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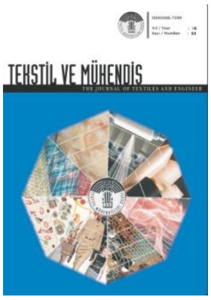

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Determination of Yarn Diameter and Relevant Applications in Various Theoretical and Practical Problems

İplik Çapının Belirlenmesi Ve Çeşitli Teorik Ve Pratik Problemlerle İlgili Uygulamalar

Güngör Başer*

Dokuz Eylül University, Department of Textile Engineering, İzmir, Turkey

Online Erişime Açıldığı Tarih (Available online):30 Haziran 2021 (30 June 2021)

Bu makaleye atıf yapmak için (To cite this article):

Güngör Başer (2021): Determination of Yarn Diameter and Relevant Applications in Various Theoretical and Practical Problems, Tekstil ve Mühendis, 28: 122, 134-148.

For online version of the article: https://doi.org/10.7216/1300759920212812207

Derleme Makale/ Review Article

DETERMINATION OF YARN DIAMETER AND RELEVANT APPLICATIONS IN VARIOUS THEORETICAL AND PRACTICAL PROBLEMS

Güngör BAŞER*

Dokuz Eylül University, Department of Textile Engineering, İzmir, Turkey

Gönderilme Tarihi / Received: 24.03.2021
Kabul Tarihi / Accepted: 24.05.2021

ABSTRACT: An introduction on the description of yarn diameter and factors affecting are given first. Methods of measurement of yarn diameter are shortly resumed and various definitions of yarn diameter are given in relation to certain practical problems. A discussion is undertaken in relation to define yarn diameter as a parameter in theoretical analyses as well as in practical problems in production and design.

Keywords: Free diameter, optical and mechanical diameter, yarn compression, obliquity effect, effective diameter, fabric geometry.

İPLİK ÇAPININ BELİRLENMESİ VE ÇEŞİTLİ TEORİK VE PRATİK PROBLEMLERLE İLGİLİ UYGULAMALAR

ÖZ: İplik çapının belirlenmesi ve etkili olan faktörler öncelikli olarak tanıtılmaktadır. İplik çapının ölçüm yöntemleri kısaca özetlenmekte ve bazı pratik problemler bağlamında çeşitli iplik çap tanımları yapılmaktadır. İplik çapının teorik analizleri yanında üretim ve tasarım problemleriyle ilgili bir parametre olarak belirlenmesi konusu tartışılmaktadır.

***Anahtar sözcükler*:** Serbest çap, optik ve mekanik çap, iplik yassılması, eğiklik etkisi, etkin çap, kumaş geometrisi.

***Sorumlu Yazar/Corresponding Author:** gungor.baser@deu.edu.tr*
***DOI:** https://doi.org/10.7216/1300759920212812207*   *www.tekstilvemuhendis.org.tr*

1 INTRODUCTION

Yarn as a structural element of woven and knitted fabrics is characterised mainly by its thickness and elastic properties. When we consider ropes which are obtained by twisting a certain number of yarns tightly, we may refer to their thickness as their diameter, since they have quite a cylindrical shape. In contrary, when we consider threads as the building material of fabrics, either as single yarn or in doubly or multi twisted forms, the diameter is a somewhat obscure dimension, which presents difficulties in properly defining and accurately measuring. It becomes necessary, therefore, to assume that yarn is a cylindrical object, and that its diameter is constant across its cross section and along its length.

Further difficulties arise from the fact that the actual yarn surface or the outline of yarn cross section is difficult to define and yarn diameter depends on tension applied to yarn without which it will not stand straight or taut, with the consequence that it cannot be handled or processed. Another complication with practical implications is that yarn count or yarn linear density, which can easily be measured and characterizes yarn thickness, does not correspond to geometrical meaning of yarn diameter which is affected by yarn twist and by packing density of fibres in yarn structure.

Yarn irregularity, defined as either the variation of the number of fibres in yarn cross section or as the variation of weight per unit length (linear density) along yarn length, depends upon variation in fibre diameter and fibre length influenced by fibre kind and yarn manufacturing technology. This will necessitate yarn properties, including yarn diameter, to be represented by average numbers. Although this will not present great problem in practice, it may give rise to serious problems in theoretical analyses.

These analyses will be concerned with how yarns behave in textile processes like spinning, twisting, winding and fabric formation, as well as how they will behave, as structural elements of fabric structure, to affect the final performance of the fabric in use.

It is considered to approach the subject by first defining yarn diameter and describing briefly its method of measurement and secondly examining the factors affecting its magnitude.

2 VARIOUS DEFINITIONS OF YARN DIAMETER

Yarn is formed by twisting together a certain number of fibres prepared as being parallel to each other and packed homogeneously in a cylindrical structure. Thus, this quasi-solid structure will have a certain thickness depending on the number of fibres in its cross section, which may be represented by the diameter of the area formed by cutting it by a plane perpendicular to yarn axis. However, this cross sectional area may not be quite circular, nor may its contour be clearly defined. It may have been distorted due to certain external forces acting and its contour may have been obscured by surface fibres. This gives rise to various definitions of yarn diameter depending on the state of fibres in yarn structure and also on method of its measurement.

2.1 Free Diameter, Optical Diameter, Mechanical Diameter

Assuming that the yarn structure is a circular cylinder and that it has a constant number of fibres in its cross section. It is possible to derive a formula to give yarn diameter in terms of yarn count, which is an accurately measurable quantity, from the weight of a unit length of yarn, provided that the yarn density is known. Yarn diameter may be calculated by the general formulae

$$d = \frac{1}{K\sqrt{N}} \quad \text{or} \quad d = K\sqrt{C} \qquad (1)$$

where d is yarn diameter, N is yarn count in indirect count systems, C yarn count in direct count systems and K is a convenient constant. Since yarn density will depend on fibre density and the degree of packing of fibres, the constant K will have to be defined for different fibres and different yarn production systems. However, there are two more problems that will make the practical use of yarn diameter formulae.

First, yarn twist affects yarn diameter since the higher the twist the more compact will be the yarn structure, consequently smaller the yarn diameter. Secondly, in twofold yarns which are widely used in fabric manufacture the yarn density, due to both yarn structure and different effect of twist, will be different. In consequence, different K constants for the same kind of yarn should be defined.

If the ***free yarn diameter*** is defined as the diameter of the right cross section of the solid body of yarn subjected to no external forces, either as tension or as compression, measure of yarn diameter defined by equation 1 may correspond to it if we assume that the yarn tension to be applied to measure yarn count is just sufficient to keep yarn and fibres in straight form.

Ashenhurst [1] gave tables which showed number of threads in one inch for cotton, worsted, woollen and linen yarns based on measurements he made, using a micrometre. For yarn diameter Ashenhurst used the general formula

$$d = \frac{1}{K\sqrt{Yards/Lb}} \text{ inch} \qquad (2)$$

and evaluated the yarn constants as K = 0.90 for fine worsted, K = 0.86 for crossbred worsted, K = 0.84 for woollen and K = 0.95 for cotton yarns. In order to use equation 1 with units of cm and metric count, we can calculate yarn constant K as 7.89 (7.9), 7.54 (7.5), 7.365 (7.4) and 8.33 (8.3) respectively for these yarns.

Peirce [2], on the other hand, evaluated the yarn constant in terms of units of British cotton count (*Ne*) and inch as 28. When this value is converted to metric count and cm units, a value for K= 8.47 (8.5) is obtained. This constant, calculated by Peirce using a specific volume value of 1.1 cm^3/g determined experimentally, is not far from Ashenhurst's value which will give slightly lower diameters. The experimental method used is based on measuring the height of fibre mass of a certain weight packed into a prismatic channel of 1 cm^2 base area.

