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PREDICTION OF THE STRESS-STRAIN PROPERTIES OF NONWOVENS

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Introduction

Nonwovens derive their ability to withstand forces and resist permanent deformation from three main sources: viz., properties of constituent fibers (both mechanical and physical), mechanical properties of the bonding agent, and the geometry of the fabric in terms of both the fiber arrangement and the bonding medium distribution. Prediction of the rupture properties of these materials has generally been very difficult, the reasons being the inherent variability in the properties of the constituent fibers and the complex nature of the structure. The literature in nonwovens consists of a number of theoretical attempts at predicting aspects of tensile behavior [1-4] but these are highly general in nature and have succeeded in most part in dealing with properties at low strains. As of yet, no specific treatment exists which has satisfactorily dealt with the rupture behavior of these structures.

Discussed in this paper is an approach which has proven highly successful in accomplishing this task in unbonded webs. Since these form the foundation of most nonwoven fabrics, this work provides the direction for the characterization of the mechanical properties of the other more complex structures. The results obtained in this study bring to light several factors which are expected to have an important bearing on the rupture behavior of fabrics in general. Among several variables of the model are the distributions of the geometrical and the mechanical properties of the fibers. It is shown that variability in such properties as fiber length, breaking elongation or stress-strain plays a highly significant role in governing the ultimate mechanical behaviors of assemblies. The theoretical predictions are validated by experiments on fully oriented and randomly laid webs of rayon.

Theoretical

The work was performed in two stages. In the first, the objective was set to predict the stress-strain behavior of a fully oriented web with fiber type, length, linear density, stress-strain properties and their distributions, and web linear density as the parameters. In the second, the objective was to accomplish the same for an unoriented web of known distribution.

Symbols

N	Total number of fibers in the web cross section
N_b	Number of fibers gripped at both ends in jaws of tensile tester and contributing by breakage
N_s	Number of fibers not gripped at both ends and contributing by frictional resistance.
F_w	Force on the web
F_f	Force on the fiber
F'	Frictional force per unit fiber length
F''	Web strength at $L^* >> L$
L^*	Gage length
L	Fiber length
L'	Maximum fiber length
χ	Fractional crimp or curl in fiber
ε	Strain
θ	Angle of orientation of fibers with respect to web axis
θ^*	Angle beyond which a fiber of length L' could not be gripped in jaws
W	Width of the test web
M	Mass per unit area of web
T	Linear density (tex) of fibers

Oriented Web

An example of an oriented web, containing short fibers, during test on Instron, is shown in Figure 1A. It should be clear that the force in the web would be composed of the deformational forces arising from the fibers griped at both ends and the frictional forces generated by the other fibers. The division between these two forces would be determined by the gage length (L^*) in relation to fiber staple length (L). If $L^* > L$, then only the frictional forces will play a role. If, on the other hand, $L^* < L$, then both the frictional and the deformational forces will determine the web force.

For a rigorous treatment, we assume that both forces play roles, i.e. $0 < L^* < L$. It would thus be necessary to know the fraction of fibers in the web cross section that are positively held at both ends. The fibers across a cross section of the web of

Figure 1A are rearranged such that their positions along the web axis are not changed but they are place in a descending order (Figure 1B). The average vertical distance, S, between the ends of successive fibers would be a function of the fiber staple length and the number of fibers in the cross section. From the value of this parameter, one can estimate the number of fibers which will be gripped and the number which will not be gripped at both ends:

$$S = f(L, N) = L/N$$
$$N_s = L^*/S = L^* N/L$$
$$N_b = N - N_s = N[1 - L^*/L] \quad (1)$$

The validity of Equation (1) can be checked by taking three special cases: $L^* = 0$, $L^* > L$, and $L = \infty$ (filament yarn). In both the first and the third cases, $N_b = N$, as expected. In the second case, N_b is either zero or negative, both implying that none of the fibers of cross section are gripped at both ends. In all computation, a negative value of N_b will be taken to mean 0.

