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Characteristics of Multi-axial Woven Structures

Abstract
This paper describes the modelling of the structure of multi-axial woven fabrics. The number of 4-, 5-, and 6-thread systems of a weave analogous to the plain weave was considered. In the case of woven fabrics with an even number of axes, structures of plain weave formed on the basis of homogenous and non-homogenous nets were analysed. A model was elaborated and a sample of a five-axial woven fabric was manufactured. The possibility of thickening the structure of multi-axial woven fabrics was analysed, accepting the value of the area cover factor as the measure of thickening.

Key words: *multi-axial woven structures, thread systems, thickening, interlacing, net.*

Introduction

It has been accepted that a flat woven product composed of at least three thread systems joined by interlacements is called a multi-axial woven structure [2, 7]. Designing such a structure lies in creating a net whose nodes are the points of intersection of not more than two threads, and next in introducing the interlacements. The net shows only the mutual thread displacement, i.e. the geometry, and presents it in the form of straight lines with directions which are in accordance with the directions of the structure's axes. The thickness of the threads is not taken into consideration at this stage of the design.

Considering the thread's spacing, the nets are divided into homogeneous and non-homogeneous. A homogeneous net is a net where each of the thread systems has a constant spacing. A non-homogeneous net is one where at least one thread system has a variable spacing. According to this accepted definition, a net which has a different but constant spacing of threads in each of the systems is deemed as homogeneous [25].

The way of interlacing the threads, which means the weave of the multi-axial woven fabric, has normally been determined along the thread of the system under consideration. A given thread may take the position 'over' (designation on the figures as 'o' or 'n') or 'below' ('b' or 'p') in relation to the threads of the remaining systems. Notwithstanding that the multi-axial woven structures have a construction which resembles flat plaits (braided structures), they are generally called multi-axial woven fabrics.

A multiaxial woven fabric can be characterised by the number of thread systems, the kind of net, the report, and the kind of thread interlacement, i.e. the weave. The weave report for a classical, two-axial woven fabric is the smallest number of warp and weft threads, after which the order of thread interlacement is repeated. For multi-functional woven fabrics, an analogue way of determining the report is impracticable, especially in the case of a larger number of thread systems. For example, for a six-axial woven fabric (e.g. with six thread systems), it should be necessary to state six report values. Therefore for multi-axial woven fabrics it has been accepted that a report is the smallest repeated element of the woven fabric's structure, consisting of an area determined by linear dimensions, such as its width *S* and height *H*. For example, a designation of the report of a multi-axial woven fabric is presented in Figure 1.

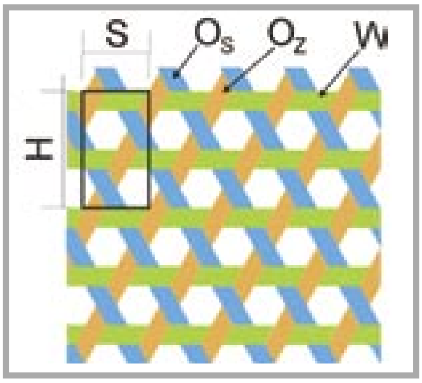

***Figure 1.** A tree-axial woven fabric; OS and OZ – warp threads, W – weft, S, H – width and height of the report; according to [6, 7].*

Structure of multi-axial woven fabrics

Three-axial woven fabrics have been long known, and are well described in the literature [2, 5, 6, 7, 10, 11, 12, 14, 15, 16, 20, 22, 23]. The information published about four-axial woven fabrics is significantly less [1, 19, 24], and is principally connected with methods of manufacturing. In the case of structures with a greater number of axes, practically no information exists in available publications, with the exception of papers written by the authors [4, 8, 9].

The configurations of threads were analysed in woven fabrics of a number of thread systems greater than three, which means clearances in the shape of polygons with the number of sides greater than four. It should be remembered here that a clearance is the element of a woven fabric's surface not filled with threads, determined by the thread system's spacing, and reduced by the transverse dimensions of the threads. In a classical woven fabric, the clearance has the shape

