PREDICTIVE MODELS FOR STRENGTH OF SPUN YARNS: AN OVERVIEW

Anindya Ghosh, Sayed Ishtiaque, Seenivasan Rengasamy, Prithwiraj Mal and Asis Patnaik

Department of Textile Technology
Indian Institute of Technology Delhi, Hauz Khas, New Delhi-110016, India
e-mail: anindya_textile@yahoo.com

Abstract

Over the past century or so, determining the predictive models of yarn strength has been the subject of a number of investigations, because yarn strength is a principle component of yarn quality. The aim of these models is to enable the yarn strength to be predicted from the properties of its component fibres as well as other parameters. The development of predictive modelling of yarn strength is always significant both in theory and in practice. In this article, a review of various predictive models of yarn strength is presented.

Key words:

yarn strength, predictive model, fibre bundle strength, tensile failure, fibre properties

Introduction

The strength of a spun yarn is recognised as one of the most important quality parameters of yarn. Predicting the strength of spun yarns is very important from a technological point of view. Yarn engineering, a long-cherished goal consistently sought by every spinner, implies the production of yarns according to consumer needs. Furthermore, yarn engineering provides information about the practical understanding of the generation of the strength of spun yarns.

Due to the inherent nonlinear relationship that exists between fibre properties, process parameters, yarn structure, and yarn strength, creating predictive models involves unravelling a web of interrelated complexities. An understanding of the way fibres behave after being spun into yarns has not been easy to come by. A large numbers of approaches have been used; some of them have led to models which allow predictions to be made about the behaviour of the yarn. The vast majority of these predictions have concerned the behaviour of yarns when subjected to tension. Even amongst tensile properties, prediction of yarn strength occupies a predominant position. There are essentially five modelling tools for predicting yarn strength, namely the mathematical model, the statistical model, the empirical model, the computer simulation model and the neural network model. In this present paper we are concerned with the mathematical, statistical and empirical models for predicting yarn tensile properties.

Models of Predicting Yarn Strength

Mathematical models have their basis in applied physics and derived from first principles. They provide a better understanding of the complex interrelationships of the different parameters that determine yarn properties. However, mathematical models may require simplifying assumptions to make the mathematics traceable, and hence the prediction errors may be large. In contrast, statistical and empirical models are easy to develop in comparison with the mathematical model. However, they require expensive trials under different conditions to obtain the data needed for modelling, and sometimes this data may be affected by measurement errors and problems with process repeatability. Also, they often fail when they are extrapolated to predict properties outside the range within which the data was obtained.

There have been several attempts to establish fundamental theories for short fibre yarns, such as those reported by Hearle, Grosberg and Backer [1], Zurek [2], Postle, Caranby and de Jong [3] using various approaches based on force deformation analysis. The complexity of applying a mathematical treatment to staple yarn structure often prevents some of the theoretical models from being useful

practical tools for prediction. There have also been studies to analyse short fibre yarns by means of the energy approach [1]. However, this method is unable to deal with the fibre slippage effect because of the energy dissipation involved. The finite element method has also been used to deal with the yarn structure [4]. This approach provides numerical solutions.

In most of the studies of mechanistic modelling of staple yarn, it is usual to assume the idealised structure of yarn proposed by Hearle [1] as follows:

I. The yarn consists of a large number of fibres of limited length.

II. Packing of fibres in the yarns is uniform.

III. The yarn is circular in cross section.

IV. Fibres are assumed to lie on perfect helices of a constant radius and angle. All those helices throughout the cross-section have the same number of turns per unit length parallel to the axis of the helix.

V. The fibres are assumed to follow ideal migration paths, in which the radial distance from the axis increases and decreases slowly and regularly between the yarn centre and the yarn periphery.

VI. The fibres are assumed to have identical dimensions and properties, are perfectly elastic, and follow Hook's and Amonton's laws.

VII. Transverse stresses between fibres at any point are assumed to be small in all directions perpendicular to the fibre axis.