For any given deformation of the web, if F_f is the average force supported by a fiber, and F' is the average frictional force per unit length of the fiber, then the force F_w in the web at that deformation will be given by:

$$F_w(\varepsilon) = N_b F_f(\varepsilon) + (N-N_b) F'L^* \quad (2)$$

F' can be estimated experimentally by measuring the strength of the web, F'', at $L^* >> L$. Since under this condition all fibers of the web would be expected to slip, F'' will represent the total frictional resistance offered by N fibers of the cross section. Thus

$$F' = F''/N \bullet L$$

Equation 2 gives the force in the web as a function of N, L^*, L, F' and ε, the elongation in the web. To accurately predict the results, four other factors must be considered; namely, the variation in the elongation at break of fibers, the variation in length of fibers, fiber disorientation and the presence of crimp or curl in fibers. Each of these factors is accounted for as shown below.

Adjustment for Variation in Elongation of Break

As a bundle is stretched, force increases. Because of the variation in the elongation at break, fibers break at different times. As each fiber breaks, the web loses its contribution. This observation had been made by Peirce in as early as 1926 [5] who had suggested that any variation present in the elongation of break of fibers significantly affected the bundle stress-strain properties. If n_i is the fraction of fibers surviving at bundle strain ε_i, and $F_f(\varepsilon_i)$ is the average force per fiber of the surviving fibers at that strain, then

$$F_w(\varepsilon_i) = N_b n_i F_f(\varepsilon_i) + (N - N_b n_i) F' L^* \quad (3)$$

Adjustment for Variation in Fiber Length

Variation in fiber length will affect the total number of fibers gripped between jaws. If in a length-frequency diagram, n_k is the fraction of fibers whose median length is L_k, then new estimate of N_b will be

$$N_b = \sum_{1}^{k} N n_k \left[1 - L^*/L_k\right] \quad (4)$$

Adjustment for Fiber Disorientation

If fibers are not oriented perfectly parallel to bundle axis, then their effective length will be reduced and so will the value of N_b. Let θ be the average angle of orientation of fibers. Effective length of a fiber in the bundle will be $L_k\cos\theta$. Substituting this in (4) gives

$$N_b = \sum_{1}^{k} N n_k \left[1 - L^* \sec\theta / L_k\right] \quad (5)$$

Equation 2 will also undergo a modification. Consider the web element shown in Figure 2 where L^* is the original test length and θ is the angle subtended by the fiber in the unstrained state with the axis. If this element is loaded through strain ε_i, then the strain in the fiber, ε_f, assuming no lateral contraction, will be given by:

$$\varepsilon_f = \left[(1+\varepsilon_i)^2 \cos^2\theta + \sin^2\theta\right]^{1/2} - 1 \qquad (6)$$

The force in the fiber is a function of the strain in the fiber, which in turn is a function of the strain in the web and the angle of orientation, or $F_f(\varepsilon_i, \theta)$. The contribution of this force to the force in the web will be $F_f(\varepsilon_i, \theta)\cos\theta'$, where θ' is the angle after strain ε_i and equals

$$\theta' = \tan^{-1}\left[\tan\theta / (1+\varepsilon_i)\right] \qquad (7)$$

The contribution of the fractional force F' is also similarly reduced, but the length over which the fibers slip is increased to $L^*\sec\theta$. Thus force in the web is now given by the following equation:

$$F_w(\varepsilon_i) = \left[N_b\, n_i\, F_f(\varepsilon_i, \theta) + (N - N_b\, n_i)F' L^* \sec\theta\right]\cos\theta' \qquad (8)$$

Adjustment for Fiber Crimp

Assuming that the fiber length L was measured in a crimpless state, i.e., by pulling it straight on a slide, the presence of crimp in the fiber in the free state of the web will further affect the value of N_b. If χ is the fractional crimp in the fiber, then the effective fiber length will be $(1 - \chi)L_k$. Using this value for L_k in Equation (5), we get

$$N_b = \sum_{1}^{k} N\, n_k \left[1 - L^* \sec\theta / (1-\chi) L_k\right] \qquad (9)$$

By substituting the above value of N_b in equation (8) and computing web stress at successively higher values of web strain, we can obtain the stress-strain curve of the oriented web.

Unoriented Web

The foregoing treatment was related to a ribbon containing fibers more or less parallel to the direction of loading. To apply this treatment to unoriented webs, modification must be made to account for the distribution of fiber orientation. This entailed determining the number of fibers lying at various angles, number of these contributing by rupture, and their contribution to the load borne by the webs in the direction of the test. Only two dimensional webs are considered. It is assumed that the fiber length distribution is independent of the orientation function, i.e., there is no preferential migration segregating long and short fibers.

