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Faculty of textile engineering

Habilitation work

Modeling of 2D & 3D woven fabric structure and properties

Submitted

by

Rajesh Mishra,B.Tech,PhD

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Annotation

The habilitation work is based on our publications in the field of modeling 2D and 3D structures of woven fabrics and characterization of their properties. The list of publications shows the different approaches involved in achieving the objectives of understanding structure property relationship in woven fabrics.

Areas of research interest as observed from the publications can be summarized as below:

1. Modeling of woven fabric structure and properties
2. Mechanics of woven structures
3. 3D weaving for composite applications
4. Characterization of woven nano-composites
5. Objective quality evaluation in textile materials

The main focus of habilitaion work is design and development of 2D as well as 3D woven structures for clothing and technical applications. Fabric properties are greatly affected by the choice of fabric parameters. The choice of fabric parameters influences the structure. The behaviour and relationship between the fabric parameters is a precursor to the optimal solution for fabric engineering problems. Many features of the cloth are essentially dependent on the geometrical relationships. The geometrical model of fabric provides some simplified formulae to facilitate calculations and specific constants which are of value for cloth engineering, problems of structure and mechanical properties. These fabric parameters are tool for an innovative fabric designer in creating fabrics for diverse applications. The theoretical relationship between the fabric parameters enables the fabric designer to play with different fibers, yarn tex, threads/cm and weave to vary texture and fabric properties.

An attempt has been made to optimize engineering attributes of a plain weave fabric as per requirement. A simplified algorithm is used to solve fabric geometrical model equations and relationships between useful fabric parameters such as thread spacing and crimp, fabric cover and crimp, warp and weft cover are obtained. Such relationships help in guiding the direction for moderating fabric parameters. The full potential of Peirce fabric geometrical model for plain weave has been exploited by soft computing. The inter-relationships between different fabric parameters for jammed structures, non jammed structures and special case in which cross threads

are straight are obtained using suitable algorithm. It is hoped that the fabric designer will be benefited by the flexibility to choose fabric parameters for achieving any end use with desired fabric properties.

Maximum weavability limit is predicted by extending the Peirce's geometrical model for non-plain weaves for circular and racetrack cross-sections by soft computing. This information is helpful to the weavers in avoiding attempts to weave impossible constructions thus saving time and money. It also helps to anticipate difficulty of weaving and take necessary steps in warp preparations. The relationship between the cover factors in warp and weft direction is demonstrated for circular and racetrack cross-section for plain, twill, basket and satin weave. Non plain weave fabric affords further flexibility for increasing fabric mass and fabric cover. As such they enlarge scope of the fabric designer.

A simplified algorithm is used to solve fabric geometrical model equations and relationships between useful fabric parameters such as thread spacing and crimp, fabric cover and crimp, warp and weft cover. Such relationships help in guiding the direction for moderating fabric parameters. Soft computing can successfully provide a platform to manoeuvre crimp in warp and weft over a wide range with only three fabric parameters; yarn tex, modular length of warp and modular length of weft yarn. Soft computing has enabled solutions by interaction of crimp interchange and crimp balance equations. This exercise offers several solutions for fabric engineering by varying the above three parameters.

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To overcome the problems associated with the production and mechanical behavior of other kinds of composites, various methods have been used. These include the application of tough resin, interleafing, and chemical or plasma treatment of fibers in order to improve their adhesion strength with the resin. These methods, however, are superseded by the textile production of composites. This is probably due to the ability to produce large volumes of textile preforms in a short time thus reducing the manufacturing cost and the cycle times. There are currently a

number of ways used to produce 3 dimensional textiles. They can be produced through stitching, weaving, knitting, braiding and non-woven structures. Woven structures are, however the mostly produced due to ease of production and diversity of different 3-dimentional structures to produce.

The research work focuses on geometric and micro-mechanical modeling of 3D Orthogonal fabrics for composite applications and employs Meso-FE (Finite Element) modeling for it. Finite Element (FE) modeling of textile composites is a powerful tool for homogenisation of mechanical properties, study of stress–strain fields inside the unit cell, determination of damage initiation conditions and sites and simulation of damage development and associated deterioration of the homogenised mechanical properties of the composite. Meso-FE can be considered as a part of the micro-meso–macro-multi-level modeling process, with micro-models (fibers in the matrix) providing material properties for homogenised impregnated yarns and fibrous plies, and macro-model (structural analysis) using results of meso-homogenisation. The model is successful to simulate the tensile properties of orthogonal fabrics. The model can be improved by incorporating fiber to fiber friction through introducing appropriate linking elements. Other mechanical properties such a compressive strength, shear stress, and bending rigidity can be tested. Fabric with similar yarn characteristics and fabric parameters can be produced to validate the results. The spaces between the yarns can be filled with the elements with the properties of required matrix, in order to conduct tests on a unit cell of composite.

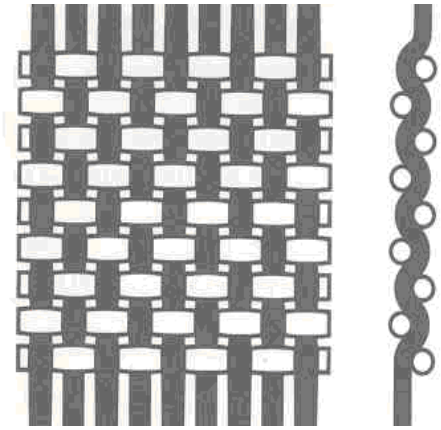
Chapter 1: Introduction

1.1 Fabric formation

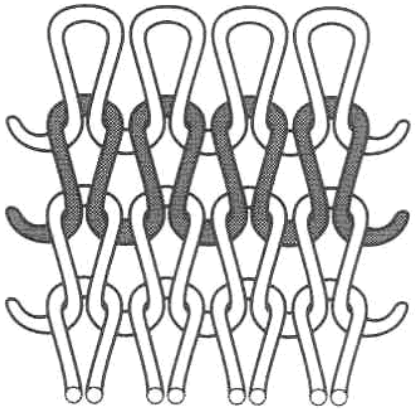
There are many ways of making fabrics from textile fibers [1]. The most common and most complex category comprises fabrics made from interlaced yarns. These are the traditional methods of manufacturing textiles. The great scope lies in choosing fibers with particular properties, arranging fibers in the yarn in several ways and organizing in multiple ways interlaced yarn within the fabric. This gives textile designer great freedom and variation for controlling and modifying the fabric. The most common form of interlacing is weaving, where two sets of threads cross and interweave with one another. The yarns are held in place due to the inter-yarn friction. Another form of interlacing where the thread in one set interlocks with the loops of neighboring thread by looping is called knitting. The interloping of yarns results in positive binding. Knitted fabrics are widely used in apparel, home furnishing and technical textiles. Lace, Crochet and different types of Net are other forms of interlaced yarn structures. Braiding is another way of thread interlacing for fabric formation. Braided fabric is formed by diagonal interlacing of yarns. Braided structures are mainly used for industrial composite materials.

Other forms of fabric manufacture use fibers or filaments laid down, without interlacing, in a web and bonded together mechanically or by using adhesive. The former are needle punched nonwovens and the latter spun bonded. The resulting fabric after bonding normally produces a flexible and porous structure. These find use mostly in industrial and disposable applications. Figure 1.1 shows the schematics of fabrics produced by the above discussed methods. All these fabrics are broadly used in three major applications such as apparel, home furnishing and industrial.

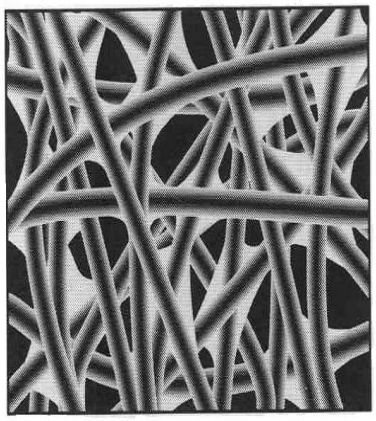
The traditional methods of weaving and hand weaving will remain supreme for high cost fabrics with a rich design content. The woven structures provide a combination of strength with flexibility. The flexibility at small strains is achieved by yarn crimp due to freedom of yarn movement, whereas at high strains the threads take the load together giving high strength.



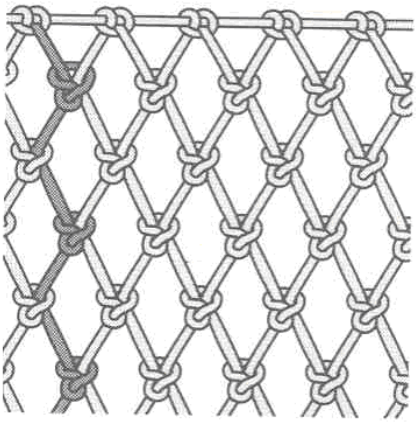
Woven structure



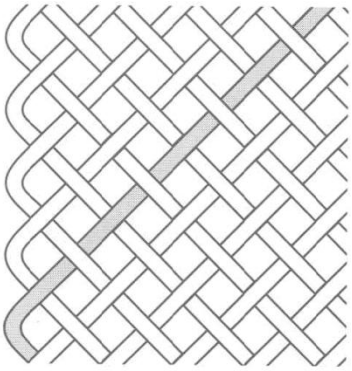
Knitted structure



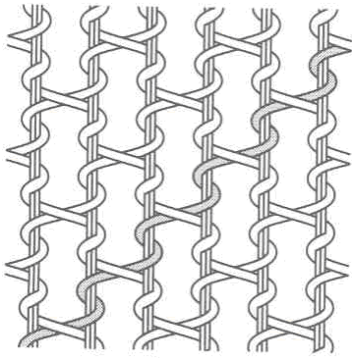
Nonwoven (Bonded)



Netting



Braided Structure



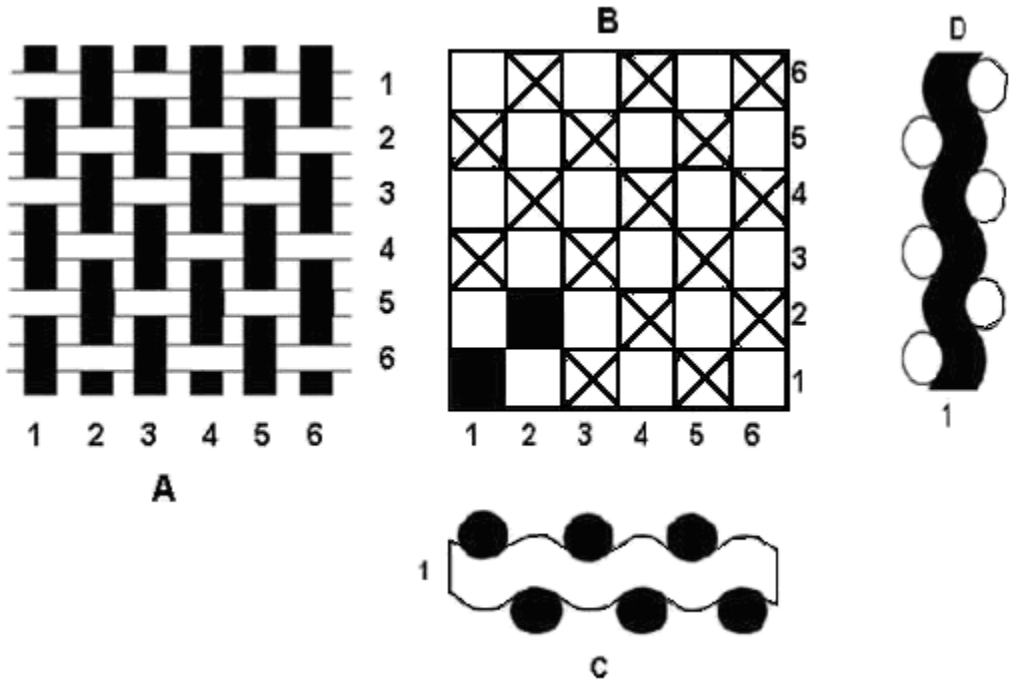
Lace

1.1 Fabric structures produced by different methods of fabric formation

1.2 Elements of fabric structure

A woven fabric is produced by interlacing two sets of yarns, the warp and the weft which are at right angles to each other in the plane of the cloth .The warp is along the length and the weft along the width of the fabric. Individual warp and weft yarns are called ends and picks. The interlacement of ends and picks with each other produces a coherent and stable structure. The repeating unit of interlacement is called the weave [2].

Plain weave has the simplest repeating unit of interlacement. It also has the maximum possible frequency of interlacements. Plain weave fabrics are firm and resist yarn slippage. Figure 1.2 shows plain weave in plan view and in cross-section along warp and weft. The weave representation is shown by a grid in which vertical lines represent warp and horizontal lines represent weft. Each square represents the crossing of an end and a pick. A mark in a square indicates that the end is over the pick at the corresponding place in the fabric that is warp up. A blank square indicates that the pick is over the end that is weft up. One repeat of the weave is indicated by filled squares and the rest by crosses. The plain weave repeats on two ends and two picks.

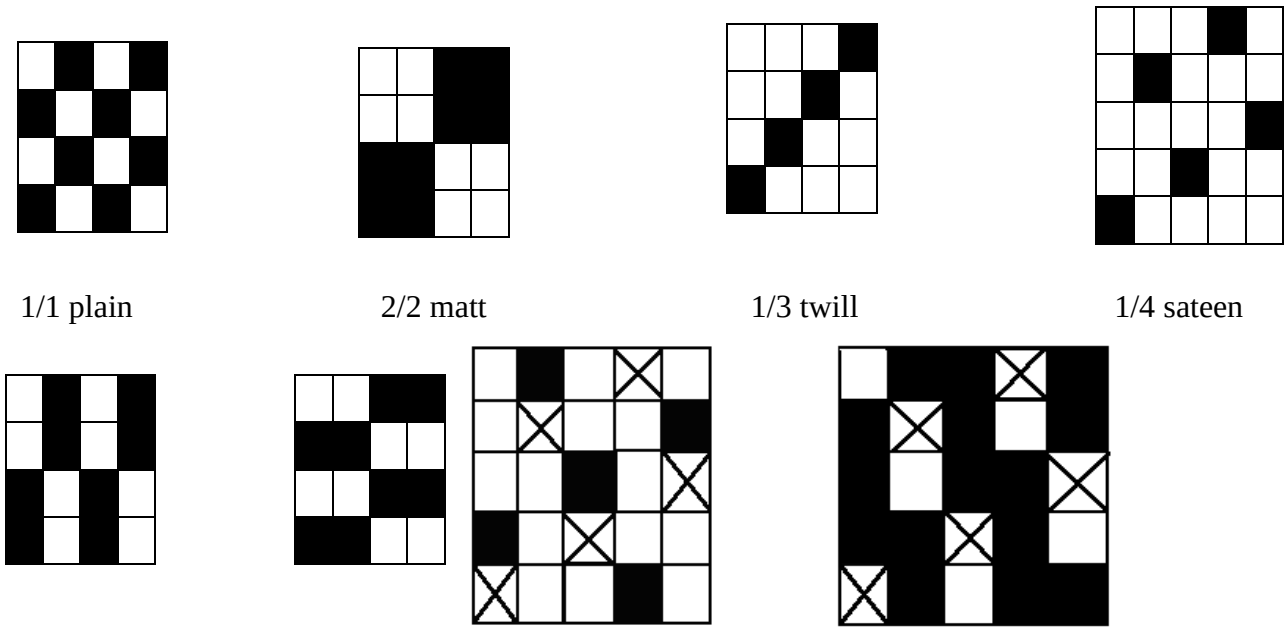


1.2 Plan (A), Weave representation (B), Cross-sectional view along weft (C), Cross-sectional view along warp (D) for plain weave

1.3 Regular and irregular weaves

1.3.1 Regular weaves

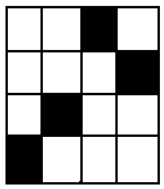
Regular weaves [3] give a uniform and specific appearance to the fabric. The properties of the fabric for such weaves can be easily predicted. Examples of some of the common regular weaves are given in figure 1.3.



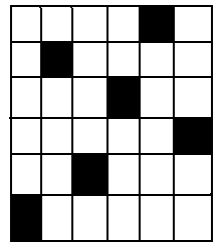
1.3 Regular weaves

1.3.2 Irregular weaves

Irregular weaves are commonly employed when the effect of interlacement is masked by the coloured yarn in the fabric. Such weaves are common in furnishing fabric. In such structures the prediction of mechanical properties is difficult. Examples of some of the common irregular weaves are given in figure 1.4.



4 end irregular sateen



6 end irregular sateen

1.4 Irregular weaves

1.4 Mathematical representation of different weaves

The firmness of a woven fabric depends on the density of threads and frequency of interlacements in a repeat. Fabrics made from different weaves cannot be compared easily with regard to their physical and mechanical properties unless the weave effect is normalized. The concept of average float has been in use since long, particularly for calculating maximum threads per cm. It is defined as the average ends per intersection in a unit repeat. Recently this ratio termed as weave factor [4,5] has been used to estimate tightness factor in fabric.

1.4.1 Weave factor

It is a number that accounts for the number of interlacements of warp and weft in a given repeat. It is also equal to average float and is expressed as:

$$M = \frac{E}{I} \qquad [1.1]$$

Where E is number of threads per repeat, I is number of intersections per repeat of the cross-thread.

The weave interlacing patterns of warp and weft yarns may be different. In such cases, weave factors are calculated separately with suffix1 and 2 for warp and weft respectively.

Therefore, $M_1 = \frac{E_1}{I_2}$; E_1 and I_2 can be found by observing individual pick in a repeat

and $M_2 = \frac{E_2}{I_1}$; E_2 and I_1 can be found by observing individual warp end in a repeat.

1.4.2 Calculation of weave factor

1.4.2.1 Regular weave

Plain weave is represented as $\frac{1}{1}$; for this weave, E_1 the number of ends per repeat is equal to 1+1=2 and I_2 the number of intersections per repeat of weft yarn =1+ number of changes from up to down (vice versa) =1+1=2.

Table 1 gives the value of warp and weft weave factors for some typical weaves.

Table 1: Weave factor for standard weaves

Weave	E_1	I_2	E_2	I_1	M_1	M_2
1/1 Plain	2	2	2	2	1	1
2/1 Twill	3	2	3	2	1.5	1.5
2/2 Warp Rib	2	2	4	2	1	2
2/2 Weft Rib	4	2	2	2	2	1

E_1 and E_2 are the threads in warp and weft direction

I_2 and I_1 are intersections for weft and warp threads

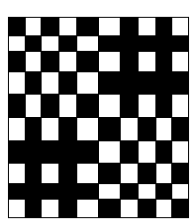
1.4.2.2 Irregular weave

In some weaves the number of intersections of each thread in the weave repeat is not equal. In such cases the weave factor is obtained as under:

$$M = \frac{\sum E}{\sum I} \qquad [1.2]$$

Using equation 1.2 the weave factors of a ten-end irregular huckaback weave shown in figure 1.5 is calculated below.

$$\text{Weave factor,} \quad M = \frac{10+10+10+10+10+10+10+10+10+10}{10+6+10+6+10+6+10+6+10+6} = \frac{100}{84} = 1.19$$



1.5 Ten-end Huck-a-back weave

Chapter 2: Geometrical model of woven structure

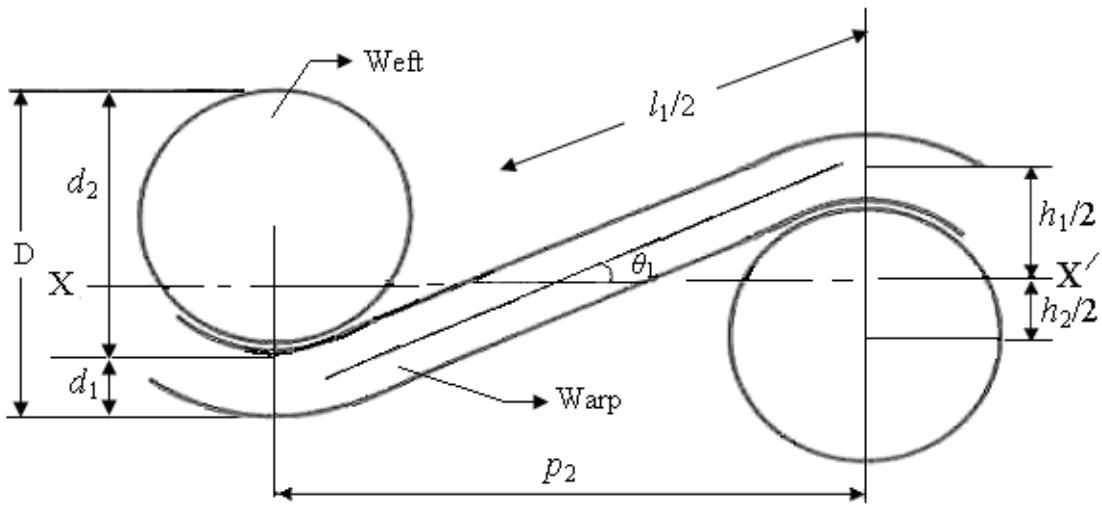
2.1 Woven structure

The properties of the fabric depend on the fabric structure. The formal structure of a woven fabric is defined by weave, thread density, crimp and yarn count. The interrelation between fabric parameters can be obtained by considering a geometrical model of the fabric. The model is not merely an exercise in mathematics. It is not only useful in determining the entire structure of a fabric from a few values given in technological terms but it also establishes a base for calculating various changes in fabric geometry when the fabric is subjected to known extensions in a given direction or known compressions or complete swelling in aqueous medium. It has been found useful for weaving of maximum sett structures and also in the analysis and interpretation of structure-property relationship of woven fabrics. Mathematical deductions obtained from simple geometrical form and physical characteristics of yarn combined together help in understanding various phenomena in fabrics.

2.2 Basic relationship between geometrical parameters

The geometrical model is mainly concerned with the shape taken up by the yarn in the warp or weft cross-section of the fabric. It helps to quantitatively describe the geometrical parameters. The basic model of Pierce's [6] analysis is shown in figure 2.1. It represents a unit cell interlacement in which the yarns are considered inextensible and flexible. The yarns have circular cross-section and consist of straight and curved segments. The main advantages in considering this simple geometry are:

(1) Helps to establish relationship between various geometrical parameters
(2) Able to calculate the resistance of the cloth to mechanical deformation such as initial extension, bending and shear in terms of the resistance to deformation of individual fibers.
(3) Provide information on the relative resistance of the cloth to the passage of air, water or light.
(4) Guide to the maximum density of yarn packing possible in the cloth.



2.1 Peirce model of plain weave

From the two-dimensional unit cell of a plain woven fabric, geometrical parameters such as thread-spacing, weave angle, crimp and fabric thickness are related by deriving a set of equations. The symbols used to denote these parameters are listed below.

d - diameter of thread

p - thread spacing

h - maximum displacement of thread axis normal to the plane of cloth (crimp height)

θ - angle of thread axis to the plane of cloth (weave angle in radians)

l - length of thread axis between the planes through the axes of consecutive cross- threads (modular length)

c - crimp (fractional)

$D = d_1 + d_2$

Suffix 1 and 2 to the above parameters represent warp and weft threads respectively.

In the above figure projection of yarn axis parallel and normal to the cloth plane gives the following equations:

$$c_1 = \frac{l_1}{p_2} - 1 \qquad [2.1]$$

$$p_2 = (l_1 - D\theta_1)\cos\theta_1 + D\sin\theta_1 \qquad [2.2]$$

$$h_1 = (l_1 - D\theta_1)\sin\theta_1 + D(1 - \cos\theta_1) \qquad [2.3]$$

Three similar equations are obtained for the weft direction by interchanging suffix from 1 to 2 or vice-versa as under:

$$c_2 = \frac{l_2}{p_1} - 1 \qquad [2.4]$$

$$p_1 = (l_2 - D\theta_2)\cos\theta_2 + D\sin\theta_2 \qquad [2.5]$$

$$h_2 = (l_2 - D\theta_2)\sin\theta_2 + D(1-\cos\theta_2) \qquad [2.6]$$

Also, $d_1 + d_2 = h_1 + h_2 = D$ [2.7]

In all there are seven equations connecting eleven variables. If any four variables are known then the equations can be solved and the remaining variables can be determined. Unfortunately, these equations are difficult to solve. Researchers have tried to solve these equations using various mathematical means to find new relationships and also some simplified useful equations.

2.3 Some derivatives

2.3.1 Relation between *p, h, θ* and *D*

From equations 2.2 and 2.3 we get:

$$(l_1 - D\theta_1) = \frac{p_2 - D\sin\theta_1}{\cos\theta_1} = \frac{h_1 - D(1-\cos\theta_1)}{\sin\theta_1}$$

or $D(\sec\theta_1 - 1) - p_2\tan\theta_1 + h_1 = 0$

substituti ng $x_1 = \frac{\tan\theta_1}{2}$

we get, $x_1^2\left(D - \frac{h_1}{2}\right) - p_2 x_1 + \frac{h_1}{2} = 0$

For real fabrics $x_1 = \frac{\tan\theta_1}{2} = p_2 - \frac{\sqrt{p_2^2 - 2h_1(D - \frac{h_1}{2})}}{2D - h_1} = \frac{p_2 - \sqrt{p_2^2 - h_2^2 - D^2}}{D + h_2}$

Using value of x_1, one can calculate θ, l and c and also other parameters.

Similarly, using equation 2.5 and 2.6, and by eliminating l and substituting x_1 as above, we will arrive at a more complex equation as:

$$\frac{c_1}{2} + x_1\frac{D}{p_2} - x_1^2\left(1 + \frac{c_1}{2}\right) = \frac{D}{p_2}(1 - x_1^2)\tan^{-1}x_1$$

It is difficult to solve this equation algebraically for x_1. However one can substitute value of x_1 obtained earlier to solve this equation just for an academic interest.

These seven equations have been solved by soft computing in order to establish several useful relationships in chapter 3. However, at this stage, one can generalize the relationship as:

$$h_1 = f(p_2, c_1)$$

This function *f* can be obtained by plotting *p* and *h* for different values of *c*.