Following the same approach Backer, Hearle and Grosberg [3] proposed a yarn diameter formula

$$d = 4.44 \times 10^{-3} \sqrt{Tex / FibreDensity}\ \text{cm} \tag{3}$$

assuming a ***yarn porosity*** value of 0.65. Yarn porosity, here, means the fraction of volume of fibre material in yarn volume, ϕ , which may be expressed as

$$\phi = \nu_f / \nu_y \tag{4}$$

where ν_f is the fibre specific volume and ν_y is the yarn specific volume. Grosberg stated that the porosity, also defined sometimes as ***packing fraction*** varied between values of 0.55 and 0.75 and proposed a more general formula for yarn diameter as

$$d = 3.57 \sqrt{\frac{Tex}{Porosity \times FibreDensity}} \times 10^{-3}\ \text{cm} \tag{5}$$

By assigning a value to yarn porosity and fibre density this formula can be used to calculate the diameter of any type of yarn.

Another yarn diameter formula is due to Shinn [4] for cotton knitting yarns as

$$d = \frac{1}{24\sqrt{Ne}}\ \text{inch} \tag{6}$$

in which Shinn [4] assumed a yarn density of 0.67 g/cm^3.

In experimental determination of yarn diameter, however, two basic approaches are made, the first being mechanical method of measurement, the second being optical. In order to measure yarn diameter by some mechanical method a certain amount of transverse pressure has to be applied to lay down surface fibres on one hand, and also to obtain a physical indication of the yarn contour on the other hand. The recording of the measured entity may be done by optical or electronic means. In optical measurement of yarn diameter, the method may be to obtain a shade or photographic image of the yarn by directing a light beam on to the yarn surface in transverse direction, in which case a certain tension, though small, must have been applied to hold it straight in space. In mechanical measurements arrangements may be made to have the yarn tensionless. In optical measurements surface hair may have appreciable effects on the values obtained.

Thus, it will be more appropriate to differentiate between yarn diameters as '***mechanical***' or '***optical***', depending on the method of measurement.

2.2 Methods of Measuring Free and Compressed Yarn Diameter

Earliest methods of measurement of optical yarn diameter are those of Barella [5] and of van Issum and Chamberlain [6].

Barella [5] obtained the actual yarn image as the projection of yarn surface on the photographic plane. The yarn was drawn from yarn bobbin through an adjustable tensioning device, which measured yarn tension, and passed over a projecting microscope. Measurement of yarn diameter was made on the magnified yarn image by means of a graduated scale.

Van Issum and Chamberlain [6], on the other hand, made measurement of yarn diameter on the photograph taken by their instrument named Chamberlain photometer which recorded the snapshots of a moving yarn on the same plate for a certain period of time. In this way, yarn images obtained continuously were somewhat averaged and a statistical evaluation of the yarn diameter was made as shown in Figure 1.

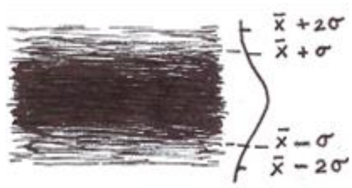


Figure 1. Yarn image obtained by Chamberlain photometer and its statistical evaluation.

In the mechanical measurement of yarn diameter, a transverse force is applied on the yarn surface so as to lay down the surface fibres by some mechanical means. In Baser' s instrument [7] yarn is held between two glass plates, the bottom one being fixed and the top one being acted upon a vertical force provided by a lever system composed of a heavy pointer arm which is balanced by a counter weight as shown in Figure 2. The counter weight is movable o by rotating it over a screw rod, by which the force acting on the yarn can be changed and measured by moment calculations.

The free diameter is measured by the movement of the pointer by a travelling microscope. The diameter measurement is started when the lever system is in balance and thus stays almost stationary with the yarn between glass plates. The compressed minor diameter is measured in similar way when the rotating disc is moved away from its balance position to apply a certain force.

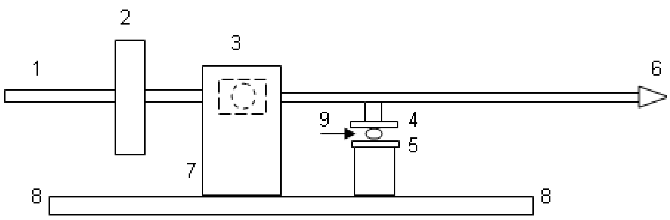


Figure 2. Yarn diameter measuring apparatus in conditions of yarn compression (1.Screwed guiding rod, 2.Rotating disc, 3.Support for bearings, 4-5.Glass plates, 6.Pointer arm, 7.Holder block, 8.Holder platform, 9.Yarn)

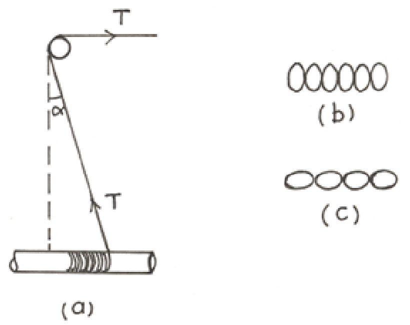


Figure 3. Measurement of yarn diameter by Hamilton's "Bocking yarn geometer" (a. Method of winding yarn coils, b. Yarn cross sections under sideways compression, c. Yarn cross sections under vertical compression).

The actual free diameter is extrapolated from the graph of force against displacement to take into account contribution of surface hairs. The major diameter, on the other hand, is measured by a microscope with a graduated scale placed over its objective.

Another instrument was devised by Onions and Oxtoby [8] to measure mechanical yarn diameter. They, however, employed an electronic sensor for the measurement of pressure.

2.3 Factors Affecting Free Yarn Diameter

Barella [5] investigated the relationships between yarn diameter measured and applied tension and yarn twist. The calculated values of specific volume of various rayon (viscose filament), spun rayon, worsted and woollen yarns from the measured diameter values at zero tension by Barella [5] are given in Table 1

Table 1. Values of yarn specific volume for some yarns [5]

Yarn type	Count m/g	Diameter mm	Specific volume cm3/g
Rayon	45 60 90	0.213 0.175 0.150	1.60 1.44 1.59
Spun rayon	30 40 60	0.213 0.184 0.148	1.07 1.06 1.03
Worsted	30 50	0.217 0.169	1.11 1.12
Woollen	10.5 12.5	0.385 0.372	1.22 1.36

It can be observed that these values are much lower than those values found by van Issum and Chamberlain [6] given in Table 2 and also by the calculated values from diameter measurements on spun nylon yarns by Hearle and Merchant [9] shown in Table 3.

Table 2. Values of specific volume of various yarns [6]

Yarn type	Specific volume cm3/g
Rayon Cotton Worsted Woollen	1.54 1.84 1.70 2.40

Table 3. Values of specific volume of various yarns calculated from diameter measurements under zero tension on spun nylon yarns by Hearle and Merchant [9]

Yarn count Ne	Twist level	Specific volume cm3/g
10	2 5	2.79 1.84 1.50
20	2 5 8	3.52 1.64 1.47
30	2 5 8	2.15 1.21 1.53
40	2 5 8	2.86 1.36 1.47

The difference between the values for filament rayon and spun rayon may be due to low twist generally applied to filament yarns.

Values of yarn specific volume of various yarns based on a mechanical method of measurement carried out under no tension by Başer [7] are shown in Table 4.

Table 4. Values of specific volume for various yarns by Başer [7]

Yarn type	Specific volume (cm3/g)
Cotton Cotton/Polyester Worsted Woollen	1.60 2.36 2.10 3.36

As a later research results, the average values of free yarn diameter for various yarns obtained by [9] using projection method of measurement are shown in Table 5. Standard yarn tensions were applied in these measurements. It will be observed that the values of yarn specific volume obtained by Okur are much lower than those given by van Issum and Chamberlain. It is also interesting that a value of 0.95 obtained for worsted yarns is even lower than that given by Peirce [2] for cotton yarns, which is 1.1.

Table 5. Values of specific volume for various yarns by Okur [9]

Yarn type	Specific volume (cm^3/g)
Cotton	1.15
Cotton/Polyester	1.15
Worsted	0.95

It is interesting that, although it is a theoretical condition, the mechanical yarn diameter measured under no tension give much higher specific volume values than the optical diameter measured under standard tension by van Issum and Chamberlain [6], Barella [5] and Okur [9]. This shows that there has not been much agreement on various experimental work on the measurement of yarn diameter and that yarn tension and yarn twist are two important factors in yarn diameter measurements and indeed in theoretical applications.