Let $f(\theta)$ be the number of fibers lying in the direction making an angle $(\theta + d\theta)$ with respect to a stipulated direction (preferably direction of loading). Associated with each test length L^* and fiber length L, there is a critical angle θ^* beyond which a fiber could not be gripped at both ends and, therefore, could not bear load. If W is the width of the test specimen, $W^* = \left[L^2 - L^{*2}\right]^{1/2}$, and $L > L^*$, this angle is given by (Figure 3):

$$\theta^* = \cos^{-1}\left(L^*/L\right) \qquad \text{for } W > W^*$$

$$\theta^* = \tan^{-1}\left(W/L^*\right) \qquad \text{for } W < W^*$$

If the gage length L^* is equal to or greater than the specimen length L, then the value of the critical angle is 0. It is interesting to note that the above equations reflect a dependence of breaking tenacity of an unoriented web on the width of the specimen if $W < \left[L^2 - L^{*2}\right]^{1/2}$ and $L^* < L$. For widths of test specimen greater than $\left[L^2 - L^{*2}\right]^{1/2}$ or for $L^* > L$, the tenacity becomes independent of the specimen width.

Thus, only fibers lying oriented between angles ($-\theta^*$) and (θ^*) could have a chance of being tripped at both ends and contribute by rupture towards the strength of the ribbon. The number of these fibers from the orientation distribution function is given by

$$N = \sum_{-\theta^*}^{\theta^*} f(\theta) = 2\sum_{0}^{\theta^*} f(\theta) \tag{10}$$

The angle θ^* in Equation (10) is an upper-bound angle and is calculated for the longest fiber L′ in the sample. This provides safe limits within which summations may be carried out but outside which they will not be meaningful.

In particular, for a perfectly random web

$$f(\theta) = \frac{N\theta}{\pi} \tag{11}$$

where N is the total number of fibers present in the cross section. A fiber of length L inclined at angle θ will be gripped only if its reduced length $L\cos\theta$ is greater than the gage length L*. And only a fraction of these will be gripped due to the fact that their positions along a given direction will be statistically determined (Equation 1). Thus, if N_θ is the number of fibers of length L oriented at angle θ, given by Equation 10, then the fraction of these gripped at both ends and contributing by rupture will be given, as before, by:

$$N_b(\theta) = N_\theta\left[1 - L^* \sec\theta / L\right] \tag{12}$$

The force in the web due to these fibers, oriented at θ, at any elongation ε of the web is given by

$$F_w(\varepsilon,\theta) = \left[N_b(\theta)\, F_f(\varepsilon,\theta) + \left(N - N_b(\theta)\right)F' L^* \sec\theta\right]\cos\theta' \tag{13}$$

In this $F_f(\varepsilon, \theta)$ is the force in the fiber at elongation ε_f given by Equation (6), and θ′ is the angle given by Equation (7). The above force is summed over all angles ($0 < \theta < \theta^*$) to obtain the force in the web, viz:

$$F_w(\varepsilon) = \sum^{\theta^*} F_w(\varepsilon,\theta) \tag{14}$$

As was found in the case of oriented webs, final predictions must involve adjustment for variability in elongation of break of fibers, variability in fiber length, and presence of crimp or curl in the fibers.

For variation in elongation of break, thus, web force contributed by fibers inclined at θ should be given by

$$F_w(\varepsilon_i,\theta) = \left[N_b(\theta) n_i\, F_i(\varepsilon_i,\theta) + \left(N - N_b(\theta) n_i\right)F' L^* \sec\theta\right]\cos\theta' \tag{15}$$

The total force in the web at strain ε_I is then obtained when the values given by Equation (15) are summed over all angles. Thus,

$$F_w(\varepsilon_i) = \sum^{\theta^*} F_w(\varepsilon_i,\theta) \tag{16}$$

To account for variation in fiber length, and for curl factor χ, the value of N_b is recomputed as follows:

$$N_b(\theta) = \sum_{1}^{k} N_\theta \, n_k \left[1 - L^* \sec\theta / (1-\chi) L_k\right] \tag{17}$$

Estimation of the Value N_θ Needed in Equation 17

In the case of the oriented webs, the total number of fibers in the cross section is simply given by the ratio of the linear density of the web strip to that of the fiber. In the case of the unoriented webs, a different procedure is necessary which is as follows.

