

# Influence of the Construction of a Four-Axial Fabric on Its Properties

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## Abstract

The article focuses on the influence of the construction of a multi-axial fabric on the surface fabric cover. Using the example of four-axial fabrics, it presents some methods of designing fully covered fabrics with numerous overlaying thread systems. The significance of the shape of the thread cross-section in the process of thickening the structure of a four-axial fabric is emphasised. The concept of the blocking knot is defined as a condition necessary to achieve a stable fabric structure. Some methods of optimising the construction of a four-axial fabric in order to maximise the fabric cover and minimise the number of overlaying threads are presented. The influence of the fabric structure on the uniformity of stress distribution in the fabric is described by means of a graphic interpretation of the stress distribution caused by a central force perpendicular to the surface of the fabric.

**Key words:** four-axial fabric, stress distribution in the fabric, optimisation of the fabric structure, fabrics formed of flat bands, blocking knot, displacements of threads in multi-axial fabrics.

## Introduction

The activities of the Institute of Architecture of Textiles of the Technical University of Lodz focus on the construction, properties and possible applications of fabrics of unconventional construction. So far, the main achievements in this area are as follows: the construction of double-layered fabrics connected by means of woven ribs, the construction and technology of multi-axial fabrics, especially fabrics of more than three axes, fabrics with radially situated warp threads, as well as a stand for testing the directional properties of fabrics.

Classic orthogonal fabrics are unstable structures if loads are imposed on them in directions incompatible with the thread arrangements. The low isotropy of double-axial fabrics, understood as a reaction to multi-directional mechanical stimuli, was the motivation for undertaking research on woven structures of a larger number of axes. As a result, fabrics of more than two axes were created and called "multi-axial fabrics". The isotropy of the mechanical properties of multi-axial fabrics, as compared to classic fabrics of orthogonal structure, makes multi-axial fabrics a unique and perfect construction material for products subjected to multi-directional loads. Up till now, three-axial fabrics- that is flat products made of three thread systems situated at an angle of  $60^\circ$  towards each other have found practical industrial applications. So far, research on three-, four- and six-axial fabrics has focused on structures in which the threads interlace, like in a plain weave (basic weave). The characteristic property of such fabrics is their openwork construction - clearances appear

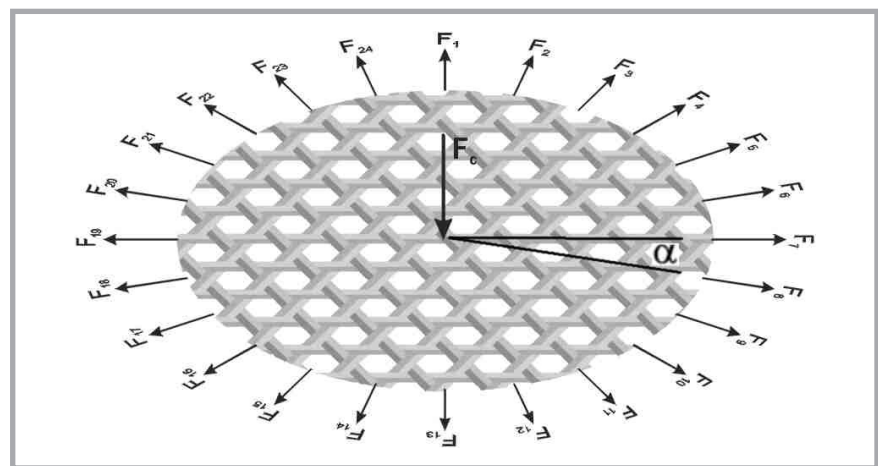
between the threads, even when their concentration in the product is maximal.

And thus, theoretically, maximum fabric cover in the case of an orthogonal fabric may equal 100% (no clearances), in the case of a three-axial fabric- 67% (23% of the fabric are clearances), in the case of a four-axial fabric - 57%, which further diminishes together with an increase in the number of thread systems. As tests have proven, on the one hand increasing the number of thread systems improves the distribution of mechanical properties, making the fabric a great reinforcement for composites, but on the other hand the clearances may make the fabric useless [4]. In composites technology a material of directionally isotropic properties has been described. It is produced by placing parallel thread systems one on the other (up to 4), turned in relation to each other by an angle depending on the number of layers. The individual thread systems are