2.3.1 Effect of Yarn Tension on Yarn Diameter

Barella [5] investigated the effect of tension on yarn diameter and tried to establish a theoretical base for it. Barella, defined a critical diameter assuming that at very high tension near break point there will remain no space between fibres and yarn specific volume will reach that of fibre and gave an empirical formula as follows:

$$d_c = d_0 - K\sqrt{F_B} \tag{7}$$

Here d_0 is the tensionless free yarn diameter, F_B breaking force, K is a coefficient related to yarn count given as

$$K = \frac{2\left(\sqrt{1/\pi\gamma'} - \sqrt{1/\pi\gamma}\right)}{\sqrt{1000L}} \tag{8}$$

where γ' and γ are the specific density of fibre and yarn respectively. By generalizing this relationship Barella showed it in a graph as shown in Figure 4. Here d_f is the yarn diameter under a tensile force F_f and F_c is the critical tensile force at break.

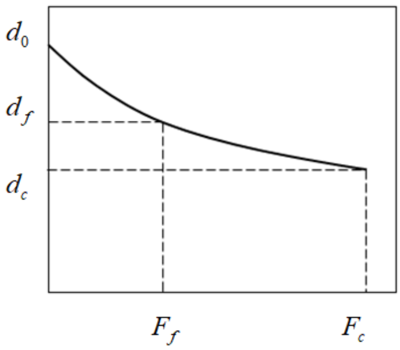


Figure 4. Relation between yarn diameter and tensile force [5]

2.3.1 Effect of Yarn Twist on Yarn Diameter

If it is assumed that packing density of fibres in yarn structure remains the same in spinning when the yarn contract due to twist then from yarn geometry, assumed to follow a path of cylindrical helix along yarn axis and by defining the mean length of fibres, it may be shown that the mean length of fibres in yarn of one turn of twist is given by

$$l = \frac{1}{2}h(1+\sec\alpha) \tag{9}$$

where h is length of yarn of one turn of twist and α is the twist angle. If the free yarn diameter is R_0 and reduces to R_1 after twisting then from constant volume assumption of the yarn cylinder of one turn od twist, the free yarn diameter may be expressed as

$$d_0 = 2R_0 = 2R_1\sqrt{\frac{2}{1+\sec\alpha}} \tag{10}$$

This relation is shown in the diagram given in Figure 5. As the assumption of constant packing density is not realistic Barella [5] gave empirical formulae that show the joint effect of twist and tension as follow:

$$\begin{aligned} \gamma' &= 0.56 + 28\times10^{-4}T \quad \text{Cotton} \\ \gamma' &= 0.58 + 25\times10^{-4}T \quad \text{Worsted} \\ \gamma' &= 0.47 + 28\times10^{-4}T \quad \text{Woollen} \\ \gamma' &= 0.60 + 27\times10^{-4}T \quad \text{Viscose rayon} \end{aligned} \tag{11}$$

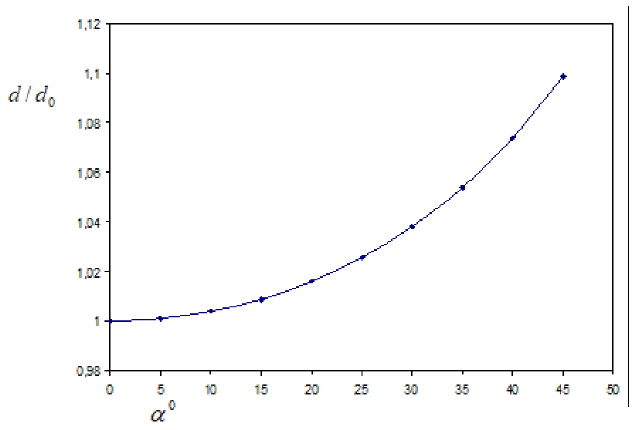


Figure 5. Variation of diameter with twist angle

Here the twist constant T is given in units of twist per meter and metric count that is as

$$T = N^{-1/2}t \quad \text{(N=Nm, t=twist/m).} \tag{12}$$

2.4. Yarn Diameter of Double Yarns

Ashenhurst [1] and others as Brierley [11] gave yarn diameter formulae irrespective of whether the yarn is single or double. However, in worsted weaving double yarns are used in general. Thus this was questioned by Okur and Başer [12].

The diameter of double yarns is defined by two single yarns of cylindrical shape twisted together at a twist angle by Okur [9] and can be evaluated as based on a geometric model given in Figure 6. Okur measured double yarns of cotton, worsted and cotton/polyester of various counts and twists by an optical diameter measurement instrument designed for the purpose, under standard tension.

From Figure 5 X coordinate is defined by

$$X = a\sqrt{\left[1-(1-a^2/b^2)\sin^2\omega\right]} + b\sin\omega \tag{13}$$

Here a and b are the major and minor diameters of single's yarn. The mean diameter of the double yarn is determined as

$$\overline{D}_{di} = \frac{2\int_0^{\pi/2} X d\omega}{\int_0^{\pi/2} d\omega} \qquad (14)$$

Integrating equation (12) the double yarn diameter is given in terms of constituent single yarn by

$$\overline{D}_{di} = (2/\pi)\left[E(k)\sec\alpha + 1\right]d_s \qquad (15)$$

where d_s is the optical diameter of single's yarn and $E(k)$ is the complete elliptic integral of the second kind with parameter k given by $k = \sqrt{1-(b/a)^2} = \sin\alpha$

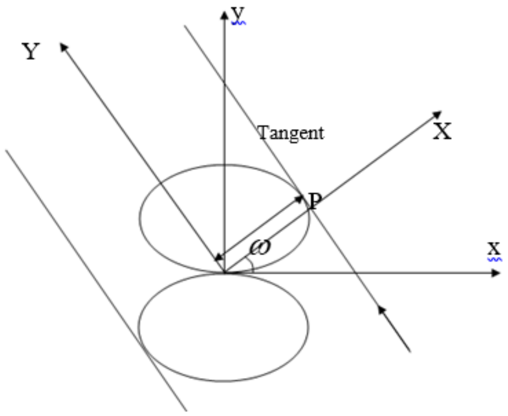


Figure 6. Geometric model to calculate mean optical diameter of double yarn

As a result of optical diameter measurements on yarns modifications on Ashenhurst's yarn coefficients in formula (1) were proposed for double yarns as 6.58 in cotton yarns, 6.98 in cotton/polyester yarns, lower than 8.33, 7.02 in worsted yarns lower than 7.9, in metric system.

2.5. Yarn Diameter in Compressed State

"Yarns do not have regular circular cross sections even in free state and in no way in fabric structures. In certain structures such as voile fabrics woven from highly twisted yarns in sparse structure a circular yarn cross section may be realistic. Crossing yarns in fabric apply pressure to each other due to warp tension during weaving. This results in yarn flattening perpendicular to fabric surface resulting in a major and a minor diameter. Yarns are flattened along the minor diameter in low and medium sett fabrics and may be flattened along the major diameter in high set and jammed fabrics [13].

Başer [7] examined experimentally the cross sectional changes in yarns under pressure as yarn flattening. For graphical analyses the cross sectional shape is assumed to be a race-track section as that proposed by Kemp [14] but instead of constant area an equivalent section of constant perimeter is adopted on the basis of a measured or assumed ratio of compression. Measurements were made using the apparatus shown in Figure 2, single worsted, woollen, cotton, acetate and viscose yarns of various twist levels were examined. For graphical analyses the ratios of the minor diameters of flattened yarns to their free diameter were plotted against those of their major diameters to free diameters. The calculated points are examined for their agreement with the lines representing various assumptions about cross sectional shapes of flattened yarns. In Figure 7 the basis of this graphical analysis is shown.