Consider the hypothetical strip shown in Figure 4 obtained from the parent web. It has width equal to the test width W and length equal to the test length L^*. Also assume that all fibers in the strip are oriented at a given angle θ with respect to the test axis. We can consider the final sample to be made up of J such strips superimposed on each other, the fibers in each of which are oriented at different angles. The angle interval between successive strips is constant and is given by:

$$\Delta\theta = \theta_i - \theta_{i-1} = \frac{\pi}{J}$$

$$\text{or} \qquad J = \frac{\pi}{\Delta\theta}$$

We can now calculate the number of fibers N_θ as follows:

$$\text{Area of the parent strip} = WL^* \ (\text{cm}^2)$$

Its mass = WL^*M(g), (M being the mass per unit area of the parent web)

$$\text{Mass of each strip} = \frac{WL^*M}{J} \ (\text{g})$$

$$\text{Linear density of parent web} = \frac{WL^*M}{L^*} 10^5 \ (\text{tex})$$

$$= WM10^5 \ (\text{tex})$$

$$\text{Linear density of each of the J strips} = \frac{WM}{J} 10^5 \ (\text{tex})$$

By dividing the linear density of each of the strips with that of the single fibers, T(tex), we can obtain the number of fibers in each strip. This number is given by the following equation:

$$N_\theta = \frac{WM}{JT} 10^5$$

$$= \frac{WM\Delta\theta}{\pi T} 10^5 \tag{18}$$

It is noted that N_θ is independent of the angle of the orientation but is dependent on the angular interval over which it is estimated. Thus, this number is easily calculated if we know the web weight, the fiber linear density, the width of the test specimen and the angular interval chosen. A comparison of Equation (9) with (17) for N_b, and of Equation (8) with (15) and

(16) for $F_w(\varepsilon_i)$, clearly shows that the former two equations, applying to oriented webs, are special cases of the latter more general equations.

Experimental

Sample Preparation

For work on oriented web, a rayon fiber of 1.5 inch staple length and 3 denier was used. A carded sliver was first prepared which was doubled and drafted on a drawing frame. The attenuated sliver was then run on a roving frame to obtain a thin bundle with minimum possible twist so that the fibers remained more or less straight. The final denier of the roving obtained was 5100 for rayon.

For work on unoriented webs, rayon of 1.5 inch staple length and 1.5 denier was used. A small quantity of the fiber was passed through a sequence of opener and step cleaner which was then fed at the back of a carding engine to produce a highly opened lightweight web. This was then collected and fed to the Rando Feeder and Rando Webber line to produce an air-laid web of 0.5 ozs/yd^2.

Testing for Fiber Properties

Stress-Strain. About 150 fibers from each of the types were randomly selected from the parent web and carefully mounted across paper windows of 0.5″ clearance for testing on Instron with 0.5″ gage length. The load-elongation curves for theses fibers were obtained using a crosshead speed of 2″/minute. The fibers were chosen from the fiber web rather than the raw stock so as to take into account any mechanical damage that may have been imparted to the fibers during processing.

FiberLength Distribution

Since there was no convenient way to accurately and instrumentally measure the fiber length distribution in the final web form, the length was measured manually on a selected number of fibers and the length-frequency diagram constructed. Fibers were gently removed from the web with a pair of forceps, and after straightening on a dark velvet board, their lengths were measured to the nearest sixteenth of an inch. About 100 fibers were pulled out randomly for this test. The length-distribution obtained by the automatic fibrograph device did not match the distribution obtained manually. Because of the critical role played by fiber length distribution in predicting web mechanical properties, the manually obtained results were utilized.