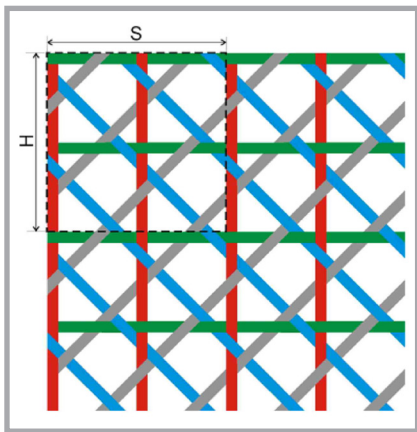
connected by sewing or gluing. Due to the lack of interlacing, the threads are, however, easily displaced, and delamination of the layers often occurs when a torsional or perpendicular load is imposed. This is of great importance, for instance, in the case of ballistic composites. Multi-axial fabrics are devoid of such faults.

Hints appearing in literature concerning other than plain weave ways of interlacing threads in a three-axial fabric refer only to the hopsack weave (basket), and a variation of plain weave known as bi-plain. No research results have been found concerning changing the interlacing method for fabrics of more than four axes, which does not mean there is no need for such products but only proves how difficult the problem is, in both scientific and practical terms.

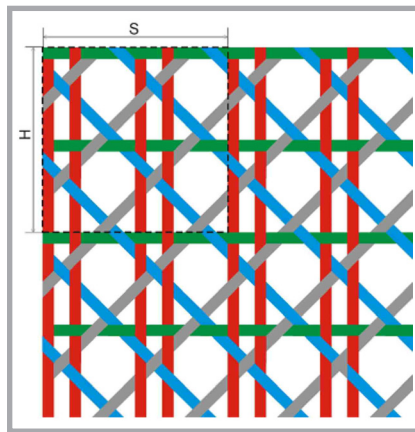
In the patents concerning the structures of multi-axial fabrics, some technologi-



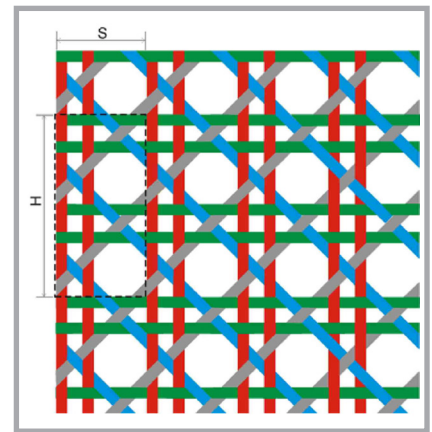
**Figure 1.** Diagram of the method of measuring a fabric's response to a load of central force;  $F_c$  – central force- input function,  $F_1 - F_{24}$  – directional forces- response,  $\alpha$ -angular graduation of the force converters.



**Figure 2.** Four-axial fabric with a plain weave and homogeneous net;  $H$  – height of the repeat,  $S$  – width of the repeat [4].



**Figure 3.** Four-axial fabric with a plain weave and heterogeneous net for one thread system ( $O - 90^\circ$ ) [4].



**Figure 4.** Four-axial fabric with a plain weave and heterogeneous net for two systems ( $O - 90^\circ$  and  $W$ ) [4].

cal solutions have also been presented, some of which have been adopted in the production of multi-layered four-axial fabrics [1].

So far the best known and most thoroughly tested group of multi-axial fabrics is the three-axial one. The state of knowledge concerning four-axial fabrics is limited to structures made of plain weave and the multi-layered structures mentioned above. Four-axial fabrics of plain weave are characterised by an openwork structure, which limits their range of applications, for example in composites. A different situation is in the case of multi-layered fabrics of a high cover factor. However, in the case of multi-directional loads, due to a large difference between the take-ups of the individual thread systems, one often has to deal with the heterogeneous structure of such a product. A special method of testing the directional properties of fabrics is presented in [2]. The method is shown in **Figure 1**.

A circular fabric sample is fastened in the 24 grips of the force converters placed on a plan of a circle of 200 mm diameter. The measuring system registers the indications of the converters while the sample is loaded with a central, concentrated force.

### A survey of the constructions of four-axial fabrics

A thesis may be put forward that by modifying the weave of a four-axial fabric it is possible to receive a fabric cover close to 100% with minimum fabric thickness, when the threads are situated on only four levels, which corresponds to the construction of a double-layered fabric.

