STRUCTURAL DESIGN ENGINEERING OF WOVEN FABRIC BY SOFT COMPUTING: PART II - NON-PLAIN WEAVE

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Abstract:

The maximum weavability limit is predicted by extending Peirce's geometrical model for non-plain weaves for circular and racetrack cross-sections by soft computing. This information is helpful to weavers in that attempts to weave impossible constructions can be avoided, thus saving time and money. It also helps in anticipating difficulties in weaving and in taking the necessary steps in warp preparation. The relationship between the cover factors in the warp and weft directions is demonstrated for circular and racetrack cross-sections 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 the scope of the fabric designer.

Key words:

Non-plain weave, circular cross-section, race track cross-section, weave factor.

Introduction

In Part 1, all of the structural possibilities for plain weave only were discussed. Jammed structures and fabrics in which the crimp in one direction is zero (or maximum crimp in one direction with zero crimp in the cross-thread) was the limiting structure. In order to be able to visualise beyond these conditions, for example to increase mass and fabric cover beyond those possible in plain weave, one has to consider non-plain weave jammed structures, which extend the range of plain weave jammed structures beyond their limit.

The first study of fabric structural design was started in 1937 by Peirce [1], which led to Peirce's model of plain-weave fabrics with a circular yarn cross-section. He also proposed a fabric model with an elliptical yarn cross-section. In 1958, Kemp proposed a racetrack model [2]. Hearle and Amirbayat proposed lenticular geometry for the calculation of fabric mechanics by the energy method in 1988 [3]. Many studies related to fabric mechanical properties on the basis of the fabric structural model were carried out by Grosberg [4], Backer [5], and Postle [6]. Lindberg [7] extensively studied fabric mechanical behaviour related to tailorability. Subsequently, a sophisticated measurement system of fabric mechanical properties was developed by Kawabata and Niwa [8], which is called the KES-FB system. Another fabric mechanical measurement system called FAST was developed by CSIRO in Australia [9]. Recently new objective measurement systems [10] such as the Virtual Image Display System (VIDS) and the Fabric Surface Analysis System (FabricEye®) have been developed for the analysis of fabric geometrical properties. On the other hand, there are currently many CAD systems [11] related to fabric design such as weave construction, colour and pattern. There is also a pattern design CAD [12,13] including a visual wearing system (VWS) for garment designers. However, there is no fabric structural design system related to the decision on fabric density according to fibre materials, yarn linear density and weave pattern. Therefore, a database system which can easily calculate warp and weft densities according to the various yarn counts, weave constructions and materials is required through the analysis of a design plan for nylon and polyester fabrics [14,15].

The maximum number of ends and picks per unit length that can be woven with a given yarn and weave defines the weavability limit. Most of the work in this area has been done using empirical relationships [16, 17]. The geometrical model for plain weave is very useful in predicting this limit for a given warp and weft yarn diameter (tex) using jammed conditions. The maximum weavability limit is predicted by extending Peirce's geometrical model for non-plain weaves for circular and racetrack cross-sections by soft computing. This information is helpful to weavers in in that attempts to weave impossible constructions can be avoided, thus saving time and money. It also helps in anticipating difficulties in weaving and in taking the necessary steps in warp preparations. Soft computing enables the fabric designer to widen the scope of selecting fabric parameters for innovations. Maximum weavability is affected by the yarn diameters and the weave. The yarn diameter is affected by several factors such as fibre type, blend composition and spinning technology. Therefore, the correct estimation of yarn diameter is critical for predicting weavability. Similarly, non-plain weaves need to be represented by suitable numerals to facilitate soft computing. This is done by using the weave factor concept.

Methodology

Estimation of yarn diameter

Two important geometrical parameters are needed for calculating weavability in general. These are yarn diameter and weave factor. Yarn diameter in terms of linear density in tex for a general case is given as:

$$d = \frac{1}{280.2}\sqrt{\frac{T}{\phi \rho_f}} \qquad [1]$$

where:
d = yarn diameter (cm) ,
T = yarn linear density (tex, i.e. g/km),
ρ_f = fibre density (g/cm^3) ,
ρ_y = yarn density (g/cm^3),
ϕ = yarn packing coefficient.