However, in practice the actual yarn varies considerably from the idealised structure. For example, actual yarns are irregular in mass per unit length, shape, twist, local fibre arrangement and in the migration paths followed by the individual fibres. It is also assumed in the idealised structure that the fibre ends are randomly distributed in the yarn without any bias. This is not always true. For example, in ring-spun yarns, it is known that the tail ends of fibres are thrown to the surface, and this affects the distribution of stress through the yarn due to slippage at the fibre ends.

Gegauff [5] was the first to theoretically analyse yarn strength in terms of yarn structure. He derived a simple mathematical relationship between twist angle and yarn strength. Gurney [6] extended that relationship by taking into account the length and frictional properties of fibres in addition to the twist in yarns. He argued that in a cotton yarn under tension, there are two kinds of forces present, viz. forces that tend to press the fibres normally, and forces that tend to cause slippage. He suggested that when the ratio of the forces tending to cause the slippage to the normal forces exceeds a certain critical value, which corresponds to the coefficient of friction (μ), then slipping would occur. He derived expressions for calculating stress developed in individual fibres that take fibre length and coefficient of friction into consideration.

Sullivan's analysis was the first theoretical approach that assumed an idealised geometry, and attempted to relate yarn strength to fibre properties and yarn twist [7]. He introduced a composite factor (a product of the coefficient of friction, length and surface area of fibre) in determining the tension developed in a twisted yarn. He also derived an expression for the maximum strength at optimum twist. In deriving the relationship, he made certain assumptions such as the development of arbitrary tension in outer layers of the yarn, the fact that all the fibres are parallel, and that they lie on perfect helices. This concept of arbitrary pressure on the surface to start the build-up of tension was necessary because Sullivan did not consider the migratory nature of the fibre. Hearle [1] introduced the concept of migration in the analysis of mechanics of staple yarns. He showed that appropriate values of twist and migration could generate a self-locking and strong structure which can take some load, and obviates the need to assume arbitrary pressure at the surface.

In his papers on cotton yarn structure, Gregory [8] addressed the problem of variability along the length of the yarn. He used artificial yarn elements to calculate the yarn count and twist at the point where the yarn failed. One striking feature brought out by this analysis is that for given cotton, the twist angle at maximum strength is practically independent of the count over a wide range of counts.

Pan [9-11] in a series of papers has shown how the entire stress-strain curve of a yarn can be predicted from fibre properties.

All these analyses discussed so far, though invaluable for a thorough understanding of the internal structure of a yarn, do not make any predictions about the breaking strength of a yarn. This is perhaps due to the extreme complexity of the structure of any given yarn. The equations derived by the researchers may have involved too many variables, which are difficult to measure in practice. Nevertheless, breaking strength is the most important property of a yarn, and any attempt to predict it is commendable, even if it involves approaches which do not give as much insight into the yarn structure as the methods discussed so far. Some important mathematical, statistical and empirical approaches for prediction of yarn strength are given next.

Bogdan has established an empirical relationship between fibre properties and yarn strength [12,13]. He has defined an intrinsic strength parameter, which has to be determined experimentally. He proposed the relation for the skein breaking strength of yarn S as:

$$S = k\left[\frac{P}{C}\left\{1 - 10^{-0.13(M-T)^2}\right\} - F\right] \quad , \tag{1}$$

where k = the correction for fibre obliquity and conversion to single thread breaking length, $\frac{160}{1+BM^2}$, B = the fibre obliquity parameter, P = the intrinsic strength parameter, C = the cotton system yarn number, M = the twist multiplier, T = the ineffective twist parameter, F= the drafting parameter. Bogdan stated that the fibre angle parameter B is found to be relatively constant for all cottons at a value of 0.014. The analysis for cotton yarns expresses the parameters in terms of the intrinsic strength parameter P. He used this parameter to describe the cotton quality parameter or quality index. Long, fine cottons, from which very strong yarns can be spun, reach their optimum strength at lower twist multipliers than do short, coarse cottons that yield low level of yarn strength. As a consequence, the value for the ineffective twist parameter T decreases as the P value increases. Bogdan also established the following empirical relationships

$$T = 4.5 - 0.15\,P \quad , \tag{2}$$

$$F = \frac{2.1}{P-8} \quad , \tag{3}$$

He rewrote Equation 1 as:

$$S = \frac{160}{1+0.014M^2}\left[\frac{P}{C}\left\{1 - 10^{-0.13(M+0.15P-4.5)^2}\right\} - \frac{2.1}{P-8}\right] \quad , \tag{4}$$

Thus, to predict the skein breaking strength, only the intrinsic yarn strength parameter (P) needed to be determined from experiments.