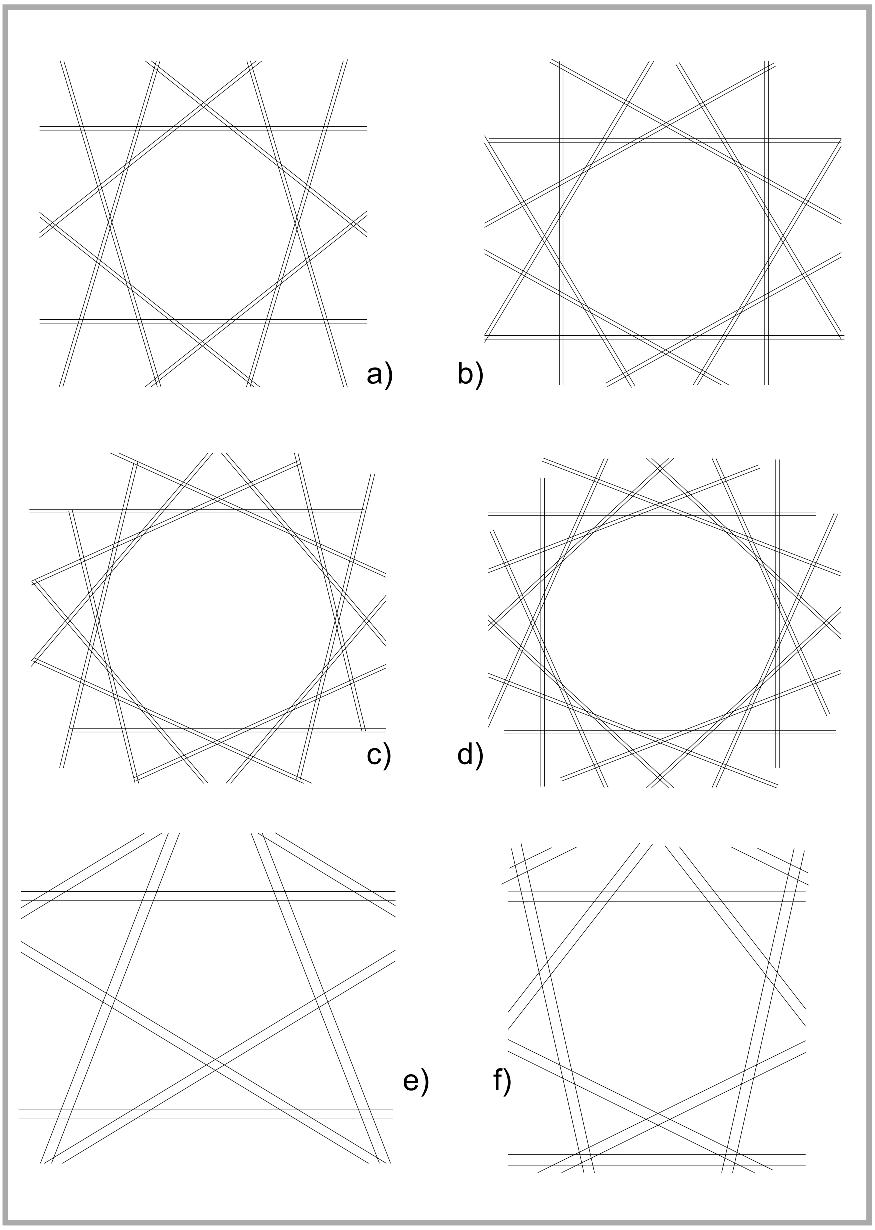

Figure 2. Constructional modules of multi-axial woven fabrics [21]; a) five-axial woven fabric with a clearance in the shape of a decagon, b) six-axial woven fabric with a clearance in the shape of a dodecagon, c) seven-axial woven fabric with a clearance in the shape of a fourteen-angle-polygon, d) eight-axial woven fabric with a clearance in the shape of a sixteen-angle-polygon, e) five-axial woven fabric with a clearance in the shape of a pentagon, f) seven-axial woven fabric with a clearance in the shape of a heptagon.

of a quadrangle, in a three-axial fabric the shape of a hexagonal. The element in the shape of a basic clearance of the woven fabric. together with the surrounding threads, is called the construction module. It may form the basis for modelling multi-axial structures. The Corel Draw program, which facilitates the creation of geometrical graphics, was used to determine the report's value of a multi-axial homogeneous woven fabric, constructed on the module of a homogenous polygon. Analyses carried out have demonstrated that in many cases determining the weave report of multi-axial woven fabrics is very difficult.

It appears that for some polygons (clearance shapes) the repeatability of the modules has not been obtained. Distinguishing the reports for a decagon, the fourteen- and sixteen-angle polygon, and even for a heptagon was impossible. The repeatability of modules systems (reports) on modelled structure fragments including up to 300 modules could be stated only for a dodecagon, i.e. a six-axial woven fabric [3, 21]. Examples of constructional modules are presented in Figure 2.

To summarise, the basic criterion for dividing the multi-axial structures is the number of thread systems (axes); the next criteria are the kind of net, and the kind of thread interlacing, i.e. the weave. The simplest weave for multi-axial woven fabrics is one for which the covers are arranged in the sequence n, p, ... , n, p in all thread systems. Analogous to two-axial woven fabrics, this weave has also been called plain weave. In the literature it is often called the basic weave.

A theoretical possibility exists that such woven fabrics can create many different kinds of weaves. Considering the weave, the fabrics may be differentiated as follows:

a) the threads of all systems are interlaced equally, creating a cover arrangement of n, p, and form a multi-axial woven fabric of plain weave;
b) the threads of one system are interlaced differently to the threads of the remaining systems, or the particular threads of one of the systems are interlaced differently;
c) the kind of thread interlacement is different for all systems.

The structures of the multi-axial woven fabrics may be oriented in relation to practically every thread system. Considering the shed-like system of manufacturing classical woven fabrics, an orientation of the multi-axial fabrics has been accepted in accordance with this system which could be accepted as weft (threads placed horizontally).