Testing for Web Properties

For testing of load-elongation curves of oriented bundles, four different gage lengths were used: 0.5″, 0.75″, 1.0″ and 1.25″. Paperboard windows were cut for each of these gage lengths with a suitable width for ease of mounting. Adequate length was unwound from the roving bobbin and the upper end of the sample was fixed with a drop of adhesive cement, which, after setting, was covered with an adhesive tape. The roving was then cut leaving just enough length to cover the window with its lower end. The open end was untwisted carefully to remove any apparent residual twist and the almost parallel bundle was then fixed in a manner akin to that for the top end. Fifteen samples for each gage length were prepared in this manner and after conditioning tested for load-elongation curves using 2″/minute crosshead speed.

Testing of unoriented web was found to be a tedious and delicate task, as without any bonding the fibers of this ultra-light weight web tended to be easily disturbed, even by slight disturbance in air. Utmost precautions were thus required in the mounting of these samples. Since only a very few fibers could possibly be expected to be gripped at relatively large gage lengths. A gage length of only 0.25″ was chosen. Paperboard window were prepared as before, but these were doubly reinforced so as to increase their rigidity. Web samples of required dimensions were obtained by cutting with a pair of sharp scissors (use of die cutter proved unsatisfactory). The samples were cemented on window using quick setting cement and an adhesive tape. They were then conditioned for 24 hours and tested on Instron as before.

Procedure for Computing Theoretical and Experimental Curves

In the present experiments, it was noted that the frictional force was extremely small. The oriented web had fibers highly drafted out, and with little or no twist, the fibers were more or less parallel to each other and to the bundle axis. The oriented web was ultra-light weight and essentially two-dimensional. Thus, with little or no mechanism to generate normal forces, the frictional force could not have been significant. In the computation of theoretical results, thus, it was considered appropriate to set the value of F' (Equation 8 and 15) to zero.

Oriented Web

1) The elongation of break of all single fibers were read off and recorded. These were then classified in subintervals of suitable length. All fibers having their values falling in a class were considered to have the class mean as their elongation of break. An attempt was also made to fit a mathematical distribution to the data. But since fitting of either

Weibull, Beta or normal distributions did not even show close comparisons with the actual distribution, it was decided to use the actual distribution.

2) Loads borne by each of the 150 single fibers at each of the class average extensions were then recorded from the curves and averaged for all fibers surviving at that extension.
3) Similarly, loads borne by the various specimens of the web were also recorded at corresponding extensions. The load values were averaged and plotted against extension to obtain the "actual" load elongation curve for the ribbon.
4) At a given web extension, the predicted load borne by the bundle was computed as the product of the number of fibers gripped at both ends and still surviving at the corresponding fiber extension and the average load borne by the fiber at that extension.
5) To account for the variability in length, the fiber length distribution obtained was classified in groups of different intervals. And with the class-mean as the length, the total number of fibers gripped for that class was determined and step 4 repeated for each of the classes.
6) To make a correction for the presence of curl or crimp and disorientation, each fiber in the assembly was reduced in length by corresponding amount (e.g., length × 0.95 × cos5°, if crimp was 5% and disorientation 5°), and the histogram revised. Steps 5 and 4 were repeated. In the case of disorientation by angle θ, the load borne by a fiber was obtained at strain given by Equation 6 and the total load computed in step 4 was multiplied with cosθ.

The load value after step (6) represented the predicted value at a given extension of the web after all corrections had been made. This procedure was repeated for other extensions and the load-elongation curve of the bundle obtained.

Unoriented Web

With the exception of step 4, all other steps were exactly the same and as discussed above. The procedure involved in step 4 for unoriented web was as follows. For the staple length used, the value of the critical angle θ^* was computed. The angular range was divided into 5° intervals. From the specifications of the web and assuming random distribution, number of fibers lying in each of these angular zones was computed using Equation 18. This gave the value of N_θ from which the value of $N_b(\theta)$ (Equation 17) could be computed. With this number known, the force in the web $F_w(\theta, \varepsilon_i)$ contributed by these fibers was determined (Equation 15). This was repeated for other angles and summed to determine the total force $F_w(\varepsilon_i)$ (Equation 16).

Results And Discussion

Oriented Webs

The distribution of the elongation of break for the rayon fiber is shown in Figure 5. It is seen that the elongation of break varied over a broad range, being 20 to 65%. Percentage of the fibers broken and the average load supported per fiber at various extensions are shown in Table 1. These values were used to predict the load-elongation cures of the webs. The peak values of the load obtained, which represented the breaking strength of the ribbon, without, at this stage, any adjustment for variability in length, presence of crimp or curl, and departure from perfect orientation, were plotted against the gage length and compared with the actual results. This comparison is shown in Figure 6 (curves B and E). Also displayed in this figure is the curve A obtained when no consideration was given to the variation in the elongation of break. Comparison of curve A with B and of these two with E clearly illustrate the important role the variation in the elongation of break plays in governing bundle properties.