After a series of basic research carried out at the Institute of Architecture of Textiles on the structure and technology of single-layered multi-axial fabrics of an openwork structure, an attempt was undertaken to design and produce a fabric made of four thread systems, with a fabric cover close to 100% and coefficient of the force variation at the sample perimeter smaller than 60%.

Two methods aimed at the maximization of the fabric cover were worked out, as well as a way of modeling the isotropy of the mechanical properties of a four-axial fabric by means of the weave [4]. It has also been proven that the level of the fabric cover depends on the shape of the cross-section of the thread or other linear product the fabric has been made of. Better effects, in terms of both the fabric cover and technology were received while using flat bands [7].

In the case of classic double-axial fabrics, it is possible to modify mechanical properties only in two directions- towards the warp and weft. For the first time the structure of multi-axial fabrics makes it possible to design the resistance and stiffness in directions other than  $0^\circ$  and  $90^\circ$  towards the weft [4]. In the case of a three-axial fabric, the axes are inclined towards the weft at an angle of  $+60^\circ$  and  $-60^\circ$ . Even better is the construction of a four-axial fabric, in which one can distinguish traditional systems - the weft and perpendicular warp, as well as oblique systems, inclined towards the weft at angles of  $+45^\circ$  and  $-45^\circ$ . Such systems are later called warp systems  $O + 45^\circ$  and  $O - 45^\circ$ .

Another advantage of multi-axial fabrics is their resistance to tearing, because a fabric in which the threads intersect at an angle different than the right one is always more resistant than a fabric of rectangular intersections [3].

Four-axial fabrics of plain weave, known from literature [4], may be produced on the basis of a homogeneous or heterogeneous net. A fabric with a homogeneous net is presented in **Figure 2**.

Such a structure can be thickened by introducing additional threads between the existing ones. The stability of the system will be maintained thanks to the blocking knots [4]. **Figure 3** presents a four-axial fabric of plain weave, thickened with the system  $O - 90^\circ$ , as a result of which the net of the fabric becomes heterogeneous.

In the structure presented in **Figure 3**, one can observe pairs of warp threads perpendicular to the weft. In such a fabric larger stress is transmitted along the system  $O - 90^\circ$  than along the other ones.

Better properties in terms of the uniformity of the stress transmitted and thickening of the structure with additional threads can be observed in the case of fabric in which the weft system was also thickened. Such a structure, known from literature [4], is presented in **Figure 4**.

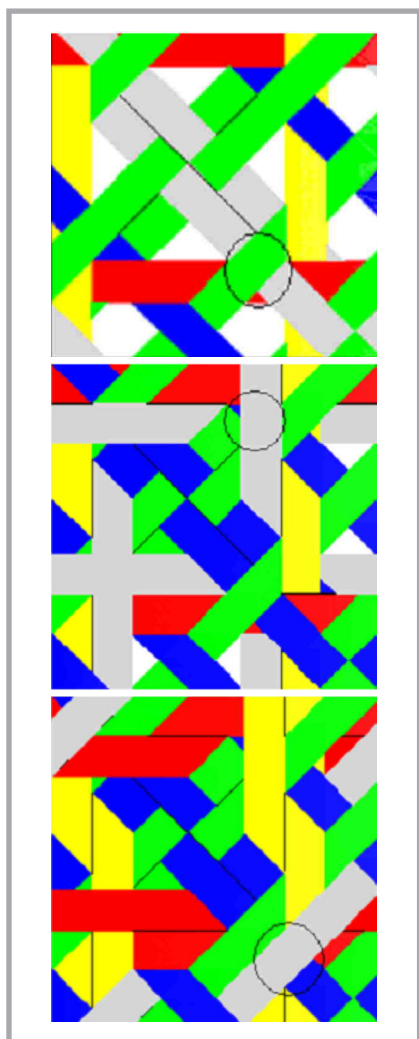
In this construction a difference can be clearly observed between the component fabrics, that is  $O/W$  and  $O - 45^\circ/O + 45^\circ$ .

As can be observed in **Figures 2, 3** and **4**, four-axial fabrics of plain weave are characterised by an openwork struc-

ture, with the clearances taking different shapes and sizes.