Equation 4 had been derived on the assumption that the same fibre properties affect both the slope and the intercept of the CSP-count line, and that the relative importance of these fibre parameters is the same for both. This may not necessarily be so. Subramanian et al [14] pointed out that if two different values of Q obtained from two sets of fibre properties could be defined and used appropriately in Equation 4, it might be possible to predict the lea strength of yarns even more accurately. They modified Bogdan's Equation 4 as follows:

$$CS = \frac{160}{1+0.014M^2}\left[P_l\left\{1 - 10^{-0.13(M+0.15P_l-4.5)^2}\right\} - \frac{2.1}{P_s-8}C\right] \quad , \tag{5}$$

where CS = the count strength product, P_1 = the strength parameter corresponding to the intercept, P_s = the strength parameter corresponding to the slope. They also showed that the intrinsic strength parameter (P) could be correlated with a modified form of the fibre quality index (Q) described by Lord [15]

$$P = R \frac{e^{0.02Q} - 1}{0.02(Q+1)} + \frac{D}{Q+1} \quad , \tag{6}$$

where R and D are constants during the spinning condition and have to be experimentally determined, and

$$Q = \frac{E\sqrt{SS_0}}{\sqrt{HH_s}} \quad , \tag{7}$$

where E = the effective length in 1/32 inch, S = the bundle strength at 1/8 inch gauge length, S_0 = the bundle strength at zero gauge length, H = the actual fibre fineness and H_s = the standard fibre fineness.

Neelakantan et al [16] compared yarn tenacity g with fibre bundle tenacity s, using the equation:

$$s = \left[\frac{N}{N - k(N)^d} \right] g \quad , \tag{8}$$

or, after solving for g,

$$g = s\left\{ 1 - k(N)^b \right\} \quad , \tag{9}$$

where N = the average number of fibres present in a cross-section, k, b and d are constants, and b, d are related as

$$b = (d-1) \quad , \tag{10}$$

According to Solovev [17], the strength of cotton yarn is basically a function of fibre and yarn properties, having the following form:

$$S_v = S_f (1 - 0.0375 \cdot H_0 - 2.65 \sqrt{\frac{Tt_f}{Tt_y}}) Z \cdot K_\alpha \eta \quad , \tag{11}$$

where S_v = the yarn strength in gf/tex, S_f = the fibre strength in gf/tex, Tt_y = the linear density of yarn (tex), Tt_f = the linear density of fibre (tex), H_0 = the index of technological process (3.5-4 for the combed cotton system, and 4.5-5 for the carded cotton system), η = the correction factor for the quality of equipment, its value being 0.95 to 1.1, for ideal machinery equal to 1, K_α = the correction factor for twist, Z = the correction factor for fibre length, which has the following expression

$$Z = 1 - \frac{5}{l_k} \quad , \tag{12}$$

where l_k = the classer's length of cotton.
The correction factor for twist (K_α) has to be read from a look-up table which gives values of the correction factor for differences between the twist factor of the given yarn (α) and its critical twist factor (α_k). The critical twist factor (α_k) is given by

$$\alpha_k = \frac{(1120 - 70F)}{l_k} + \frac{57}{\sqrt{Tt_y}} \quad , \tag{13}$$

Usenko [18] has adapted the Solovev formula to viscose staple yarn. He kept the same principle which was admitted for cotton, but has introduced somewhat different values for certain constants. The formula transformed in this way is as follows:

$$S_y = S_f (1 - 0.0375 \cdot P_0 - \frac{2.8}{\sqrt{n}}) Z \cdot K_\alpha \beta \quad , \tag{14}$$

where S_y = the breaking length of yarn in Km, S_f = the breaking length of fibres in Km, P_0 = the coefficient of processing techniques, e.g., for carded cotton system adapted to the spinning of viscose staple fibre it is 2.5 to 3.5, Z = the correction factor of fibre length, β = the coefficient for effects of the irregularity of fibre length, K_α = the coefficient for effect of yarn twist, which is a function of the difference between the twist of yarn and the critical twist, n = the mean number of fibres in a yarn cross-section, found from the following equation:

$$n = \frac{Tt_y}{Tt_f} \quad , \tag{15}$$

Usenko used the following expression for calculating the factor Z:

$$Z = 1 - \frac{1.8}{\mu l_k} \quad , \tag{16}$$

where μ = the coefficient of friction of fibres, l_k = the length of fibre.