The next correction applied was for the variation in fiber length. Actual lengths were measured on 100 randomly selected fibers. The length-distribution found was used in the prediction procedure. The corrected curve so obtained (C) is illustrated in Figure 6 which shows a significant further improvement in predicted values.

Examination of the bundle under a microscope showed that although highly oriented, the fibers were still inclined on an average with the axis. This angle was estimated to be of the order of 5°. Similarly, it was noted that during the measurement of fiber lengths on velvet board, all crimp and curl had been largely removed from the fibers although they existed in the free state of the bundle. A rough estimate of this factor was made to be about 8%, i.e., the free length in the bundle was about 8% shorter than the straighten length. Combining the disorientation and the crimp factors together gave about 9% reduction in the length of the fibers of the bundle. This could be expected to reduce the number of fibers contributing to the strength of the bundle by direct rupture. Also the fact that the fibers were inclined at some angle to the web axis reduced their contribution to the web force. It is clearly seen that the curve D obtained after applying all corrections fell within close proximity of the curve found experimentally. Values related to the prediction of entire load-elongation curves of oriented webs at the four gage lengths were also computed. The data related to gage length of 0.75″ are given in Table 2. The results for this gage length, as well as those for 1.25″, are illustrated in Figures 7 and 8, respectively. It is clear that the predicted curves after accounting for various factors matched closely the experimental curves. At the higher end of the extensions, the curves tended to cluster together which is expected due to the relatively low levels of load supported in that region. It is also interesting to note (from a comparison of the results in Figures 7 and 8) that as the gage length approached the fiber staple length, the variability in fiber length played an increasingly significant role in governing web tensile properties.

Unoriented Webs

The average weight of the rayon web was 0.34 oz/yd^2. Calculations gave the number of fibers gripped in each angular interval as 14.5. Table 3 gives the data of the computations of load value after various corrections. The results corresponding to gage length of 0.75″ are shown in Figure 9. It is seen that the experimental and the predicted values agree reasonably close over the entire range of elongations, although this agreement is not as close as found with the oriented web. The reasons for this difference are expected to be as follows: (1) the webs were ultra-thin and unbonded and thus most susceptible to damage in handling; (2) the web being ultra-light weight, the total number of fibers gripped in the jaws was of low order (~150); (3) the webs of such dimensions were expected to lack in uniformity in fiber arrangement, and (4) departure from perfectly random arrangement which had been assumed for theoretical computations could be expected in these webs.

These problems could generally be expected to be absent from the oriented webs which contained an order of magnitude, or more, greater number of fibers and were subjected to drafting and doubling operations which provided a uniform bundle. It can, thus, be concluded that the theoretical model was sound and any lack of agreement noted in the case of unoriented web was mostly due to the difficulty of producing a uniform web of predictable distribution.

Summary

The focus of this study has been on an understanding of the stress-strain behavior of unbonded webs. The importance of this work lay in the facts that (1) these webs formed the foundation of most nonwoven fabrics, and (2) the mechanical integrity of these webs related to their ability to be handled and processed.

The validity of the proposed model for predicting the stress-strain behavior of unbonded webs has been demonstrated. It has been shown that in spite of the complex nature of the structure, the rupture properties could be predicted to a high degree of accuracy. The factors which played important roles were the average tensile and dimensional properties of the fibers, the linear density of the web, the testing conditions, the orientation functions, and the variability in properties, specially elongation at break and fiber length. Presence of crimp and curl also affected the results.

Consideration of some of these factors has been neglected in past studies. It is quite clear that the rupture or large strain behavior could not possibly be predicted without accounting for variability in certain properties. On bonded nonwovens, additional factors that must be considered in future studies are the variability in (1) the bond to bond distances, (2) the tensile properties of the segments between the bonding points and (3) the properties of the bonds.