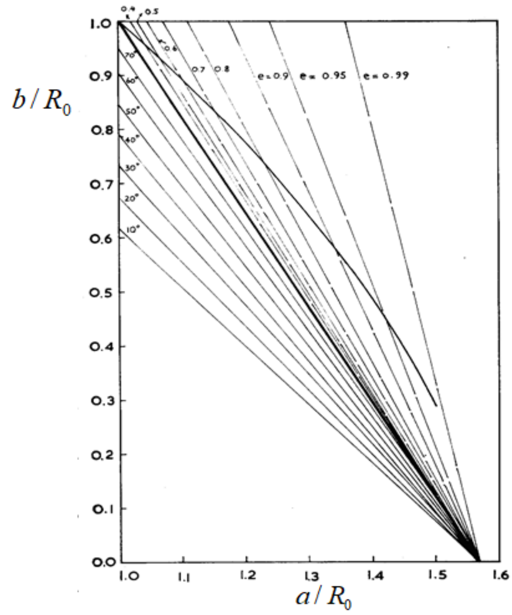


Figure 7. Analysis of changes in yarn cross-sectional shape

The curved line in Figure 8 shows constant perimeter elliptic section, the bold line the constant perimeter race-track section with circular side sections. However, the racetrack section can be formed in two different ways as shown in Figure 7.

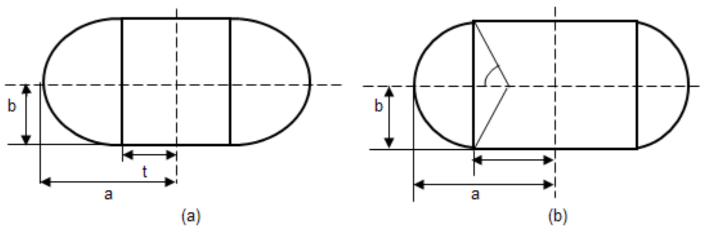


Figure 8. Two ways of formation of race-track section

The perimeter of the cross-sectional shape shown in Figure 5b is given

$$S = 4r\beta + 4(a - r + r\cos\beta) = 2\pi R_0 \qquad (16)$$

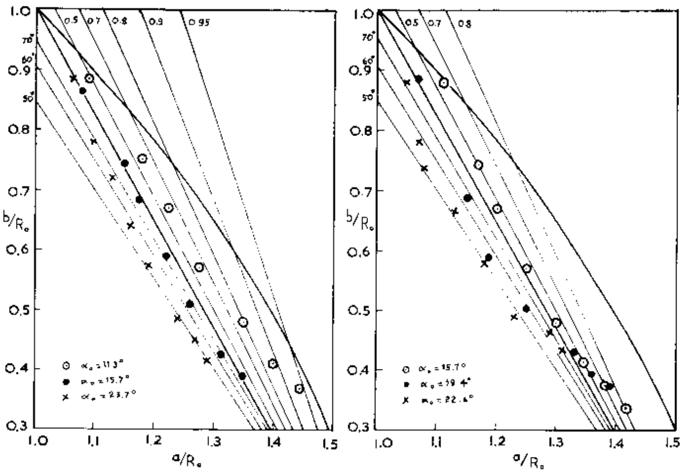
Substituting $r = b/\sin\beta$ we get

$$\frac{a}{R_0} + \frac{b}{R_0}\left(\frac{\beta - 1}{\sin\beta} + \cot\beta\right) = \frac{\pi}{2} \qquad (17)$$

and when $\beta = \pi / 2$ this equation becomes as

$$a / R_0 + b / R_0 (\pi / 2 - 1) = \pi / 2 \quad (18)$$

which represents the normal race-trac section. The measurements made on 24 Nm and 36 Nm worsted yarns are shown in Figure 9a, those on 12 Ne and 20 Ne cotton yarns in 9b.



(a) (b)

Figure 9. Graphical analysis of cross-sectional shapes in compression

Baser [7] also proposed a theoretical analysis of yarn compression due to a vertical pressure. Based on stress analyses according to a geometric model given in Figure 8 Baser [7] gave a formula for the compression of a circular helix as

$$\delta = k \frac{Pa^3}{B_f} \quad (19)$$

on the assumption of small deformations, where δ is the decrease of the diameter in vertical direction, P is the applied pressure, a is the free radius, B_f is the bending rigidity of fibre and k is a constant that varies with helix angle α . In Figure 10 the variation of k with respect to helix angle is shown. Baser [7] proposed two geometrical model of yarn compression one which fit better with staple yarns, the other with filament yarns. They are both based on concentric shells in yarn cross-sectional structure but the application of pressure is in different fashions as accepted assumptions, as shown in Figures 11.

Examples which show calculation algorithms are given by Baser [15]. These include the calculations of number of layers (or shells) calculable from the number of fibres in yarn cross-section and on the assumption of yarn packing model as open circular packing or hexagonal close packing [3].

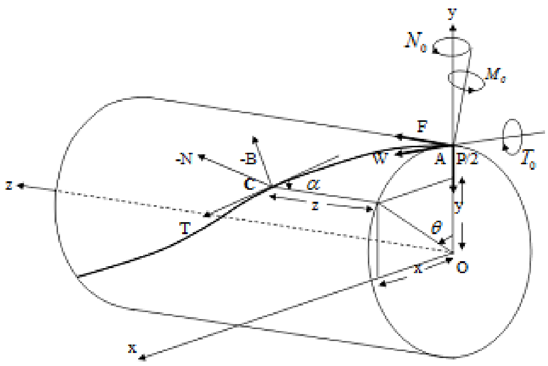


Figure 10. Geometric-mechanical model of transverse compression of a Helix

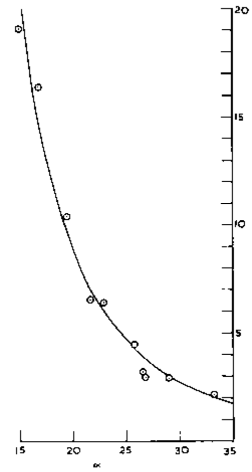


Figure 11. Variation of *k* with respect to α .

The formula given for staple yarns is as follows:

$$P_m = \frac{\delta B_f}{m(\Delta r)} \left(\frac{m \sin \alpha_0}{k_0 r_0^3} + \frac{(m-1)\sin \alpha_1}{k_1 r_1^3} + \frac{(m-2)\sin_2}{k_2 r_2^3} ..... \right)$$

$$\delta = \frac{m P_m (\Delta r)}{B_f \left(\frac{m \sin \alpha_0}{k_0 r_0^3} + \frac{(m-1)\sin \alpha_1}{k_1 r_1^3} + \frac{(m-2)\sin \alpha_2}{k_2 r_2^3} + ... \right)} \quad (20)$$

where δ is the amount of reduction in yarn diameter, m is the number of layers that are in contact.

The formula given for filament yarn is as follows:

$$\delta = \frac{P R_0^2}{B_f n_0 \left(\frac{\sin \alpha_0}{k_0 R_0^2} + \frac{\sin \alpha_1}{k_1 r_1^2} + \frac{\sin \alpha_2}{k_2 r_2^2} + ... \right)} \quad (21)$$

where n_0 is the total number of layers calculated.

Baser [15] also showed how a similar approach can be made for double yarns based on research by Okur [9] that presents a model for the cross-sectional shape of double yarns.