### Designing the construction of a four-axial fabric with a full fabric cover

A thesis may be put forward that by modifying the weave of a four-axial fabric it is possible to receive a fabric cover close to 100%, maintaining at the same time the minimum thickness of the fabric. It means the threads are situated on only four levels, which in terms of construction corresponds to a double-layered fabric. At the Institute of Architecture of Textiles of Technical University of Lodz, after a series of basic research concerning the structure and technology of single-layered multi-axial fabrics of an openwork structure, an attempt was undertaken to design and produce a fabric made of four thread systems, as well as a fabric



**Figure 5.** Model of the four-axial fabric of plain weave from Figure 4, after the thickening of systems  $O + 45^\circ$  and  $O - 45^\circ$ ,  $W$  and  $O 90^\circ$ .

cover close to 100% and force variation coefficient at the perimeter of the sample smaller than 60%. Two methods aimed at maximising the fabric cover, as well as a method of modelling the isotropy of the mechanical properties of a four-axial fabric by means of the weave were worked out [4]. It was also proven that the level of the fabric cover depends on the shape of the cross-section of the thread or other linear product the fabric is made of. Better effects, not only in terms of the fabric cover but also in terms of the technology, were achieved in the case of flat bands [7].

In order to minimise the openwork properties of the fabric presented in **Figure 4**, an attempt was made to thicken the model of such a fabric, and subsequent systems of additional threads were introduced, the results of which are presented in **Figure 5**.

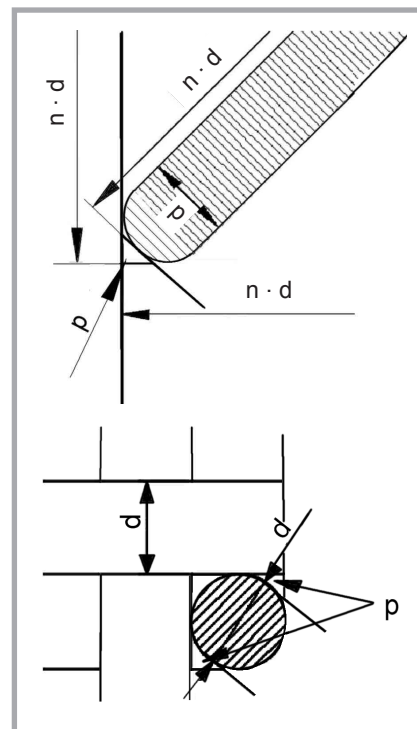
As a result of the process, the stages of which are presented by fabric models in **Figure 5**. A 100% fabric cover was achieved after eight layers of thread were overlaid. The weave of a fabric thickened in such a way can be reproduced, and if adequate technology is available, it will be possible to mechanise the production. However, it is difficult to imagine possible practical applications of such fabrics, because they are characterised by a high degree of unevenness of the thread take-up and relatively long non-interlaced sections. Such a disadvantageous structure is the result of the process described above, based on interlacing threads into the clearances of a ready-made fabric. When the cover of the fabric repeat increases, the interlaced bands tend to cover one another, as a result of which a fabric is produced in which only 45% of the bands participate in the effective covering of the surface of the repeat, signifying that most of the bands overlap. The bands may be used more effectively when their overlaying is limited, preferably to two bands, and when every clearance is covered by only one band. This is the first condition which has to be fulfilled to achieve a correct construction of a four-axial fabric of maximum fabric cover.

### Influence of the shape of the thread cross-section on the fabric cover

The problem discussed below is well known in the technology of highly resist-

ant composites based on multi-layered reinforcements of glass fiber. More and more often in these specific applications a glass rowing of circular cross-section is replaced with a specially formed rowing of a flat band cross-section. However, it should be emphasised that the technology of orthogonal fabrics made of such threads has not yet been fully mastered.

The possibility of thickening multi-axial fabrics depends not only on the weave and thread overlay but also on the geometry of the cross-section of the thread, which determines the shape and size of the clearance next to its interfection. The problem is illustrated in **Figure 6**. The total clearance on the surface of the repeat is the sum of the clearances which appear next to the thread forming the interlacement. The mistake can be estimated, but in this case it is negligible, and it can be assumed that the clearance formed next to the thread forming the inflection at the point of the interlacement stays in relation to the difference of the clearance area between the threads of the main system and a circle of diameter 'd', which is the thickness of the thread or band. This means the relative clearance, counted as a relation of the absolute clearance to the clearance area between the threads forming the base orthogonal fabric, which can



**Figure 6.** Interlacement of a thread of circular cross-section and a flat band in the blocking knot;  $p$ - clearances next to the thread

be expressed by means of dependences 1 and 2.