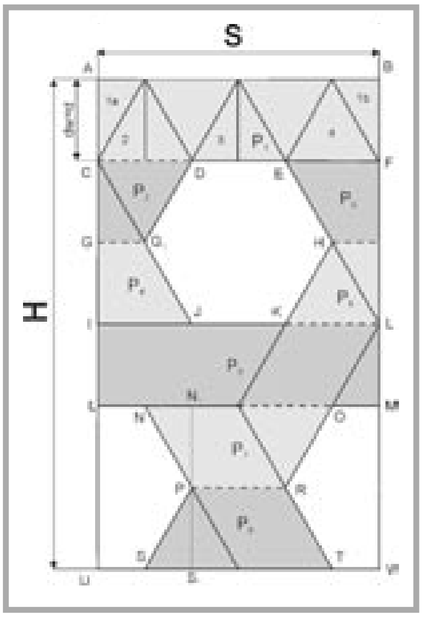

Figure 3. Maximally thickened three-axial woven fabric with plain weave: projection of the threads on the woven fabric plane; S, H – report dimensions, d – thread diameter [13].

Three-axial woven fabrics

In a three-axial woven fabric with plain weave (Figure 1), one system of warp threads, the left-oblique (OS), is always placed over the second warp thread system, the right- oblique (OZ), and crosses with it at the angle of 60^0. All warp threads OS are always placed in the woven fabric below the weft threads, whereas all warp threads OZ are always over the weft threads. The weft threads form an angle of 60^0 with both of the warp thread systems, which causes the weave of all systems, and of all threads in one particular system, to be equal ('over' and 'below' – n, p). A woven fabric manufactured with the use of the plain weave is characterised by good dimensional stability, and is porous. The hexagonal holes in the woven fabric have dimensions approximately equal to twice the thread diameter [17].

Cover factor of a three-axial woven fabric [18, 19]

The projection of the threads of a maximally thickened three-axial woven fabric, on a plane parallel to the fabric, is shown in Figure 3.

The cover factor is expressed as the quotient of the sum of areas covered by threads P_n and the total area of an element of the woven fabric. According to this definition, the cover factor of a three-axial woven fabric Z_{3A} can be determined by the expression:

$$Z_{3A} = \frac{P_n}{S \cdot H}$$

where:
S and H are the dimensions of the report of the three-axial woven fabric.

To calculate the width S of the report, the properties of the congruent equilateral triangles 2, 3, and 4 were considered (Figure 3).

The length of triangle *1* was calculated by using the equation describing the height of an equilateral triangle with side-length c:

$$c = \frac{2\sqrt{3}}{3}d$$

so that:

$$S = 3 \cdot \frac{2\sqrt{3}}{3}d = \frac{6\sqrt{3}}{3}d = 2\sqrt{3}d$$

As:

$$|AC| = |CG| = |GI| = |IŁ| = |1/2ŁU| = d$$

so that $H = 6d$.

This gives the area of the report surface:

$$P_R = S \cdot H = 12\sqrt{3}d$$

The area P_n covered by the thread projections is calculated according to the scheme below:

According to Figure 3, we have:

$$P_n = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8$$

Using simple geometrical dependencies, we obtain:

$$P_1 = 2\sqrt{3}d^2; \; P_2=P_3=P_4=P_5=\frac{\sqrt{3}}{2}d^2$$

$$P_6 = 2\sqrt{3}d^2; \; P_7 = P_8 = \sqrt{3}d^2;$$

After adding up we have; $P_n = 8\sqrt{3}d^2$

By substituting the expressions obtained, we can calculate the cover factor for the maximally thickened three-axial woven fabric formed of treads with equal diameter, as follows:

$$Z_{3A} = \frac{8\sqrt{3}d^2}{2\sqrt{3}d \cdot 6d} = \frac{8\sqrt{3}d^2}{12\sqrt{3}d^2} = 0{,}667$$

Compared to a two-axial classical woven fabric with plain weave, for which the maximum cover factor is *1*, the analogous three-axial fabric is characterised by a significantly lower ability to thicken.

Four-axial woven fabrics

Four-axial woven fabrics can be formed from three warp thread systems and a single weft thread system. Two warp systems are situated in relation to the wefts, as in the three-axial fabric, whereas the third warp system is perpendicular to the weft (perpendicular warp). Clearances are formed between the threads of these systems, whose shapes are homogenously dependent on the weave and the value of spacing.

Four-axial woven fabrics with plain weave can be formed on the basis of homogeneous or non-homogeneous nets. A four-axial woven fabric with plain weave and a homogeneous net is shown in Figure 4. The thread spacing is equal in each of the systems.

An analysis of the structure of such a fabric demonstrates that an additional possibility of thickening exists by introducing additional threads of the warp which is perpendicular to the weft, and by additional weft threads. Such procedure allows us to obtain four-axial woven fabrics with a non-homogenous net for a perpendicular warp system or weft system (Figure 5).