Leaf and Oxenham [16] investigated the problem by applying large deformations theory by considering the relation between pressure and elastic energy stored in compression based on a model shown in Figure 12, 13 and 14 as follows:

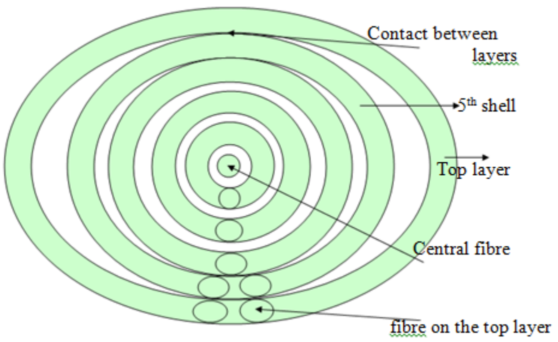


Figure 12. Geometric-mechanical model for staple fibres

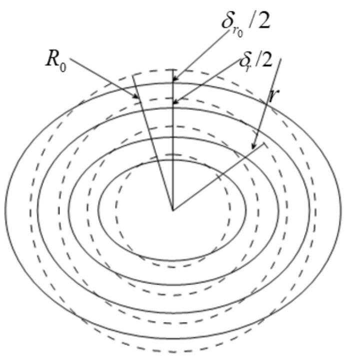


Figure 13. Geometric-mechanical model for filament yarns

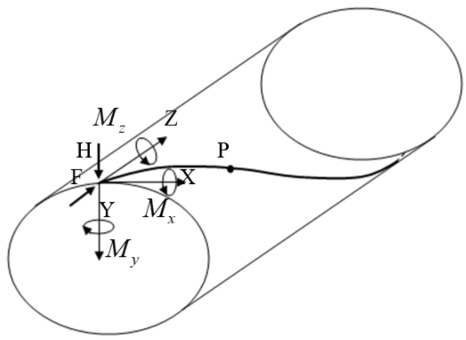


Figure 14. Leaf and Oxenham's geometric-mechanical model

If the free and compressed radial of yarn are R_0 and R respectively, the compression ratio for the yarn will be $\lambda_R = R / R_0$ and that for a fibre of radius r_0 be $\lambda_r = r / r_0$. If there is *n* twist in unit length of yarn and the twist angle is α at the surface, the twist angle of a fibre of radius *r* is will be given by $\tan q = 2\pi r_0 n$ when $\tan \alpha = 2\pi r_0 n$ and the energy function may be shown as $E(q, \lambda)$.

If fibre packing density is constant and is k_1, the number of fibres in a shell of thickness dr_0 will be

$$(2\pi k_1 \cos q) r_0 . dr_0 \quad (22)$$

Then

$$dE(q, \lambda_r) = \{2\pi k_1 E(q, \lambda_r) \cos q\} r_0 . dr_0 \quad (23)$$

On integration, the total energy of the compressed yarn may be expressed as

$$W_y = E(\alpha, \lambda_R) = 2\pi k_1 \int_0^{R_0} \{E(q, \lambda_r) \cos q\} r_0 . dr_0 \quad (24)$$

Substituting the linear density of fibre and yarn as m_f and m_y respectively Leaf and Oxenham [16] defined W_y as

$$W_y = \frac{m_y \cot \alpha}{\pi R_0 m_f} \int_0^{\alpha} E(q, \lambda_r) \tan q \sec q . dq \quad (25)$$

and proposed an empirical equation

$$E_n(q, \lambda_r) = a(1 - \lambda_r)^b (\tan q)^c \quad (26)$$

obtained from a regression analysis undertaken. Here a, b and c are constants defined for fibre type. These constants are given in Table 6 for wool for two different states. In state 1 the yarn is allowed to both extend and twist in compression, in state 2 it is only allowed to twist.

Table 6. Regression analysis results

State	a	b	c	R_d^2
1	16.18	1.93	1.84	0.9998
2	7.93	1.96	2.02	0.9991

The relation between λ_r and force $E(q, \lambda)$ are given in Figure 15 for two different state of compression. In state 1 yarn is allowed to both extend and twist in state 2 to only twist.

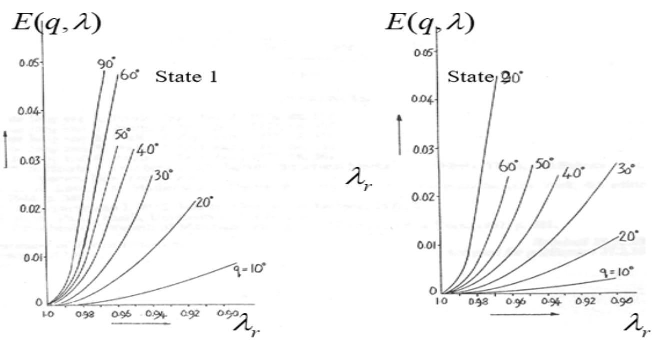


Figure 15. Relation between elastic energy and compression ratio

$$P = b(1-\lambda_R)^{b-1}C(\alpha)/2R_0 \quad (27)$$

where $C(\alpha) = \dfrac{Bm_y}{\pi^2 R_0{}^2 m_f}\{I(\alpha) or J(\alpha)\}$,

$I(\alpha) = \int_0^\alpha a(\tan q)^{c+1} dq$,

$J(\alpha) = a(\tan\alpha)^{-b}\int_0^\alpha (\tan q)^{b+c+1} dq$

2.6 Yarn compression under both tension and pressure

As the yarn diameter depend on tension the compressed yarn diameter will depend on both tension and vertical pressure. Although in relaxed fabric the tension on the constituent yarns may be accepted as zero, in fabric formation in the loom flattening will be the result of both tension and inter-yarn pressure. A research work was carried by Ozmen [17] to investigate joint effect of tension and pressure. An instrument was designed to measure yarn compression under tension shown in Figures 16 and 17 which was based on the method of measurement by that of Baser [7] shown in Figure 17.

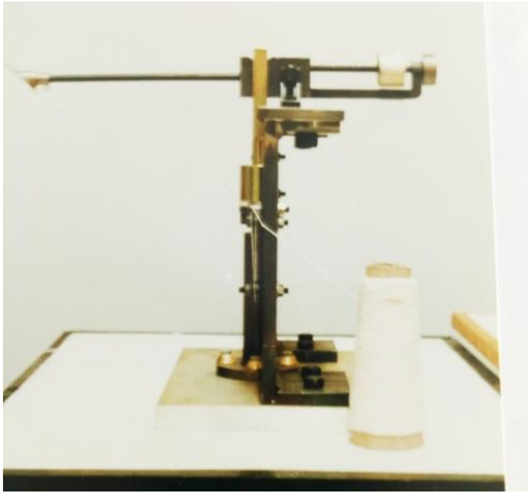


Figure 16. Yarn compression Measuring apparatus: Top view [17]

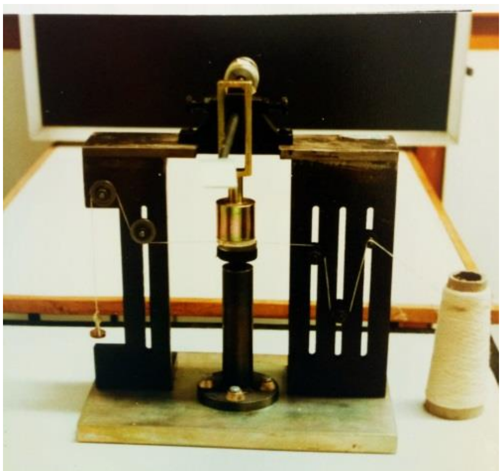


Figure 17. Yarn compression Measuring apparatus: Side view [17]

In Table 7 the results of yarn diameter measurements made on some cotton and worsted yarns under various tension levels and pressure per 1 cm yarn length are given.

The mechanical diameters obtained are compared with the optical diameters and it is observed that the mechanical diameter is reduced until a ratio of 0. is reached at 50 g tension by a ratio of around 70 %

Table 7. Effect of tension on mechanical diameter

Yarn type	Ten. (g)	Pres. (g)	Optic. Diam. (mm)	Mech Diam. (mm)	Mech Diam/. Optic. Diam.	Comp. D./ Free Dd
24 Ne cotton $\alpha_e = 3.5$	5	1	0.206	0.162	0.791	-
	10	1		0.143	0.694	0.82
	30	1		0.127	0.617	0.74
	50	1		0.105	0.510	0.68
36 Ne cotton $\alpha_e = 3.5$	5	1	0.163	0.131	0.803	-
	10	1		0.109	0.669	0.83
	30	1		0097	0.595	0.74
	50	1		0.089	0.546	0.68
52/2 Nm worsted $\alpha_m = 110$	5	1	0.277	0.186	0.671	-
	10	1		0.179	0.646	0.96
	30	1		0.158	0.570	0.85
	50	1		0.128	0.462	0.69

The mechanical diameters measured under both tension and compression are shown in Table 8.