Frydrych [19] evolved the following mathematical equation to estimate yarn strength as:

$$Q_\gamma = Q_h \left[1 - 3.64 v_{Fh} \left(1 - q^{-\frac{1}{7}} \right) \right] \quad , \tag{17}$$

where Q_γ = the predicted yarn strength (cN/tex), Q_h = stress in the breaking zone of the yarn (cN/tex), V_{fh} = the variation coefficient of the breaking force in the length of the fracture zone, which is also related by the following equation:

$$v_{Fh} = \beta \sqrt{\frac{Tt_y}{Tt_f}} \quad , \tag{18}$$

where β = the coefficient depending on the spinning system: on carded $\beta = 2$ and on combed $\beta = 1.35$, T_{ty} = yarn tex, T_{tf} = fibre tex
and,

$$q = \frac{l_y}{l_h} \quad , \tag{19}$$

where l_y = the yarn gauge length in mm, l_h = the fracture zone length.

The parameter v_{Fh} was shown to be dependent on the coefficient of variation of yarn strength, the actual mass variation of the yarn, Martindale's limit mass variation [20], fibre fineness and yarn count. The model used by Frydrych [19] to predict the strength of cotton yarns incorporates the migrating

properties of a fibre. The relevant equations for evaluating the fibre length and the stress and strain generated in it were developed in accordance with the yarn structure described by Zurek [2]. Many equations described by Frydrych [19] owe their origin to previous works by Zurek [2] and Zurek, Frydrych and Zakrzewski [21].

Ghosh et al [22] developed the following equation for spun yarn tenacity (Q_t) as:

$$Q_t = \frac{n_h}{n_e} \cdot F_h \cdot \frac{\varphi_b}{100} \cdot cos^2\theta' \quad , \tag{20}$$

where n_h = the number of fibres at the place of yarn break, n_e = the average number of fibres in the yarn cross section, F_h = the fibre bundle tenacity measured at a gauge length equal to the actual length of the weakest zone in the yarn, φ_b = the percentage of broken fibre in the yarn failure zone, θ' = the average helix angle of fibre at the time of yarn failure.

Krause et al [23] established the mathematical model of the air-jet spun yarn strength. They derived the expression of air-jet yarn strength for the following two cases.
For 100% fibre slippage of core, occurring when the frictional force f_s acting on the fibres is smaller than the breaking strength of fibre, the equation of yarn strength (F_1) is:

$$F_1 = \frac{ABfZ\,cos\,\alpha_0}{(1+e_f)}\left[(1+e_y)+\frac{\mu}{\pi}y\,tan^2\,\alpha_0(1+e_r)^2\right] \quad , \tag{21}$$

For partial slippage and partial fibre breakage of core, occurring when the frictional force f_s reaches the breaking load f of some fibres, the yarn strength (F_2) is:

$$F_2 = fZ\left[(1-AB)+cos\,\alpha_0 AB\frac{(1+e_y)}{(1+e_f)}-\frac{\pi(1+e_f)(1-AB)^2}{4\mu yAB\,cos\,\alpha_0\,tan^2\,\alpha_0(1+e_r)^2}\right] \quad , \tag{22}$$

where A = the portion of edge fibres, B = the ratio between the average wrapping length of edge fibre and fibre length, Z = the number of fibres in the yarn cross-section, α_0 = the average helix angle of wrapping fibre for the unstrained condition of the yarn, e_f = fibre strain (neglecting the initial fibre strain), e_y = yarn strain, e_r = yarn radius strain, μ = the co-efficient of friction of core fibre, y = the slenderness ratio of the fibre.