2.3.2 Functional relationship between *p, h, c*

Trigonometric expansion of equations 2.2 and 2.3 gives:

$$p_2 = l_1 - \frac{l_1\theta_1^2}{2} + \frac{D\theta_1^3}{3} + \frac{l_1\theta_1^4}{24} + ----$$

$$h_1 = l_1\theta_1 - \frac{D\theta_1^2}{2} - \frac{l_1\theta_1^3}{6} + \frac{D\theta_1^4}{8} + ----$$

When θ is small, higher power of θ can be neglected which gives:

$$h_1 = l_1\theta_1,\ p_2 = l_1,\ c_2 = \frac{\theta_1^2}{2},\ \mathrm{h}_1 = p_2\sqrt{2c_1}$$

and these equations reduce to:

$$\theta_1 = \left(c_1\right)^{\frac{1}{2}} \qquad [2.8]$$

$$\theta_2 = \left(c_2\right)^{\frac{1}{2}} \qquad [2.9]$$

$$h_1 = \frac{4}{3}p_2\sqrt{c_1} \qquad [2.10]$$

$$h_2 = \frac{4}{3}p_1\sqrt{c_2} \qquad [2.11]$$

These four equations are not new equations in this exercise. They are derived from the previous seven original equations. However they give simple and direct relationships between four fabric parameters *h, p, c* and θ.

2.3.3 Jammed structures

A woven fabric in which warp and weft yarns do not have mobility within the structure as they are in intimate contact with each other are called jammed structures. In such a structure the warp

and weft yarns will have minimum thread spacing. These are closely woven fabrics and find applications in wind-proof, water-proof and bullet-proof requirements.

During jamming the straight portion of the intersecting yarn in figure 2.1 will vanish so that in equation 2.2 and 2.3, $l_1 - D\theta_1 = 0$

$$\frac{l_1}{D} = \theta_1$$

Equations 2.2 and 2.3 will reduce to

$$h_1 = D(1 - \cos\theta_1)$$

$$p_2 = D\sin\theta_1$$

Similarly, for jamming in the weft direction $l_2 - D\theta_2 = 0$, equations 2.7 and 2.8 will reduce to the above equations with suffix interchanged from 1 to 2 and vice-versa.

For a fabric being jammed in both directions we have:

$$D = h_1 + h_2 = D(1 - \cos\theta_1) + D(1 - \cos\theta_2)$$

or $\cos\theta_1 + \cos\theta_2 = 1$ [2.12]

$$\sqrt{1 - \left(\frac{p_1}{D}\right)^2} + \sqrt{1 - \left(\frac{p_2}{D}\right)^2} = 1 \qquad [2.13]$$

This is an equation relating warp and weft spacing of a most closely woven fabric.

2.3.4 Cross threads pulled straight

If the weft yarn is pulled straight $h_2 = 0$ and $h_1 = D$,

Equation 2.3 will give $D = (l_1 - D\theta_1)\sin\theta_1 + D(1 - \cos\theta_1)$

$$\cos\theta_1 = \left(\frac{l_1}{D} - \theta_1\right)\sin\theta_1$$

or $\theta_1 + \cot\theta_1 = \dfrac{l_1}{D}$ [2.14]

This equation gives maximum value of θ_1 for a given value of l_1/D

The above equation will be valid for warp yarn being straight by interchange of suffix from 1 to 2.

However, the weft thread can be restricted in being pulled straight by the jamming of warp threads.

In such a case,

$$l_1 - D\theta_1 = 0$$

or $\theta_1 = \dfrac{l_1}{D}$

Equation 2.3 will become

$$h_2 = D - h_1 = D - D(1 - \cos\theta_1) = D\cos\frac{l_1}{D} \qquad [2.15]$$

If the weft thread is pulled straight and warp is just jammed

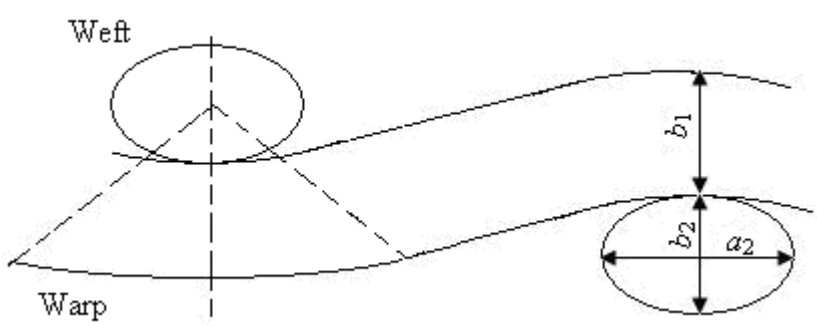
Then $\dfrac{l_1}{D} = \theta_1 = \dfrac{\pi}{2}$ [2.16]

These are useful conditions for special fabric structure.

2.3.5 Non circular cross-section

So far, it is assumed that yarn cross-section is circular and yarn is incompressible. However, the actual cross-section of yarn in fabric is far from circular due to the system of forces acting between the warp and weft yarns after weaving and the yarn can never be incompressible. This inter-yarn pressure results in considerable yarn flattening normal to the plane of the cloth even in a highly twisted yarn. Therefore many researchers have tried to correct Peirce's original relationship by assuming various shapes for the cross-section of yarn. Two important cross-sectional shapes such as elliptical and race-track are discussed below.

2.3.6 Elliptical cross-section



2.2 Elliptical cross-section

Peirce elliptical yarn cross-section is shown in figure 2.2; the flattening factor is defined as

$$e = \sqrt{\frac{b}{a}}$$

Where b = minor axis of ellipse, a = major axis of ellipse

The area of ellipse is $(\pi/4)ab$. If d is assumed as the diameter of the equivalent circular cross–section yarn, then $d = \sqrt{ab}$

$$h_1 + h_2 = d_1 + d_2 = b_1 + b_2$$

$$b_1 + b_1 = h_1 + h_2 = \frac{4}{3}\left(p_1\sqrt{c_2} + p_2\sqrt{c_1}\right) \qquad [2.17]$$

Yarn diameter is given by its specific volume, v and yarn count as under:

$$d_{\text{mils}} = 34.14\frac{\sqrt{v}}{\sqrt{N}}$$, N is the English count.

$$d_{\text{cm}} = \frac{\sqrt{\text{Tex}}}{280.2\sqrt{\phi\rho_{\text{f}}}} = \frac{\sqrt{\text{Tex}}}{280}, \quad \text{assuming } \phi = 0.65, \rho_{\text{f}} = 1.52 \text{ for cotton fibre}$$

This can be used to relate yarn diameter and crimp height by simply substituting in equation 2.17 to obtain:

$$h_1 + h_2 = d_1 + d_2 = D = 34.14\left(\sqrt{\frac{v_1}{N_1}} + \sqrt{\frac{v_2}{N_2}}\right) \qquad [2.18]$$

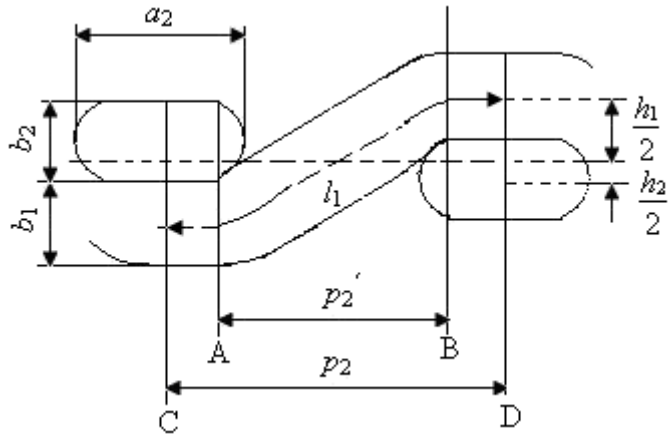
$$h_1 + h_2 = d_1 + d_2 = \frac{1}{280.2}\left(\sqrt{\frac{T_1}{\phi_1\rho_{\text{f}1}}} + \sqrt{\frac{T_2}{\phi_2\rho_{\text{f}2}}}\right) \qquad [2.19]$$

$$= \frac{1}{280}\left(\sqrt{T_1} + \sqrt{T_2}\right) \qquad [2.20]$$

assuming $\phi = 0.65, \rho_{\text{f}} = 1.52$ for cotton fibre

These are useful equation to be used subsequently in the crimp interchange derivation.

2.3.7 Race track cross-section



2.3 Race track cross-section

In race track model [7,8] given in figure 2.3, *a* and *b* are maximum and minimum diameters of the cross-section. The fabric parameters with superscript refer to the zone AB, which is analogous to the circular thread geometry; the parameters without superscript refer to the race track geometry, a repeat of this is between CD. Then the basic equations will be modified as under:

$$p_2^{'} = p_2 - (a_2 - b_2) \qquad [2.19]$$

$$l_1^{'} = l_1 - (a_2 - b_2) \qquad [2.20]$$

$$c_1^{'} = \frac{l_1^{'} - p_2^{'}}{p_2^{'}} = \frac{c_1 p_2}{p_2 - (a_2 - b_2)} \qquad [2.21]$$

Similarly,

$$c_2^{'} = \frac{c_2 p_1}{p_1 - (a_1 - b_1)} \qquad [2.22]$$

$$h_1 = \frac{4}{3} p_2^{'} \sqrt{c_1^{'}} \qquad [2.23]$$

$$h_2 = \frac{4}{3} p_1^{'} \sqrt{c_2^{'}} \qquad [2.24]$$

$$h_1 + h_2 = B = b_1 + b_2$$

And also if both warp and weft threads are jammed, the relationship becomes

$$\sqrt{B^2 - \left(b_1'\right)^2} + \sqrt{B^2 - \left(b_2'\right)^2} = B \qquad [2.25]$$

2.4 Prediction of fabric properties

Using the fabric parameters discussed in the previous section it is possible to calculate the *Fabric thickness, Fabric cover, Fabric mass and Fabric specific volume.*

2.4.1 Fabric thickness

Fabric thickness for a circular yarn cross-section is given by

h_1+d_1 *or* h_2+d_2, whichever is greater. [2.26]

When the two threads project equally, then $h_1+d_1 = h_2+d_2$

In this case the fabric gives *minimum thickness* $=1/2(h_1+d_1+ h_2+d_2) =D$; $h_1=D - d_1$

Such a fabric produces a smooth surface and ensures uniform abrasive wear.

In a fabric with coarse and fine threads in the two directions and by stretching the fine thread straight, maximum crimp is obtained for the coarse thread. In this case the fabric gives *maximum thickness* as under;

Maximum Thickness $=D + d_{\text{coarse}}$, since $h_{\text{coarse}} = \text{D}$

When yarn cross- section is flattened, the fabric thickness can be expressed as

h_1+b_1 or h_2+b_2, whichever is greater

2.4.2 Fabric cover

In fabric, cover is considered as fraction of the total fabric area covered by the component yarns. For a circular cross-section cover factor is given as:

$$\frac{d}{p} = \frac{E\sqrt{T}}{280.2\sqrt{\phi\rho_{\text{f}}}} = \frac{K}{28.02\sqrt{\phi\rho_{\text{f}}}}$$

$$K = E\sqrt{T} \times 10^{-1} \; K \text{ is cover factor}$$

T is yarn tex, E is threads per cm = $1/p$

suffix 1 and 2 will give warp and weft cover factors

for $\frac{d}{p} = 1$, cover factor is maximum and given by,

$$K_{max} = 28.02\sqrt{\phi\,\rho_f}$$

Fractional fabric cover is given by:

$$\frac{d_1}{p_1} + \frac{d_2}{p_2} - \frac{d_1 d_2}{p_1 p_2}$$

$$= \frac{1}{28.02}\left[K_1 + K_2 - \frac{K_1 K_2}{28.02}\right]$$

Multiplying by 28.02 and taking 28.02 ≈ 28 we get fabric cover factor as under:

$$\text{Fabric cover factor} = K_1 + K_2 - \frac{K_1 K_2}{28} \qquad [2.27]$$

For race track cross-section the equation will be

$$\frac{a}{p} = \frac{d}{e\,p\sqrt{1+\frac{4}{\pi}\left(\frac{1}{e}-1\right)} \times 28.02\sqrt{\phi\,\rho_f}} \quad \text{here } e = b/a$$

$$= \frac{K}{e\sqrt{1+\frac{4}{\pi}\left(\frac{1}{e}-1\right)} \times 28.02\sqrt{\phi\,\rho_f}} \qquad [2.28]$$

For elliptical cross-section the equation will be;

$$\frac{a}{p} = \frac{d}{e\,p} = \frac{E\sqrt{T}}{280.2\,e\,\sqrt{\phi\,\rho_f}} = \frac{K}{28.02\,e\sqrt{\phi\,\rho_f}} \qquad [2.29]$$

Here $e = \sqrt{\frac{b}{a}}$ and $d = \sqrt{ab}$

2.4.3 Fabric mass (Areal density)

$$\text{gsm} = [T_1E_1(1+c_1)+T_2E_2(1+c_2)]\times 10^{-1} \qquad [2.30]$$

$$\text{gsm} = \sqrt{T_1}\,[(1+c_1)\,K_1 + (1+c_2)\,K_2\beta] \qquad [2.31]$$

E_1, E_2 are ends and picks per cm.

T_1, T_2 are warp and weft yarn tex

Here K_1 and K_2 are the warp and weft cover factors, c is the fractional crimp and $d_2/d_1 = \beta$.

In practice the comparison between different fabrics is usually made in terms of gsm. The fabric engineer tries to optimize the fabric parameters for a given gsm. The relationship between the

important fabric parameters such as cloth cover and gsm is warranted. This is shown in figure 3.8 for jammed fabric.

2.4.4 Fabric specific volume

The apparent specific volume of fabric, v_F is calculated by using the following formula:

$$v_F = \frac{\text{fabric thickness (cm)}}{\text{fabric mass (g/cm}^2)} \qquad [3.6]$$

$$\text{Fabric mass (g/cm}^2) = 10^{-4} \times \text{gsm}$$

$$\text{Fabric packing factor}, \phi = \frac{v_f}{v_F} \qquad [3.7]$$

Here v_f, v_F are respectively fiber and fabric specific volume.

A knowledge of fiber specific volume helps in calculating the packing of fibers in the fabric. Such studies are useful in evaluating the fabric properties such as warmth, permeability to air or liquid.

2.5 Maximum cover and its importance

Maximum cover in a jammed fabric is only possible by keeping the two consecutive yarns (say warp) in two planes so that their projections are touching each other and the cross thread (weft) interlaces between them. In this case the weft will be almost straight and maximum bending will be done by the warp.

$$\frac{d_1}{p_1} = 1 \text{ will give } K_1 = K_{max}$$

and the spacing between the weft yarn

$p_2 = D \sin\theta_1 = D$ (for $\theta = 90^0$)

$p_2 = d_1 + d_2$

$$\frac{d_2}{p_2} = \frac{d_2}{d_1 + d_2} = \frac{2}{3} \quad \text{for } d_2 = 2d_1$$

This will give $K_2 = 2/3\ K_{max}$,

If $d_1 = d_2$ then $d_1 = d_2/p_2 = 0.5$ and $K_2 = 0.5\ K_{max}$

This is the logic for getting maximum cover in any fabric.

The principles are as under:

(1) Use fine yarn in the direction where maximum cover is desired and keep them in two planes so that their projections touch each other and use coarse yarn in the cross direction.

(2) As in (1) instead of coarse yarn insert two fine yarns in the same shed.

Both options will give maximum cover in warp and weft but first option will give more thickness than the second case.

The cover factor indicates the area covered by the projection of the thread. The ooziness of yarn, flattening in finishing and regularity further improves the cover of cloth. It also gives a basis of comparison of hardness, crimp, permeability, transparency. Higher cover factor can be obtained by the lateral compression of the threads. It is possible to get very high values only in one direction where threads have higher crimp. Fabrics differing in yarn counts and average yarn spacing can be compared based on the fabric cover. The degree of flattening for race track and elliptical cross-section can be estimated from fabric thickness measurements to evaluate *b* and *a* from microscopic measurement of the fabric surface.

The classical example in this case is that of a poplin cloth in which for warp threads

$p_1 = d_1$ and for $d_1 = d_2 = D/2$ and for jamming in both directions

$p_1 = D \sin \theta_2$

$d = D/2 = D \sin \theta_2$

$\theta_2 = 30^o = 0.5236$

$\theta_1 = 82^0 18' 1.4364 (\text{using } \cos\theta_1 + \cos\theta_2 = 1)$

$p_2 = D\sin\theta_1 = 0.991D \approx 2p_1$

$l_1 = D\theta_1 = 1.14364$

$l_2 = D\theta_2 = 0.5236$

$c_1' = 0.45$, $c_2' = 0.0472$

This is a specification of good quality poplin which has maximum cover and ends per cm is twice that of picks per cm.

Chapter 3: Application of geometrical model

3.1 Introduction

The actual behavior of fabric structure is not precisely calculable by geometry but many features of the cloth are essentially dependent on the geometrical relationships. These fabric parameters are a tool for an innovative fabric designer in creating fabrics for diverse applications. The theoretical relationship between fabric parameters enable the fabric designer to play with different fibers, yarn tex, threads per centimeter and weave to vary texture and fabric properties. The following applications can be made by using the parameters from the geometrical model:

(1) Obtain relationship between different fabric parameters and estimate fabric mass, gsm.

(2) Calculate maximum picks per centimeter of a cloth of low reed and when ends are cramped. As a guidance it helps in knowing the maximum weavability limit; maximum ends and picks which can be inserted for a given yarn and weave. The weaver avoids attempts to weave impossible constructions and also estimates the difficulty of weaving, yarn breakage rate and measures for appropriate yarn and weaving preparation.

(3) The limits to the stretch along warp or weft direction in the cloth and prediction of fabric dimensions, crimp and the changes in the fabric parameters.

(4) Prediction of crimp in the fabric, this has a marked influence on the fabric properties.

(5) Estimate cloth porosity to the passage of air, light, fluid and guide to the maximum density of packing that can be achieved.

(6) Prediction of fabric thickness and estimation of apparent fabric specific volume and porosity. This knowledge is useful for estimating fabric warmth, moisture absorption and flow and absorption of liquid.

(7) Prediction of fabric shrinkage.

The geometry provides simplified formulae to facilitate calculations and specific constants which are of value for cloth engineering, problems of structure and mechanical properties.

3.2 Computation of fabric parameters

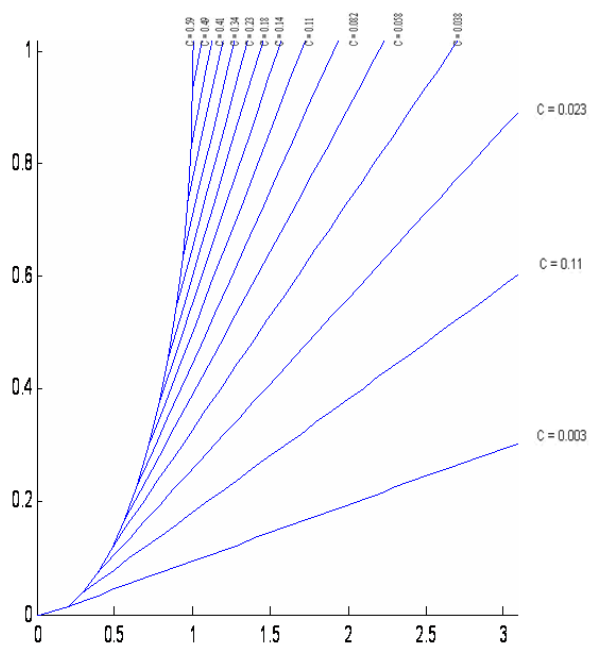
The basic equations derived from the geometrical model are not easy to handle. Research workers [9,10] obtained solutions in the form of graphs and tables. These are quite difficult to use in practice. It is possible to predict fabric parameters and their effect on the fabric properties by soft computing [11]. This information is helpful in taking a decision regarding specific buyers need. A simplified algorithm is used to solve these equations and obtain relationships between useful fabric parameters such as thread spacing and crimp, fabric cover and crimp, warp and weft cover. Such relationships help in guiding the directions for moderating fabric parameters.

Peirce's geometrical relationships can be written as

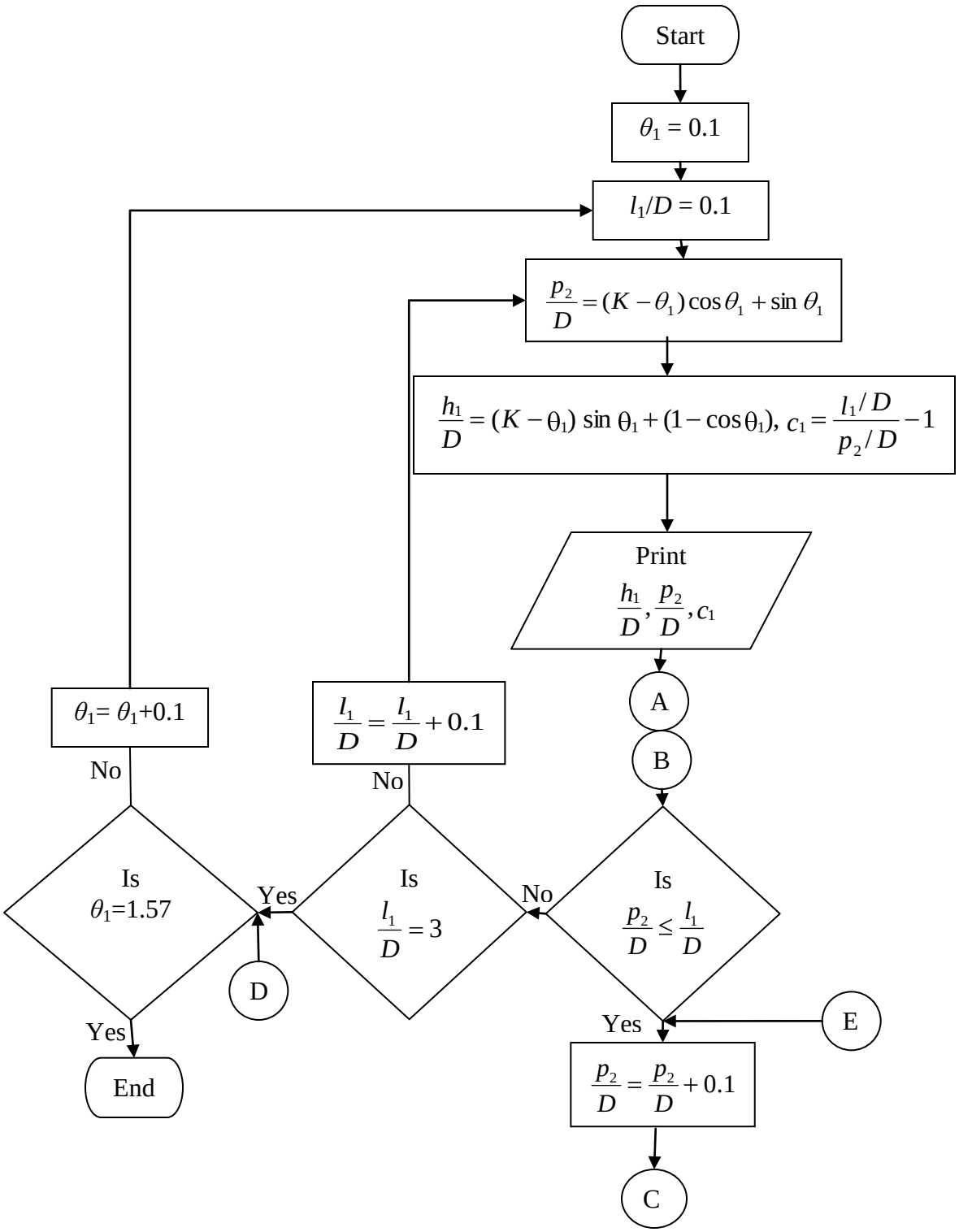
$$\frac{p_2}{D} = (\mathbf{K_1} - \theta_1)\cos\theta_1 + \sin\theta_1 \qquad [3.1]$$

$$\frac{h_1}{D} = (\mathbf{K_1} - \theta_1)\sin\theta_1 + (1 - \cos\theta_1) \qquad [3.2]$$

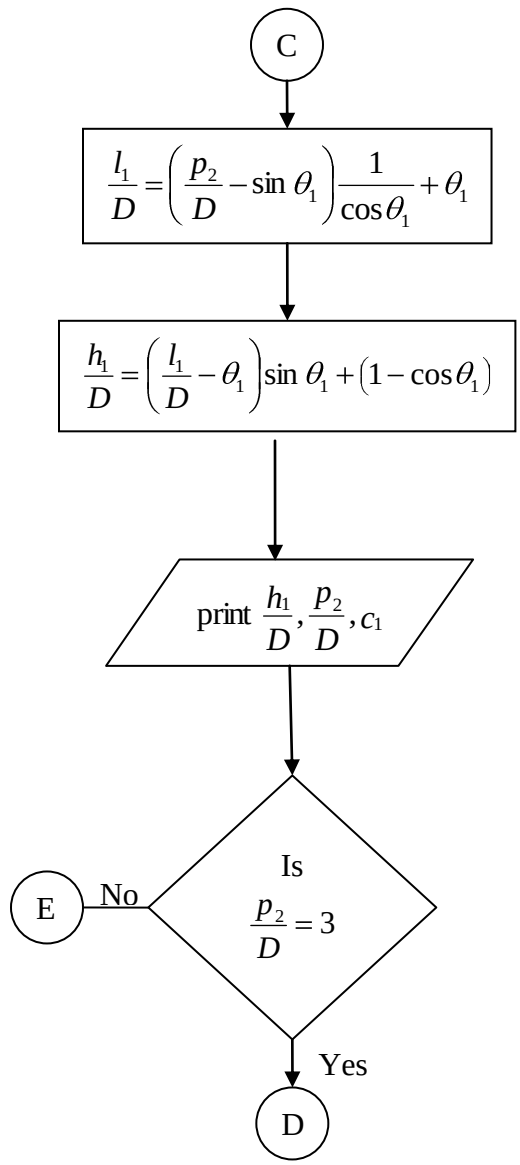
Where $\mathbf{K_1} = l_1/D$ and two similar equations for the weft direction will be obtained by interchanging the suffix 1 with 2 and vice versa. The solution of p_2/D and h_1/D is obtained for different values of θ_1 (weave angle) ranging from 0.1– π/2 radians. Such a relationship is shown in figure 3.1.