This equation for yarn diameter is applicable for any yarn type and fibre type. The packing factor depends on fibre variables such as fibre crimp, length, tex and cross-section shape. For blended yarns, the average fibre density is given by the following equation

$$\frac{1}{\rho} = \sum_{1}^{n} \frac{p_i}{p_{fi}} \quad [2]$$

where:
ρ = average fibre density,
p_i = weight fraction of the ith component,
p_{fi} = fibre density of the ith component and,
n = number of components of the blend.

Estimation of Weave Factor

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

$$M = \frac{E}{I} \quad [3]$$

where:
E - the number of threads/repeat,
I - number of intersections/repeat of the cross-thread.

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

Table 1. Weave factor for standard weaves

Weave	E_1	I_1	E_2	I_2	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/repeat in the warp/weft direction, I_1 and I_2 are the intersections for the weft and warp threads.

Example:

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

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 by:

$$M = \frac{\sum E}{\sum I} \quad [4]$$

Results and discussion

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

The weave factor is useful in translating the effect of weave on fabric properties. For circular cross-section yarns, the general equation for jammed cloth is desired.

Thread spacing Pt1 for a non-plain weave per repeat is shown in Figure 1 and is given as:

$$P_{t1} = I_2 p_1 + (E_1 - I_2) d_1 \quad [5]$$

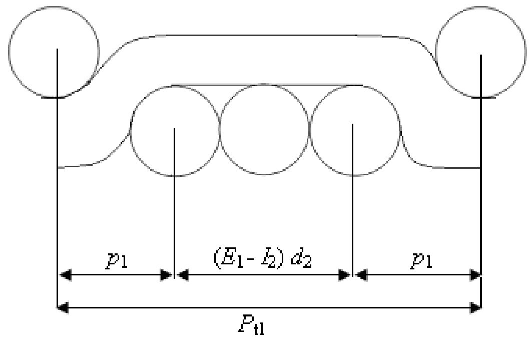

Figure 1. Configuration of a jammed structure for a 3/1 weave (cross-section along warp)

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

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

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

$$\frac{p_1}{D} = M_1 \frac{\overline{P_1}}{D} - (M_1 - 1)\frac{d_1}{D} \quad [6]$$

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

where, $\beta = d_2/d_1$.

Similarly, by interchanging suffix 1 and 2, we get

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

$$\frac{p_2}{D} = M_2 \frac{\overline{P_2}}{D} - (M_2 - 1)\frac{\beta}{1+\beta} \quad [7]$$

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 (K1 and K2):

$$\sqrt{1 - \left[\left(\frac{28.02\sqrt{\phi \rho_f} M_1}{K_1} - (M_1 - 1)\right)\frac{1}{1+\beta}\right]^2} + \sqrt{1 - \left[\left(\frac{28.02\sqrt{\phi \rho_f} M_2}{K_2} - (M_2 - 1)\right)\frac{\beta}{1+\beta}\right]^2} = 1 \quad [8]$$

Relationship between fabric parameters for circular cross-section yarns for different weaves

The effect of weave on jammed structures was examined using the above equations for plain, twill, basket and satin weave. *M*, the weave factor value (average float length) for these weaves, is 1, 1.5, 2 and 2.5 respectively, for the discussion which follows. The flowchart of the algorithm used to determine the relationship between various parameters is shown in Figure 2.

Figure 3 shows the relationship between p_{1avg}/D and p_{2avg}/D. It can be seen that with an increase in float length, the sensitivity of the curve decreases in general. Also, the range of p_1/D and p_2/D values is reduced. This means that a weave with a longer float length decreases the flexibility for making structures.

