - \alpha) \Omega(\varphi - \alpha) d\varphi \quad \text{... (37)}$$

The reader is referred to the references [8-13] for obtaining detailed mathematical treatments for formulation of tensile, bending and compressional models of thermally bonded nonwoven structure.

## 6. Experimental

The tensile, compressional and bending models are validated with the two thermally bonded nonwoven structures, i.e. TB1 and TB2 supplied by the company, i.e. *Libeltex* in our previous research work [8]. The

mass per unit area of TB1 and TB2 are 31.09 and 28.46 g/m$^2$, respectively and the corresponding thicknesses are found to be 0.44 and 0.43 mm, respectively. The nonwoven strips of 20 × 15 cm were tested on an Instron tensile testing machine under uniaxial loading at a strain rate of 10 mm/min in a "grab" test with the width and gauge length of 50 and 150 mm, respectively. Furthermore, Poisson's ratios of thermally bonded nonwoven structures were obtained at different strain levels using Messphysik® videoextensometer. The compression properties of thermally bonded nonwoven structures were determined using KES-F B3 (Compression Tester) where the pressure has been increased incrementally and approached up to 50 g/cm$^2$. The bending rigidity of the nonwoven fabrics was determined using cantilever test according to ASTM test method D 5732-01. Various input parameters desired for experimental validation of above models are given in the references [8-13].

## 7. Results and Discussion

### *Comparison of Theoretical and Experimental Results*

A comparison is made between the theoretical and experimental results of tensile, compressional and bending properties of thermally bonded nonwoven structures. Fig. 5 shows the initial tensile behaviour of thermally bonded nonwoven structures and the tensile strengths have also been predicted based upon the *maximum* pull-out stress (see equation 20) as shown in Table 1. In general, there is a good agreement between the theoretical and experimental results. However, the experimental stress-strain curves specifically in the 0$^o$ test direction are non-linear in nature. Since, the fibres oriented at a certain angle to the loading direction tend to reorientate

**Table 1: Theoretical and experimental tensile strengths of thermally bonded nonwoven structures**

| Nonwoven type | Tensile strength (MPa) | |
|---|---|---|
| | Theoretical | Experimental |
| TB1 | 1.2 | 1.4 |
| TB2 | 1.0 | 1.2 |

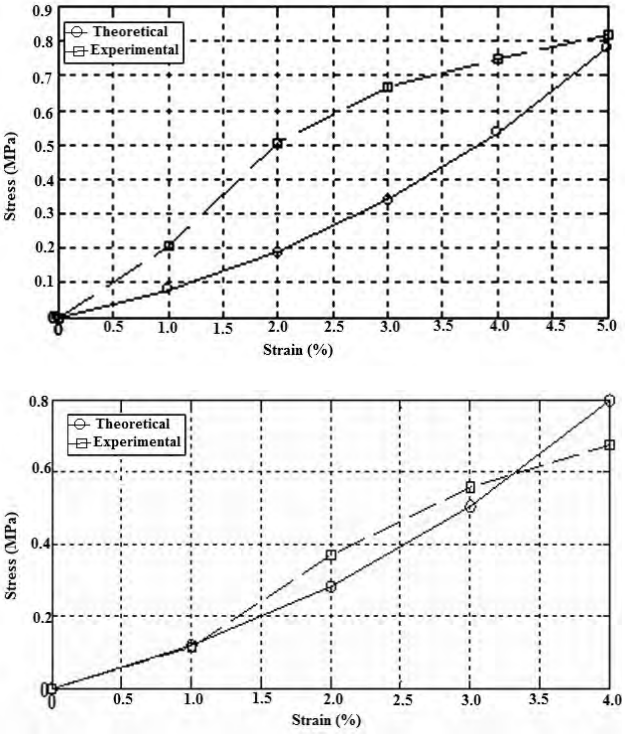


**Fig. 5: Comparison between experimental and theoretical stress-strain curves of thermally bonded nonwoven structure (a) TB1 (b) TB2 in the machine direction**