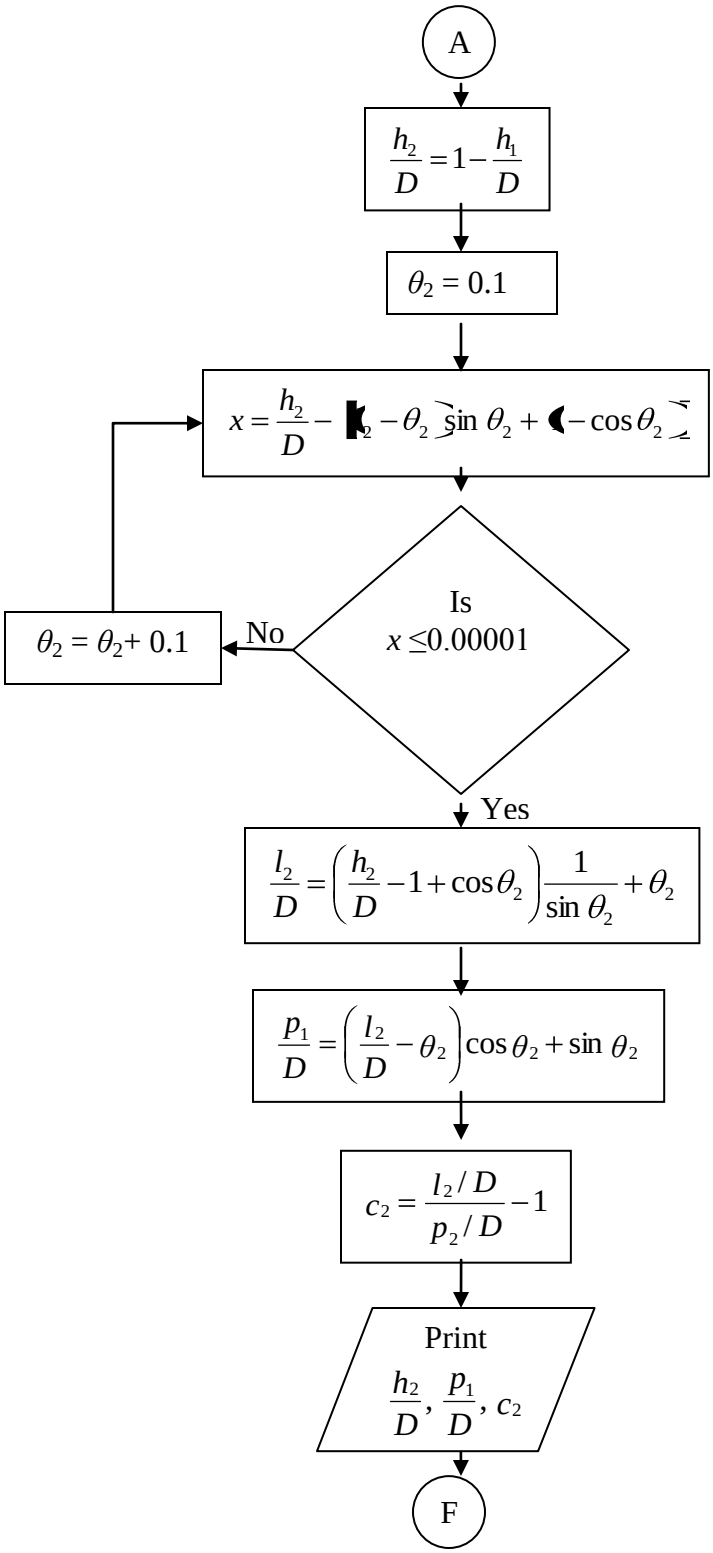
3.1 Relation between thread spacing and crimp height



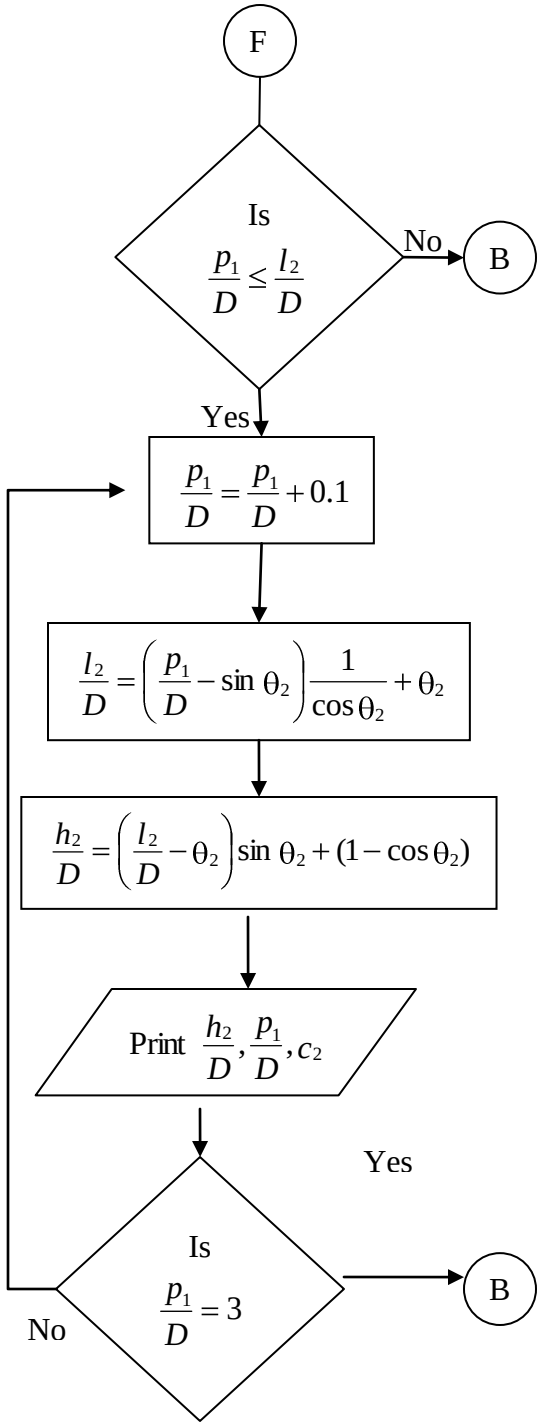
3.2 Flow chart for solving Peirce's seven equations



3.2a Module connector at C of figure 3.2



3.2b Module connector at A of figure 3.2



3.2c Module connector at F of figure 3.2b

The Flow chart for this algorithm is shown in figure 3.2 along with associated module connectors at figures 3.2a, 3.2b and 3.2c.

The figure 3.1 is similar to that given by Peirce [6]. It is a very useful relationship between fabric parameters for engineering desired fabric constructions. One can see its utility for the following three cases

(1) Jammed structures
(2) Non-jammed fabrics
(3) Special case in which cross-threads are straight

3.2.1 Jammed structures

Figure 3.1 shows non linear relationship between the two fabric parameters *p* and *h* on the extreme left. In fact, this curve is for jamming in the warp direction. It can be seen that the jamming curve shows different values of p_2/D for increasing h_1/D, that is warp crimp. The theoretical range for p_2/D and h_1/D varies from 0-1. Interestingly this curve is a part of circle and its equation is:

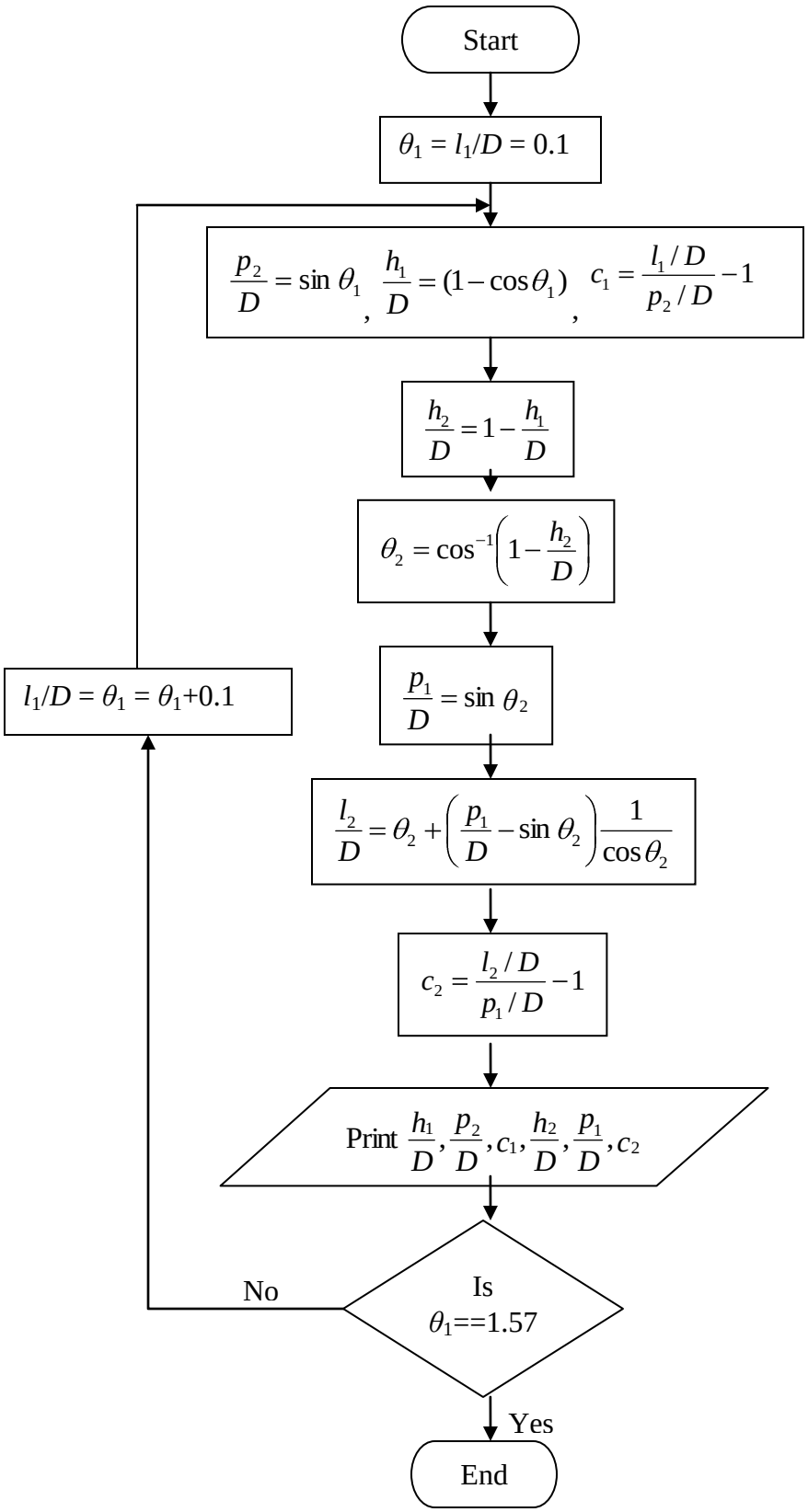
$$\left(\frac{p_2}{D}\right)^2 + \left(\frac{h_1}{D} - 1\right)^2 = 1 \qquad [3.3]$$

with centre at (0, 1) and radius equal to 1.

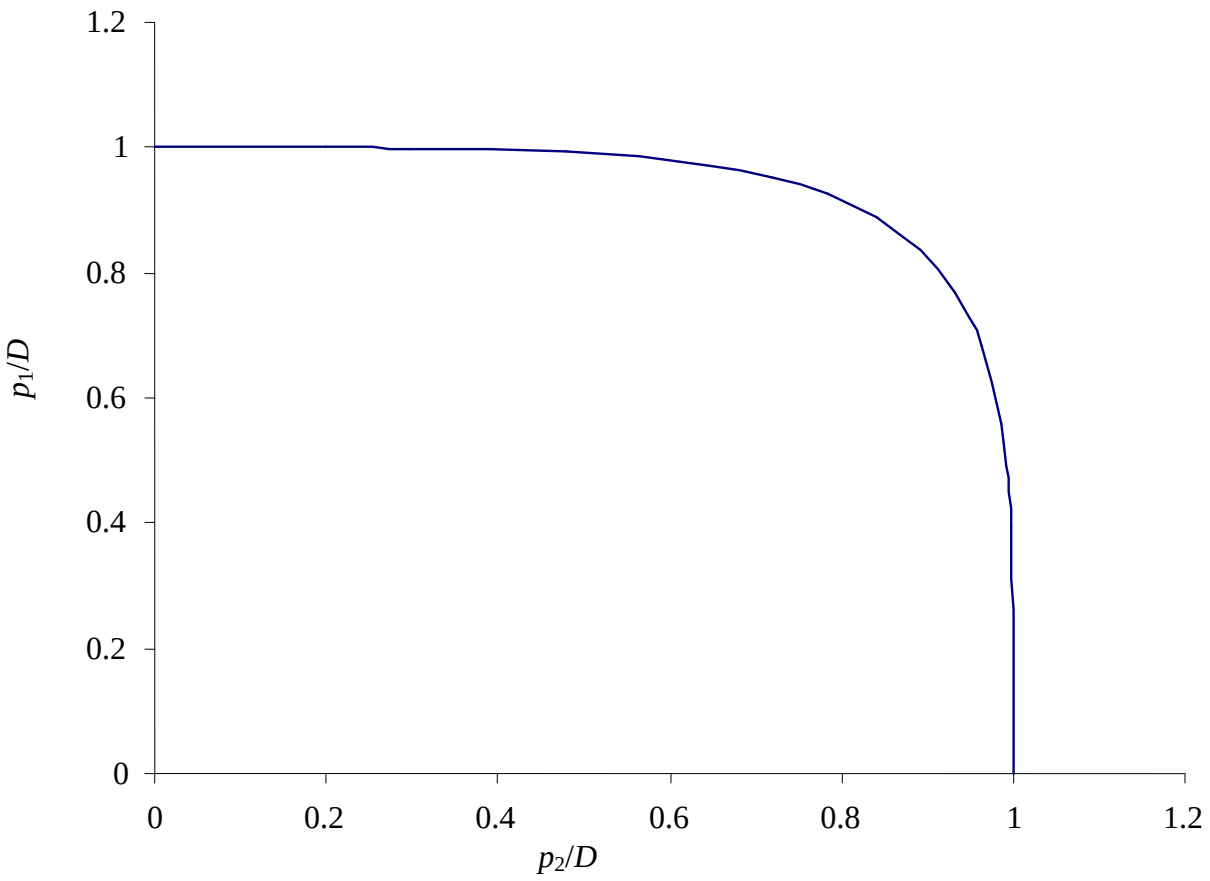
For jamming in the warp direction of the fabric the parameters p_2/D and corresponding h_1/D can be obtained either from this figure or from the above equation.

The relationship between the fabric parameters over the whole domain of structure being jammed in both directions can be obtained by using an algorithm involving equations from the previous section. The flow chart for this algorithm is given in figure 3.3.

From these computations the relationship between different useful fabric parameters are obtained and are shown in the Figures 3.4-3.8. Figure 3.4 gives the relationship between weft and warp thread spacing in a dimensionless form; that is between p_2/D and p_1/D. This figure shows that the relationship between these parameters is less sensitive at the two extreme ends. The relationship is sensitive in a *p/D* domain close to 1. In fact this sensitive range corresponds to maximum crimp in one direction only.



3.3 Flowchart for fabric parameters in jammed structures

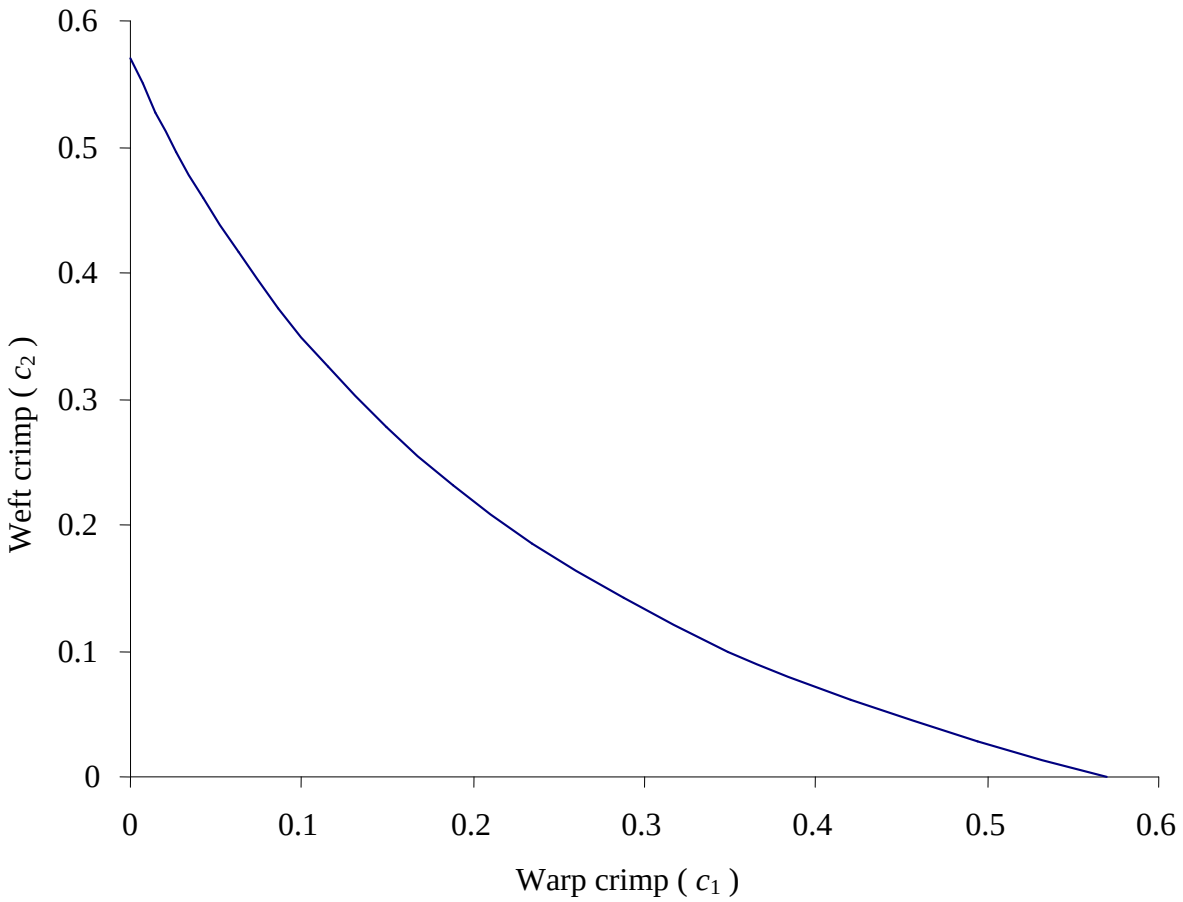


3.4 Relation between weft and warp thread spacing for jammed fabric

Another useful relationship between the crimps in the two directions is shown in figure 3.5. It indicates inverse non-linear relationship between c_1 and c_2. The intercepts on the X and Y axis gives maximum crimp values with zero crimp in the cross-direction. This is a fabric configuration in which cross-threads are straight and all the bending is being done by the intersecting threads.

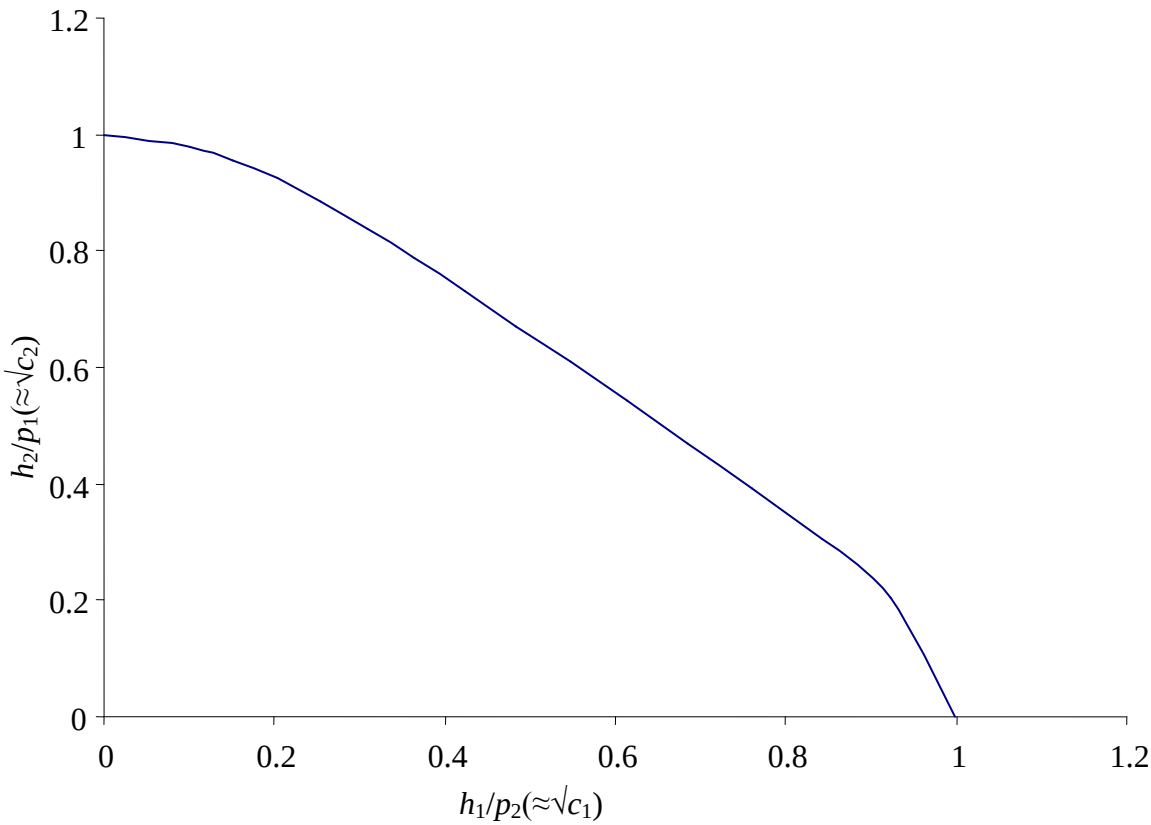
Figure 3.6 shows the relation between h_1/p_2 and h_2/p_1. The figure shows inverse linearity between them except at the two extremes. This behavior is in fact a relationship between the square root of crimp in the two directions of the fabric.

Other practical relations are obtained between the warp and weft cover factor and between cloth cover factor and fabric mass (gsm).

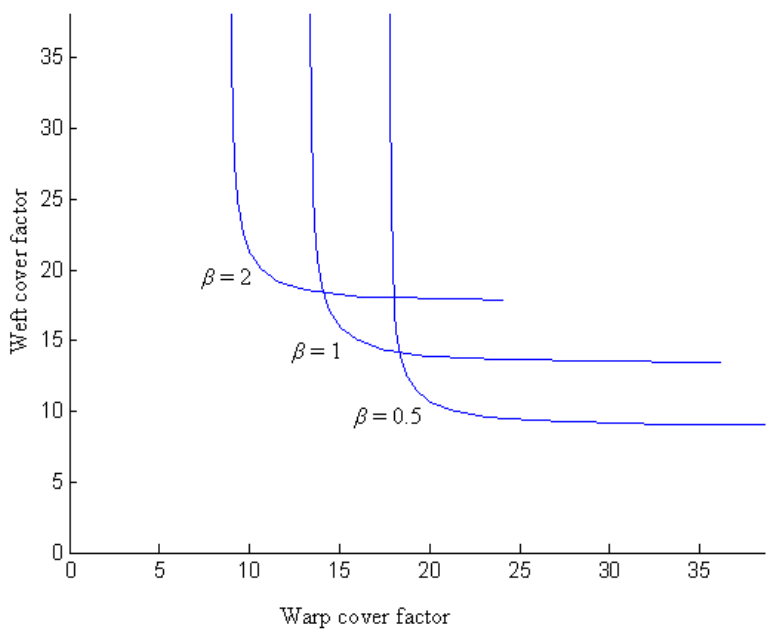


3.5 Relation between warp and weft crimp for jammed fabric

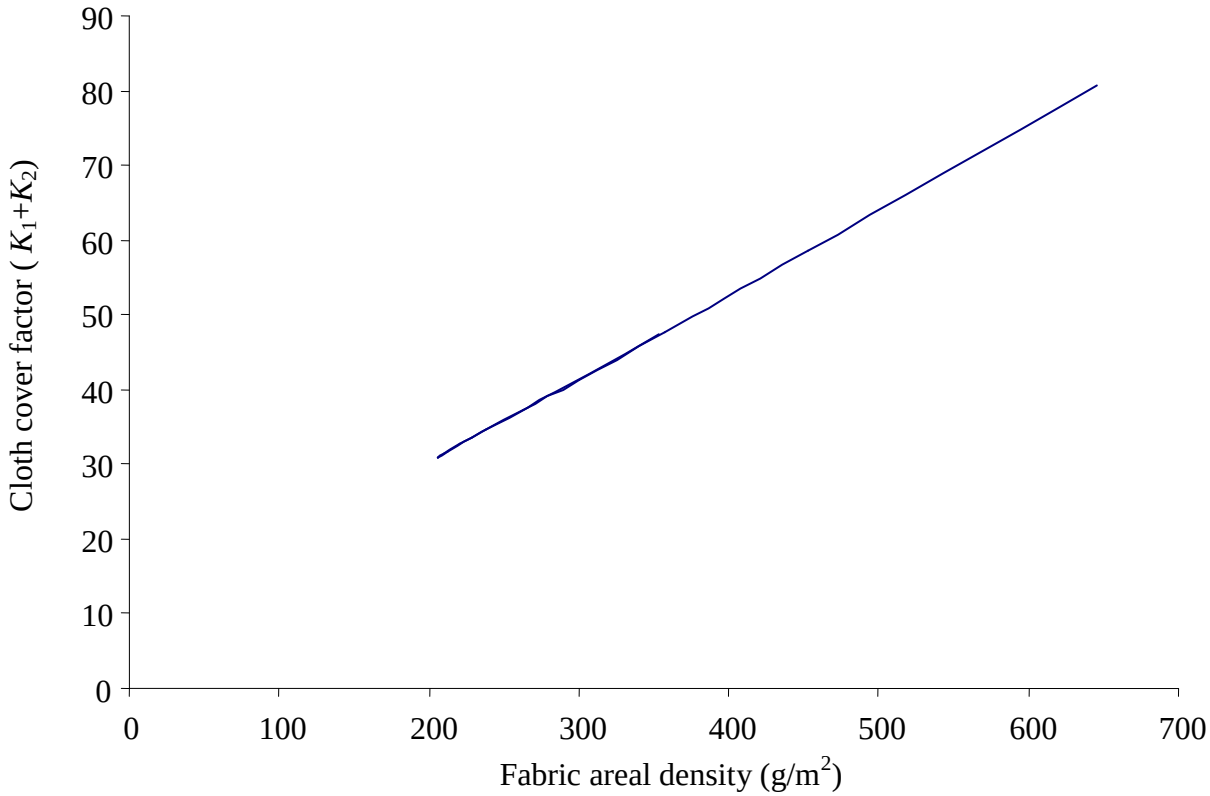
Figure 3.7 gives the relation between warp and weft cover factor for different ratio of weft to warp yarn diameters (β). The relation between the cover factors in the two directions is sensitive only in a narrow range for all values of β. The relation between the cover factors in the two directions are inter- dependent for jammed structures. Maximum threads in the warp or weft direction depend on yarn count and weave. Maximum threads in one direction of the fabric will give unique maximum threads in the cross-direction. The change in the value of β causes a distinct shift in the curve. A comparatively coarse yarn in one direction with respect to the other direction helps in increasing the cover factor. For β = 0.5, the warp yarn is coarser than the weft, this increases the warp cover factor and decrease the weft cover factor. This is due to the coarse yarn bending less than the fine yarn. Similar effect can be noticed for β =2, in which the weft yarn is coarser than the warp yarn. These results are similar to earlier work reported by Newton [11, 12], Seyam [13].