A simultaneous thickening of the thread systems of perpendicular warp and weft

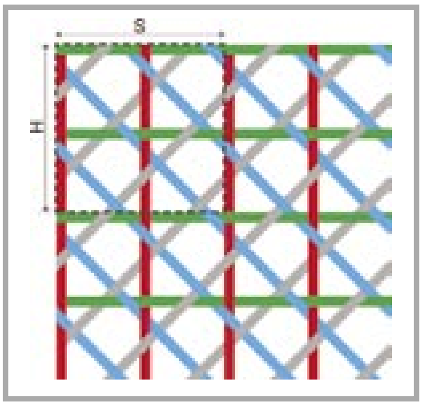

Figure 4. *Four-axial woven fabric with plain weave and a homogenous net; H – report height, S – report width.*

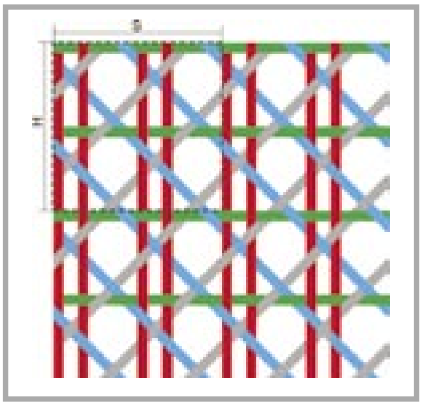

Figure 5. *Four-axial woven fabric with plain weave and a non-homogenous net for a single thread systems (vertical warp).*

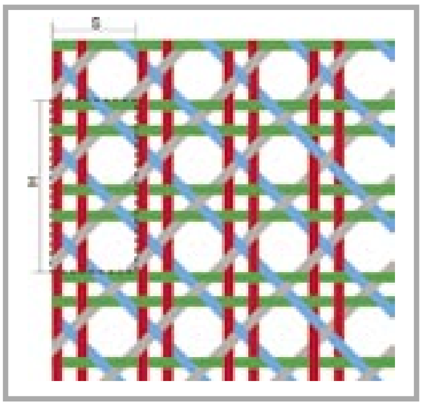

Figure 6. *Four-axial woven fabric with plain weave and a non-homogenous net for two thread systems (vertical warp and weft perpendicular to this warp).*

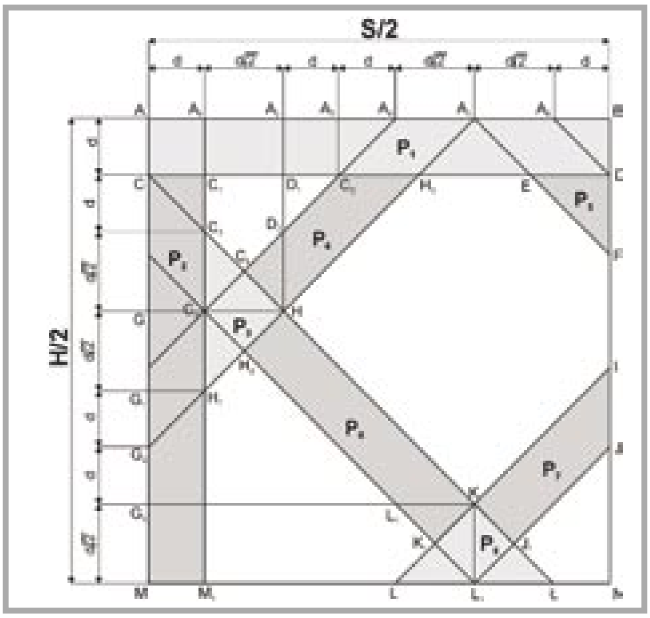

Figure 7. *A maximally tightened four-axial woven fabric with a homogenous net: thread projection on the fabric's surface.*

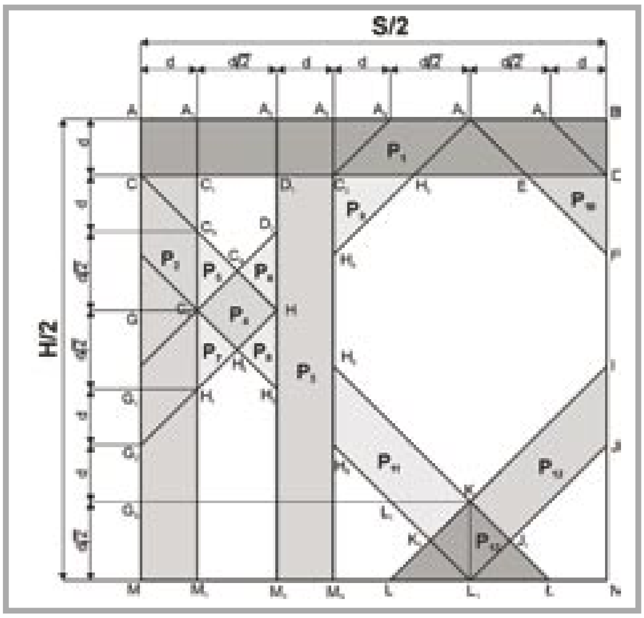

Figure 8. *Maximally thickened four-axial woven fabric with a non-homogenous net: thread projection on the fabric plane.*

yields a structure described in an earlier publication [24], and presented in Figure 6. As can be seen in Figures 4, 5, and 6, the four-axial woven fabrics with plain weave differ in the shape of clearances. In the case of a fabric with a homogenous net, the basic (i.e. the greatest) clearance takes the shape of a non-homogenous hexagonal. Woven fabrics with non-homogenous nets have clearances in the shape of a non-homogenous heptagon (Figure 5) and a homogenous octagon. It is clearly visible that the shape of the clearance bears no relation to the number of axes of the woven fabric.