Rajamanickam et al [24] developed an expression for computing air-jet yarn strength. Their model of air-jet yarn strength is based on the force contribution of the wrapper as well as of core fibres under the applied load to the yarn.

Pan [25] proposed the following expression of the normal twisted staple yarn strength, $<\sigma_y>$, for Weibull-type fibres:

$$<\sigma_y>=\eta_q\eta_l V_f\left(l_c\alpha\beta\right)^{-1/\beta}\exp(-\frac{1}{\beta}) \quad , \tag{23}$$

where η_q = the orientation efficiency factor, η_l = the length efficiency factor, V_f = the fibre volume fraction, l_c = the critical length, α = the scale parameter , β = the shape parameter. Pan derived the above relationship based on the statistical theory.

In another paper Pan, Hua and Qiu [26] showed the relationship between yarn strength and fibre bundle strength as follows:

$$\frac{<\sigma_y>}{<\sigma_b>} = \left(\frac{l_f}{l_c}\right)^{1/\beta} V_f \eta_q \quad , \tag{24}$$

where $<\sigma_b>$ = the fibre bundle strength, l_f = the fibre length.

They also showed the relationship between yarn strength and its constituent fibre strength as

$$\frac{<\sigma_y>}{<\sigma_f>} = \left(\frac{l_f}{l_c}\right)^{1/\beta} \frac{V_f \eta_q}{\beta^{1/\beta} \exp\left(\frac{1}{\beta}\right) \Gamma\left(1 + \frac{1}{\beta}\right)} \quad , \tag{25}$$

Iyengar et al. [27, 28] developed certain functions involving fibre length, fineness, tenacity and uniformity of length from scientific considerations for estimating the tenacity of yarns spun under standard processing techniques. The equation for estimating yarn tenacity was given as:

$$R = \left\{\frac{L-10}{\sqrt{F}}\right\} \cdot S \cdot U \quad , \tag{26}$$

where L = the mean length of the fibre, F = the fibre weight per unit length, S = the fibre tenacity, U = the fibre uniformity ratio.

El Mogahzy [29] gave the following regression equation for calculating the count strength product (*CSP*) of yarns:

$$CSP = -4184.4 + 1141.2\,FL + 71.2\,LU + 49.4\,FE + 32.4\,FS - 22.7\,Rd + 2041/FF \quad , \tag{27}$$

where *FL* = the fibre's upper half mean length in inches, *LU* = length uniformity, *FE* = fibre elongation, *FS* = fibre strength, *Rd* = reflectance, *FF* = the fibre micronaire.

Hafez [30] has given the following formulae for predicting lea strength and single yarn strength

$$S = (T.t)\,[b\,log\,(\,tl^2\,i^2\,) + a] \quad , \tag{28}$$

where S = lea strength (Newton), T = twist per meter, t = yarn count (mg/m), l = the mean length of fibre (mm), i = the fibre bundle tenacity at zero gauge length in a Pressley tester (mN/mg/m), b = 23.53 for carded yarns and 33.27 for combed yarns, a = -196.87 for carded yarns and –287.89 for combed yarns, and

$$H = (T.t)\,[0.278\,log\,(\,tl^2\,i^2\,) - 2.39] \quad , \tag{29}$$

where H = the single yarn strength (mN).

Hunter [31] has proposed a range of regression equations for predicting the strength of ring and rotor spun yarns from a range of fibre properties. Some of his equations are as follows

Ring yarn *CSP = 43 UR+125 BT-103BE-65Mc+10.5YC+47.3TF-3601* , (30)

Ring yarn *CSP =0.057 UR$^{1.03}$ BT$^{1.15}$ BE$^{-0.27}$ Mc$^{-0.14}$ YC$^{0.18}$ TF$^{0.87}$* , (31)

Rotor yarn *CSP = 19.1 UR$^{0.32}$ BT$^{0.71}$ BE$^{-0.39}$ Mc$^{-0.34}$ TC$^{-0.14}$ YC$^{0.37}$ TF$^{0.29}$* , (32)

Ring yarn tenacity (cN/tex) = $0.31UR + 0.80BT - 1.1BE - 0.73Mc + 0.062YC + 0.35TF - 21.8$,   (33)