3.6 Relation between $\sqrt{c_1}$ and $\sqrt{c_2}$ for jammed fabric



3.7 Relation between warp and weft cover factor for different β in jammed fabric



3.8 Relation between fabric cover factor and fabric mass for jammed structure

The relation between fabric mass, (gsm) with the cloth cover (K_1+K_2) is positively linear as shown in the figure 3.8 [14]. The trend may appear to be self explanatory. Practically an increase in fabric mass and cloth cover factor for jammed fabrics can be achieved in several ways such as with zero crimp in the warp direction and maximum crimp in the weft direction; zero crimp in the weft direction and maximum crimp in the warp direction; equal or dissimilar crimp in both directions. This explanation can be understood by referring to the non-linear part of the curve in figure 3.1.

3.2.2 Non-jammed structure

It can be seen that the relation between p_2/D and corresponding h_1/D is linear for different values of crimp. This relationship is useful for engineering non-jammed structures for a range of values of crimp. The fabric parameters can be calculated from the above non-jammed linear relation between p_2/D and h_1/D for any desired value of warp crimp. Then h_2/D can be obtained from (1–h_1/D) and for this value of h_2/D one can obtain the corresponding value of p_1/D for the desired

values of weft crimp. Thus all fabric parameters can be obtained for desired value of p_2/D, picks per cm, warp and weft yarn tex, warp and weft crimp. One can choose any other four parameters to get all fabric parameters. The algorithm mentioned in figure 3.2 can be used to get several solutions for the non-jammed fabric.

3.2.3 Straight cross-threads

In the figure 3.1 the intersection of horizontal line corresponding to h_1/D=1 gives all possible structures ranging from relatively open to jammed configurations. In this case h_2= 0, h_1= D; This gives interesting structures which have stretch in one direction only, enabling maximum fabric thickness and also being able to use brittle yarns. The fabric designer gets the options to choose from the several possible fabric constructions. These options include jamming and other non jammed constructions. Using the above logic it is also possible to get fabric parameters for:

(1) fabric jammed in both directions.
(2) fabric with maximum crimp in one direction and cross-threads being straight.
(3) fabric which is neither jammed nor has zero crimp in the cross-threads.

3.3 Weavability limit

The maximum number of ends and picks per unit length that can be woven with a given yarn and weave defines weavability limit [15]. This information is helpful to the weavers in avoiding attempts to weave impossible constructions thus saving time and money. It also helps to anticipate difficulty of weaving and take necessary preparations. Dickson [16] demonstrated the usefulness of theoretical weavability limit and found agreement with the loom performance. Most of the work in this area was done using empirical relationships. The geometrical model is very useful in predicting this limit for a given warp, weft diameter (tex) and any weave. Maximum weavability limit is calculated in the model by using jamming conditions for plain and non-plain weaves for circular and race track cross-sections.

3.3.1 Yarn diameter

Two important geometrical parameters are needed for calculating weavability for a general case. These are yarn diameter and weave factor.

Yarn diameter in terms of linear density in tex for a general case is given as:

$$d = \frac{\sqrt{T}}{280.2\sqrt{\phi\,\rho_{\mathrm{f}}}} \qquad [3.4]$$

Where d = yarn diameter (cm), T = yarn linear density (tex, i.e. g/km),

ρ_{f} = fiber density(g/cm^3), ρ_{y} = yarn density(g/cm^3), ϕ = yarn packing factor

This equation for the yarn diameter is applicable for any yarn type and fiber type. The packing factor depends on fiber variables such as fiber crimp, length, tex and cross-section shape.

Table 2 and 3 give the fiber density and yarn packing factor for different fiber and yarn type respectively.

Table 2: Fiber Density, g/cm^3

Acetate	1.32
Cotton	1.52
Lycra	1.20
Nylon 6	1.14
Nylon 66	1.13-1.14
Polyester	1.38
Polypropylene	0.91
Rayon	1.52
Wool	1.32

Table 3: Yarn Packing Factor

Ring-spun	0.60
Open-end-spun	0.55
Worsted	0.60
Woolen	0.55
Continuous-filament	0.65

For blended yarns, average fiber density is given by the following

$$\frac{1}{\rho} = \sum_{1}^{n} \frac{p_i}{p_{ft}} \qquad [3.5]$$

where $\overline{\rho}$ = average fiber density ,

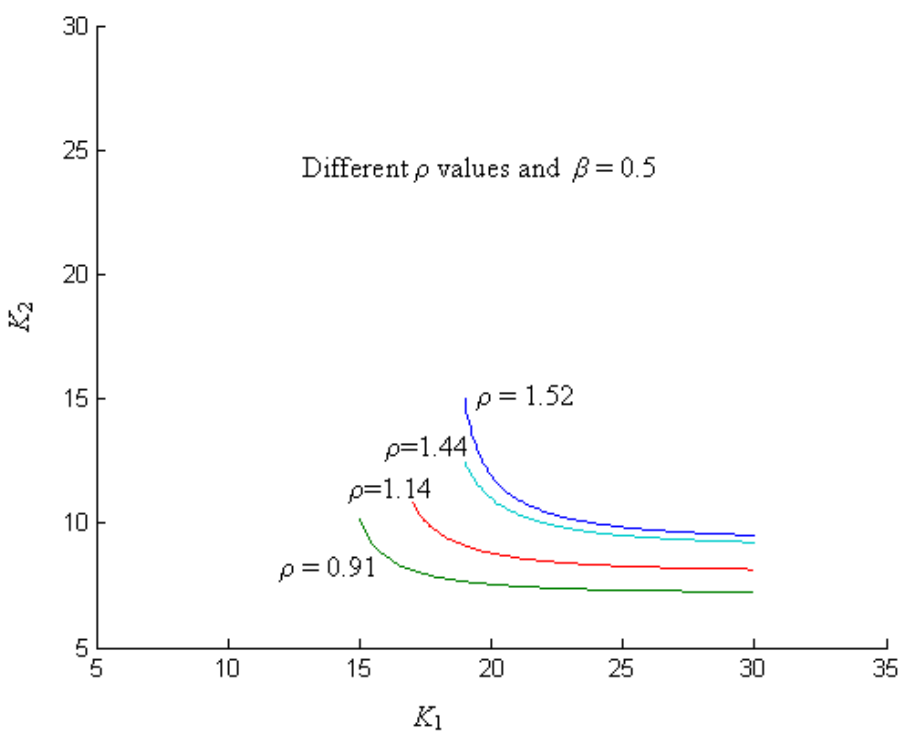
p_i = weight fraction of the ith component,

p_{ft} = fiber density of the ith component and

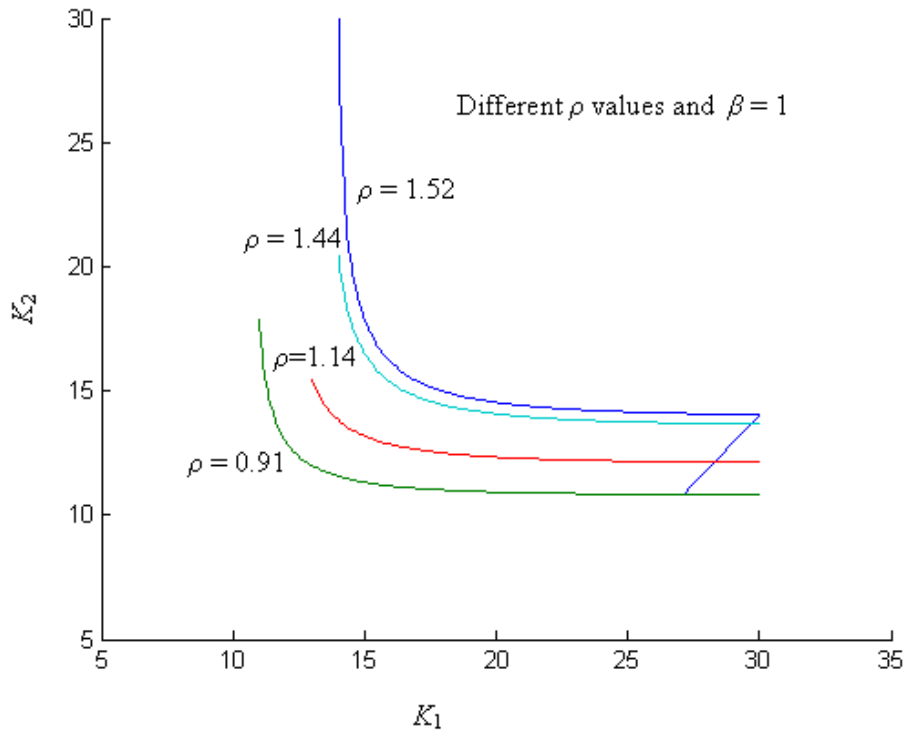
n = number of components of the blend

3.3.2 Effect of variation in fiber density on the relation between warp and weft cover factor for jammed fabrics

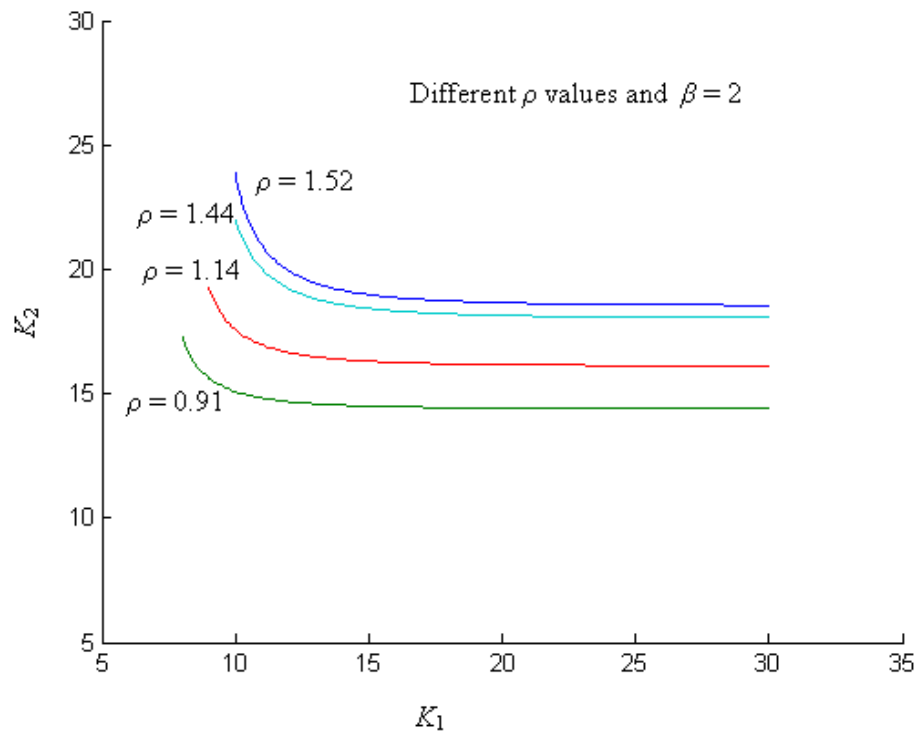
The change in the fiber density affects the relation between the warp and weft cover factors for jammed structures. It can be seen from the following three figures 3.9 a,b,c; with an increase in fiber density from 0.91-1.52 g/cm^3 the sensitivity in the relation between K_1 and K_2 increases. The base level and range of cover factor K_2 increases, the range of cover factor K_1 decreases but shifts to a higher level. Lower values of beta (d_2/d_1) show greater sensitivity in the relation between cover factors. It is a useful ploy to increase the range of cover factors in jammed structures and enables flexibility in designing jammed woven structures.



3.9a Effect of fiber density on the relation between warp and weft cover factor



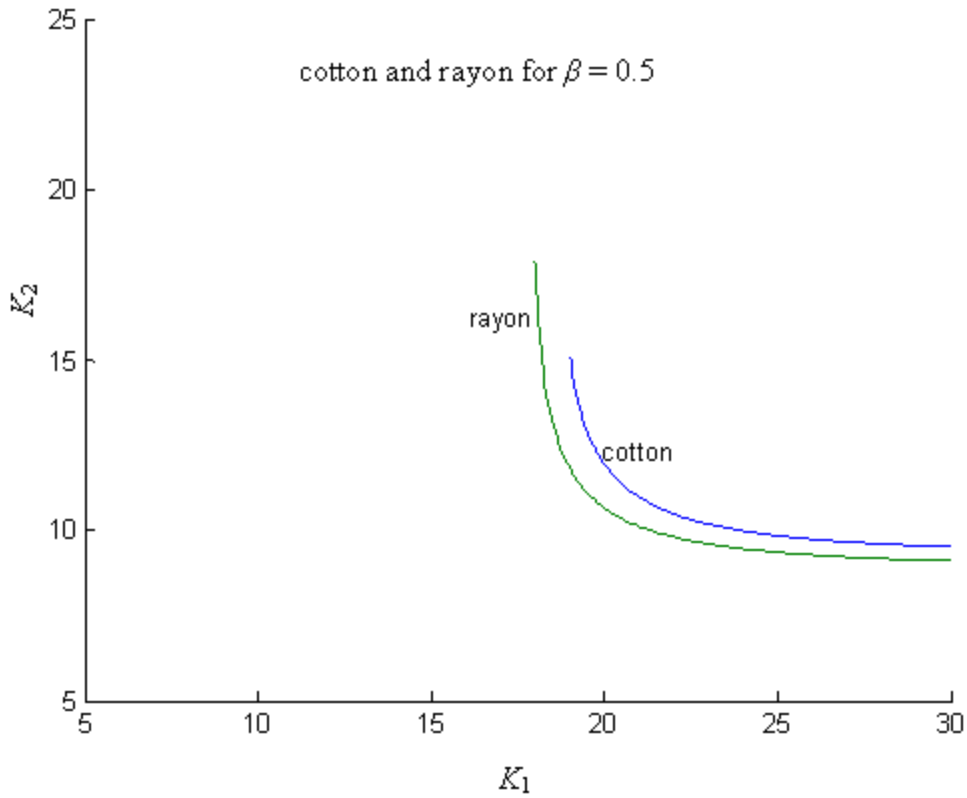
3.9b Effect of fiber density on the relation between warp and weft cover factor



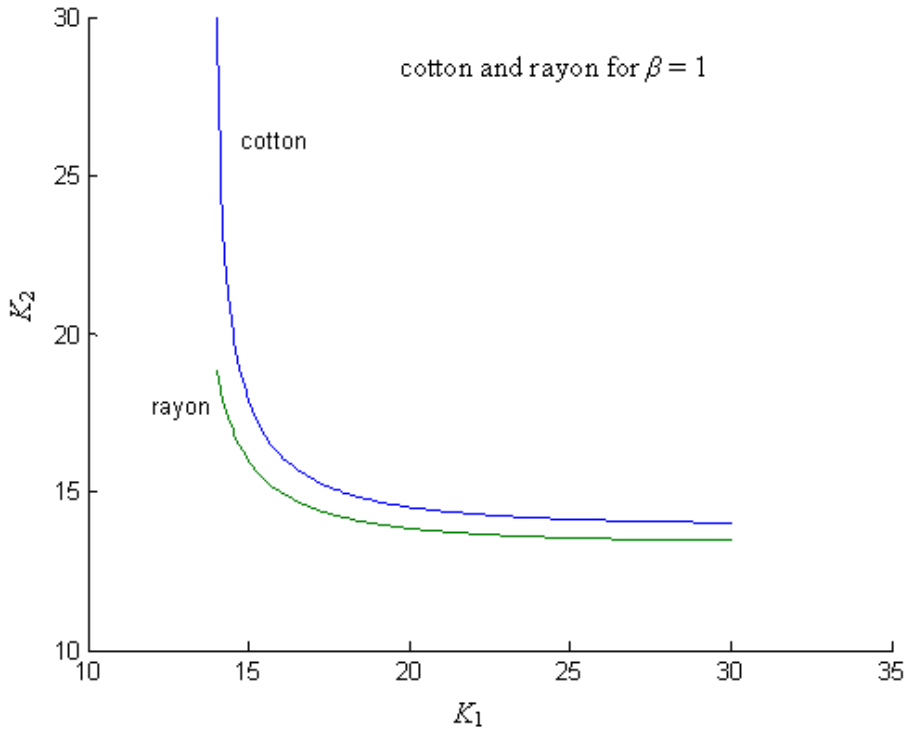
3.9c Effect of fiber density on the relation between warp and weft cover factor

3.3.3 Effect of variation in yarn packing factor on the relation between warp and weft cover factor for jammed fabrics

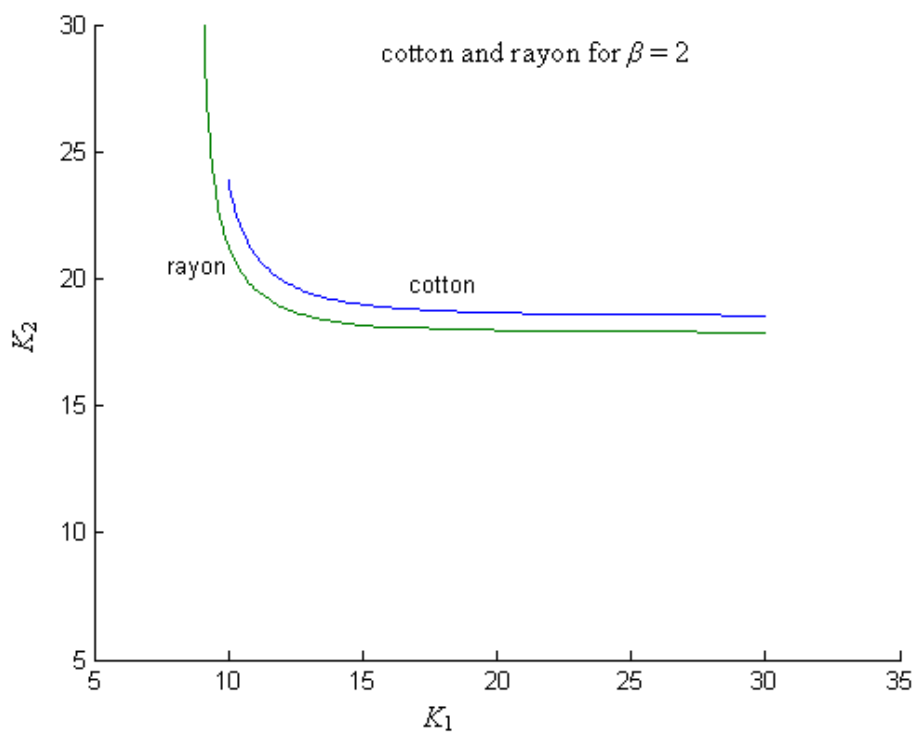
Rayon and cotton fiber have same density, In the yarn packing factor of 0.60 is taken for rayon and 0.65 for cotton. The effect of change in yarn packing factor from 0.60 to 0.65 on the relation between warp and weft cover factors can be seen in the figures 3.10 a,b,c for beta ranging from 0.5-2. The higher yarn packing factor results in increasing the levels of warp and weft cover factors. The increase in beta helps in attaining higher weft cover factors and gives a wider range of sensitivity between the warp and weft cover factors.



3.10a Effect of yarn packing factor on the relation between warp and weft cover factor



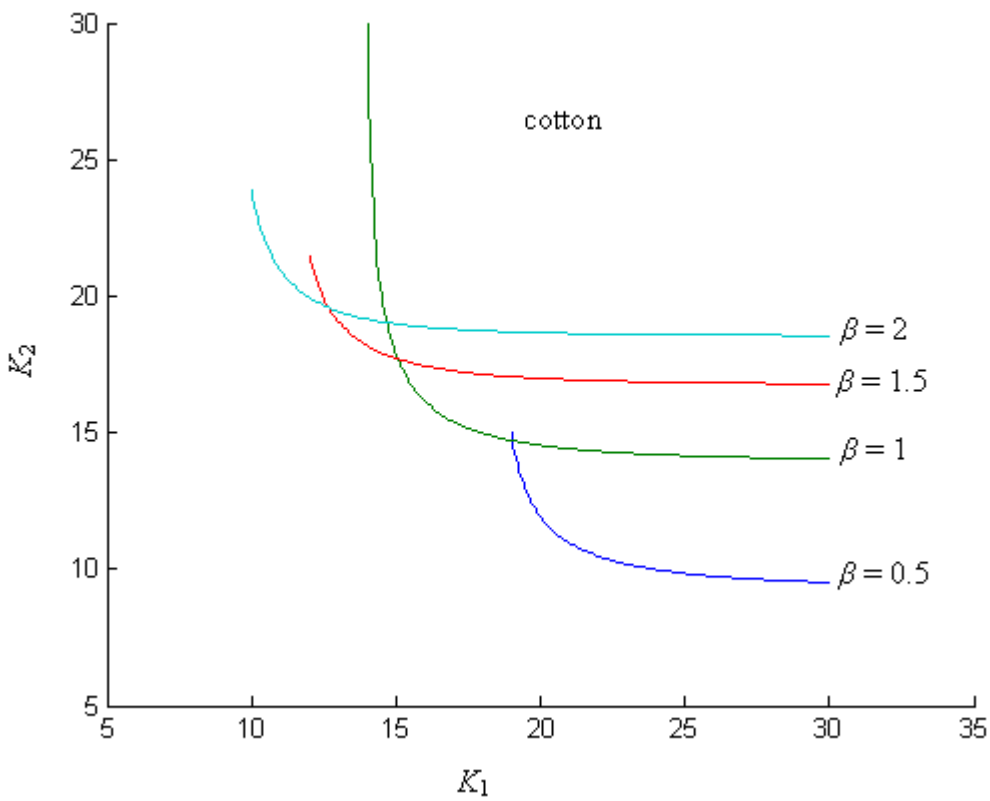
3.10b Effect of yarn packing factor on the relation between warp and weft cover factor



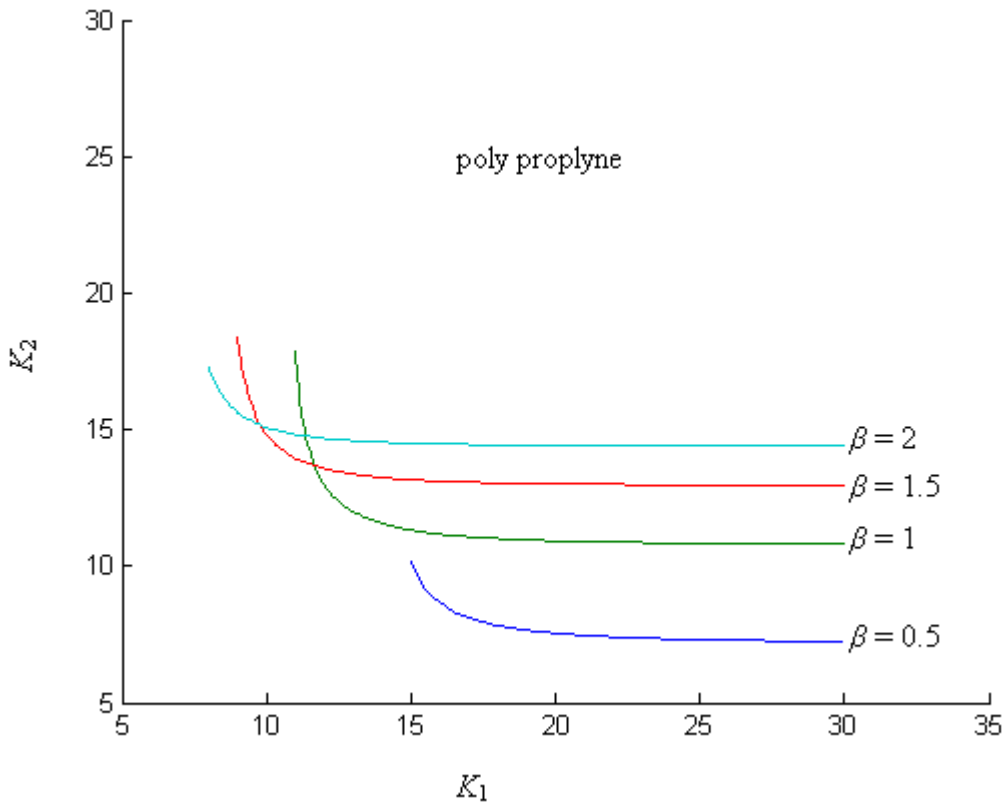
3.10c Effect of yarn packing factor on the relation between warp and weft cover factor

3.3.4 Effect of variation in beta (d_2/d_1) on the relation between warp and weft cover factor for jammed fabrics

An increase in the value of beta from 0.5-2 increases the range of warp cover factors but raises the level for the weft cover factor. This means with an increase in beta higher weft cover factors are achievable and vice-versa. However it may be noted that for cotton fibers having higher fiber density the sensitivity range between the warp and weft cover factor is relatively large compared to polypropylene fiber as shown in figure 3.11a and 3.11b. This shows a very important role played by fiber density in deciding warp and weft cover factors for the jammed fabrics.



3.11a Effect of β on the relation between warp and weft cover factor



3.11b Effect of β on the relation between warp and weft cover factor

3.3.5 Equation for jammed structure for circular cross-section in terms of weave factor

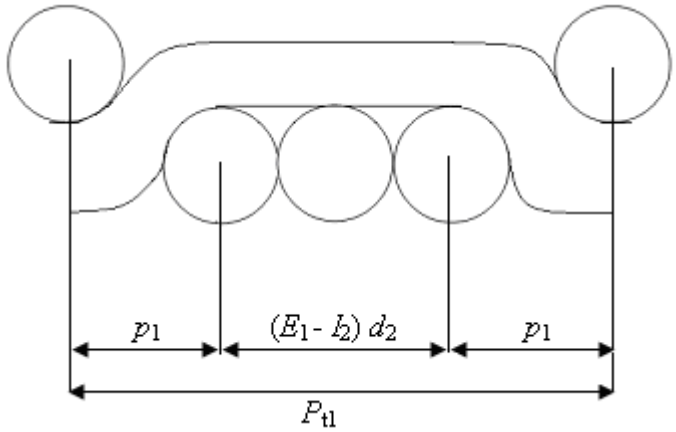
Weave factor is useful in translating the effect of weave on the fabric properties. This has been discussed in part 1 at 1.4.2. For circular cross-section the general equation for jammed cloth is desired.