Cover factor of four-axial woven fabrics [25]

The cover factor does not depend on the kind of thread interlacing, and so in the case of four-axial woven fabrics, the smallest repeatable fabric element is the area determined by the dimensions S/2×H/2 (Figures 4 and 5) and S×H/2 (Figure 6). Figure 7 shows the projection of threads of a four-axial woven fabric on a plane parallel to the fabric's surface.

As can be seen from Figure 7, the total area of an element of the fabric is

$$\frac{S}{2}\cdot\frac{H}{2} = (4d + 3d\sqrt{2})^2 = d^2(34 + 24\sqrt{2})^2$$

as $S/2 = H/2$

The area covered by threads

$$P_w = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8$$

where:

$$P_1 = P_{ABDC} = d^2(4 + 3\sqrt{2})$$
$$P_2 = P_{CC_1M_1M} = d^2(3 + 3\sqrt{2}$$
$$P_3 = P_{C_3HH_1} = 2d^2$$
$$P_4 = P_{C_4HH_3C_2} = d^2(\frac{3}{2} + \sqrt{2})$$
$$P_5 = P_{EDF} = d^2$$
$$P_6 = P_{HH_2K_1K} = d^2(2 + 2\sqrt{2})$$
$$P_7 = P_{IJJ_1K} = P_4$$
$$P_8 = P_{KLŁ} = 2d^2$$

By adding, we obtain:

$$P_w = d^2(17 + 10\sqrt{2})$$

Therefore the cover factor of a four-axial woven fabric with plain weave, homogenous net, and homogenous spacing Z_{4Areg} will be:

$$Z_{4Areg} = \frac{d^2(17 + 10\sqrt{2})}{d^2(34 + 24\sqrt{2})} = 0.458$$

Figure 8 presents the projection of threads of a four-axial woven fabric with a non-homogenous net (Figure 5) on the plane $S \times H/2$ for a single system.

As demonstrated in Figure 8, the total area of a woven fabric element is:

$$\frac{S}{2}\cdot\frac{H}{2} = (4d + 3d\sqrt{2})^2 = d^2(34 + 24\sqrt{2})^2$$

as $S/2 = H/2$,

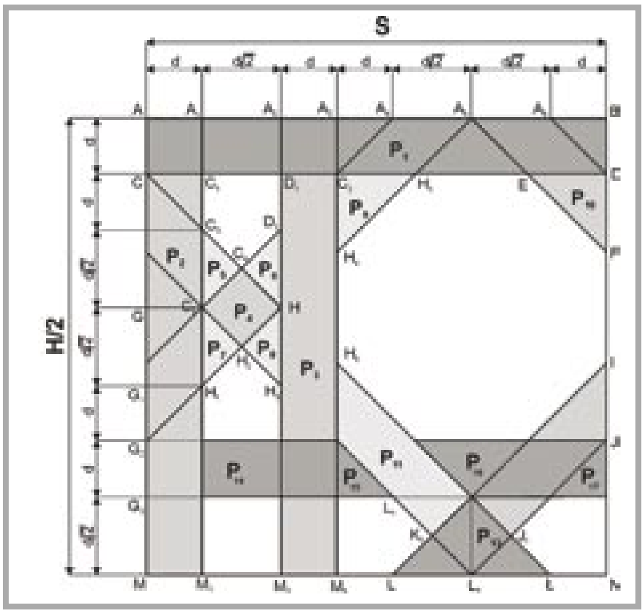

Figure 9. *Maximally thickened four-axial woven fabric with a non-homogenous netand two systems: thread projection on the fabric's plane S×H/2 (according to Figure 6).*

whereas the area covered by threads is:

$P_n = P_1+P_2+P_3+P_4+P_5+P_6+P_7+$
$+P_8+P_9+P_{10}+P_{11}+P_{12}+P_{13}$

where:

$$P_1 = P_{ABDC} = d^2(4+3\sqrt{2})$$
$$P_2 = P_{CC_1M_1M} = d^2(3+3\sqrt{2})$$
$$P_3 = P_2$$
$$P_4 = P_{C_4HH_2C_5} = d^2$$
$$P_5 = P_6 = P_7 = P_8 = 2d^2$$
$$P_9 = P_{C_2H_3H_4} = d^2$$
$$P_{10} = P_{DFE} = P_9$$
$$P_{11} = P_{H_5KK_1H_6} = d^2(\frac{3}{2}+\sqrt{2})$$
$$P_{12} = P_{IJJ_1K} = P_{11}$$
$$P_{13} = P_{KLŁ} = 2d^2$$

After adding, we obtain:

$$P_n = d^2(20+11\sqrt{2})$$

Thus, the cover factor Z_{4Nreg} of a four-axial woven fabric with non-homogenous spacing, and the non-homogenous net will be:

$$Z_{4Nreg} = \frac{d^2(20+11\sqrt{2})}{d^2(34+24\sqrt{2})} = 0.523$$

The ability to mutually gather warp threads perpendicular to the weft results in an increase in the cover factor compared with the structure of a four-axial woven fabric with homogenous net.