Table 8. Yarn diameter measurements under both tension and pressure

Material	Load		Diameter				Comp. D./ Stand. D
	Tension g	Pressure g	Free mm	Mechh. D. Mm	Comp. D. mm	CV %	
24 Ne Cotton	30	20	0.162	0.127 T=5 g	0.118	3.61	0.93
		30			0.112	3.37	0.88
		40			0.102	4.46	0.80
	60	20		0.105 T=50 g	0.113	5.3	1.08
		30			0.105	4.6	1.00
		40			0.099	4.7	0.94
36 Ne Cotton	30	20	0.131	0.097 T=5 g	0.090	4.92	0.93
		30			0.086	5.47	0.89
		40			0.076	5.08	0.78
	60	20		0.089 T=50 g	0.084	6.55	0.94
		30			0.075	5.11	0.84
		40			0.067	8.47	0.75
52/2 Nm Worsted	30	20	0.186	0.158 T=5 g	0.149	4.86	0.94
		30			0.132	4.69	0.84
		40			0.125	3.48	0.79
	60	20		0.128 T=50 g	0.135	4.76	1.05
		30			0.112	3.88	0.88
		40			0.101	4.48	0.79

3 APPLICATIONS

Yarn compression becomes an important problem in winding process and in fabric formation both in weaving and knitting.

In winding the yarn is wound on paper, wooden or plastic cop having a cylindrical or conical surface under a certain tension. The final product is a package which is a bobbin or a weft cop known as pirn. The diameter of the package increases due to the yarn thickness as the compressed diameter under the pressure created by yarn tension. Thus both the package diameter and the softness of the package depend on winding tension and the compressibility of the yarn wound as well as the amount of yarn in a certain package size. This is important in production calculations and production planning. Package size and the length of yarn in a given package are also factors to be considered in machine design.

The yarns which form the woven fabric structure follow planar curves showing a crimped shape lying in planes parallel to yarn axis and perpendicular to fabric plane. They are also flattened in the cross section in perpendicular direction. Crimped shape of yarns is due to intersection of crossing yarns resulting in bending deformation and the final flattened shape of yarn cross section is due to pressure acting between them. In considering the woven fabric geometry in relaxed state the yarn cross sections are assumed to be either elliptical or race-track in which the constituent yarns bear no tension. The actual shape of fabric cross sections are given by Meric [18] as shown in Figure 18.

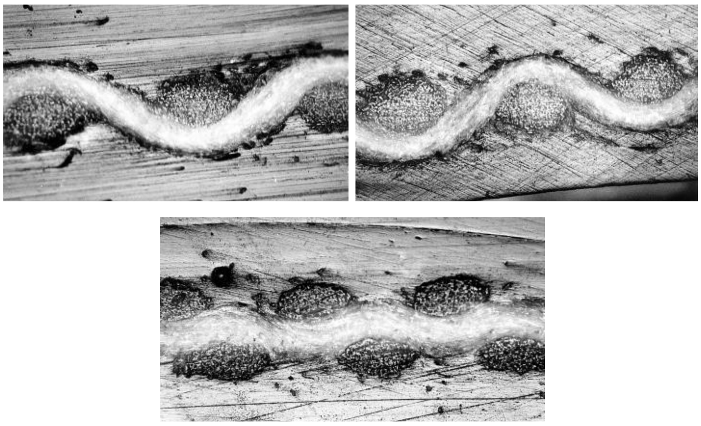


Figure 18. Plain woven fabric cross-sections: (1. slack woven, 2. Normal woven, 3. Tight woven) [18]

"Yarns are flattened along the minor diameter in low and medium sett fabrics and may be flattened along the major diameter in high sett and jammed fabrics [13]". So, it may be assumed that for the majority of cases yarn cross section accepted initially as circular would be transformed to an elliptical one to simulate yarn flattening.

It was found that a constant perimeter deformation of the cross sectional yarn shape in flattening is more realistic than constant area deformation especially in cotton yarns which are more compressible [7].

Although the sinus curve quite resembles in shape to the elastica curve being a little more curved, by assuming a realistic value for the weave angle θ, the application of the elastica in plain weave geometry presents no difficulty. A weave angle of 40° represents medium to high sett fabrics, but if the weave angle is calculated, using Peirce's simplified formulas, for a fabric sett according to Ashenhurst's 1st theory, a value of 30° is obtained and this represents a medium or normal sett fabric giving a crimp factor of 1,14. On the other hand, applying the model of sinus curve, the crimp factor was found to be 1.33 which is not a realistic value" [19].

Hamilton [13] developed a plain woven fabric geometry based on Kemp's [14] race-track geometry as shown in Figure 19 by considering unit repeat of plain weave.

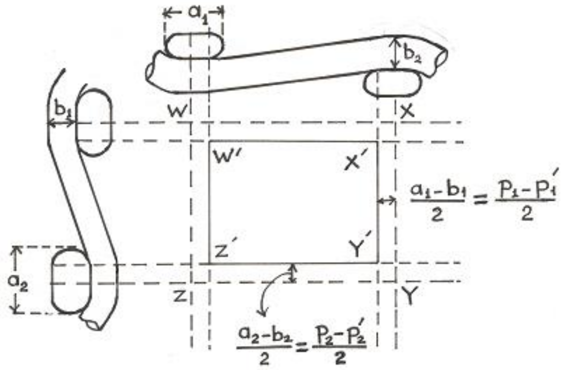


Figure 19. Hamilton's generalized plain woven fabric geometry

Hamilton defined the area $X'Y'Z'W'$ as a section which conforms with Pierce's plain weave geometry and defined this section with $l_1', l_2', p_1', p_2', h_1', h_2'$ and showed the crimp amplitudes as

$$h_1 = \frac{4}{3} p_2' \sqrt{c_1'}\ ,\ h_2 = \frac{4}{3} p_1' \sqrt{c_2'} \tag{28}$$

By defining the crimp ratios c_1', c_2' in terms of these parameters and squaring equations (1) the equations

$$h_1^2 = \frac{16}{9}(p_2')^2(\frac{l_1'}{p_2'}-1)\ ,\ h_2^2 = \frac{16}{9}(p_1')^2(\frac{l'_2}{p_1'}-1) \tag{29}$$

$$l_1' = p_2'\left[1+\frac{9}{16}\frac{h_1^2}{(p_2')^2}\right], \tag{30}$$

$$l_2' = p_1'\left[1+\frac{9}{16}\frac{h_2^2}{(p_1')^2}\right] \tag{31}$$

are obtained.

Hamilton generalized this approach to weave structures other than plain weave by proposing a formula which include the dimensions of the yarn sections in fabric cross section as flat and intersecting parts giving the relation between them as

$$p_i = \frac{p_r - \sum_1^{n_f} p_f}{n_i} \tag{32}$$

where p_i is the length of intersecting part and p_f is the length of flats.

These dimensions are defined as shown in the example of 2/2 twill weave fabric section shown in Figure 20. Here the problem is the determination of the flat lengths which depend on the change of yarn cross sections under flattening and jamming conditions in weaving, also on the weave structure.

Hamilton [13] proposed a method to determine flat lengths for three different conditions defined in Figure 21 for 2/2 twill 13 twill and 2/2 matt.

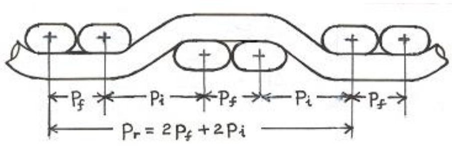


Figure 20. 2/2 Twill weave section

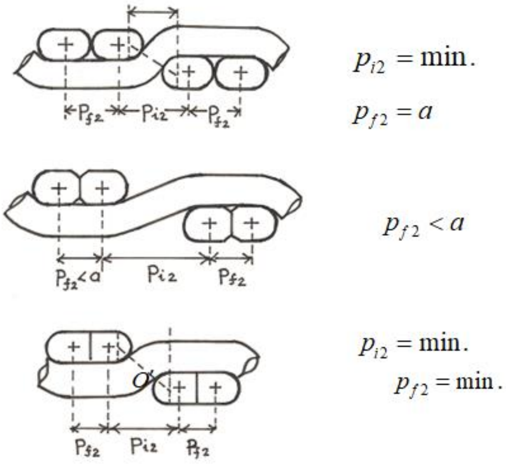


Figure 21. Yarn flattening and jamming conditions in three different weave structures

In jamming conditions Hamilton gave the value for p_f as

$$p_f = a - 0.215b \qquad (33)$$

and for $p_{f2} < a$ proposed a value between a and the above value which is like $p_f = a - 0.1b$. Hamilton's proposal may be supported by fabric cross section photographs given by Turan [20] as shown in Figure 22.