Thread spacing P_{t1} for a non-plain weave per repeat is shown in figure 3.12 and is given as:

$$P_{t1} = I_2 p_1 + (E_1 - I_2) d_1 \qquad [3.6]$$

The average thread spacing, $\overline{P_1} = \dfrac{I_2 p_1 + (E_1 - I_2) d_1}{E_1}$

$$\frac{E_1 \overline{P_1}}{I_2} = p_1 + \left(\frac{E_1}{I_2} - 1 \right) d_1$$



3.12 Jammed structure for 1/3 weave (circular cross-section along warp)

$$M_1\overline{P_1} = p_1 + (M_1 - 1)\, d_1$$

$$\frac{p_1}{D} = M_1\frac{\overline{P_1}}{D} - (M_1 - 1)\frac{d_1}{D}$$

$$\frac{p_1}{D} = M_1\frac{\overline{P_1}}{D} - \frac{(M_1 - 1)}{1+\beta} \qquad [3.7]$$

where $\beta = d_2/d_1$

Similarly, interchanging suffix 1, 2 we get

$$\frac{p_2}{D} = M_2\frac{\overline{P_2}}{D} - (M_2 - 1)\frac{d_2}{D}$$

$$\frac{p_2}{D} = M_2\frac{\overline{P_2}}{D} - (M_2 - 1)\frac{\beta}{1+\beta} \qquad [3.8]$$

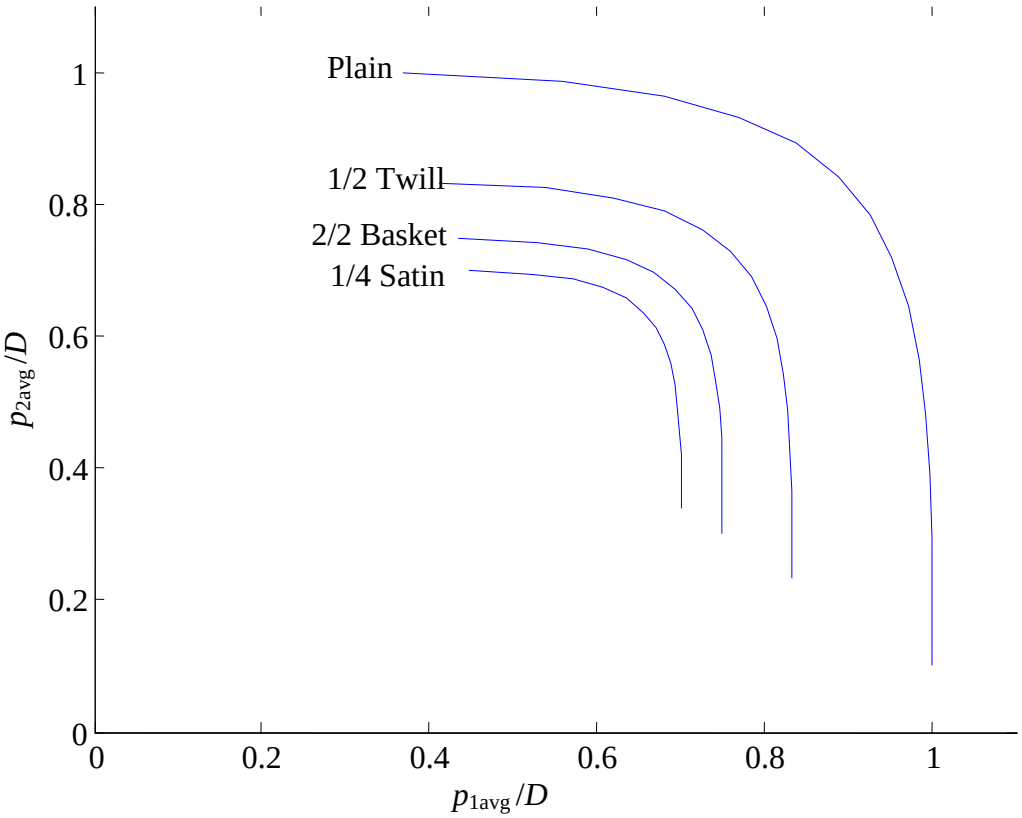
For a jammed fabric the following equation is valid:

$$\sqrt{1-\left(\frac{p_1}{D}\right)^2} + \sqrt{1-\left(\frac{p_2}{D}\right)^2} = 1$$

$$\sqrt{1-\left(M_1\frac{\overline{P_1}}{D} - \frac{(M_1-1)}{1+\beta}\right)^2} + \sqrt{1-\left(M_2\frac{\overline{P_2}}{D} - \frac{(M_2-1)\beta}{1+\beta}\right)^2} = 1$$

This equation can easily be transformed in terms of warp and weft cover factor (K_1 and K_2)

$$\sqrt{1-\left[\left(\frac{28.02\sqrt{\phi\rho_f}\,M_1}{K_1} - (M_1-1)\right)\frac{1}{1+\beta}\right]^2} + \sqrt{1-\left[\left(\frac{28.02\sqrt{\phi\rho_f}\,M_2}{K_2} - (M_2-1)\right)\frac{\beta}{1+\beta}\right]^2} = 1 \qquad [3.9]$$



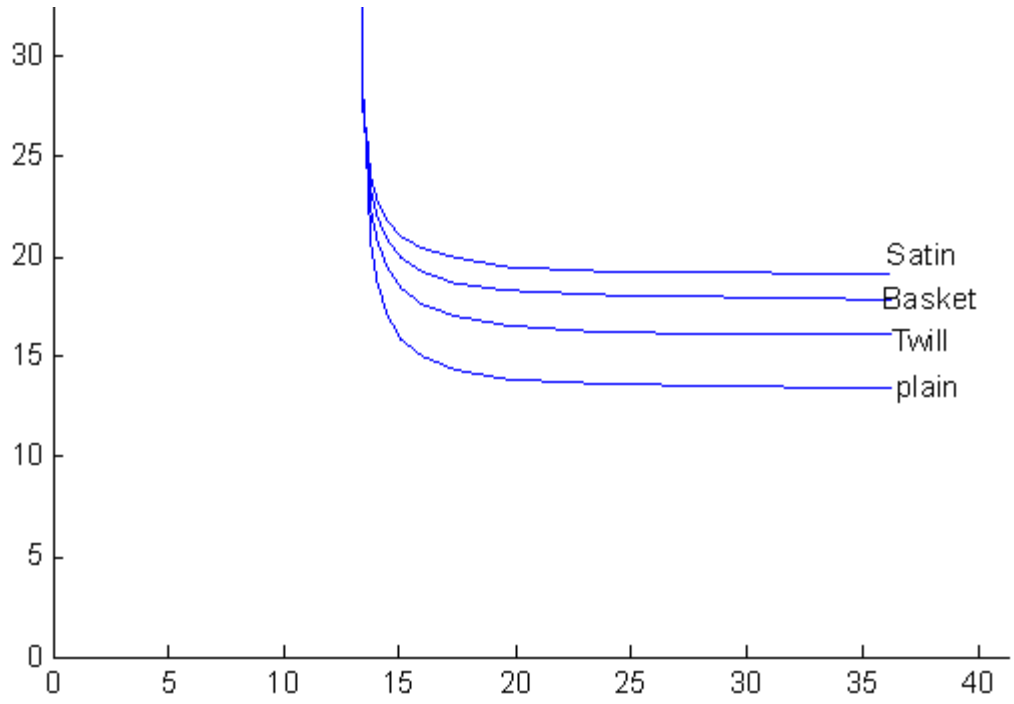
3.13 Relation between average thread spacing in warp and weft for jammed fabric (circular cross-section)

Relation between fabric parameters for circular cross-section for different weave

The effect of weave in the jammed structures is examined using the above equations for plain, twill, basket and satin weave. *M*, the weave factor value (average float length) for these weaves are 1, 1.5, 2 and 2.5 respectively for all the discussion which follows.

Figure 3.13 shows the relation between p_{1avg}/D and p_{2avg}/D. it can be seen that with the increase in float length, the sensitivity of the curve decreases in general. Also the range of p_1/D and p_2/D values gets reduced. This means a weave with longer float length decreases the flexibility for making structures.

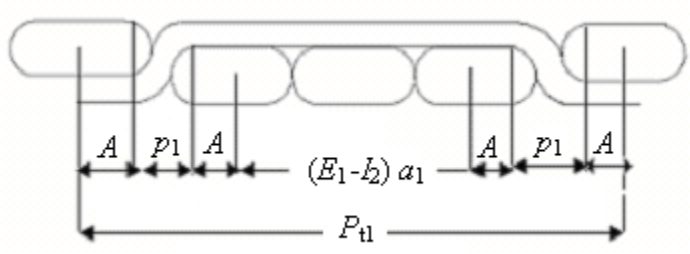
Figure 3.14 shows the relationship between the warp and weft cover factor for circular cross-section. It is interesting to note that the behavior is similar for different weaves. However with the increase in float, the curve shifts towards higher values of weft cover factor. It should be borne in mind that the behavior shown in this figure is for virtual fabrics. In real fabrics jammed structure is unlikely to retain circular cross-section.



3.14 Relation between warp and weft cover factor for jammed fabric (circular cross-section)

3.3.6 Equation for jammed structure for race track cross-section in terms of weave factor

In jammed fabrics, the yarn cross-section cannot remain circular. The cross-section will change. It is easy to modify the geometry for circular cross-section by considering race track cross-section. Figure 3.15 shows the configuration of jammed structure for 1/3 weave for race track cross-section along weft direction of the fabric.



3.15 Jammed structure for 1/3 weave (race track cross-section along warp)

Here, $A = \left(\frac{a_1 - b_1}{2} \right)$

Thread spacing P_{t1} for a non-plain weave per repeat is given as:

$$P_{t1} = I_2 p_1 + (E_1 - I_2) a_1 + 4\left(\frac{a_1 - b_1}{2} \right) \qquad [3.10]$$

similarly , $P_{t2} = I_1 p_2 + (E_2 - I_1) a_2 + 4\left(\frac{a_2 - b_2}{2} \right)$ [3.11]

Where, p_1 and p_2 are horizontal spacing between the semi-circular threads in the intersection zone. Here, a and b are the major and minor diameters of race track cross-section.

The average thread spacing, $\overline{P_1} = \frac{p_1}{M_1} + \left(1 - \frac{1}{M_1} \right) a_1 + \frac{4}{M_1 I_2} \left(\frac{a_1 - b_1}{2} \right)$ [3.12]

Similarly,

$$\overline{P_2} = \frac{p_2}{M_2} + \left(1 - \frac{1}{M_2} \right) a_2 + \frac{4}{M_2 I_1} \left(\frac{a_2 - b_2}{2} \right) \qquad [3.13]$$

As such analysis of circular thread geometry can be applied for the intersection zone of the race track cross-section.

$$L_1 = 4\left(\frac{a_2 - b_2}{2} \right) + (E_2 - I_1) a_2 + I_1 \times l_1 \qquad [3.14]$$

Total warp crimp in the fabric is given by:

$$C_1 = \frac{L_1}{P_{t2}} - 1$$

p_1 and p_2 can be calculated from the jamming considerations of the circular thread geometry using:

$$\sqrt{1 - \left(\frac{p_1}{B} \right)^2} + \sqrt{1 - \left(\frac{p_2}{B} \right)^2} = 1$$

It should be remembered that p/B corresponds to the semi-circular region of the race track cross-section and is similar to p/D for circular cross-section. As such the values of p/D ratio from figure 3.1 can be used for p/B

$$\sqrt{1-\left(M_1\frac{\overline{P_1}}{B}-\frac{4}{BI_2}\left(\frac{a_1-b_1}{2}\right)-(M_1-1)\frac{a_1}{B}\right)^2}+\sqrt{1-\left(M_2\frac{\overline{P_2}}{B}-\frac{4}{BI_1}\left(\frac{a_2-b_2}{2}\right)-(M_2-1)\frac{a_2}{B}\right)^2}=1$$

This equation can be simplified to the following usable forms.

$$\sqrt{1-\left(M_1\frac{\overline{P_1}}{B}-\frac{2(1-e)}{e(1+\beta)I_2}-\frac{(M_1-1)}{e(1+\beta)}\right)^2}+\sqrt{1-\left(M_2\frac{\overline{P_2}}{B}-\frac{2(1-e)\beta}{e(1+\beta)I_1}-\frac{(M_2-1)}{e(1+\beta)}\right)^2}=1$$

It is assumed that $e_1 = e_2 = e$

where $e=b/a$

The above equation can easily be transformed in terms of warp and weft cover factor as under:

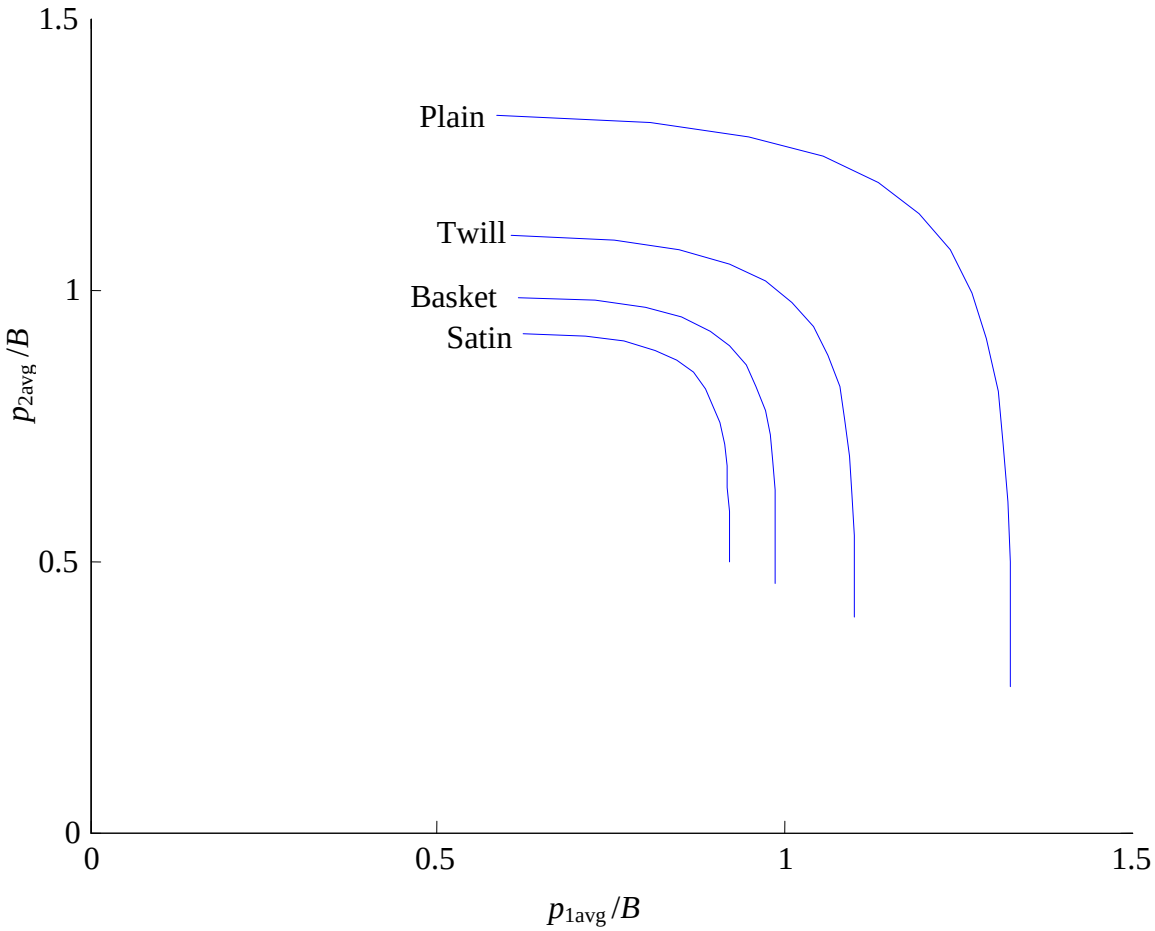
$$\sqrt{1-\left(\frac{28.02\sqrt{\phi\rho_f}M_1}{(1+\beta)K_1}\sqrt{1+\frac{4}{\pi}\left(\frac{1}{e}-1\right)}-\frac{2(1-e)}{e(1+\beta)I}-\frac{(M_1-1)}{e(1+\beta)}\right)^2}$$

$$+\sqrt{1-\left(\frac{28.02\sqrt{\phi\rho_f}M_2\beta}{(1+\beta)K_2}\sqrt{1+\frac{4}{\pi}\left(\frac{1}{e}-1\right)}-\frac{2(1-e)\beta}{e(1+\beta)I}-\frac{(M_2-1)\beta}{e(1+\beta)}\right)^2}=1 \qquad [3.15]$$

3.3.7 Relationship between fabric parameters in race track cross-section

The relationship between fabric parameters such as p_2 and p_1, p_1 and c_2 for the race track cross-section in jammed condition is discussed below.

Figure 3.16 shows the behavior between these pair of parameters is similar to that for the circular cross-section but it shifts towards higher values of thread spacing. This figure shows the behavior of real fabrics.

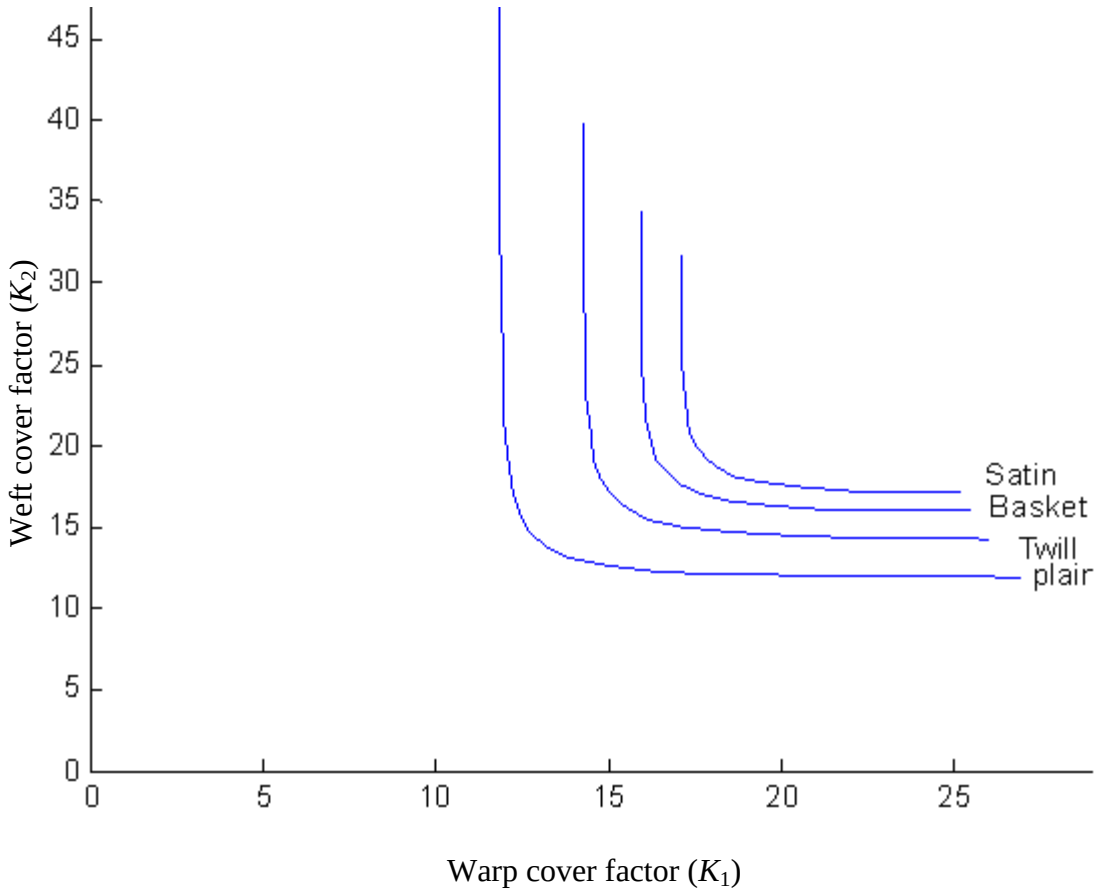


3.16 Relation between average thread spacing in warp and weft for jammed fabric (race track cross-section, β=1)

Figure 3.17 shows the relationship between warp and weft cover factors for different weaves. As discussed above in real fabrics the weaves show distinct differences between them unlike in circular cross-section. Increase in float length decreases the scope of cover factors.

From these equations crimp and fabric cover can be evaluated using the above two equations along with:

$$d^2 = b^2\left[\frac{\pi}{4} + \left(\frac{1}{e} - 1\right)\right] \text{ and } \frac{b_2}{b_1} = \beta \qquad [3.16]$$



3.17 Relation between warp and weft cover factor for jammed fabric (race track cross-section)

3.4 Special structure

3.4.1 Square cloth

A truly square fabric has equal diameter, spacing and crimp.

$p_1 = p_2,\ c_1 = c_2,\ d_1 = d_2,\ h_1 = h_2 = D/2,\ \theta_1 = \theta_2$

From the basic equations of the geometrical model from the previous chapter we have:

$$\tan\theta/2 = \frac{2}{3}\left[\frac{p}{D} - \sqrt{\left(\frac{p}{D}\right)^2 - 0.75}\right] \qquad [3.17]$$

This is valid for all values of $(p/D)\ 2 \geq 0.75$ or $p/D \geq 0.866$

$p/d \geq 1.732$; $d/p \leq 0.5773$

Also $D = 2d = h_1 + h_2 = 2\times(4/3)p\sqrt{c}$

$$\sqrt{c} = \frac{3}{4}\frac{d}{p} = \frac{0.75}{p} \times \frac{\sqrt{Tex}}{280.2\sqrt{\phi\,\rho_{\mathrm{f}}}}$$

$$c = \left(\frac{0.02677K}{\sqrt{\phi\rho_{\mathrm{f}}}}\right)^2 \qquad [3.18]$$

crimp in percentage can be calculated from $\%c = \left(\frac{K}{3.57}\right)^2$

For jammed square cloth

$\cos\theta_1 + \cos\theta_2 = 1$ will give

$\cos\theta = 1/2$ and $\theta = 60^0$

$p = 2d\sin\theta, 1 = D\theta = 2d\frac{\theta}{3}$

$\therefore \frac{1}{d} = 2\frac{\theta}{3}$

$\frac{p}{d} = \sqrt{3} = 1.732$

$=> \frac{p}{d} = 0.5773$

crimp $= \frac{1/d}{p/d} - 1 = 0.2092 = 20.9\%$

Therefore complete cover is not possible with square cloth.

3.4.2 Similar cloth

Cloths can be made from same fibers which may differ in respect of yarn count, ratio of yarn count in warp and weft, ratio of yarn spacing, average yarn spacing and weave.

Such cloths can be compared in terms of fabric cover. It is possible to consider cloth which differ in many ways as being similar if they posses the same fractional covering power.

While comparing cloths for cover only such comparison are perfectly justifiable for cloths differing in yarn count and average yarn spacing. It will not be correct to say cloths which have equal cover are equally acceptable, equally difficult to make and equally tight. Cloths which differ in the ratio of spacing or weave cannot be made similar by fabric cover concept. Some

examples for change of weave, yarn count, threads per cm and fabric mass for square constructions are shown below for similar fabrics that have the same firmness. The mathematical logic for these variables and some examples are given below:

3.4.2.1 Effect of change in weave on thread density

$$\left(\frac{\text{Threads}}{\text{cm}}\right)_{\text{New}} = \left(\frac{\text{Threads}}{\text{cm}}\right)_{\text{Old}} \times \frac{\left(\frac{M}{M+1}\right)_{\text{New}}}{\left(\frac{M}{M+1}\right)_{\text{Old}}}$$

3.4.2.2 Effect of change in weave on yarn count

$$d \;\alpha\; \frac{1}{\sqrt{N}} \Rightarrow d = \frac{k}{\sqrt{N}}$$

where k is a constant for proportionality

$$\Rightarrow (\text{threads per cm})_{\text{Old}} = \left(\frac{M}{M+1}\right)_{\text{Old}} \left(\frac{\sqrt{N_{\text{Old}}}}{k}\right)$$

$$\Rightarrow (\text{threads per cm})_{\text{Old}} = \left(\frac{M}{M+1}\right)_{\text{New}} \left(\frac{\sqrt{N_{\text{New}}}}{k}\right)$$

$$\sqrt{\frac{N_{New}}{N_{Old}}} = \frac{\left(\frac{M}{M+1}\right)_{\text{Old}}}{\left(\frac{M}{M+1}\right)_{\text{New}}}$$

3.4.2.3 Effect of change in thread density on yarn count

$$\Rightarrow \text{threads/cm} = W \times \left(\frac{\sqrt{N_{\text{Old}}}}{k}\right)$$

$$\therefore \sqrt{\frac{N_{New}}{N_{Old}}} = \frac{T_{New}}{T_{Old}}$$

3.4.2.4 Effect of change in fabric mass on thread density and yarn count

The change in the fabric mass (gsm) by maintaining the same firmness can be done by: using fewer and coarser threads if the fabric is to be heavier and increased number of fine threads if the fabric is to be lighter.

$$\Rightarrow \frac{\text{fabric mass}_{\text{Old}}}{\text{fabric mass}_{\text{New}}} = \left(\frac{\sqrt{N_{\text{New}}}}{\sqrt{N_{\text{Old}}}}\right)$$

$$\frac{\text{threads/cm}_{\text{New}}}{\text{threads/cm}_{\text{Old}}} = \frac{\text{fabric mass}_{\text{Old}}}{\text{fabric mass}_{\text{New}}}$$

Some examples

1) 3/3 twill with 48 ends per cm is to be changed to 3-end twill, how many threads per cm are required in the new weave to give the same firmness as old weave?

M_{Old}=6/2=3

M_{New}=3/2=1.5

(threads per cm)$_{\text{New}}$=48(1.5/2.5)/(3/4)=38.4

2) A 4-end twill cloth is required with the same number of threads per cm as a plain cloth woven with 36 yarns. Find the count of the yarn to be used to give a twill cloth with the same firmness as the plain cloth.

$$\sqrt{\frac{N_{\text{New}}}{N_{\text{Old}}}} = \frac{1/3}{2/3}$$

$$\sqrt{N_{\text{New}}} = \frac{1\times 3}{2\times 2}\sqrt{N_{\text{Old}}} = \frac{3}{4}\sqrt{36} = 4.5$$

N_{New} = (4.5)2=20.25.

3) If a given cloth is woven with 28 threads of 64^S yarn per cm. It is desired to keep the same weave but to have only 25 threads per cm .what counts must be used?

$$\sqrt{N_{\text{New}}} = \frac{25}{28}\sqrt{64} = 7.143$$

N_{New} =51^S.