Figure 9 presents the projection of threads of a four-axial woven fabric with a non-homogenous net and two systems (Figure 6) on the fabric's plane $S \times H/2$.

By a procedure similar to the foregoing case, we obtain the total area of a woven fabric's element:

$$S\frac{H}{2} = (4d+3d\sqrt{2})^2 = d^2(34+24\sqrt{2})$$

as $S = H/2$

The area covered by threads is:

$P_n = P_1+P_2+P_3+P_4+P_5+P_6+P_7+$
$+P_8+P_9+P_{10}+P_{11}+P_{12}+P_{13}+$
$+P_{14}+P_{15}+P_{16}+P_{17}$

and is equal to

$$P_n = d^2(22+11\sqrt{2})$$

Therefore, the cover factor Z_{4Nreg} of such a four-axial fabric is:

$$Z_{4Nreg} = \frac{d^2(22+11\sqrt{2})}{d^2(34+24\sqrt{2})} = 0.553$$

Five-axial woven fabrics

In a five-axial woven fabric, the greatest clearance has the shape of a pentagon. this kind of fabric is formed from four warp thread systems and a single weft system. Together with wefts, they form the following angles (counting in an anticlockwise direction) also presented in Figure 10:

0^0 – weft threads (indicated black),
36^0 – warp threads (indicated red),
71^0 – warp threads (indicated blue),
109^0 – warp threads (indicated light brown), and
144^0 – warp threads (indicated green).

Unlike the maximally thickened three- and four-axial woven fabrics, for which the positions of all warps in the report are stable, the five-axial fabric is characterised not only by stable warps, but also by warps which theoretically have the ability to displace 'upwards' and 'downwards' in the fabric. In the weave presented in Figure 10, warps 1 and 4 have stable positions. Warps 2 and 5 can, within a limited range, be displaced 'upwards', whereas warps 3 and 6 can

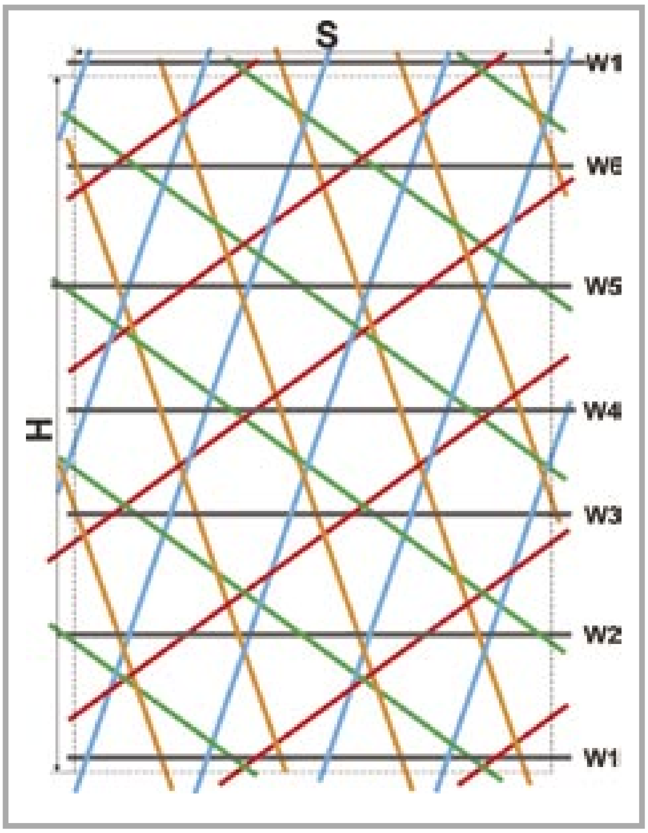

Figure 10. Report of a maximally thickened five-axial woven fabric with plain weave; W1 – W6 are the numbers of the consecutive wefts in the weave's report. Remark: Considering the report's dimensions, the figure was drawn on a different scale than Figures 1, 4, 5, and 6.