It seems so that the deformed yarn cross sectional shape and its dimensions are crucial in defining a realistic woven fabric geometry and the compressed yarn diameter under condition of weaving is an important parameter both in theory and practice.

A length of yarn representing warp is mounted between the ends of one arm of the instrument with one end fixed and tensioned on the other end of the yarn which passes over a pulley carrying a weight. Then a length of yarn representing the weft is intersected with the warp at right angles by fixing it between the ends of the other arms of the instrument to make a weave angle of a certain degree. The diameter measurement is made optically on the crossover point as the sum of two yarn diameters as shown in Figure 24. The tension developing on the weft yarn can be calculated by geometric-mechanical principles. The results of measurements carried out for three types of yarns are given in Table 9.

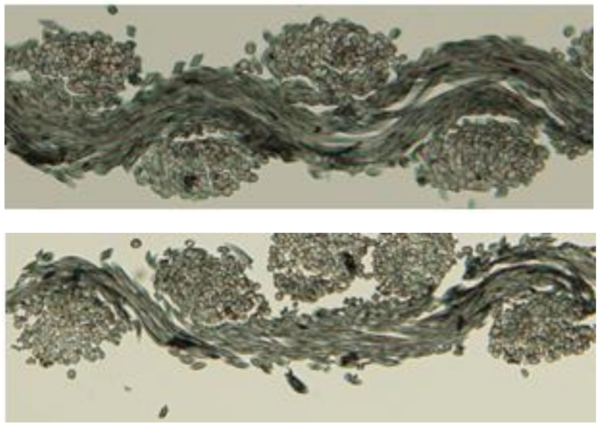


Figure 22. Plain weave and 1/3 twill weave fabric sections [20]

Following this line of thought a research work Ozmen [17] measured the compressed yarn diameter under conditions simulating those in actual weaving process by measuring the sum of warp and weft yarn diameters optically using an apparatus designed for this purpose shown in Figure 23.

Figure 23. Yarn compression in weaving conditions [17]

Figure 24. Yarn compression measuring apparatus in weaving conditions [17]

Table 9. Results of measurements of sums of two yarn diameters

Material	Mean weave angle (degree)	Warp Tension	Sum of optical diameters	Sum of compressed diameters	Compressed. diameters/ Optical diameters
24 Ne Cotton	Maximum 11^0	30	0.412	0.275	0.68
		60	0.412	0.245	0.59
		90	0.412	0.205	0.49
	Medium 7.9^0	30	0.412	0.306	0.74
		60	0.412	0.270	0.65
		90	0.412	0.249	0.60
	Minimum 6.3^0	30	0.412	0.332	0.82
		60	0.412	0.298	0.72
		90	0.412	0.287	0.69
36 Ne Cotton Cotton	Maximum 11^0	30	0.325	0.188	0.58
		60	0.325	0.157	0.49
		90	0.325	0.152	0.46
	Medium 7.9^0	30	0.325	0.204	0.63
		60	0.325	0.181	0.55
		90	0.325	0.165	0.49
	Minimum 6.3^0	30	0.325	0.225	0.69
		60	0.325	0.195	0.59
		90	0.325	0.181	0.55
52/2 Nm Worsted	Maximum 11^0	30	0554	0.369	0.66
		60	0.554	0.321	0.58
		90	0.554	0.258	0.46
	Medium 7.9^0	30	0.554	0.388	0.70
		60	0.554	0.343	0.61
		90	0.554	0.328	0.59
	Minimum 6.3^0	30	0.554	0.426	0.76
		60	0.554	0.410	0.73
		90	0.554	0.374	0.67

It is seen that the mean compression ratio for a medium tension of 60 g and a medium weave angle of 7.9 degrees is 0.59, for a high tension of 90 g and a high weave angle of 11 degrees is 0.50, for a low tension of 30 g and a low weave angle of 6.3 degrees is 0.76. These results which conform to some extent with practical data show that in theoretical applications quite realistic assumptions for compression ratio can be employed in accordance with yarn type and weave intersections. Hamilton [13] defined three states of yarn cross-sectional deformation as shown in Figure 25. As for the values of free diameter mechanical measurement methods are more suitable. The racetrack section and constant perimeter deformation model may be realistic approaches.

In researches on mechanical behaviour of fabrics the effect of yarn diameter in jamming conditions presents a serious problem. Experimental data show that compression ratios of 0.5 to 0.4 can be observed depending on yarn density and pressure level. Constant rate of extension fabric strength test of plain woven fabrics was simulated by assuming a 50 % compression at extreme levels of extension by Yildirim and Baser [21].

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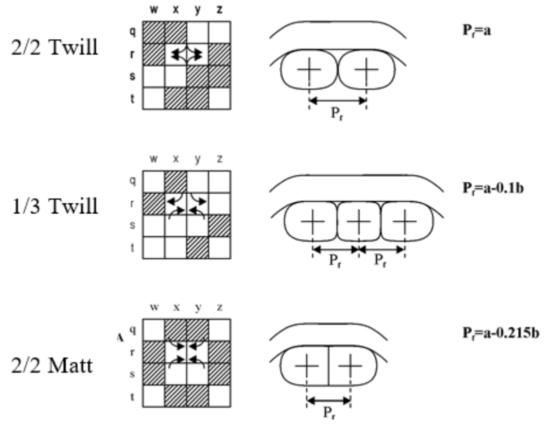

Figure 25. Models of yarn compression

In practice of woven fabric design and preparation of weaving production orders the conventional methods by using setting theories and making use of past production data may be adequate. The various setting theories are based on the limit number of yarn diameters that can be placed in unit area of the fabric and may be expressed by a general formula given as

$$S = kF_w K_m V\sqrt{Nm} \text{ per cm} \quad (34)$$

$$S = kF_w K_e V\sqrt{Ne} \text{ per inch} \quad (35)$$

where S is the number of yarns in finished fabric, K_m, K_e are yarn constants, V is firmness factor to adjust fabric tightness, F_w is weave factor which characterizes weave effect and k is the crimp factor . In diameter-intersection theories such as that of Ashenhurst [1] can be evaluated by the weave intersections in unit weave as

$$F_w = \frac{i}{i+w} \quad (36)$$

where i is the number of intersections and w is the number of yarns in unit weave. Figure 26 shows how weave factor can be evaluated. Brierley [11] proposed an empirical formula based on experimental data given as

$$\log S = \log a + m\log F \quad (37)$$

In metric system this formula is equivalent to

$$S = F^m K\sqrt{N} \quad (38)$$

where S is yarn density in loom state fabric, F is average float length in unit weave and m is a constant depending on weave type. In metric system the weave constant m is given as 0.39 for twill weaves, 0.42 for sateen weaves, 0.45 for plain and matt weaves [22]. Baser [22] showed how a woven fabric can be designed to apply setting theories using computer aid to satisfy design objectives.

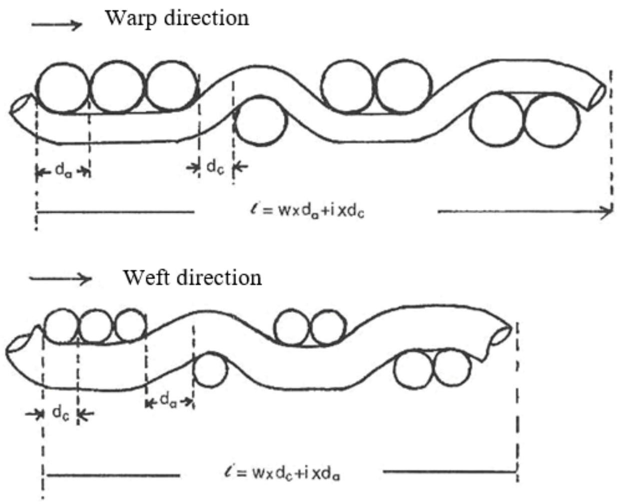

Figure 26. Evaluation of the weave factor in diameter-intersection theories

In complex woven fabrics such as carpets and velvets fabric geometrical models may be developed to calculate consumption of each yarn type and to investigate the construction that allows the required pile density. Baser, Kirtay and Onder [23] carried out research on these topics based on geometric models of carpets developed by Baser. The geometrical model of Axminster Kardax carpet structure is shown in Figure 27.