4) If we wish to make a cloth from 64^S yarn to be of the same firmness as one with 28 threads per cm of 36^S yarn. How many threads per cm will be required?

$$\therefore \sqrt{\frac{64}{36}} = \frac{N_{\text{New}}}{28}$$

$$T_{\text{New}} = 28\sqrt{\frac{64}{36}} = 37.3$$

5) A fabric contains 32 threads per cm of 52^S yarn in both warp and weft. If gsm = 100. What count and threads per cm will be required to increase the gsm to 125?

$$\sqrt{\frac{N_{\text{New}}}{52}} = \frac{100}{125}$$

$$\therefore \sqrt{N_{\text{New}}} = \frac{100}{125}\sqrt{52} = 5.7688$$

$$N_{\text{New}} = 33.28$$

$$(\text{threads per cm})_{\text{New}} = (\text{threads per cm})_{\text{Old}} \times \frac{(\text{Fabric mass})_{\text{Old}}}{(\text{Fabric mass})_{\text{New}}} = \frac{100}{125} \times 32 = 25.6$$

3.6 Application

It is easy to consider cloth which differ in many ways as being similar if they posses the same fractional covering power. In comparing cloth for cover only such comparison are preferably justifiable, but it will not be correct to say cloths which have same cover are equally acceptable, equally difficult to make and equally tight.

Total fabric cover factor when jamming occurs varies with ratio of thread spacing and weave. The ratio of actual fabric cover to maximum fabric cover factor is a measure of tightness, relative acceptability. This concept has been used by several researchers using weave value.

3.6.1 Tightness factor

Recent research efforts were directed towards establishing a standard or a reference fabric which can be objectively compared. Reference fabric is normally of maximum construction. The comparison is expressed in terms of ratio of a construction parameter of a given fabric to that of the standard fabric. This ratio is called firmness or tightness. The physical, mechanical, aesthetic part of the fabric can be related to its degree of tightness. This is a rational basis for constructing fabrics with predetermined end use performance.

Russell [17] suggested tightness factor as the ratio of threads per cm to the maximum threads per cm in a fabric. This ratio can be obtained for the warp and weft directions of the fabric. For a fabric it is given as:

$$C_{\mathrm{f}} = \frac{t_1 + t_2}{t_{1\max} + t_{2\max}}$$

$$C_1 = \frac{t_1}{t_{1\max}}$$

$$C_2 = \frac{t_2}{t_{2\max}}$$

This concept can be used to compare tightness values of fabric for different weave with a standard fabric. The modified equation considering weave will be as under:

For circular cross-section the total thread spacing is given as:

$$P_{\mathrm{t}} = I \times p + (E - I)d$$

The maximum threads will be given by:

$$t_{\max} = \frac{E}{I \times p + (E - I)d}$$

$$= \frac{M}{p + (M - 1)d}$$

$$= \frac{M}{(M - 1)d + D\sin\theta} \qquad [3.19]$$

This is a general equation for $t_{\max}$ for any crimp (θ).

However the maximum threads in a fabric are possible when cross threads are straight. In such a situation the intersecting yarn will have maximum crimp and weave angle is 90º.

$$\text{In this case, } t_{\max} = \frac{M}{(M - 1)d + D} \qquad [3.20]$$

For a standard fabric one can assume maximum cover in the fabric and corresponding maximum possible ends and picks per cm. In this case as mentioned before cross threads must be straight and maximum bending will be done by the interlacing yarn. The maximum possible threads in the two directions will be different.

If weft yarn remains straight, θ_1=90^0

the maximum picks per cm from equation 3.30 will be

$$t_{2\max} = \frac{M_2}{(M_2 - 1)d_2 + D} \qquad [3.21]$$

and the maximum ends per cm will be for θ_2=0^0

$$t_{1\max} = \frac{M_1}{(M_1 - 1)d_1} \qquad [3.22]$$

However these equations are valid for M>1

It will be fair to use these equations rather than equation 3.31 for both warp and weft directions.

For the race track cross-section:

$$P_t = I \times p + 2(a - b) + (E - I)a$$

The maximum threads will be given by:

$$t_{\max} = \frac{E}{I \times p + 2(a - b) + (E - I)a}$$

$$= \frac{M}{p + \frac{2(a-b)}{I} + (M - 1)a}$$

$$= \frac{M}{B\sin\theta + \frac{2(a-b)}{I} + (M - 1)a} \qquad [3.23]$$

as discussed above for maximum threads the weave angle is 90º

so, $$t_{\max} = \frac{M}{B + \frac{2(a-b)}{I} + (M - 1)a} \qquad [3.24]$$

similarly for standard fabric the relevant equations will be:

$$t_{2\max} = \frac{M_2}{B + \frac{2(a_2 - b_2)}{I_2} + (M_2 - 1)a_2} \qquad [3.25]$$

$$t_{1\max} = \frac{M_1}{\frac{2(a_1 - b_1)}{I_1} + (M_1 - 1)a_1} \qquad [3.26]$$

These are equations which a designer can use to construct fabrics with different texture and tightness by varying the yarn and fabric parameters.

Chapter 4: Structural modifications

4.1 Introduction

A fabric structure is specified by any four parameters, for example ends per cm, picks per cm, warp crimp, weft crimp; one can calculate all other fabric parameters. Now the question is what will happen or exactly what changes occur in the structure when dimensions are changed? Sometimes after weaving fabric specifications are not according to what is desired. Some structures are impossible to weave on the weaving machines. In such cases the corrections to the fabric can be made by pulling it either in the warp or in the weft direction. The effect of stretch along warp or weft on fabric parameters can be predicted and any desired requirement can be perfectly accomplished. However it should be remembered that such changes in the fabric parameters do not involve yarn stretch or compression. A very important practical application of Peirce's geometrical model [6] is for determining the fabric parameters after modification.

4.2 Crimp interchange phenomena

A stretch in the fabric for example in the warp direction will reduce the warp crimp and increase the weft crimp in general. This phenomenon is termed as crimp interchange. It is equivalent to stretch in one direction accompanied by contraction in the cross-direction and vice versa. This is a geometrical change between the fabric parameters in one direction vis-à-vis the cross-direction. The practical implementation of this concept can be carried out by weft stretch in the stenter machine and by warp stretch in the calendar. This implies that the mechanical act can cause a direct change only in thread spacing, p_1 or p_2 and the changes in other fabric parameters will be indirect due to the effect of changes in p_1 or p_2.

The following equation gives a useful relationship between the two directions of the fabric.

$$D = h_1 + h_2 = h_1^{'} + h_2^{'}$$

Superscript represents changes in the fabric parameter after modification

$$D = h_1^{'} + h_2^{'} = \frac{4}{3}\left[p_2^{'}\sqrt{c_1^{'}} + p_1^{'}\sqrt{c_2^{'}} \right]$$

$$D = \frac{4}{3}\left[\frac{l_1\sqrt{c_1^{'}}}{1+c_1^{'}} + \frac{l_2\sqrt{c_2^{'}}}{1+c_2^{'}}\right]$$

$$\frac{l_1\sqrt{c_1^{'}}}{(1+c_1^{'})} + \frac{l_2\sqrt{c_2^{'}}}{(1+c_2^{'})} = \frac{3D}{4} \qquad [4.1]$$

Equation 4.1 is called crimp interchange equation. It gives the relationship between the warp and weft crimp for the new configuration after the application of stretch in the warp/weft direction. It may be noted that the parameters l_1, l_2 and D are invariant; that is they have the same value in the original fabric and in the new configuration. This basically means that there is a geometrical change in the deformed fabric with respect to the undeformed fabric.

In the crimp interchange equation one of the parameter $c_1^{'}$ or $c_2^{'}$ is determined based on the requirement of modification and the other parameter is calculated from the equation 4.1.

One of the following options can be initiated for getting parameters of the new fabric

Fabric dimensions changed

Fabric dimensions either the length or the width can be pulled by a certain extent to change the fabric parameters.

1. Extension or contraction of fabric length is made by α_l%; New weft spacing,

$p_2^{'} = p_2(1 \pm \frac{\alpha_{l\%}}{100})$, valid for no jamming in the weft direction

2. Extension or contraction of fabric width is made by α_w%; New warp spacing,

$p_1^{'} = p_1(1 \pm \frac{\alpha_{w\%}}{100})$, valid for no jamming in the warp direction

Fabric crimps changed

Fabric crimp in either the warp or weft direction can be changed by extension to change the fabric parameters.

1. New crimp, $c_1^{'} = c_1\left(1 \pm \frac{\alpha_c}{100}\right)$, where α_c is percent change in the warp crimp

2. New crimp, $c_2^{'} = 2\left(1 \pm \frac{\beta_c}{100}\right)$, β_c is percent change in the weft crimp

3. $c_1^{'}$=0, or $c_2^{'}$ =0, or $c_1^{'}$= $c_2^{'}$

Fabric crimp amplitude changed

1. New $h_1^{'} = h_1\left(1 \pm \frac{\gamma_1\%}{100}\right)$, where γ_1 is percent change

2. New $h_2^{'} = h_2\left(1 \pm \frac{\gamma_2\%}{100}\right)$, where γ_2 is percent change

3. $h_1^{'}$=0, or $h_2^{'}$ =0, or $h_1^{'}$= $h_2^{'}$

4.3 Maximum fabric extension

The maximum fabric extension will be limited to the following two options:

(1) When the crimp in the direction being pulled becomes zero, in this case the threads will be pulled straight and the changes in the cross-thread will not cause interference. For example, the maximum warp stretch will be equal to the warp crimp.

new crimp, $c_1^{'} = 0$

new weft spacing, $p_2^{'} = l_1$

$$\text{maximum percent warp stretch} = \frac{p_2^{'} - p_2}{p_2} \times 100\%$$

Similar logic can be applied for extensions in the weft direction.

(2) The maximum warp stretch will be limited to jamming in the cross-threads. For example maximum stretch in warp will be limited by the weft yarn getting jammed. It can be calculated as under:

$$\text{new warp spacing}, \; p_1^{'} = D \sin \frac{l_2}{D}$$

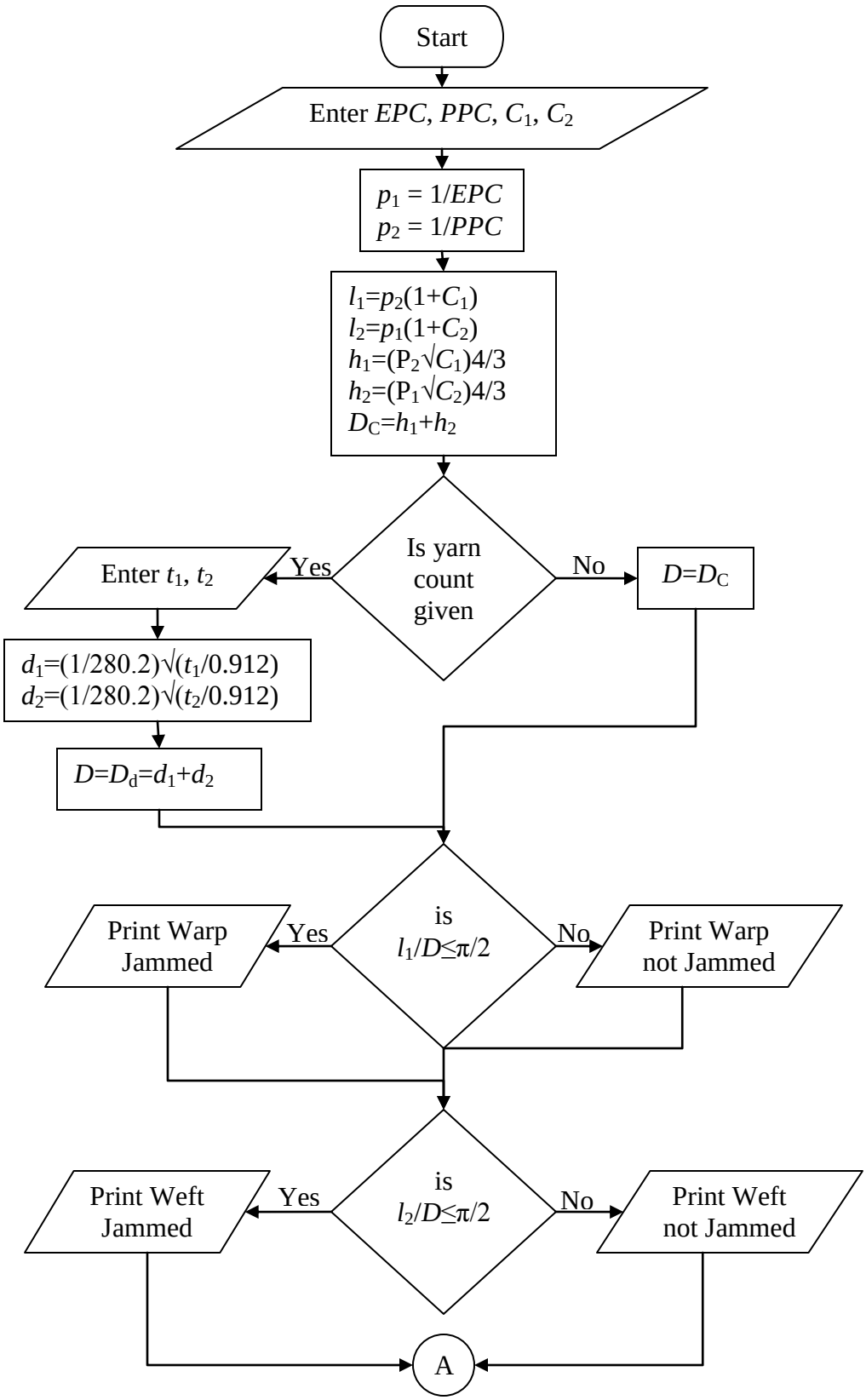
$$\text{new weft crimp}, \; c_2^{'} = \frac{l_2}{p_1^{'}} - 1$$

$c_1^{'}$ can be calculated from equation 4.1 and the corresponding $p_2^{'}$ can be obtained.

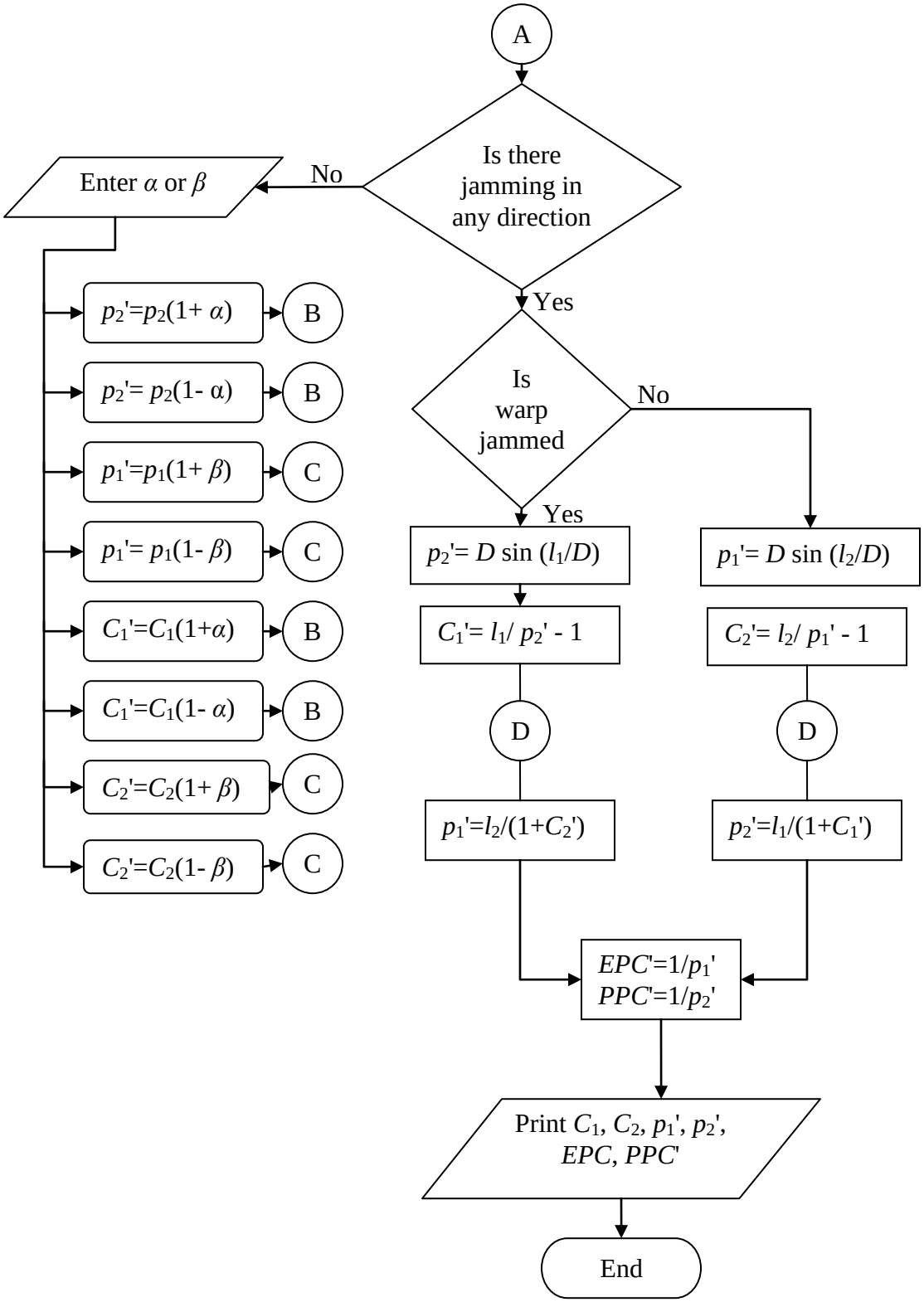
$$\text{maximum percent warp stretch} = \frac{p_2^{'} - p_2}{p_2} \times 100\%$$

Similar logic can be applied for the other direction.

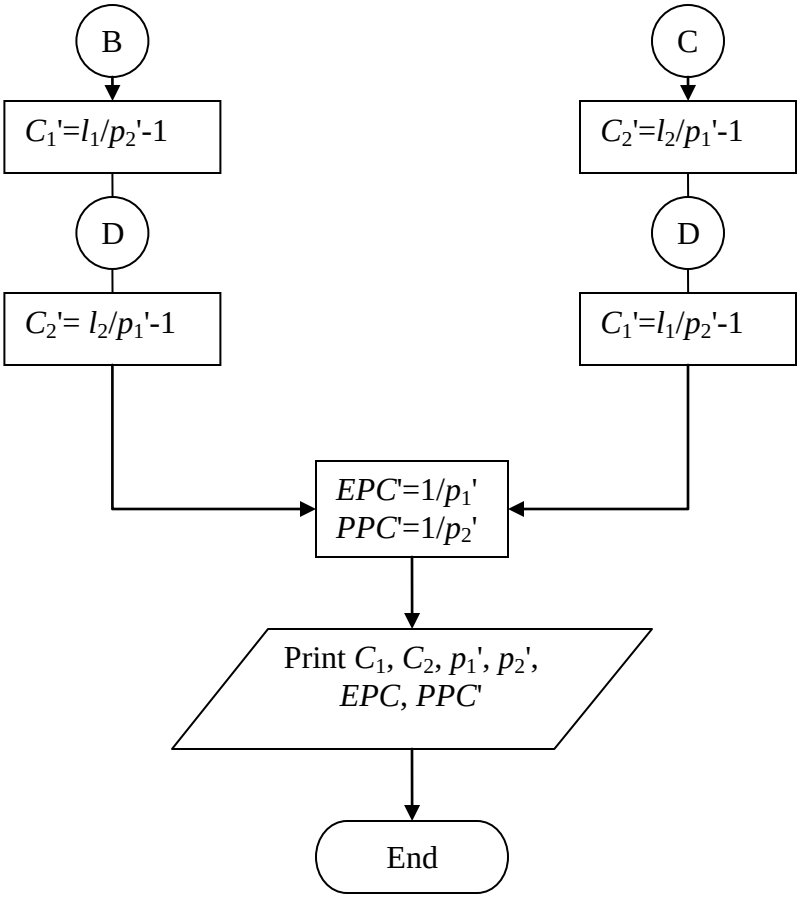
The flow chart shown in figure 4.1 gives the logic of the algorithm for computing the parameters of the new fabric configuration on the application of options mentioned under 4.1.

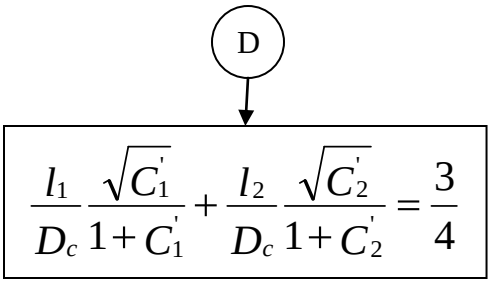


4.1 Flow chart for solving crimp interchange equation



4.1a Module connector A of figure 4.1





$$\frac{l_1}{D_c}\frac{\sqrt{C_1'}}{1+C_1'}+\frac{l_2}{D_c}\frac{\sqrt{C_2'}}{1+C_2'}=\frac{3}{4}$$

4.1b Module connector at B, C figure 4.1a

4.4 Other structural changes

Once the new fabric parameters are calculated the following can be obtained.

New fabric thickness

The new $h_1^{'}$ and $h_2^{'}$ can be calculated by using the equation 2.10, 2.11

New thickness will be $h_1^{'} + d_1$ or $h_2^{'} + d_2$ whichever is greater.

New fabric mass

This can be calculated using equations 2.30 and 2.31

New fabric cover factor

This can be calculated using equation 2.27.

New fabric specific volume

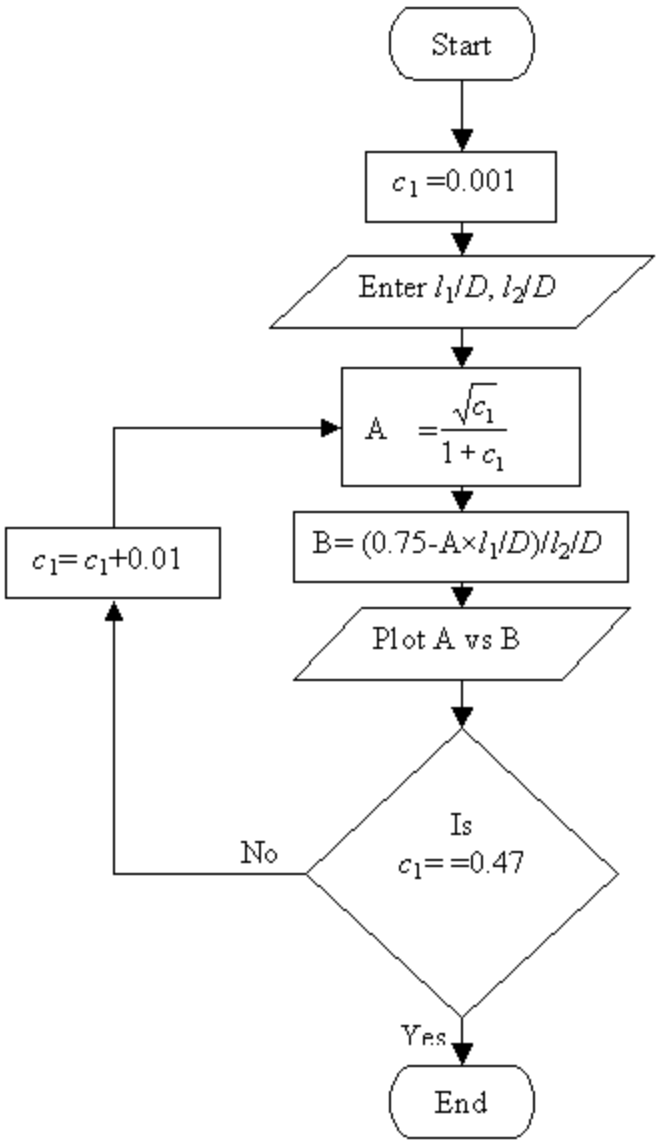
The importance of this concept is for altering the fabric properties. A reduction in the values of parameters in one direction will be accompanied by an increase in the values of parameters in the cross-direction.

An extension along warp will cause a contraction in the fabric width and vice-versa. This will primarily change thread spacing in warp and weft as such the ends and picks per cm. It will result in a change in the warp and weft cover factor and the cloth cover factor. The extension of warp will also result in reducing warp crimp and crimp amplitude. It is likely to affect fabric thickness and fabric mass.

4.5 Structural design of fabric by soft computing

The crimp in fabric is the most important parameter which influences several fabric properties such as extensibility, thickness, compressibility and handle. Normally crimp interchange equation is used to predict the change in crimp in the fabric when it is extended in any direction by keeping the ratio of modular length to the sum of thread diameter (l_1/D and l_2/D) constant.

An attempt is made by soft computing to exploit the crimp interchange equation in a different way instead of keeping the usual three invariants l_1, l_2 and D, the relationship between warp crimp,c_1 and weft crimp, c_2 is determined by varying l_1/D and l_2/D. The algorithm for this strategy is shown in figure 4.2. Such a strategy enables bias of crimp in a preferred direction. This is a new concept and entirely a different use of crimp interchange equation.

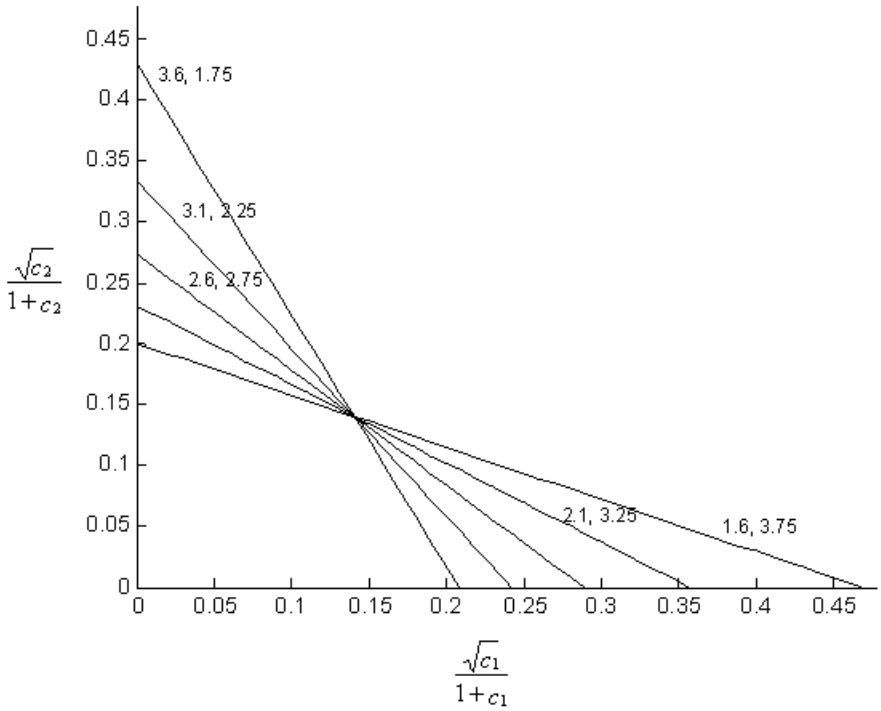


4.2 Flowchart for solving crimp interchange equation in terms of l_1/D and l_2/D as variable

4.5.1 Effect of varying l_1/D and l_2/D on relation between c_1 and c_2

It was thought appropriate to exploit this equation as a designer tool by varying l_1/D and l_2/D to alter the domain of c_1 and c_2. This attempt is shown in figures 4.3, 4.4 and 4.5.