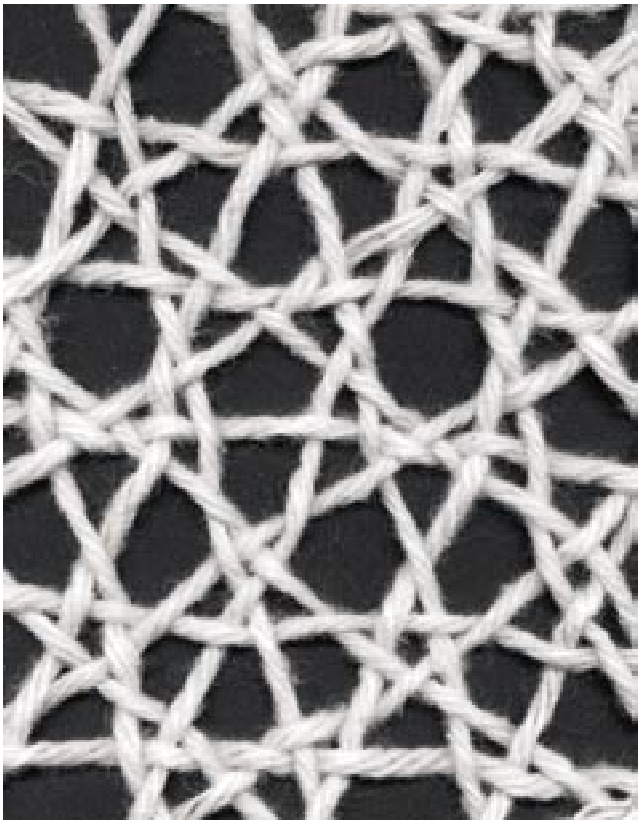

Figure 11. Image of a hand-plained five-axial woven fabric with plain weave presented schematically in Figure 10; material: carpet wood 4 × 400 tex (natural wool). Clearly visible are the different possibilities of yarn displacements.

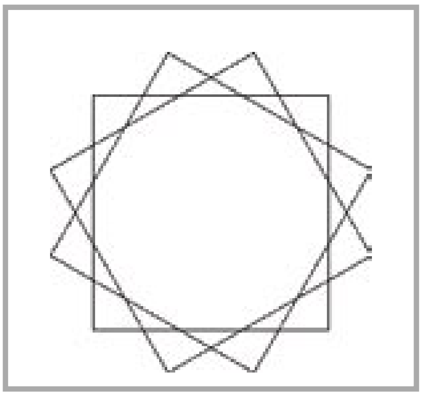

Figure 12. *Basis for modelling a six-axial net.*

be displaced 'downwards'. Despite the fact that a woven fabric of such a type has hitherto not been manufactured or tested, it can be predicted in advance that its practical importance would be insignificant, because of the instability of its structure.

If the threads are located in their extreme positions, the threads' spacings, as measured by the multiplication factor of the threads diameters d, can be determined as follows:
the spacings of the weft thread system 0^0:

A_0=141.36d 170.31d 170.31d,

and the spacings of the warp systems:

A_{36} =195.33d,
A_{71} =156.30d,
A_{109}=156.30d,
A_{144}=195.33d.

Cover factor of five-axial woven fabrics

The determination of the cover factor for a five-axial woven fabric is time-consuming considering its asymmetry. For this reason, we transformed the report of a five-axial woven fabric into a black-and-white bit map, where the threads are marked black and the clearances white. Next a histogram was built, which for this case indicates two values: the numbers of black and white pixels determined from the report's area.

The dimensions of the report and the area of the surface covered by threads were determined experimentally by analysing the image of the bit map. All the values determined were related to the thread diameter at the structure maximally covered. Therefore, the empirically determined values can be applied in designing such five-axial structures for other thread diameters also.

The report dimensions amounted to

$S = 37d$, $H = 54d$,

the report area

$P_r = 1998d^2$, and

the area covered by treads

$P_c = 477.522d^2$.

The cover factor Z_{5A} was calculated by dividing the number of black pixels by the total number of pixels in the report of the structure. The maximum cover factor amounted to $Z_{5A} = 0.2$

Figure 11 presents an image of a five-axial woven structure hand-plaited, whose weave is shown in Figure 10.

The thread undulation visible in the figure is the result of thread tensions which are too small and different among themselves, and not of the fabric structure.

Six-axial fabrics

A six-axial woven fabric is formed by six thread systems: five warp systems and a single weft system. The nets of these fabrics can be modelled by configurating appropriately rotated classical fabrics [25]. Figure 12 shows a net module of a six-axial woven fabric. It was formed by rotating the module of a two-axial fabric's homogenous net (a quadrangle) by π/3 rad.

On this basis a six-axial woven fabric with plain weave was formed (Figure 13), all of whose thread systems interlace equally: 1n, 1p. This kind of fabric is characterised by large clearances; the largest of them have the shape of a dodecagon. This fabric belongs to the group of fabrics with non-homogenous spacing [8].

The warp threads with the weft threads form the following angles:
0^0 – black thread (weft),
30^0 – dark blue thread,
60^0 – red thread,
90^0 – green thread,
120^0 – blue thread, and
150^0 – grey thread.