$$Z_o = \frac{\approx \frac{1}{2} \left( d^2 - \frac{\pi d^2}{4} \right)}{d^2} \quad (1)$$

$$Z_p = \frac{\approx \frac{1}{2} \left( d^2 - \frac{\pi d^2}{4} \right)}{(n \cdot d)^2} \quad (2)$$

If, instead of threads, whose cross-section is circular, one uses flat bands, the thickness of which equals the diameter of the threads, and whose width is „ $n$ ” times larger, then the absolute clearance next to the blocking knot will be identical to the clearance in a fabric made of threads, and the relative clearance in a fabric made of flat bands of  $n \cdot d$  width will be  $n^2$  smaller than that in a fabric made of threads of thickness  $d$ . Thus, for the production of fully covered multi-axial structures, it is better to use bands or other flat structures, whose width is a multiple of their thickness [7].

### Optimisation of the construction of a four-axial fabric

The basic shape of a clearance created by a traditional thread system in an orthogonal fabric is a rectangle. A specific example of a rectangle is a square, whose diagonals are inclined towards the sides at an angle of  $45^\circ$ , which is of great importance regarding the construction of four-axial fabrics. Thus, while designing graduations of bands in a basic orthogonal fabric, which is the starting point for a four-axial fabric, one should try to achieve a square clearance whose diagonal will be the same length as the width of the band (*Figure 7.a*).

To realise this idea, the distance between the edges of adjacent bands should equal  $d/\sqrt{2}$ , which guarantees that the oblique system covers the clearance maximally, shown in *Figure 7.b*. If one knows the width of the band, it is the basis for designing thread graduations in the basic fabric. As a result, the basic fabric for the structure designed, consisting of 0 - 90 threads and W interlaced in a plain weave, ensures the stability of the oblique system introduced thanks to a proper number of blocking knots. An example of a blocking knot is shown in *Figure 8*.

On the basis of the method of covering the clearances with threads of the oblique system presented in *Figure 7.b*,

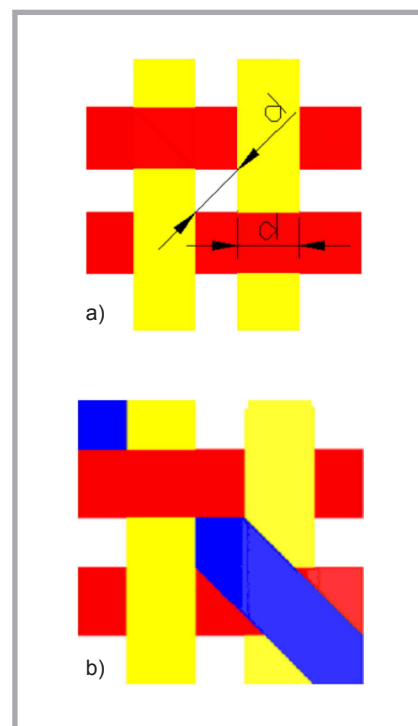
weaves were designed for two constructions of four-axial fabrics of maximum fabric cover. The first one was designed according to the O/U (over/under) rule, which means the oblique systems interlace with the intersections of the threads of the basic fabric according to the rules of plain weave and appear in turns over and under the basic fabric. A diagram illustrating this construction is presented in *Figure 9*. A diagram of a weave with the repeat indicated is presented in *Figure 10*.

The so-called full fabric presented in *fig. 10* is characterised by a simpler construction in comparison to fabrics with three or four overlaying layers, some examples of which are presented in *Figure 5*. The repeat of the fabric is smaller, and the threads have fewer inflections within this repeat. The band is effectively used in about 72% of the surface of the fabric. The fault of this fabric is the difference between the take-ups of the traditional and oblique systems. The threads of the traditional systems 0-90 and W, being more „upright”, will carry more stress than those of the oblique system, which cross from one side of the basic fabric to the other, and thus are more taken-up. As a result, the isotropy coefficient will be smaller when compared to a fabric with the same take-ups of both thread systems. This is the next postulate of a proper construction of a four-axial fabric.