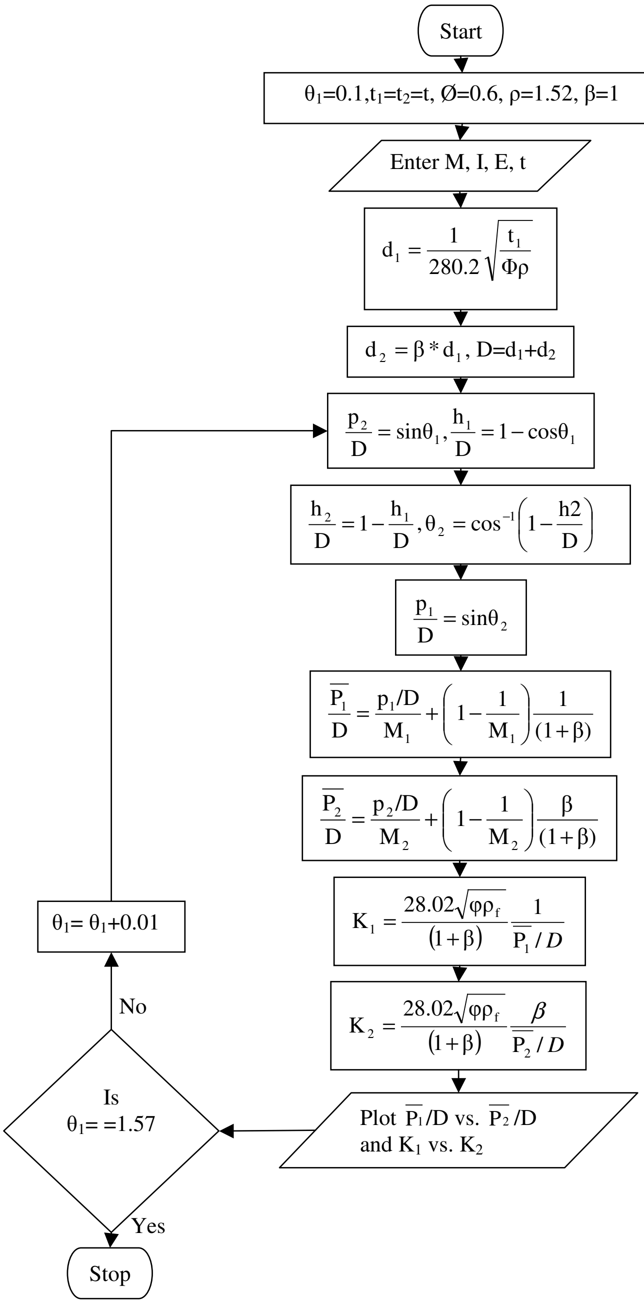

Figure 2. Flowchart for jammed structures to determine thread spacing and cover factor in circular cross-section yarns

Figure 4 shows the relationship between the warp and weft cover factor for a circular cross-section. It is interesting to note that the behaviour is similar for different weaves. However, with the increase in float, the curve shifts towards higher values for the weft cover factor. It should be noted that the behaviour shown in this figure is for virtual fabrics. In real fabrics, a jammed structure is unlikely to retain a circular cross-section.

Equation for a jammed structure for a racetrack cross-section in terms of weave factor

In jammed fabrics, the yarn cross-section cannot remain circular. It is easy to modify the geometry for a circular cross-section by considering a race track cross-section. Figure 5 shows the configuration of a jammed structure for 1/3 weave

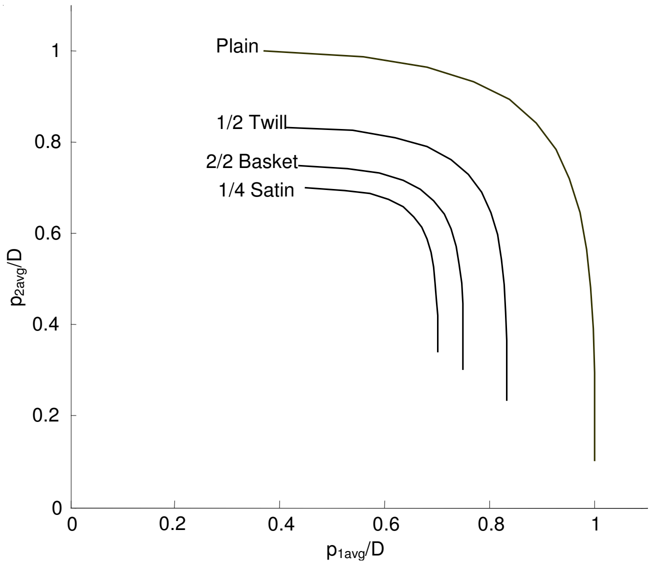

Figure 3. Relationship between average thread spacing in the warp and weft directions for a jammed fabric (circular cross-section, yarn tex =30, Ø=0.6, ρ=1.52)