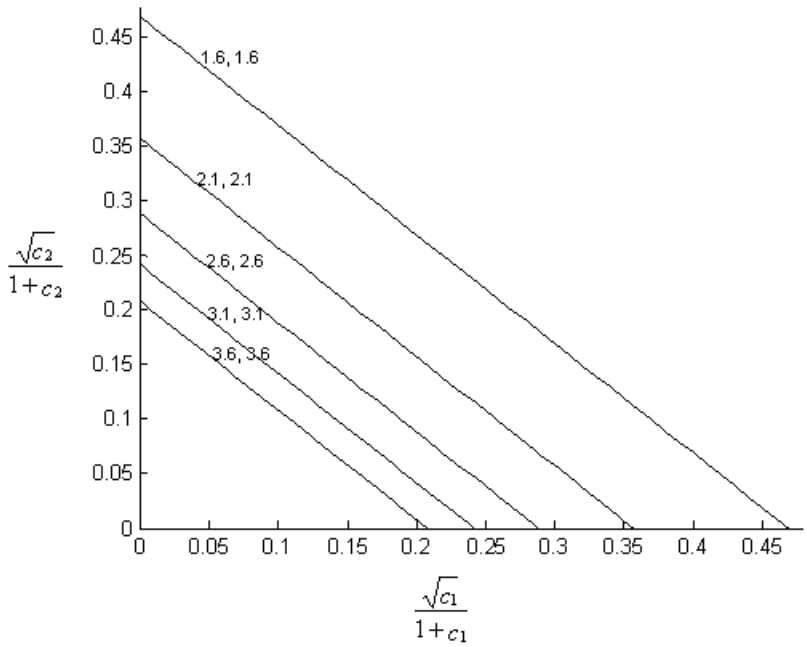
Figure 4.3 shows that the relation between $(\sqrt{c_1})/(1+c_1)$ and $(\sqrt{c_2})/(1+c_2)$ is linear for given values of l_1/D and l_2/D. The relation between warp and weft crimp will be dictated by the unique straight line for crimp interchange.



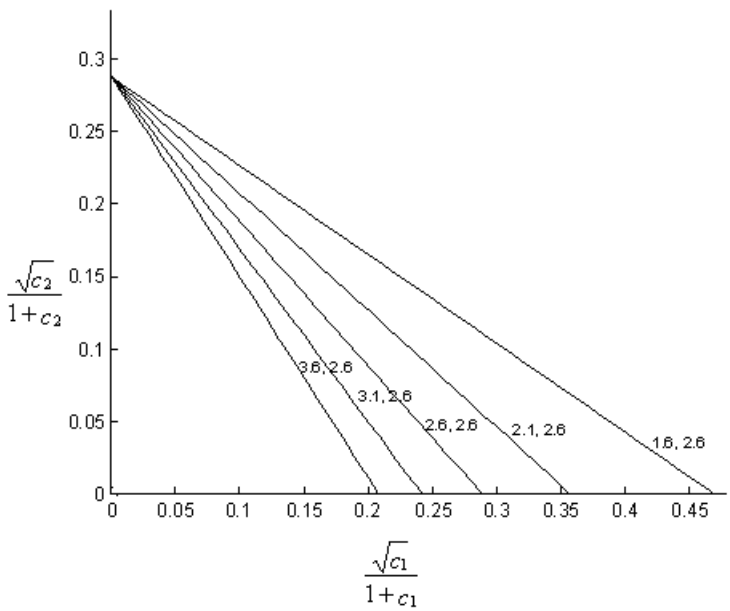
4.3 Relation between c_1 and c_2 with varying l_1/D, l_2/D

An attempt was made to investigate the effect by progressively decreasing the value of l_1/D and increasing the value of l_2/D by the same amount. It can be seen that all these lines pass through a point. The domain of relationship between warp and weft crimp gets altered, shifting to higher values of warp crimp by increasing l_2/D in relation to l_1/D and vice-versa.

Figure 4.4 shows the effect of decreasing l_1/D and l_2/D by the same amount increases the domain of the two axis without altering any ratio of $(\sqrt{c_1})/(1+c_1)$ and $(\sqrt{c_2})/(1+c_2)$. Whereas greater increment in l_2/D compared with l_1/D gives non-parallel lines in figure 4.5 unlike figure 4.4.



4.4 Relation between c_1 and c_2 with equal decrease in l_1/D and l_2/D



4.5 Relation between c_1 and c_2 with decrease in l_1/D for constant l_2/D

In this case the ratio of $(\sqrt{c_1})/(1+c_1)$ and $(\sqrt{c_2})/(1+c_2)$ will be altered and straight line will be biased towards the X-axis. Any line shows the relation between c_1 and c_2 for constant value of l_1/D and l_2/D. thus depicting the operating range of c_1 and c_2 for desired change in any one of them. Thus l_1/D and l_2/D can be chosen to dictate desired imbalance between c_1 and c_2.

Chapter 5: Modeling of 3D woven structures

5.1 Introduction

Fiber-reinforced composite materials have many advantages and are frequently used in a wide variety of applications [18]. Most of them are two-dimensional (2D) laminated composites, and interlaminar delamination is, therefore, the weakest failure mode in such materials. Various techniques have been introduced for increasing the interlaminar strength and the most effective one, is supposed to employ three-dimensional (3D) textile technologies [19,20]. Several types of 3D fabrics have been developed and have provided unique characteristics.
Among them, the orthogonal fabric composite, as shown in Fig. 5.1, provides a fiber architecture aimed at retaining in-plane performance while increasing interlaminar toughness, by introducing only a small amount of through-thickness (z) reinforcements [21-23].

This part discusses modelling of such structures by stages of the meso-FE analysis and proposes a succession of steps (‘‘roadmap’’) and the corresponding algorithms are:

- Building a model of internal geometry of the reinforcement
- Modelling the geometry in a solid modeller like ANSYS Multiphysics
- Preparation for meshing: correction of the interpenetration of volumes of yarns in the solid model and providing space for the thin matrix layers between the yarns
- Meshing: Dividing the solid into small elements.
- Assigning local material properties of the impregnated yarns and the matrix;
- Application of the loads
- Generating results – Deformed shape, contour plots, nodal solutions etc.

In this fabric basically the yarns are in 3 directions. All the yarn in 3 directions are mutually perpendicular to each other. There are layers of warp and weft yarn and Z-binding yarn (yarn in z axis) binds all these layers. The best property with these type of fabric is that there is no crimp in the yarns which thereby increases the young’s modulus of the fabric. There is only some crimp in Z-binding yarn which is at the boundary of fabric and can be neglected [24].

5.1.1 Finite element method

The finite element method (FEM) which in practical application often known as finite element analysis (FEA) is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as of integral equations. The solution approach is based either on eliminating the differential equation completely (steady state problems), or rendering the PDE into an approximating system of ordinary differential equations, which are then numerically integrated using standard techniques such as Euler's method, Runge-Kutta, etc.

In solving partial differential equations, the primary challenge is to create an equation that approximates the equation to be studied, but is numerically stable, meaning that errors in the input and intermediate calculations do not accumulate and cause the resulting output to be meaningless. There are many ways of doing this.

5.1.2 ANSYS

ANSYS is a general purpose finite element modelling package for numerically solving a wide variety of mechanical problems. These problems include: static/dynamic structural analysis (both linear and non-linear), heat transfer and fluid problems, as well as acoustic and electro-magnetic problems. It uses a pre-processor software engine to create geometry. Then it uses a solution routine to apply loads to the meshed geometry. Finally it outputs desired results in post-processing.

5.1.3 Geometry

The analysis was done on unit cell of 3D orthogonal fabric. The fabric has three layers of stuffer yarns, four layers of feeder yarn and two binder yarns. The cross section of yarn is choosen as race-track because it gives best practical results.

Analysis is done on unit cell instead of full fabric because the number of elements will be very high in case of full fabric and ansys couldn’t be able to converge the solution. So, unit cell of fabric is taken for analysis using proper boundary conditions so that practical conditions are acheived.

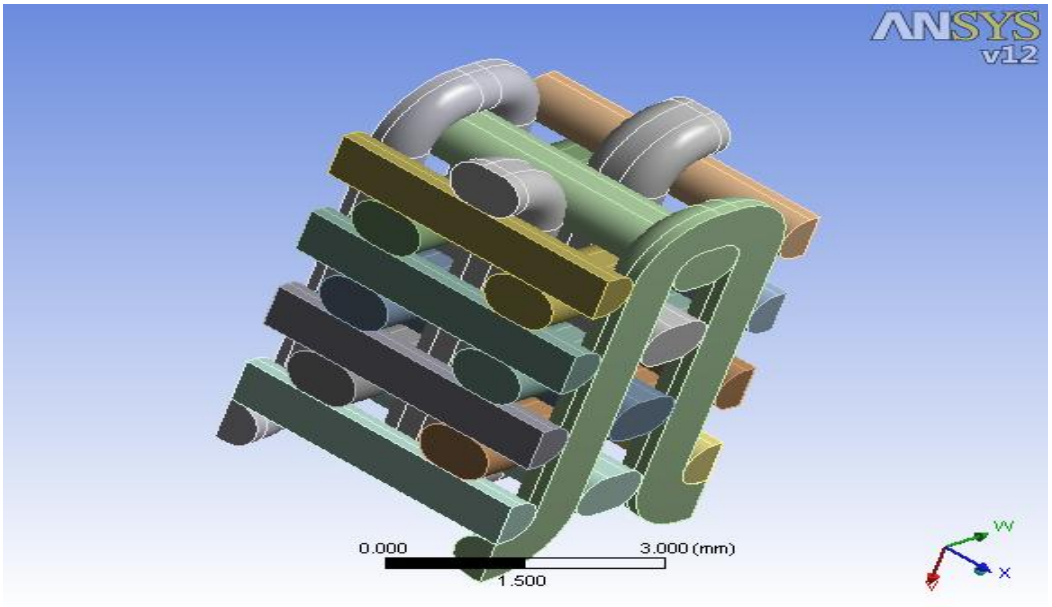
The dimension of unit cell is 4mm(width) * 6.3mm(height) * 2.7.mm(length).

Effective number of stuffer yarn = 6

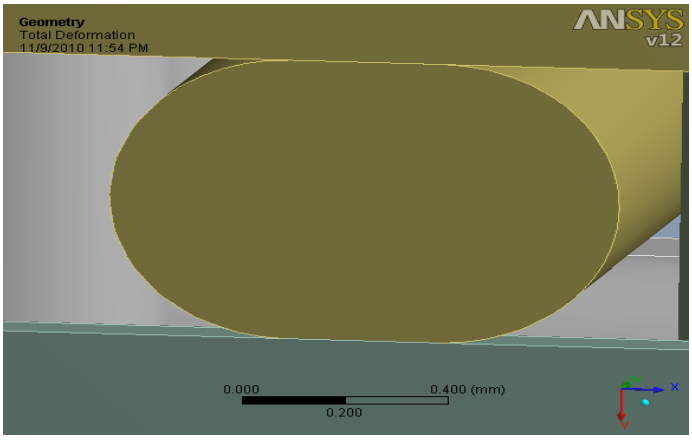
Effective number of filler yarn = 8

Effective number of binder yarn = 2

The reason why race-track cross-section is used is that, in other geomerties like circular, elliptical and lenticular, the contact between two bodies will be line, area of contact will be very low, thus for very low load, stress developed will be too high. That is why they will not give accurate results.



5.1 Unit cell structure of 3D orthogonal fabric.



5.2 Race-track cross-section of yarns.

The major axis = 1mm

The minor axis =0 .7mm

5.2 Material property

The material used is **glass fiber** having the following properties.

Young's modulus = 86000 MPa

Poisson's ratio = 0.22.

Density of material is 2540kg/m^3

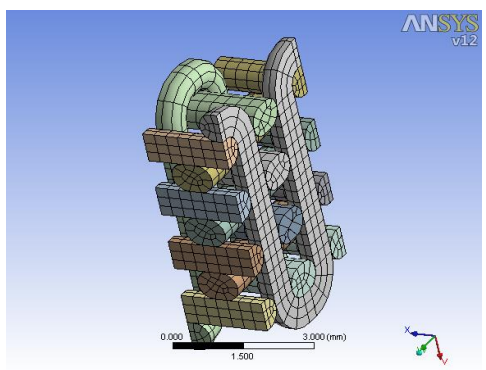
Tensile yield strength = 1.538E9

Tensile ultimate strength = 3.1E9

Coiefficent of inter yarn friction = .3

5.2.1 Mesh formation

For analysis purpose, the structure is divided into small elements. Mesh statistics constitute number of elements = 2273, and number of nodes = 13318.



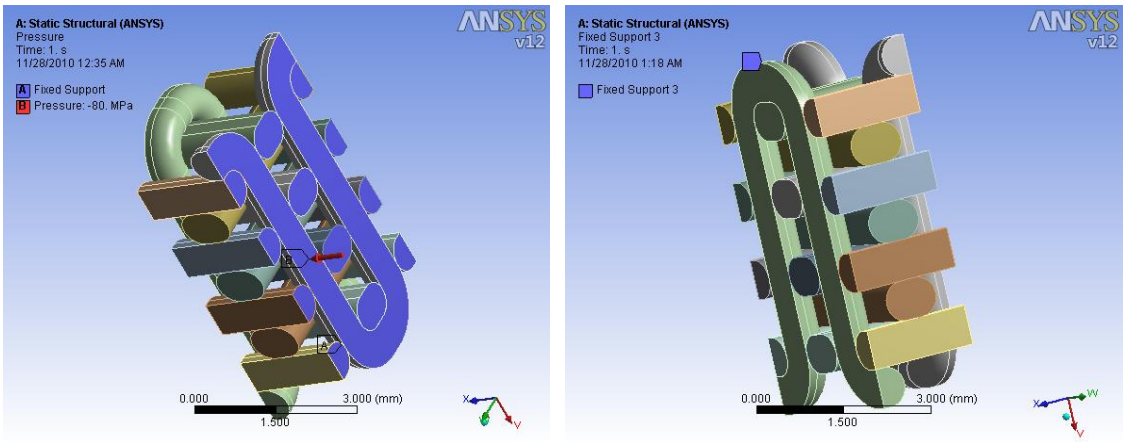
5.3 Mesh generation on the unit cell.

5.2.2 Boundary condition

1. **Fixed support on one side**

   The plane of symmetry will not move if equal and opposite forces are applied on the surface of the unit cell. Therefore, the unit cell is divided by this plane of symmetry and

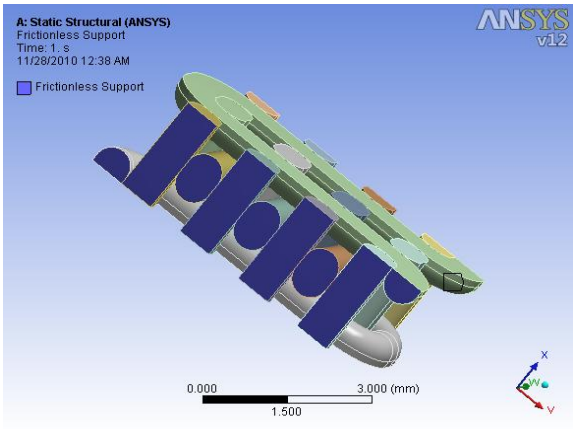
one side is welded with fixed support to prevent the rigid body motion. The blue colour surface indicates the welded zone of the fixed support in Fig. 5.4 .



5.4 Fixed support zones.

2. **Frictionless support**

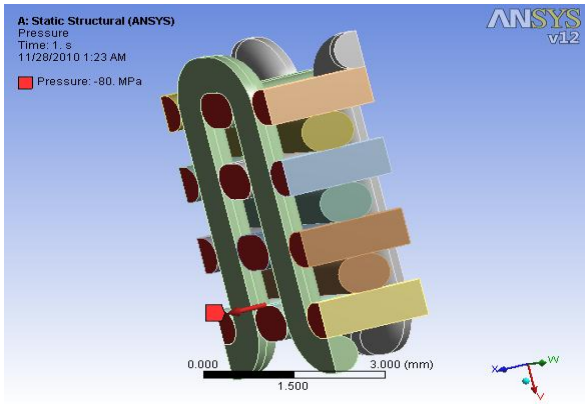
To prevent the intermessing of unit cell, surfaces are provided with frictionless support so that there is no motion in the direction perpendicular to the surface.



5.5 Friction-less support zone.

3. **Loading**

The stuffer yarns are provided with load. Pressure load is applied, so that uniform force can be exerted on each yarn.



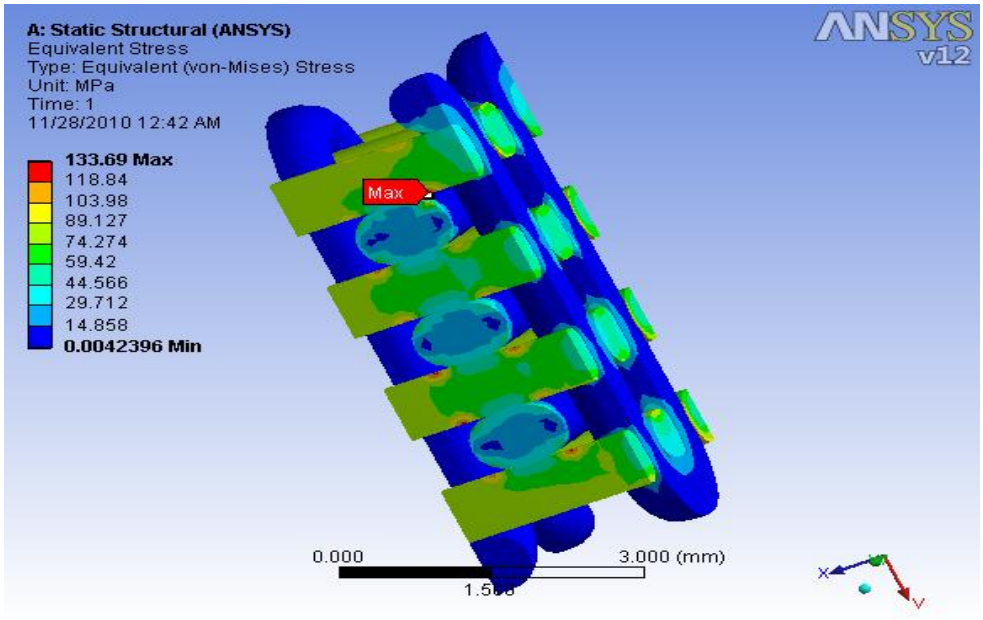
5.6 Pressure is applied to one of the face as shown above.

5.3 Result and discussion

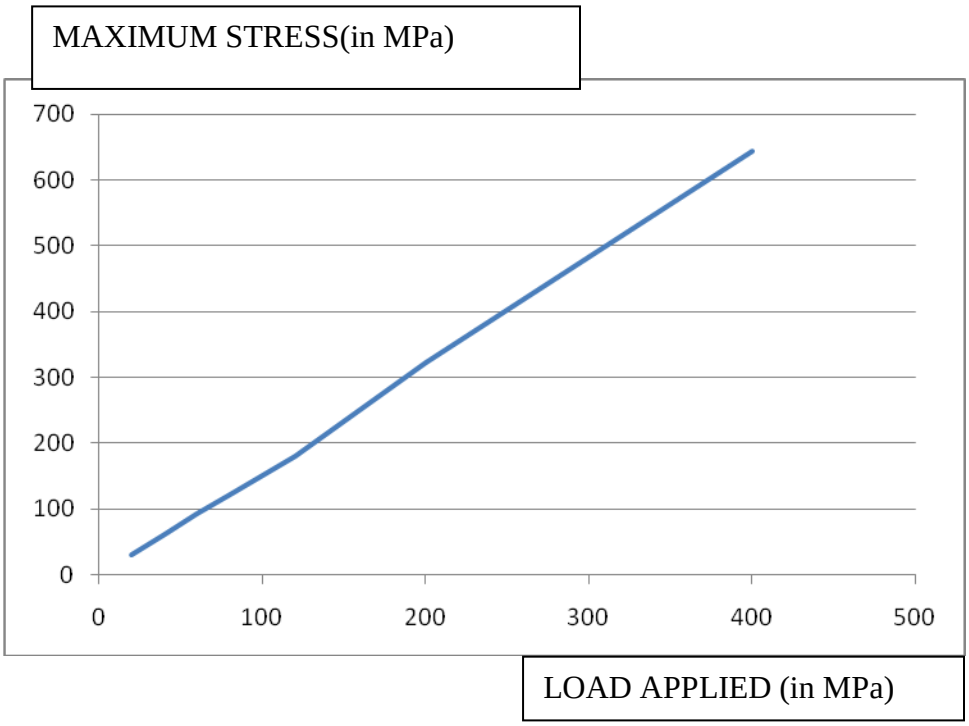
The maximum stress is in the stuffer yarn, this is the place where fabric will start to break. The image obtained from ansys simulation given in Fig. 5.7 shows stress distribution in the unit cell. The simulated value of maximum stress at different loads is given in Table 4. The stress-strain behaviour obtained in FEM simulation is given in Fig. 5.8, which shows that the relation is almost linear.

Table 4: Simulated value of maximum stress

Pressure applied (in MPa)	Maximum stress (in MPa)
20	31.12
40	61.56
60	91.78
80	122.53
120	181.23
200	322.31
400	644.18
1790	3122.23



5.7 Stress distribution.



5.8 Simulated stress analysis.

5.3.1 Experimental results

Sample size

Length= 250mm, Width = 25mm and Thickness = 1.87mm

Table 5: Load applied

Sample No.	Load (in kg)
1	893
2	1024
3	946
4	976
Avg.	959.74

So, the average breaking stress = 201.186 MPa

Ideally the break should occur at ultimate tensile stress. However, in this experiment it appears earlier due to various type of failure like fatigue, manufacturing errors, corrosion etc.

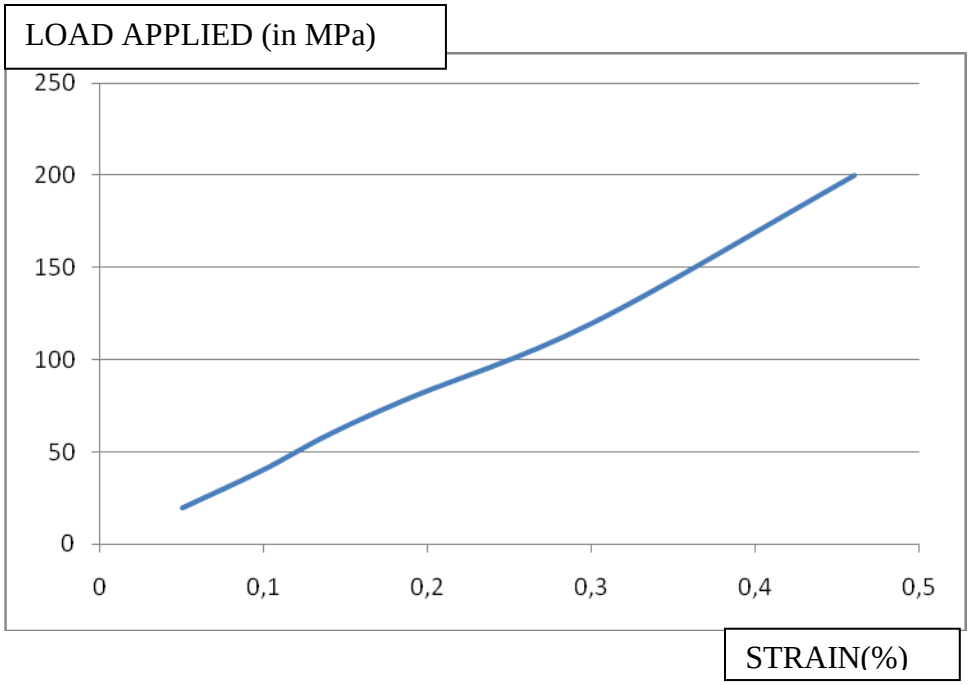
5.3.2 Deformation

The deformation graphs in Fig. 5.9 & 5.10 show maximum displacement of an element. With this maximum displacement, strain is calculated and the result is shown in Table 6.

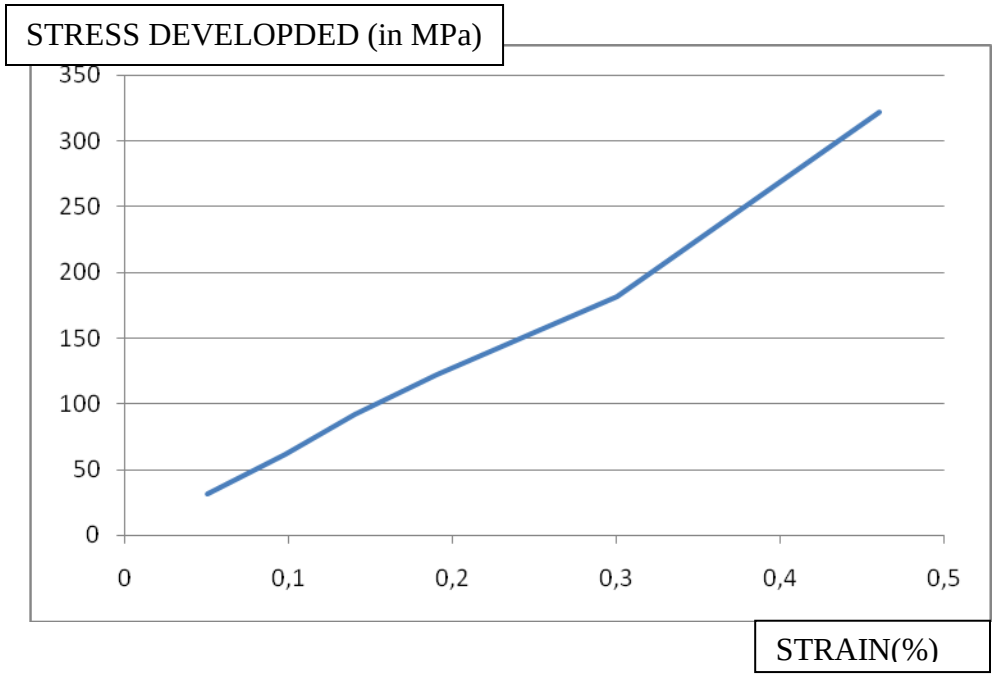
Table 6: Strain rate

Pressure applied (in MPa)	Strain (in %)
20	0.05
40	0.098
60	0.14
80	0.19
120	0.30
200	0.46

.