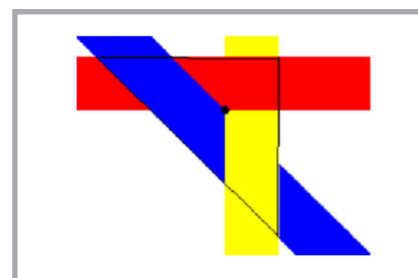
In *Figure 11* (see page 44), showing a fragment of a four-axial fabric of O/U weave with light shining through, it can be observed that there are four types of thread overlays in the fabric:

- lack of overlays; triangular areas created by a single band,
- double overlay; square areas created by two bands intersecting at a right angle,
- triple overlay; triangular areas, double built-up fragments covered by a single oblique band,
- quadruple overlay; the darkest square fragments can be noticed in *Figure 11*.

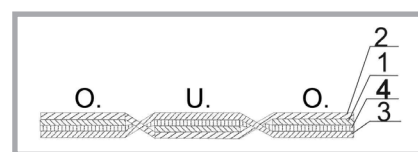
In order to fulfill the condition concerning the equality of the thread take-



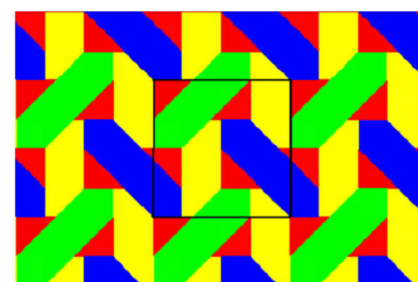
*Figure 7. Basic fabric a - method of designing clearances, b - covering the clearance with a thread of an oblique system.*



*Figure 8. Blocking knot in a multi-axial fabric.*



*Figure 9. Course of threads in a O/U weave; 1, 4 - warp and weft of the basic fabric, 2, 3 - warp threads O -  $45^\circ$  and O +  $45^\circ$ .*



*Figure 10. Full fabric of N/P weave (the repeat is outlined by a square).*

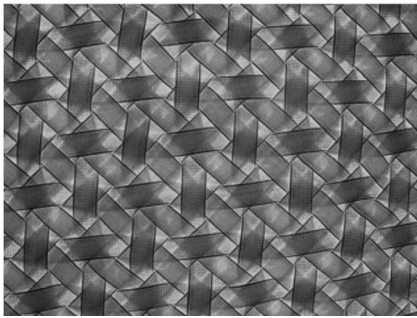


Figure 11. Four-axial fabric of O/U weave, with light shining through.

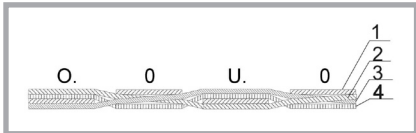


Figure 12. Diagram of the thread course in a O/0/U/0 weave; 1, 4 - warp and weft of the basic fabric, 2, 3 - warp threads O-45 and O+45.

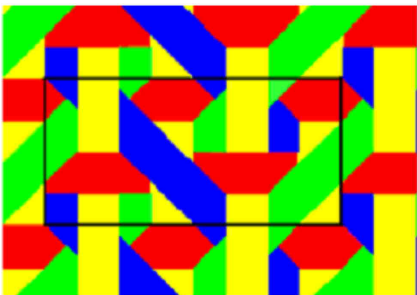


Figure 13. Full fabric of modified O/0/U/0 weave.

ups, a full fabric of O/0/U/0 weave was designed. In the weave denotation, the symbol “0” means that the bands of the oblique systems crossing from one side of the basic orthogonal fabric to the other go through its centre, between the warp and weft threads. In order to minimise the difference in the take-up of the threads of oblique systems in relation to the traditional system, an attempt was undertaken to balance the take-ups in all four systems. Systems O-45 and O+45 interlace under the threads crossings of the traditional system rather than between and over them. On their way back under the fabric, they again go through the centre of the basic fabric, that is the centre of the crossing O90 and W, which is presented in **Figure 12**. A structure created according to this rule is presented in **Figure 13**.

It is assumed that the interlacing method described above will ensure similar take-ups in all the systems. It will also make it

possible to achieve a multi-system fabric surface, which means that, as opposed to a full O/U fabric, the surface of O/0/U/0, affected by mechanical factors, is built of more than two systems.