References

Cox, H.L., “The Elasticity and Strength of Paper and Other Fibrous Materials, “Britt. J. of Applied Physics, 3, 72-79 (1952).

Backer, S. and Petterson, D.R., “Mechanics of Nonwovens: Orthotropic Behavior, “Textile Research J., 33, 809-816 (1963).

Hearle, J.W.S. and Stevenson, P.J., “Study in Nonwoven Fabrics: Prediction of Tensile Properties, “ Textile Research J., 34, 181-191 (1964).

Hearle, J.W.S. and Newton, A., “Derivation of Generalized Mechanics by the Energy Method, “Textile Research J., 37, 778-797 (1967).

Peirce, F.T., “Theorem on the Strength of Long and of Composite Elements, “J. Textile Institute, 17, T355-T368 (1926).

Table 1. Percent Fibers Broken and Average Load per Fiber at Various Extensions. Single Fiber Tests (Rayon 1.5 inch, 3.0 denier).

Extension (%)	Fibers Broken (%)	Cumulative (%)	Avg. Load per fiber (gf)
20	1.744	1.744	4.30
25	5.814	7.558	5.50
30	9.883	17.441	7.50
35	13.953	31.394	10.98
40	18.023	49.417	13.70
45	16.660	66.277	13.91
50	12.209	78.486	14.44
55	9.302	87.788	14.74
60	7.558	95.346	14.56
65	4.651	99.999	14.60

Table 2. Comparative Load Values (gf) for Oriented Web Gage. Length = 0.75 inch. (Rayon 1.5 inch, 3.0 denier).

Extension	Theoretically Predicted Value			Actual
%	B	C	D	Values, E
20	3490	2750	2100	2150
25	4100	3100	2500	2540
30	5000	3600	3000	3000
35	5900	4250	3175	3100
40	5500	3750	3000	2980
45	3750	3000	2125	2500
50	2500	2000	1500	1875
55	1500	1100	600	1000
60	500	250	100	600

B: After adjustment for variation in elongation of break.
C: After adjustment for variation in fiber length.
D: After adjustment for 5° disorientation and 8% crimp or curl.

Table 3. Comparative Load Values (gf) for Unoriented Web. Gage Length = 0.75 inch. (Rayon 1.5 inch, 3.0 denier).

Extension	Theoretically Predicted Value			Actual
%	B	C	D	Values, E
6	80	76	75	85
9	137	130	128	135
12	172	163	161	185
15	149	141	139	100
18	116	111	109	69
21	61	58	57	29
24	34	33	32	8
27	14	13	13	6

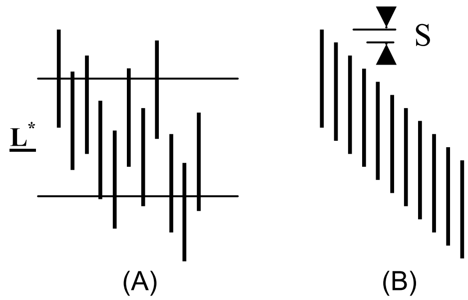

Figure 1. A model of oriented web between jaws. (A) Actual position of fibers, (B) Position after rearranging in descending order of upper ends.

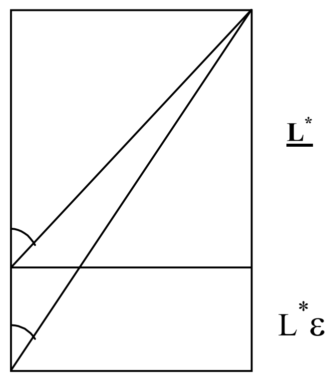

Figure 2. Strain in single fiber element.

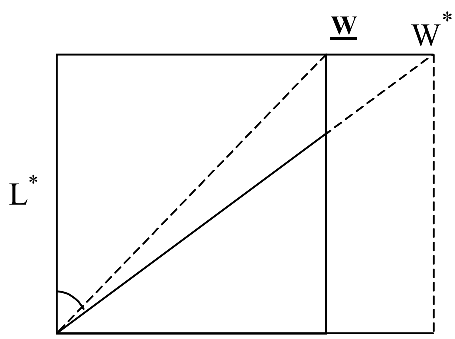

Figure 3. A model of unoriented web between jaws.