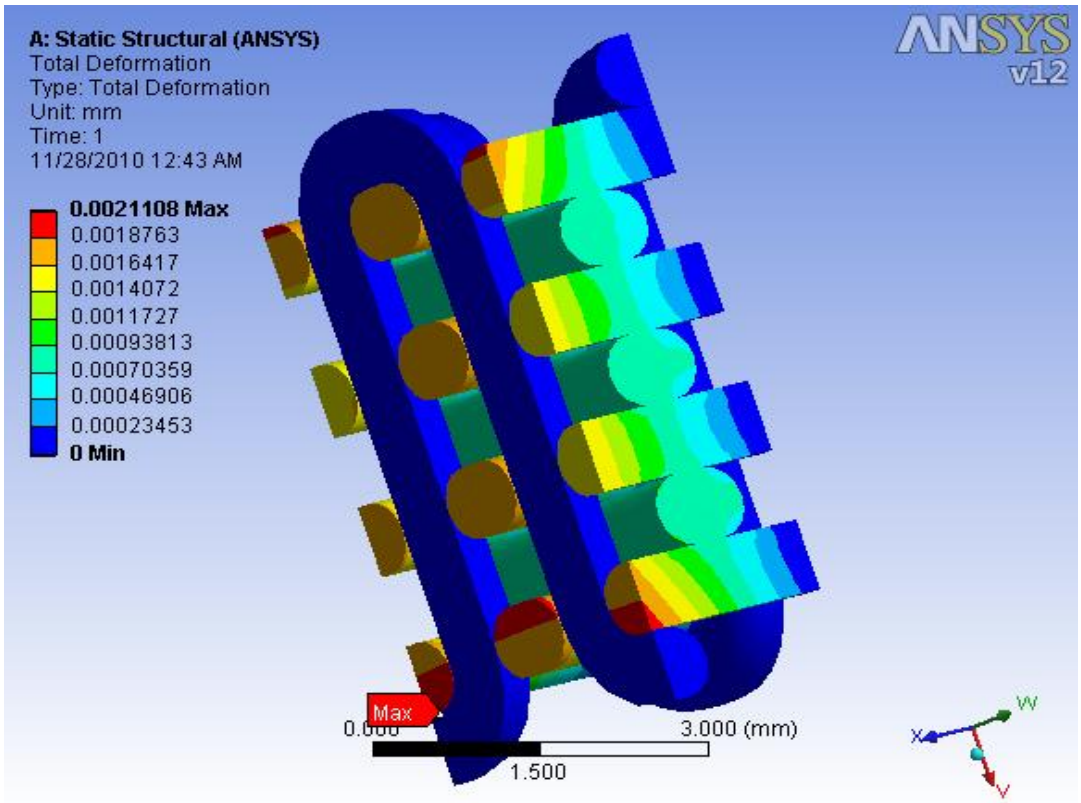


5.9 Applied load vs strain %.



5.10 Stress strain behaviour.

Fig. 5.11 shows the total deformation of the unit cell.



5.11 Total deformation.

5.4 Conclusion

The model is successful to simulate the tensile properties of orthogonal fabrics. The model can be improved by incorporating fibre to fibre friction through introducing appropriate linking elements. Other mechanical properties such a compressive strength, shear stress, and bending rigidity can be tested. Fabric with similar yarn characteristics and fabric parameters can be produced to validate the results. The spaces between the yarns can be filled with the elements with the properties of required matrix, in order to conduct tests on a unit cell of composite.

Chapter 6: Characterization of woven fabric properties

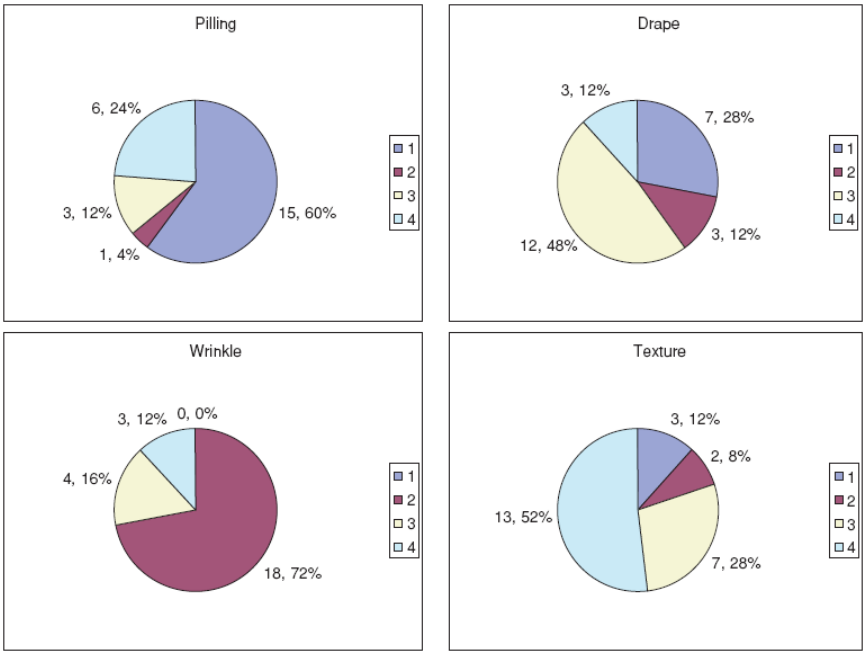
6.1 Objective measurement of fabric appearance using digital image processing

Fabric appearance is very essential for characterizing and determining the acceptability of textile products. Drape, pilling, texture and wrinkle are recognized as major aesthetic attributes of a woven apparel fabric and measured by the digital image processing technique. An integrated appearance index is estimated from these attributes after judiciously evaluating the weightage of individual parameter with an expert opinion. It has a good correlation with some of the existing subjective methods of analysing fabric appearance.

As standards of living continue to improve, aesthetic characteristics of clothing become a primary consideration in determining serviceability and longevity of apparel fabrics. Apparel and household goods are often discarded for no other reason than that the fabrics lose aesthetic appeal. Fabric appearance is normally evaluated from the traditional appearance attributes such as wrinkling, staining, creasing, texture, pilling, drapes and colour. Most of these attributes are measured using subjective methods which lack reproducibility and often cause controversy due to large variation in perception and skill of the evaluator. Moreover, there is no method available which can combine all aesthetic attributes to express the fabric quality from appearance point of view. In this work a computer vision system is proposed to measure and integrate most important aesthetic attributes of an apparel fabric such as pilling, drape, texture and wrinkle so as to develop an index called fabric appearance index (FAI).

The appearance of a fabric mainly depends on the fabric design and characteristics of raw material used for it. The design of a fabric could be an artistic design and/or engineering design. The artistic design includes weave structure, pattern and colour of the material whereas the engineering design is mainly concerned with constructional details. The weave design is also an integral part of the engineering design. However, the colour selection for a given end use mainly depends on the user’s choice. The weave design, pattern and fabric sett combined together attribute to texture of the cloth. Material characteristics along with engineering design specification determine fabric mechanical prosperities. The properties which directly linked to

the aesthetic appearance are therefore drape (mechanical properties), texture (constructional parameters), wrinkle (irregular surface deformations) and pilling (surface abrasion).



6.1 Contribution of appearance attributes on total appearance of fabric

Each of these four parameters is quantified based on scientific principles using digital image processing and integrated together to estimate a parameter called fabric appearance index (FAI) as follows:

$$\mathrm{FAI} = \sum_{i=1}^{n} A_i W_i \qquad (1)$$

The image processing technique is successfully used for objective measurement of fabric appearance. Drape, wrinkle, pilling and texture characteristics of a fabric are considered the major attributes of fabric appearance. These attributes are objectively evaluated by developing suitable image processing software and summed up at a suitable proportion suggested by a team of experienced fabric technologists to derive an index called fabric appearance index (FAI). The individual attribute measured by the image processing method holds very good correlation with

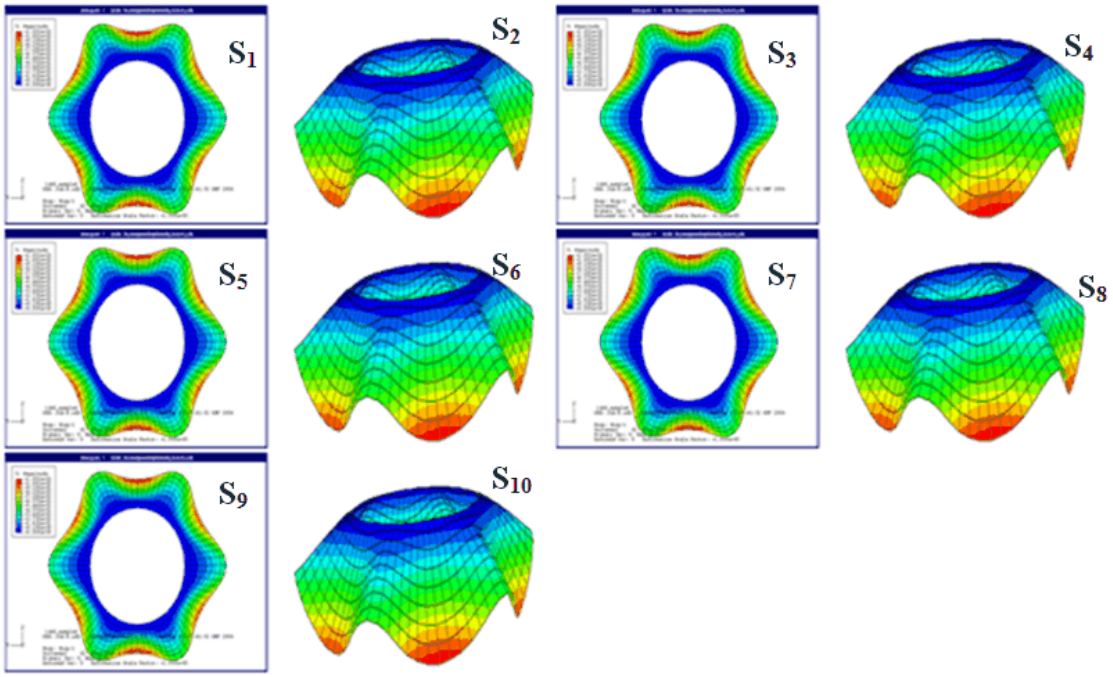
the conventional method of measurement. The newly developed appearance index also gives a very strong correlation with overall appearance of the fabric subjectively assessed by the experts.

6.2 Prediction of fabric drape behavior using finite element method

In this study, an alternative instrument with customized software is developed to measure the planner (2D) and spatial (3D) parameters of fabric drape. The principle of software is based on the digital image processing algorithm. This image processing based instrument along with customized software is capable of measuring the drape coefficient and the newly defined drape parameters. These newly defined parameters are drape distance ratio (DDR), fold depth index (FDI), amplitude and number of nodes (N). The reason for these additional drape parameters are for the complete understanding of the drape profile. This proposed measurement system is verified by comparing the drape coefficient results with the traditional drapemeter. The comparison of results shows excellent agreement with the traditional results. The advantage of this instrument is the ease of operation as this method does not require much time and skill. This instrument is also capable of measuring the newly defined shape parameters for better understanding of the drape profile.

Apart from accurate measurement, a trial has also been made to predict the various drape parameters by different techniques. Finite element method has been used for the prediction of the drape parameters. Finite element analysis is carried out by the commercial package “ABAQUS”. The standard procedure has been followed for the modeling and analysis of the results. The results obtained from this model are compared with results estimated by digital image processing technique and cusik method for the verification of models. The correlation between digital image processing and finite element analysis gives very good result.

The five drape parameters such as drape coefficient (DC), drape distance ratio (DDR), fold depth index (FDI), amplitude and number of nodes (N) are calculated with consideration of non-linear relationship between the input fabric mechanical properties with the various fabric drape parameters.



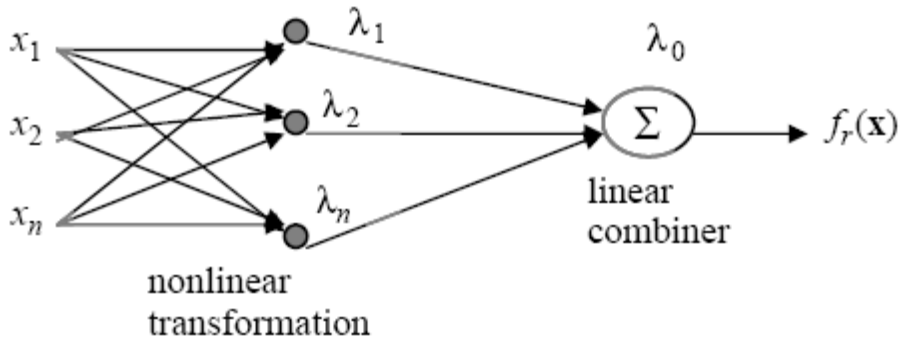
6.2 FEM simulation of drape profiles

6.3 Artificial neural network-based prediction of aesthetic and functional properties of woven fabrics

An engineered approach to fabric development is described in which a radial basis function network is trained with worsted fabric constructional parameters to predict functional and aesthetic properties of fabrics. An objective method of fabric appearance evaluation with the help of digital image processing is introduced. The prediction of fabric properties by the network with changing basic fiber characteristics and fabric constructional parameters is found to have good correlation with the experimental values of fabric functional and aesthetic properties. The radial basis function network can successfully predict the fabric functional and aesthetic properties from basic fiber characteristics and fabric constructional parameters with considerable accuracy. The network prediction is in good correlation with the actual experimental data. There is some error in predicting the fabric properties from the constructional parameters. The variation in the actual values and predicted values is because of small sample size. Moreover, the properties of worsted fabrics are greatly influenced by the finishing parameters which are not taken into consideration in the training of the network. Prediction performance can be further improved by

including these parameters as input, during the training phase. In few cases, the network has predicted contradictory trends, which are found difficult to be explained.

In this study, 58 worsted suiting fabric samples were tested for their constructional parameters as well as aesthetic and functional properties. Aesthetic properties include total appearance value, fabric appearance index (FAI) and drape coefficient. The functional properties are restricted to handle and comfort properties like total hand value, formability, air permeability, relative water vapour permeability and thermal insulation. Functional properties are taken from KES and fabric assurance by simple testing (FAST) equipment, where as for appearance an image processing-based system was developed for evaluation of FAI by objective measurement of appearance attributes. A radial basis function neural network model was used for prediction of the fabric appearance values and comfort properties using fabric constructional parameters and some primary fiber mechanical properties as input parameters of the network.



6.3 Architecture of radial basis function neural network model

It can be concluded that the radial basis function network can successfully predict the fabric functional and aesthetic properties from basic fiber characteristics and fabric constructional parameters with considerable accuracy. The network prediction is in good correlation with the actual experimental data. There is some error in predicting the fabric properties from the constructional parameters. The variation in the actual values and predicted values is because of small sample size. Moreover, the properties of worsted fabrics are greatly influenced by the finishing parameters which are not taken into consideration in the training of the network.

Prediction performance can be further improved by including these parameters as input, during the training phase. In few cases, the network has predicted contradictory trends, which are found difficult to be explained.

6.4 Fabric drape and mechanical properties

Today's consumers are more quality conscious than ever before. They now prefer to have less clothing but of higher quality. Among various properties, aesthetic characteristics of clothing have become the primary consideration in determining serviceability of apparel fabrics. Normally fabric appearance is determined from traditional attributes like wrinkle, crease, texture, pilling, colour and drape etc. Among all these parameters drapability of a fabric plays an important role, particularly when the garment is required to provide an elegant look.

There is a strong correlation (R^2 = 0.93) between fabric bending rigidity and drape coefficient value. Negative correlation is is observed between bending rigidity and number of nodes. In most cases a higher drape coefficient is accompanied by fewer nodes. Wool and its blends give nodes between 4 and 6 depending on fabric areal density and flexural rigidity. There is a direct relationship between fiber bending rigidity and fabric bending rigidity. Fibers having higher crimp do have a lower bending rigidity, reflected in low bending rigidity of fabric resulting in low drape coefficient.

A higher formability is normally accompanied with a lower drape coefficient value. It is due to the fact that formability depends on bending as well as longitudinal compression/tensile properties. A good correlation between tensile energy and drape coefficient indicates that a fabric with higher tensile energy is less susceptible to draping or falling from the edge of a contour. A higher extensibility always favours the folding and hanging of fabric at the edges of the platform and thus a smaller shadow is formed giving lower drape coefficient.

The shear rigidity of worsted fabrics shows very good correlation (R^2 = 0.91) with the drape coefficient values. A higher rigidity to tangential deformation prevents folding or hanging and thus a high drape coefficient is obtained. A highly compressible fabric does have high compressional energy and can absorb/withstand compressive loads to a greater extent at the deforming points. This prevents the folding at the deforming points and resulting in a higher drape coefficient value.

6.5 Carpet grading by digital processing

Appearance, a key attribute of carpets, is often considered as more important than its durability. Of particular concern now is the rate at which a carpet looses its original appearance due to fiber shedding, abrassive wear, shading, soiling, development of surface roughness and colour change. Most of these factors influence the perceived texture of the pile.

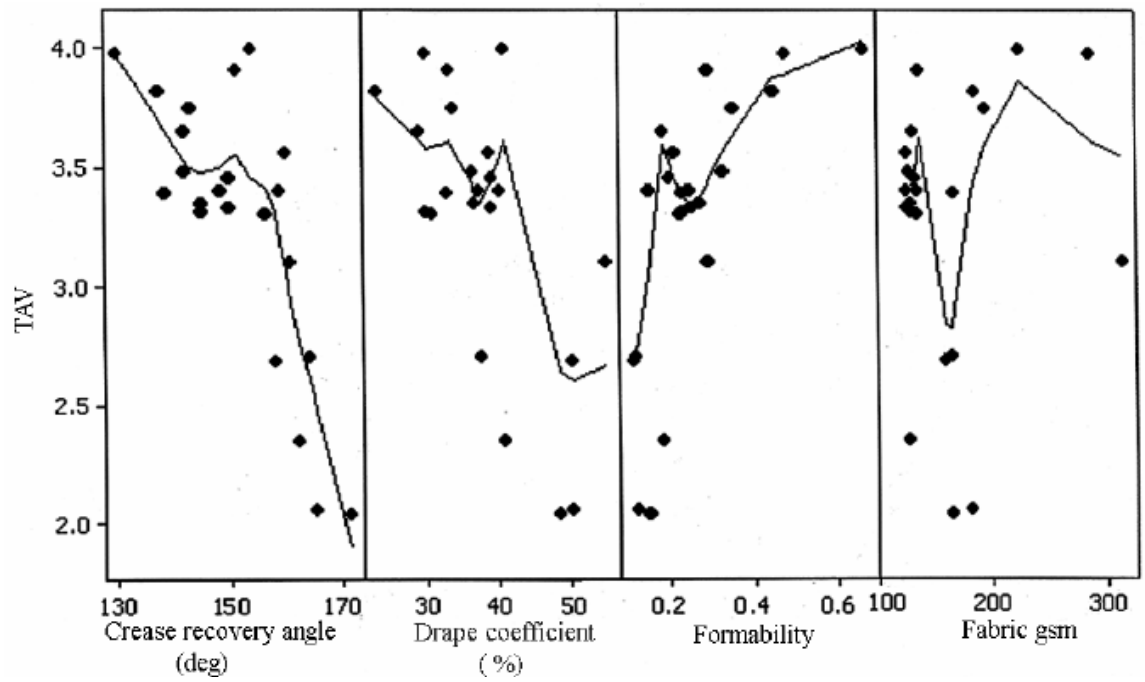
In assessing carpet serviceability, appearance retention is a key attribute. Different structural prameters like pile density, pile orientation etc. affect the aesthetic properties of a carpet, so an objective method was developed to evaluate these parameters by image processing.

It has been found that with increasing strokes of dynamic loading, the piles get flattened and absolute value of pile disorientation increases. It is also observed that with increasing strokes, the value of energy decreases showing poorer texture. The digital image processing based system developed to measure the aesthetic properties of carpet shows good correlation with the expected results and the subjectively evaluated grades. Hence, the technique can be used effectively to evaluate carpets objectively.

6.6 Effect of crease behaviour, drape and formability on appearance of light weight worsted suiting fabrics

Fabric appearance is a major criterion for its consumer acceptance. Fabric tailorability depends largely on its formability. Thus, the formability is a major determiner of the final garment appearance. Pressing performance is yet another important aspect for good aesthetic appeal of a suit. Crease recovery angle can be treated as an index to predict the pressing performance of fabrics. Apart from crease retention property, drapability of a cloth significantly contributes to graceful appearance of a suiting cloth. This is strongly related to the low-stress mechanical properties of the fabric, like bending rigidity. Thus, the measurement of drape and its correlation to the total appearance value of the fabric would make the understanding of the inter-dependence of these parameters more relevant and object oriented. A shift towards the use of light weight suiting fabrics has been observed globally for almost a decade. When fabric areal density decreases substantially, the major appearance attributes which are normally secondary determinants of fabric mechanical properties are significantly affected. Because these attributes, such as drape, crease recovery angle and wrinkle, have direct influence on human vision

perception, it is very crucial to study the inter-dependence of creasing, drape and formability to develop fabrics of acceptable appearance level. Creasing behaviour of conventional worsted fabrics has already been established by several researchers. However, the present trend of light weight suiting fabrics with introduction of various natural fibers has made it necessary to investigate the formability as well as aesthetic properties of these new fabrics. This concerned study was aimed at examining the use of simple measurement of fabric crease recovery angle and drapability to predict the aesthetic performance of worsted fabrics or the suit made there of. As pressing performance has a greater influence on garment appearance for light weight fabrics as compared to heavy weight fabrics, other fabric properties which may influence tailorability have also been examined.



6.4 Correlation of fabric parameters with TAV (Total Appearance Value)

It is observed that irrespective of the composition of the fabrics the crease recovery angle is negatively related to the total appearance value. This indicates that the lower crease recovery angle or high crease retention is related to better appearance. The fiber properties play a major role in determining crease behaviour and appearance of fabrics. Basically, creasing and recovery

are the functions of fiber bending rigidity. However, the deviation is observed in the linen blended fabrics. This is because of very high degree of orientation of polymeric chains in the fiber structure, leading to a notoriously bad creasing property. For worsted fabrics a lower drape coefficient is favorable with respect to appearance. Drape coefficients of 30-40% are most common in these kinds of fabrics. However, too low value of drape coefficient sometimes may prove detrimental to fabric appearance. Again the fiber properties can be very well correlated to the drape behaviour. Coarser fibers have higher bending rigidity and lead to higher drape coefficient of fabric but poor appearance value. As the appearance of fabric depends on several other parameters, a more intensive study of fiber properties is essential. Thus, drape alone cannot be considered as a deciding factor for fabric appearance. A higher formability is required for better appearance value. This may be attributed to the fact that in case of suiting fabrics a graceful appearance resulting from slightly higher bending rigidity is preferable.

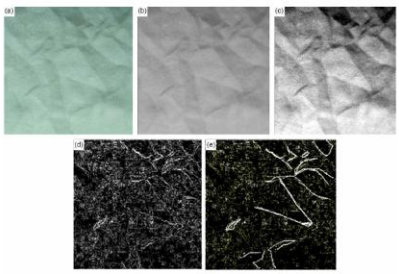
Finer fibers for the same linear density of yarn facilitate for more number of fibers in the crosssection. Thus, a higher specific surface area is available for fiber interaction and this generates more cohesivity between fibers, leading to higher bending rigidity. This increases fabric formability and at the same time a better appearance is achieved. An optimum warp formability of 0.4-0.6 is most favorable with respect to worsted suiting fabrics appearance. In case of very light constructions, sometimes a formability lower than 0.25 is obtained which may prove detrimental to appearance.

6.7 Measurement of fabric wrinkle using digital image processing

Wrinkle formation is one of the most important parameters which decides the aesthetic appearance of the fabric. Easy care garments are often made from fabrics processed by wrinkle-resistant treatments. This property of fabric is reflected in the criteria of a consumer's choice through the appearance of fabrics during ordinary wear. Wrinkles are defined as undesirable creases or short and irregular deformations in a fabric. These deformations depend on the viscoelastic properties of the fabric. There are three dimensional versions of creases, formed when legs and sleeves are bent along the opposite direction and kept in such a position for either a long period of time or intermittently.

The most standardized methods which are widely used in the industry for the evaluation of fabric wrinkle are AATCC and ASTM D-123. Technically these standardized methods are always based on the visual assessment of multiple observers. Hence, there has been a need for instrumental test methods. The subjective method allows observers to assign the numerical grade or rating of the specimen which most nearly matches the wrinkling characteristics of a photograph or replica. Though these methods are relatively simple to conduct and easy to perform but these are subjective, time consuming, slow and sensitive to biases in perception. Also, the standard replicas may not have equal intervals in the degree of wrinkling. This visual evaluation is unreliable and time inefficient. In particular, a specimen's embedded color and/or pattern does not result in consistent evaluation of fabric wrinkling . Objective and automated fabric evaluation methods are needed as alternatives to existing visual inspection methods. On the basis of the previous research work in computer application to the textile products, it is realized that an imaging system will be the best solution for objective evaluation of the fabric wrinkling. Computer vision technology provides one of the best solutions for the objective evaluation of fabric aesthetic properties. Wrinkle slope, height, density and isotropy index are determined to distinguish various wrinkled surfaces quantitatively. These parameters in fabric are measured using the coordinates.

This research work was, therefore, aimed at designing and developing a system to measure the surface characteristics of a fabric, based on the method of image processing. Various samples have been evaluated with the system developed and the results are compared with the conventional AATCC method.



6.5 Images of wrinkled fabric after different steps of processing

By comparing subjective ratings with those obtained by digital image processing, it was found that the two sets of ratings are comparable to each other. Correlation analysis is used to determine the strength of linear relationship of these two evaluation systems. An excellent

correlation (R^2=0.8401) is observed between subjective method and digital image processing based system.

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