In a fabric of N/0/P/0 weave, just like in the case of fabric of O/U weave, four types of thread built-ups can be distinguished. A comparative analysis of the appearance of both fabrics proves that the positions of the threads of the basic systems O and W in a four-axial fabric of O/U weave are unstable. Despite the fact that in a O/0/U/0 fabric the interlacements of the oblique systems are longer, its construction is more stable. It should be assumed that it results from the configuration of the blocking knots. In a O/U fabric the blocking knots, created by the basic system, are situated far from one another and alternate, which leads to transverse sinking, not only of the threads of the oblique systems (**Figure 11**). In a O/0/U/0 fabric the blocking knots are placed opposite one another, which means they are situated symmetrically and do not disturb the rectilinear thread course. Due to the similar take-ups of the oblique, traditional, and orthogonal systems, the new structure should be more isotropic than the N/P structure. In order to verify this hypothesis, three samples of a full fabric of O/0/U/0 weave were woven on a hand loom [6], **fig. 14**, and tested on a stand, described in [2].

### Assessment of the mechanical properties of the new four-axial fabrics

The test results of a classic fabric, N/P fabric and N/0/P/0 fabric are presented in the form of diagrams in **Figure 16**.

The character of the force distribution in the O/U fabric in **Figure 16.b** proves that the isotropy of its mechanical properties may reach higher values. The reason for the reduced isotropy of the mechanical properties is probably the weave. Oblique systems, crossing from the left side of the fabric to the right, surround the traditional systems, which are naturally more upright as they are situated in the middle layer. As a result, a centrally imposed force is at first transmitted by the system O90 and W, the threads of which are less taken-up, and later by the system O+45 and O-45. This disproportion in force transmission by the individual sys-

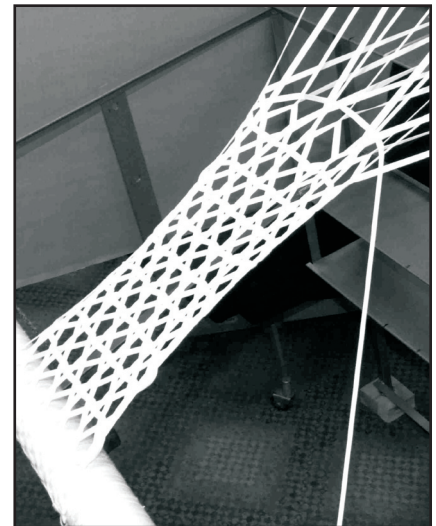


Figure 14. Fragment of a loom for weaving multi-axial fabrics.

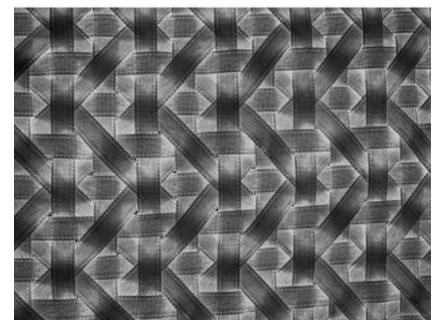
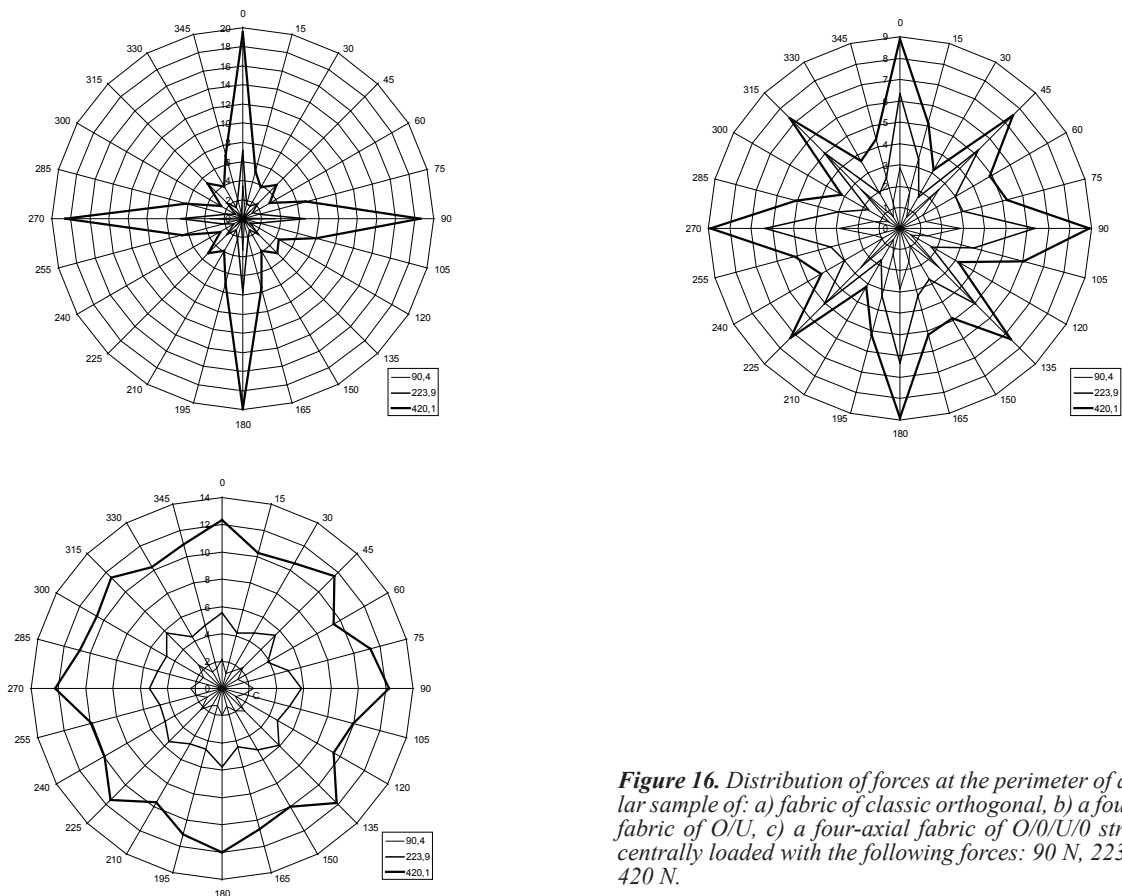