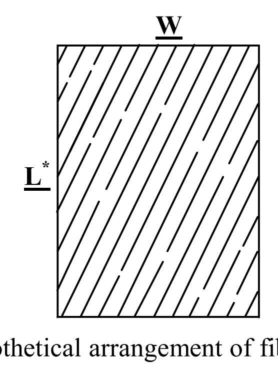

Figure 4. Hypothetical arrangement of fibers in one of the many superimposed layers of a randomly oriented web.

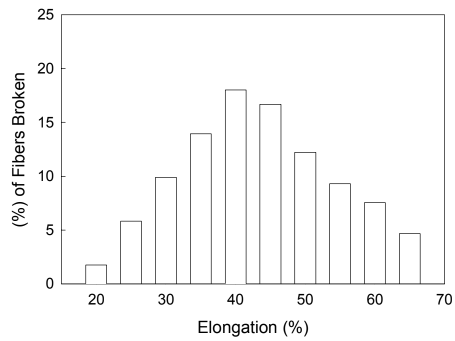

Figure 5. Distribution of elongation at break for rayon (1.5″, 3.0 denier).

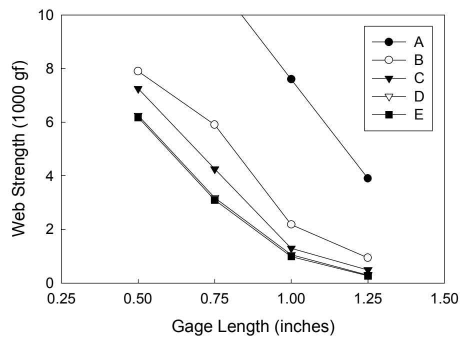

Figure 6. Comparison of the predicted and the actual values of breaking strength of oriented web of rayon (1.5″, 3.0 denier).
A: Theoretical curve without any adjustments.
B: Theoretical curve after adjusting for variation in breaking elongation.
C: Theoretical curve after additionally adjusting for variation in fiber length.
D: Theoretical curve after additionally adjusting for disorientation and crimp.
E: Actual curve (experimental).

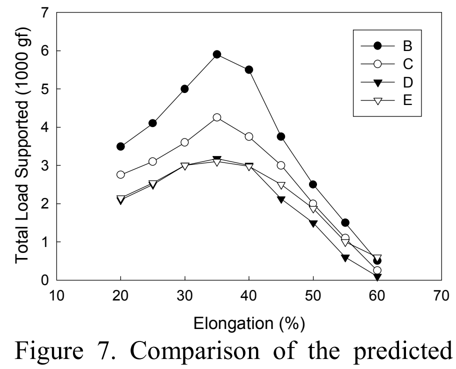

Figure 7. Comparison of the predicted and actual load-elongation curves of oriented web of rayon (1.5″, 3.0 denier) for the gage length of 0.75″.

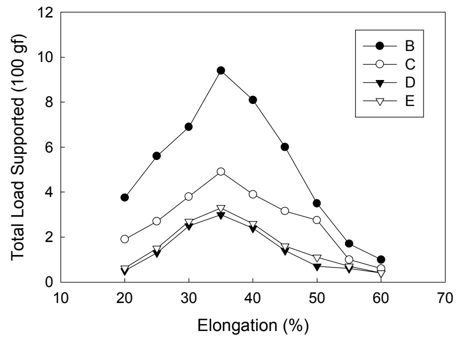

Figure 8. Comparison of the predicted and actual load-elongation curves of oriented web of rayon (1.5″, 3.0 denier) for the gage length of 1.25″.

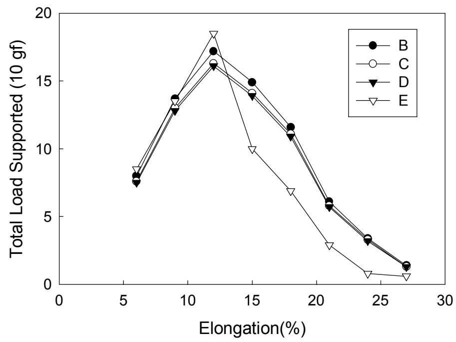

Figure 9. Comparison of the predicted and actual load-elongation curves of unoriented web of rayon (1.5″, 3.0 denier) for the gage length of 0.75″.