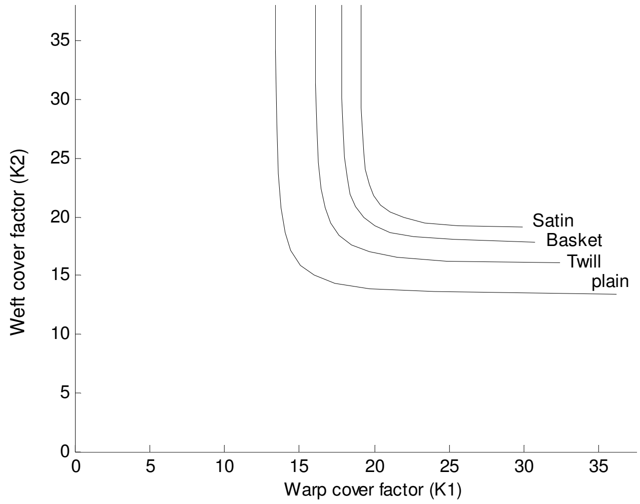

Figure 4. Relationship between the warp and weft cover factor for a jammed fabric (circular cross-section, yarn tex =30, Ø=0.6, ρ=1.52)

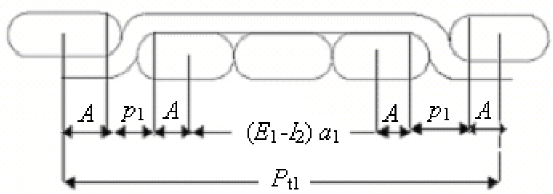

Figure 5. Configuration of a jammed structure for 3/1 weave (cross-section along the warp)

for with a racetrack cross-section along the weft direction of the fabric.

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

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

$$P_{t1}=I_2 p_1+(E_1-I_2)a_1+4\left(\frac{a_1-b_1}{2}\right) \quad [9]$$

Similarly, $P_{t2}=I_1 p_2+(E_2-I_1)a_2+4\left(\frac{a_2-b_2}{2}\right)$ [10]

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 the racetrack cross-section.

The average thread spacing,

$$\overline{P_1} = \frac{p_1}{M_1} + \left(1-\frac{1}{M_1}\right)a_1 + \frac{4}{M_1 I_2}\left(\frac{a_1-b_1}{2}\right) \quad [11]$$

Similarly,

$$\overline{P_2} = \frac{p_2}{M_2} + \left(1-\frac{1}{M_2}\right)a_2 + \frac{4}{M_2 I_1}\left(\frac{a_2-b_2}{2}\right) \quad [12]$$

As such, the analysis of circular thread geometry can be applied for the intersection zone of the racetrack cross-section,

$$L_1 = 4\left(\frac{a_2-b_2}{2}\right) + (E_2 - I_1)a_2 + I_1 \times l_1 \quad [13]$$

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 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 racetrack cross-section and is similar to *p/D* for a circular cross-section. As such, the values of the *p/D* ratio from Figure 3 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:

$$\sqrt{1-\left(\frac{28.02\sqrt{\phi\rho_f}M_1}{(1+\beta)K_1}\sqrt{1+\frac{4}{\pi}\left(\frac{1}{e}-1\right)} - \frac{2(1-e)}{e(1+\beta)I} - \frac{(M_1-1)}{e(1+\beta)}\right)^2} + \quad [14]$$

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

Relationship between fabric parameters in the racetrack cross-section

The flowchart of the algorithm used to determine thread spacing and cover factor in a jammed racetrack cross-section is shown in Figure 6. The relationship between fabric parameters such as p2 and p1, p1 and c2 for the racetrack cross-section in the jammed condition was studied. Figure 7 shows that the behaviour between this 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 behaviour of real fabrics.