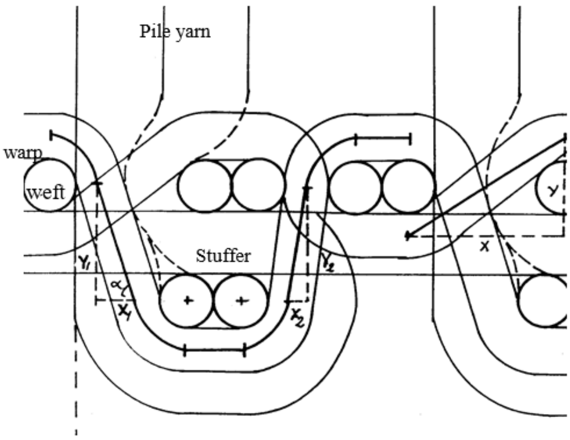

Figure 27. Geometric model of Axminster Kardax carpet

Here for pile yarns compressed between two weft couples a compression ratio of 0.40 was assumed since the pile yarn is usually selected as coarse woollen yarn. Satisfactory results were obtained by theoretical results when compared with experimental values obtained on carpet samples analysed.

In knitted fabrics Pierce [2] introduced the term "normally knitted structure" which has maximum amount of yarn without jamming which was based on Doyle' original model. In Peirce's model shown in Figure 28 loop tops touch each other in wale direction and loop legs in course direction. The loop length is thus calculated as $l = 16.66d$ in terms of yarn diameter. A shape factor is also calculated to be 1.2 as the ratio of loop height to loop width.

A more realistic plain knitted fabric geometry is shown in Figure 29.

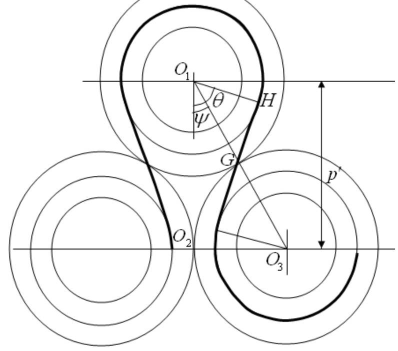

Figure 28. Peirce's plain knitted fabric geometry

Considering that the yarn loop is a curve of elastica deformed by parallel and opposite forces at interlacing points Munden [24] first proposed empirical formulae for loop shape based on experimental data as

$$c = \frac{k_c}{l},\; w = \frac{k_w}{l},\; S = \frac{k_s}{l^2},\; R = \frac{k_c}{k_w},\; k_s = k_c k_w \qquad (38)$$

where kc = 5.0 ± 0.2, kw = 3.8 ±0.1, $k_s = 19.0 \pm 1.0$, and $R = 1.30 \pm 0.05$.

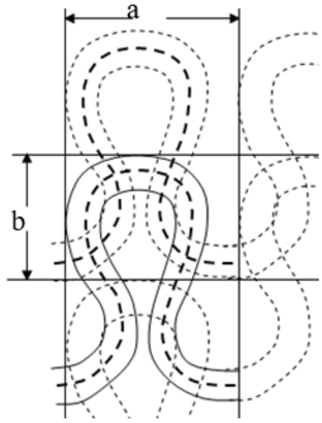

Figure 29. Plain knitted fabric geometry

The cover obtained in terms of d/l in practice is 1.25. In British system of units, it can be expressed as

$$g = \frac{Kd}{l} = \frac{1}{l\sqrt{N}} = 1.25, \quad K = 28 \qquad (39)$$

From the above values the loop length can be calculated as $l = 22.4d$. For worsted yarns and using worsted count system K=22.8. In this case, the loop length will be $l = 18.2d$. Thus, these values can be used in the design of relaxed knitted fabrics of medium tightness.

The geometry of knitted structures has, in fact, to be considered in three dimensions because of intersection of yarns to occur both in planar and in depth or thickness direction. Changes in yarn diameter are observed in knitted fabrics in relaxed state as well as in extension in course or wale direction.

In rib structures the yarn path in thickness direction is important as it affects loop length appreciably. Kurbak [25] developed the geometry for 1X1 rib structure based on the criticism of Smirfitt' s [26] model in which the wale loops did not touch contact with each other and revised the new model later in 2009 as shown in its geometric simulation given in Figure 30. Kurbak [27] argues that changes in yarn diameter are observed as flattening and sometimes as increasing depending on processing conditions. This is illustrated in Figure 31.

Kurbak [27] gives values of the constants k_c and k_w for 1x1 rib fabrics knitted from worsted, acrylic and cotton yarns in Table 10.

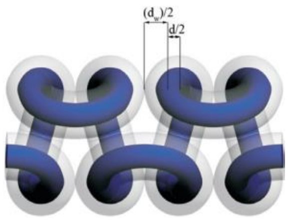

Figure 30. Simulation of 1x1 rib structure in dry and washing relaxation conditions [27]

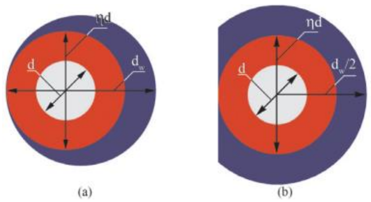

Figure 31. Two different model of yarn cross-section (a) Eccentric model, (b) Semi-circular model

Table 10. k_c and k_w for 1x1 rib fabrics

k	Relaxation method	Wool	Acrylic	Cotton
k_c	Dry Wet Washing	3.70 4.15 5.92	3.64 3.94 4.02	2.97 4.33 5.00
k_w	Dry Wet Washing	4.57 3.11 3.67	2.90 2.71 2.84	2.84 3.49 2.14

In fabrics subjected to washing relaxation Kurbak proposed the formula

$$a = w/4 + \eta d/2 \qquad (40)$$

which also allows for diameter increase in course direction at all tightnes levels. Here a is the width of loop top, μ is a constant 1 for medium tightness. When the yarn assumes the cross sectional shape the diameter increase in course direction is given as

$$d_w = 2(w/2 - a) \qquad (41)$$

and for very slack fabrics a value is proposed that includes the maximum value of the diameter as

$$a = w/2 - d_{w(\max)}/2 \qquad (42)$$

For $l/d = 22.5$ a value of $d_{w(\max)} = 1.68d$ is faund. Kurbak argues that in the jamming of loops in course direction yarn diameter increases in thickness direction.

4 DISCUSSION AND CONCLUSIONS

It will be appreciated that yarn diameter is a crucial parameter in fabric formation and fabric performance as well as in fabric design work. There have been quite reliable methods developed for its measurement but these methods do not give same results because of the inherent differences in measuring principles. Thus different definitions of yarn diameter have been made and used depending on the aim of the intended research or application.

The yarn diameter under compressive forces is to be examined separately and taken into account in theoretical and practical applications. The relationship between applied vertical force and the resultant change in yarn cross sectional shape have been studied both theoretically and experimentally in many ways and relevant methods of calculation and experimental data are available. It has been explained above how yarn compression is taken into account in fabric design practice. A comprehensive and computer aided woven fabric design method, which takes account the implications of yarn diameter and weave structure, is introduced by Baser [22].

In theoretical analyses of fabric performance such as fabric extension and bending, or of more complex problems like fabric drape and three dimensional deformations, compression in directions other than vertical may occur. Moreover, yarns in fabric structure may not always act as point forces. The case where yarn is subjected to a combination of tension, bending and compression and to distributed load was studied by Goktepe, Lawrence and Leaf [28]. It seems to be possible to carry out such comprehensive theoretical analyses taking into account changes in yarn cross sectional shape, but their practical use should be well considered. Making an assumption for a reasonable compression ratio and a simple cross sectional shape model may facilitate the theoretical analyses and may provide meaningful results that will throw light to practical problems.

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