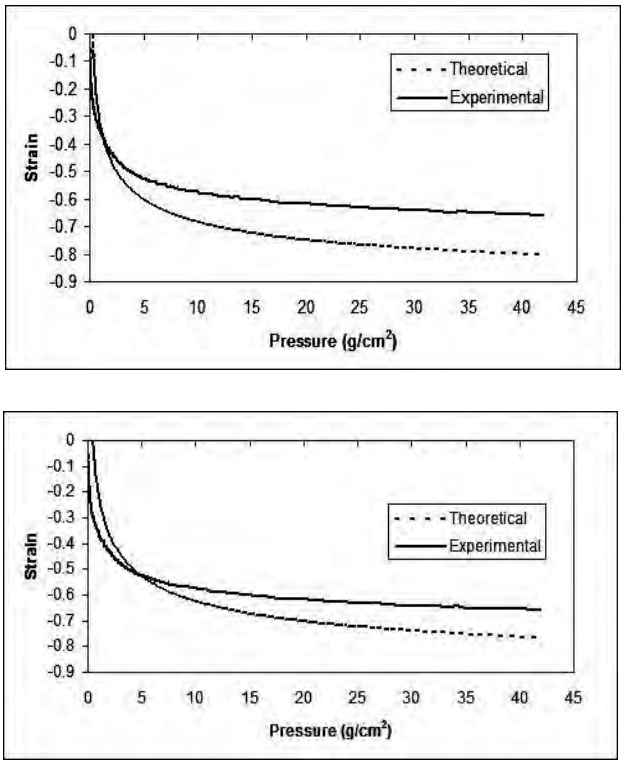


**Fig. 6: Comparison between theoretical and experimental results of pressure-strain curves of thermally bonded nonwoven structure (a) TB1 (b) TB2**

resulting in a dwell period causing non-linearity in the stress–strain curve [19].

Figure 6 shows a comparison between theoretical and experimental pressure-strain curves of thermally bonded nonwoven structures. A good agreement has been obtained between the theoretical and experimental results however, in case of through-air bonded structure, TB1, the proportion of free fibre length calculated between the two bonds ($m_l$) may be higher than the actual proportion of free elements leading to relatively lower deflection of free element length at higher levels of strains [11]. Thus, there is a discernable difference between the theoretical and experimental pressure-strain curves of TB1.

Figure 7 illustrates a comparison between the theoretical and experimental results of bending rigidity for two thermally bonded nonwovens, i.e. TB1 and TB2. The differences between theoretical and experimental values of bending rigidities are found to increase with an increase in test direction. Since, the three-dimensional orientation of the fibres has been simplified to two-dimensional (2D) fibre orientation using Dirac's delta function which led to unavoidable errors. Moreover, the fibres in the nonwoven structures oriented in test directions other than orientated in the machine and cross-machine directions are subjected to out of plane bending as the fibre distribution is not symmetrical about the axis of bending [18].

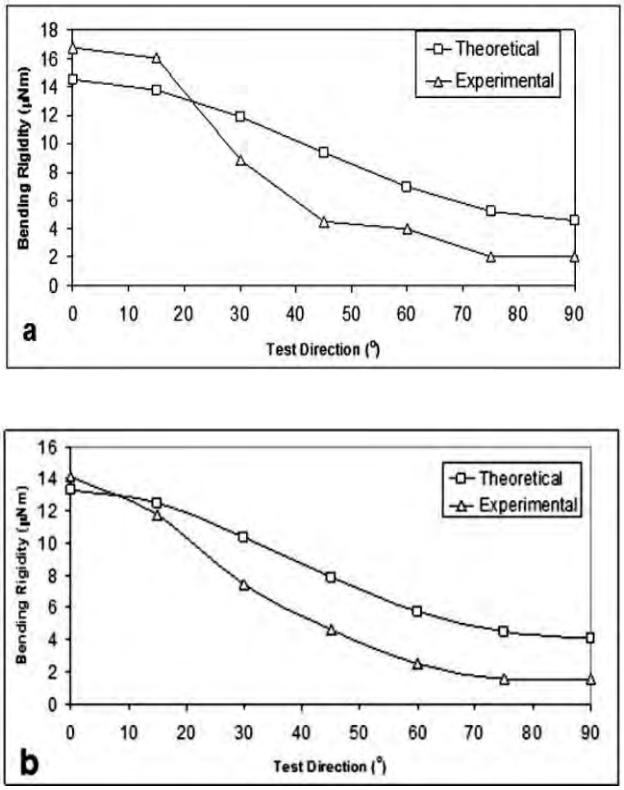


**Fig. 7: Comparison between theoretical and experimental results of bending rigidity of thermally bonded nonwoven structure (a) TB1 (b) TB2**

## 8. Conclusions

2D micromechanical models based on theory of fibre contacts for predicting the tensile, bending and compressional properties of thermally bonded nonwoven structures have been proposed and validated with the experimental work, carried out in previous studies [8-13]. In general, a good agreement is obtained between the theoretical and experimental results. However, an accurate measurement of 3D fibre orientation is a pre-requisite to predict the mechanical behaviour of thermally bonded nonwoven structures. These analytical models can be easily used for any industrial application of thermally bonded nonwoven structures for predicting their desired mechanical properties. It is anticipated that other mechanical properties including shear and tear characteristics of nonwoven structures can be modelled using theory of fibre contacts.

## 9. Acknowledgement

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