Figure 8 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

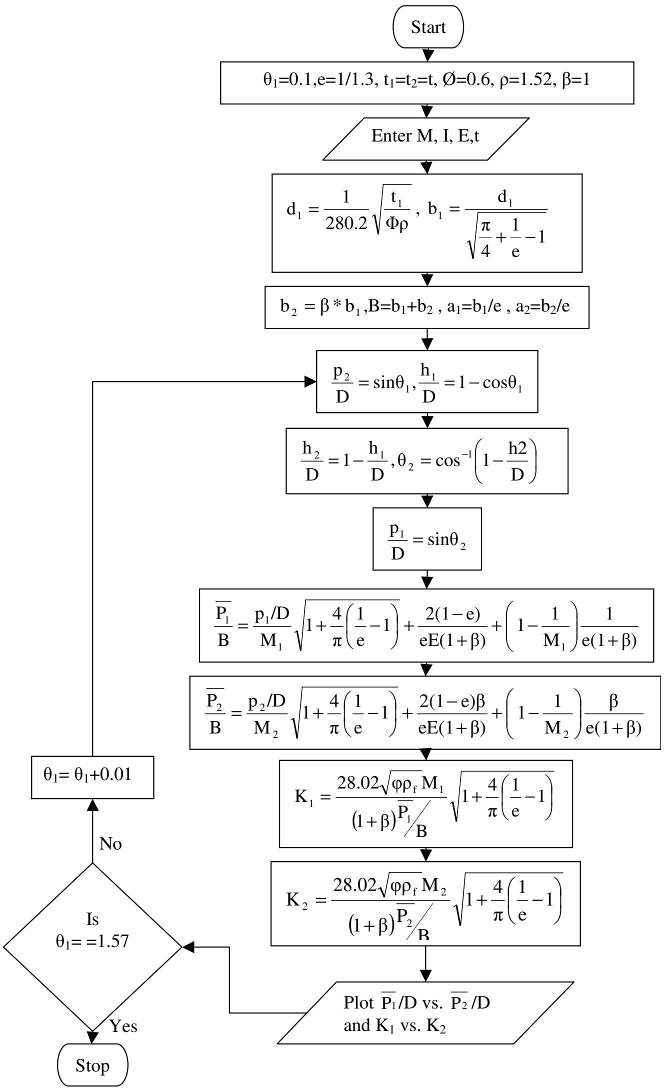

Figure 6. Flowchart for jammed structures to determine thread spacing and cover factor in a racetrack cross-section

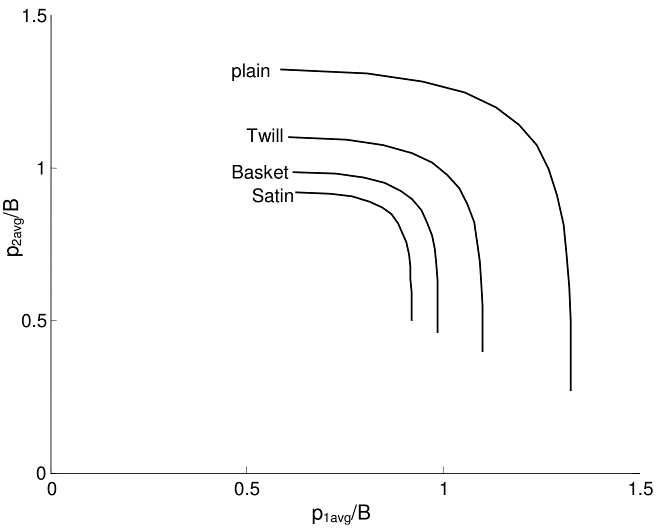

Figure 7. Relationship between average thread spacing in warp and weft for a jammed fabric (racetrack cross-section, β=1, yarn tex =30, Ø=0.6, ρ=1.52)

what was observed with a circular cross-section. An increase in float length decreases the scope of cover factors. From these