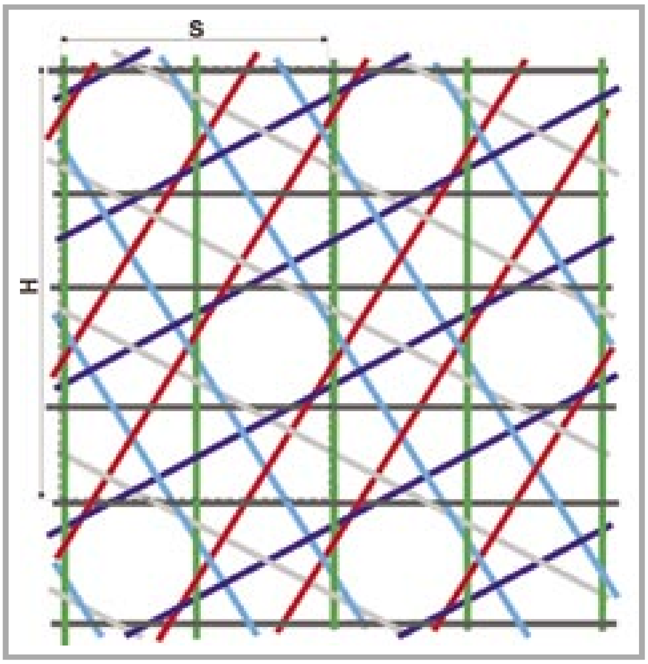

Figure 13. *Report of a six-axial woven fabric with plain weave and a non-homogenous net.*

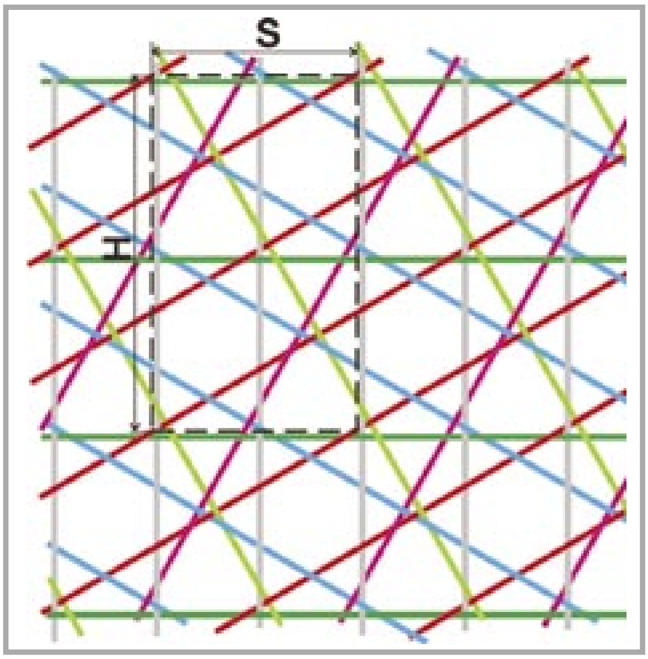

Figure 14. *Report of a six-axial woven fabric with plain weave and homogenous net.*

Table 1. Influence of the number of axes and the kind of net on the ability of thickening a multi-axial woven fabric by threads.

Number of axes (thread systems)	Kind of net	Maximal area covering
Three	homogenous	0.667
Four	homogenous	0.458
	non-homogenous in one system	0.523
	non-homogenous in two systems	0.553
Five	non-homogenous	0.200
Six	homogenous	0.294
	non-homogenous	0.300

Attempts to obtain a six-axial woven fabric with plain weave and a homogenous net on the basis of a quadrangle-net were not successful. In such a case, a rectangle should be the basis for forming the module. Furthermore, to ensure a structure's repeatability, the proportions of the sides and the rotation angle of the rectangle, as well as the relative displacements of the basic rectangle and the rectangle created as the result of the rotation 0+α and -α, should be determined analytically in relation to the thread diameter. An example of such a structure is shown in Figure 14.

The fabric presented is characterised by a homogenous thread spacing and at the same time by a at great non-homogeneausness of the clearances. The largest of the clearances have the shape of hexagonals and hendecagons.

Cover factor of six-axial woven fabrics

The area cover factors for six-axial woven fabrics were determined by the image analysis method, as for the five-axial fabric. We stated that the values of the cover factors differed only slightly, despite the differences in thread spacing. The cover factor for a woven fabric with a homogenous net was equal to 0.294, whereas for those with a non-homogenous net was equal to 0.300.

Summary

The structure of multi-axial woven fabrics was modelled for fabrics with 4, 5, and 6 numbers of thread systems and a weave similar to the plain weave. In the case of fabrics with even numbers of axes (4 and 6), structures with plain weave can be formed on the basis of homogenous and non-homogenous nets. The plain weave does not enable a homogenous five-axial net or a non-homogenous three-axial net to be designed. The ability to thicken the structures of multi-axial woven fabrics was analysed. The value of the cover factor defined classically, i.e. as the quotient of the area covered by threads and the total fabric area, was accepted as a measure of thickening.

In Table 1, the results of the thickening ability of the multi-axial woven fabric's structure are listed.

We stated that with the increase in the number of thread systems, the covering of a multi-axial woven fabric decreases. An exception occurs for a five-axial fabric, which as a specific structure of complex non-homogeneausness, has the smallest area-covering factor of all the fabrics analysed.

Non-homogenous nets create the possibility of increasing the thickness of the thread systems. For four- and six-axial woven fabrics with plain weave, structures of a homogenous and non-homogenous net can be formed, whereas a maximally thickened three-axial fabric has a homogenous net, and the five-axial has a non-homogenous one.

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