Ring yarn tenacity (cN/tex) = $1.22 \times 10^{-3} UR^{0.97} BT^{1.03} BE^{-0.39} Mc^{-0.29} YC^{0.14} NTP^{-0.036} TF^{0.92}$,   (34)

Rotor yarn tenacity (cN/tex) = $0.0304 SL_{50\%}^{-0.62} UR^{1.07} BT^{1.02} BE^{-0.64} Mc^{-0.18} YC^{0.24} NTP^{-0.078} TF^{0.29}$,   (35)

where UR = the uniformity ratio, BT = the bundle tenacity, BE = the bundle elongation, Mc = the micronaire, YC = yarn count in tex, TF = twist factor, TC = the trash content (measured by a Shirley Trash Analyser), NTP = the number of trash particles, $SL_{50\%}$ = 50% span length.

Ethridge et al [32] found a linear empirical relationship between rotor yarn strength, fibre strength, micronaire, fibre length uniformity ratio and fibre greyness. They defined the CSP of the rotor yarn as:

$CSP = -6487.01 + 728.84lnS - 2913.89M + 658.41M^2 - 50.10M^3 + 2258.54lnU - 0.00003(G \times Y)^2$, (36)

where InS = the natural logarithm of fibre strength, M^i = the micronaire index raised to the ith power, InU = the natural logarithm of length uniformity ratio, and $(G \times Y)^2$ = the square of the product of greyness multiplied by yellowness.

The above equation shows that fibre strength and length uniformity have a positive correlation with the yarn strength, whereas greyness and yellowness have a slight negative impact on CSP. The micronaire value has the highest significant impact on rotor yarn CSP. However, recent studies by Ramey et al [33] failed to find any significant relationship between CSP and the micronaire value of the fibre. This is due to a certain range of micronaire for which the change of CSP is insignificant.

In another study, Swiech et al. [34] found a linear regression equation representing the rotor yarn strength in relation to the fibre properties as follows:

$Wp = 13.1434 + 0.1371 Ww - 0.0221 Ttw + 0.4125 Mic - 0.0173 K - 0.0899 Dk + 0.0050 Zz$,   (37)

where Wp = the yarn strength, Ww = the fibre strength, Ttw = fineness, $Mic.$ = the micronaire, K = the dust content, Dk = the staple length, Zz = the trash content.

Chasmawala et al [35] arrived at the following regression equation for air-jet yarn strength:

$$Breaking\ load = 515 - (3.12 \times \#core)\ ,$$ (38)

where #core is the number of core fibres. Therefore, as the number of core fibres increases, the breaking load decreases.

The correlation between yarn strength and fibre bundle strength

A considerable amount of work has been done to identify the appropriate strength parameter of the fibres in order to relate it with ring yarn strength. Brown [36], who did exhaustive work on 105 cottons regarding the correlation between yarn strength and fibre strength measured at different gauge lengths, viz. 0, 2, 4, 6, and 8 mm, found that the correlation was highest for 2 and 4 mm gauge lengths. Hence it was concluded that the "equivalent gripping distance" on individual fibres in yarn breaks was approximately 3 mm. This is how the 1/8-inch testing of fibre strength came into practice.

However, work done at ATIRA [37] showed that the square root of the product of fibre bundle strength at zero and 1/8-inch gauge lengths has a better correlation with the lea strength of cotton yarn than either of the other two. But Tallant et al [38], found that cotton fibre bundle strength at zero gauge was superior to that at 1/8-inch gauge as a criterion for relating fibre bundle strength to yarn strength as modified by the effective weight. They speculated that fibre strength measurement at the 1/8-inch gauge length with present instruments and techniques might in some manner take the length distribution characteristics into account.