Figure 15. Four-axial fabric of N/0/P/0 weave with light shining through.

tems is proven by the tests results, presented in **Figure 16.c**.

The coefficients of variation of the force distribution at the perimeters of the test structures were counted. The highest value of the coefficient of variation of the force distribution can be observed at the perimeter of a classic orthogonal fabric, equaling 74%. For a double-layered four-axial fabric of O/U structure, this coefficient equals 45%, and for the modified four-axial fabric of O/0/U/0 structure it is a bit more than 8.5%. Correspondingly, the isotropy factor (4) for a classic fabric equals 34.8%, for a four-axial O/U fabric- 60.9% and for a four-axial O/0/U/0 fabric- 83.7%.

In accordance with what was expected, the values of the coefficients of variation of the force distribution at the perimeter of the fabrics loaded with a central force of 90 N were much higher, equaling, respectively, for a classic fabric - 113%, for a four-axial N/P fabric - 68%, and for a four-axial N/0/P/0 fabric - 23%.



**Figure 16.** Distribution of forces at the perimeter of a circular sample of: a) fabric of classic orthogonal, b) a four-axial fabric of O/U, c) a four-axial fabric of O/O/U/O structure, centrally loaded with the following forces: 90 N, 223 N and 420 N.

It should be emphasised that in accordance with the assumptions made, weave modification from N/P to N/OP/O resulted in an equalisation of the distribution of forces registered by individual sensors. As a result of the changed structure of the four-axial fabric the value of the coefficient of variation of the force distribution at the perimeter of the fabric diminished by 36%, which means an improvement of 81%. As a result of the modification, the fabric of N/O/P/O weave has much better isotropic properties, with the distribution of forces in this fabric being more uniform in all directions. It would be perfect if the diagram of the force distribution in the fabric tested was a regular polygon, where the number of its sides would be the same as the number of grips of the device on which the assessment was made. This is possible when the test fabric is of a twelve-axial structure.

## Conclusions

1. The method of designing four-axial fabrics worked out made it possible to receive fabric cover structures close to 100% and a similar take-up of all the thread systems.

2. In the case of four-axial fabrics, maximisation of the fabric cover may be easily obtained by forming systems of many layers.
3. Maximisation of the fabric cover in a four-axial fabric may also be achieved by optimising the shape and size of clearances in the basic fabric. The clearances should take the form of a square with a diagonal equal to the thread thickness, which guarantees that the oblique system interlaced through the clearance will cover it 100%.
4. By using bands whose width is  $n$ -times larger than their thickness in the construction of a four-axial fabric, it is possible to receive structures in which the area of the clearances will be  $n^2$  smaller.

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Received 16.11.2010 Reviewed 09.06.2011