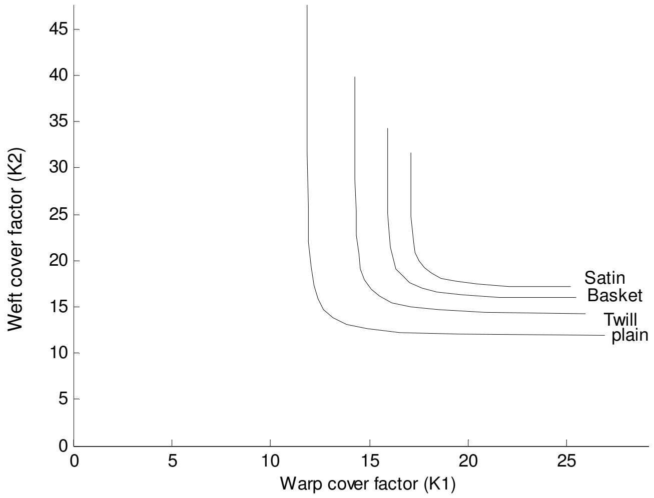

Figure 8. Relationship between warp and weft cover factor for a jammed fabric (racetrack cross-section, yarn tex =30, Ø=0.6, ρ=1.52, β=1)

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

$$d^2 = b^2\left[\frac{\pi}{4} + \left(\frac{1}{e} - 1\right)\right] \text{ and } \frac{b_2}{b_1} = \beta \quad [15]$$

Conclusion

The power of soft computing has been further demonstrated for non-plain weave fabrics. It is possible to predict the maximum threads per cm of a yarn spun from any fibre and the fabric made from any weave. The relationship between the cover factors in the warp and weft directions was demonstrated for circular and racetrack cross-sections for plain, twill, basket and satin weave fabrics. Non-plain weave fabric affords further flexibility for increasing fabric mass and fabric cover. As such, they enlarge the scope of the fabric designer.

References:

1. *F. T. Peirce, J. Text. Inst., 28, 3 (1937).*
2. *A. Kemp, J. Text. Inst., 49, 1 (1958).*
3. *J. W. S. Hearle and J. Amirbayat, J. Text. Inst., 79, 4 (1988).*
4. *P. Grosberg and S. Kedia, Text. Res. J., 36, 1 (1966).*
5. *S. Backer, Text. Res. J., 22, 10 (1952).*
6. *R. Postle, G. A. Carnaby and De S. Jong, "The Mechanics of Wool Structures", pp.307-365, Halsted Press New York, 1988.*
7. *J. Lindberg, B. Behre and B. Dahlberg, Text. Res. J., 31, 2 (1961).*
8. *S. Kawabata, R. Postle and M. Niwa, "Objective Specification of Fabric Quality, Mechanical Properties and Performance", The Textile Machinery Society of Japan, 1982.*
9. *N. G. Ly, D. H. Tester, P. Buckenham, A. F. Roczniok, A. L. Adriaansen, F. Scaysbrook and De S. Jong, Text. Res. J., 61, 7 (1991).*
10. *J. Hu, "Structure and Mechanics of Woven Fabrics", pp.91-186, Woodhead Publishing Limited, Great Abington, 2004.*
11. *http://www.i-designer.co.kr, i-Designer.*
12. *http://www.texclub.com, Texpro.*
13. *T. Harada and M. Saito, Sen-I Gakkaishi, 45, 305 (1986).*
14. *S. J. Kim, "Proceedings of 2nd International Fibre Symposium in Fukui", p.10, Japan, 2002.*
15. *S. J. Kim, "Proceedings of 3rd International Conference on Advanced Fibre/Textile Materials in Ueda", p.32, Japan, 2005.*
16. *J. B. Dickson, "Practical Loom Experience on Weavability Limits", Textile Research Journal, 24, No. 12, 1083 (1954).*
17. *A. M. Seyam, "The Structural Design of Woven Fabrics: Theory and Practice", Textile Progress, 31, No. 3 (2003).*

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