Lord [15] proposed that cotton fibre tensile strength measured at 1/8-inch test length is related more closely to yarn lea strength than tensile strength corresponding to zero test length. This applies more particularly to carded yarns than to combed yarns. In carded cotton yarns the fibre arrangement is far

from uniform. When a length of yarn is stressed, the tension is not distributed uniformly along the length of the fibre. The yarn is composed of successive elements in the form of sections of fibre bundle. Amongst many other factors, the strength of the yarn will depend on the bundle strength of the elements, and in turn of the length of the elements. For carded yarns, the bundle strength measured at zero test length provides information which is less useful than that from measurements at 1/8 inch. The increased regularity and parallelisation of fibre arrangements in combed yarns suggests a decrease in the effective length of yarn element, a feature which may also occur in doubling when fibres are brought into more intimate contact with each other. For such material, the best test length for fibre bundle strength determination may be one closer to zero than that found suitable for the looser, carded yarn.

Conclusion

The foregoing discussion gives an overview of the various mechanistic statistics, as well as the empirical predictive models of spun yarn strength that have been reported so far in the literature since the interest of this topic first arose. During the discussion, the theoretical and empirical models of strength of yarns representing different spinning technologies have also beenexamined. An inference may be drawn that the discussion made in this article is useful for spinners and textile researchers as a tool for further research in the area of yarn engineering.

References

1. Hearle, J. W. S., Grosberg, P., and Backer, S., 'Structural Mechanics of Fibres, Yarns and Fabrics,' Wiley-Interscience, New York, 1969.
2. Zurek, W.,'The Structure of Yarn,' Warsaw, Poland, 1975.
3. Postle, R., Caranby, G. A. and de Jong, S.,'The Mechanics of Wool Structure,' John Willy & Sons, New York, 1988.
4. Langenhove, L. V., 'Simulating the Mechanical Properties of a Yarn Based on the Properties and Arrangement of its Fibres, Part I: The Finite Element Model,' Text. Res. J., 67,263-268, 1997.
5. Gegauff, C., 'Strength and Elasticity of Cotton Threads.' Bull. Soc. Ind. Mulhouse, 77, 153-176, 1907.
6. Gurney, H. P., 'The distribution of stress in cotton products,' J. Textile Inst., 16, T269-289, 1925.
7. Sullivan, R. R., 'A Theoretical Approach to the Problem of Yarn Strength,' J. Appl. Phys., 13, 157, 1942.
8. Gregory, J., 'Cotton Yarn Structure, Part III: The Strength of Artificial Yarn Elements in Relation to Bulk and Yarn Twist,' J. Textile Inst., 41, T30-52, 1950.
9. Pan, N., 'Development of a Constitutive Theory for Short Fibre Yarns, Part I: Mechanics of Staple Yarn Without Slippage Effect,' Text. Res. J. 62, 749-765, 1992.
10. Pan, N., 'Development of a Constitutive Theory for Short Fibre Yarns, Part II: Mechanics of Staple Yarn With Slippage Effect,' Text. Res. J. 63, 504-515, 1993.
11. Pan, N., 'Development of a Constitutive Theory for Short Fibre Yarns, Part III: Effects of Fibre Orientation and Bending Deformation,' Text. Res. J. 63, 565-572, 1993.
12. Bogdan, J. E., 'The Characterization of Spinning Quality,' Text. Res. J., 720-730,1956.
13. Bogdan, J. E., 'The Prediction of Cotton Yarn Strength,' Text. Res. J., 536-537, 1967.
14. Subramanian, T. A., Ganesh, K. and Bandyopadhyay, S., 'A Generalized Equation for Predicting the Lea Strength of Ring-Spun Cotton Yarns,' J. Text. Inst., 65, 307-313, 1974.
15. Lord,E., 'The Characteristics of Raw Cotton, Manual of Cotton Spinning, Vol. II, Part 1,' Manchester, 1961.
16. Neelkantan, P., Subramanian, T. A., 'An Attempt to Quantify the Translation of Fibre Bundle Tenacity into Yarn Tenacity,' Text. Res. J., 46,822-827,1976.
17. Solovev, A. N., 'Proektirovanie svoistv pryazhi v khlopchatobumazhnom proizvodstve (The Prediction of Yarn Properties in Cotton Processing),' Moskva, 1958.
18. Usenko, V. A., 'Ispolzovanie shtapelnogo volokna v pryadenii (The Use of Staple Fibres in Spinning),' Moskva, 1958.
19. Fredrych, I., 'A New Approach for Predicting Strength Properties of Yarn,' Text. Res. J., 62, 340-348, 1992.