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Assessment of Transversal Deformations of Multi-Axial Woven Fabrics Stretched One-Directionally

Abstract
The coefficient of the transversal deformation of woven fabrics while stretched one-directionally was determined by experiments. Three-axial fabrics, four-axial fabrics with homogeneous and inhomogeneous nets, and six-axial fabrics with an inhomogeneous net were the subjects of our investigation. Classical, two-dimensional fabrics with area masses of a similar order of magnitude were accepted for comparison. An analysis indicated that the transversal deformability of woven fabrics decreases with the increase in the number of thread systems.

Key words: *multi-axial fabrics, thread systems, one-directional stretching, deformability of woven fabrics, homogeneous net, inhomogeneous net.*

Introduction

Classical woven fabrics, loaded multi-directionally, manifest clearly different properties in directions which do not correspond with the directions of warp and weft, compared with the properties in the corresponding directions. It has been demonstrated that multi-axial woven fabrics are characterised by a significantly higher directional uniformity of their mechanical properties [1 - 4]. This is why these fabrics are appropriate for use under conditions of multi-axial loads. Considering the safety of a construction working under hazardous conditions, it would be important to know the behaviour of multi-axial fabrics stretched one-directionally. The aim of our work was to discover to what degree the multidirectional fabrics are able to transmit one-directional loads, and how their structure would respond under such conditions. The deformation of the sample stretched can be the measure of the response of the multi-axial woven fabric's structure.

Type of structure	Weave	Maximum relative cover factor -	Area mass, g/m²	Working-in of the particular thread systems, %
Three-axial	1/1	0.667	831	12.3:12.0:15.7
Four axial inhomogeneous	1/1	0.523	747	11.2; 40.1; 60.0; 10.4
Four axial homogeneous	1/1	0.458	632	15.4; 14.9; 17.2; 16.3
Six axial inhomogeneous	1/1	0.3	586	10.8; 11.8; 13.8; 10.9; 11.3; 16.4
1st reference woven fabric compared with the four-axial homogeneous and the six-axial woven fabrics	1/1	0.93	606	9.4; 10.4
2nd reference woven fabric compared with the four-axial inhomogeneous woven fabric,	1/1	0.98	713	7.6; 11.4
3rd reference woven fabric compared with the three-axial woven fabric	1/1	0.99	841	13.8; 11.6

***Table 1.** Selected parameters of two- and multi-axial woven fabrics.*

Three-axial fabrics, four-axial fabrics with homogeneous and inhomogeneous nets, and six-axial fabrics with inhomogeneous nets were the object of our investigation. All fabrics were manufactured with plain weave, of carded woollen threads with a linear density of 344 tex × 4 [5, 6]. The multi-axial woven fabrics were thickened to the maximum, which is why they were compared with classical woven fabrics whoch were also thickened maximally (see Table 1).

The fabrics were manufactured by hand, interlaced with the use of templates. The appropriate values of thread spacing were established by position marks. The fabrics were formed by the method of subsequent addition of the thread systems, and each thread was individually tensioned. The method accepted enabled us to obtain reproducible fabric structures for the given number of thread systems.

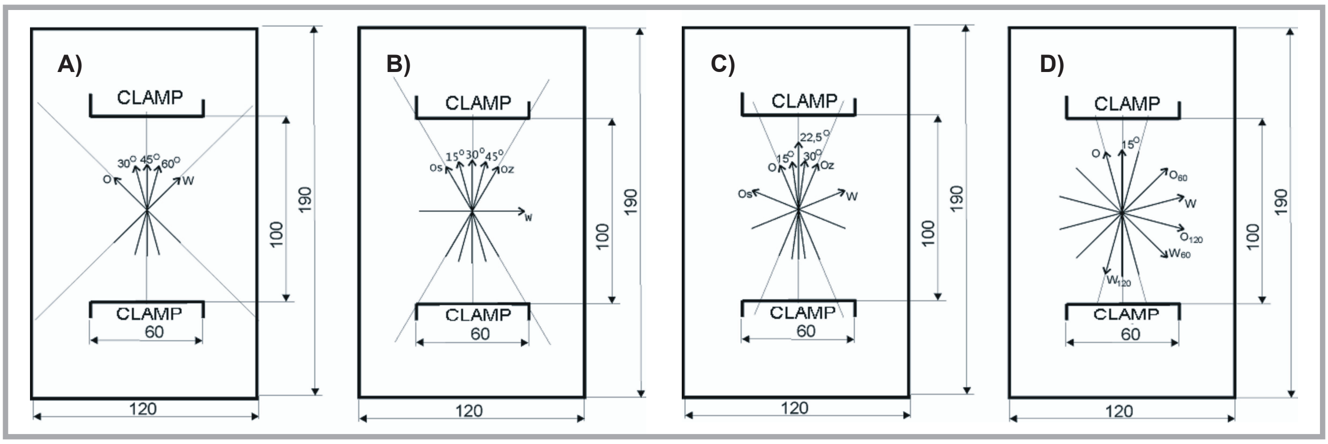

***Figure 1.** Sample dimensions and their orientations in the stretching directions: A) two-axial woven fabric, B) three-axial woven fabric, C) four-axial woven fabric, D) six-axial woven fabric.*

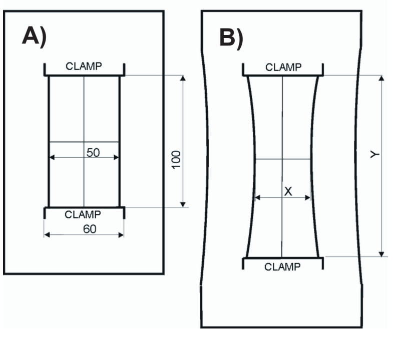

Figure 2. A scheme of the estimation method of deformation the woven fabric during stretching; A) sample with the dimensions 190 × 120 mm before stretching, B) sample during stretching; the sample surface is marked by a 50 mm wide rectangle.

Research methods

The woven fabric's breaking strength P_{max}, in N, and the relative elongation of the fabric related to the maximum force ε_{Pmax}, in %, were assessed in accordance with standard PN-EN ISO 13934-1 [7], under the following measuring conditions:

- spacing of the tensile tester's clamps: 100 mm.
- stretching velocity:100 mm/min, and
- initial load of the woven fabric: 5 N.

The sample length of 190 mm resulted from the accepted clamp spacing for the tensile tester, whereas the width of 120 mm which we used was greater than that provided by the used standard, for the following reasons:

- It was assumed that the samples should be stretched in the directions corresponding with the thread systems and in the intermediate directions. It may occur that a sample stretched in this way does not break, but the thread systems may be mutually displaced. This especially concerns two-axial woven fabrics, where during stretching in the direction of 45ş in relation to warp, a situation arises where not all the threads are jammed at the same time in both the clamps.
- When simultaneously tearing the sample, deformations of the woven fabric were recorded by marking the fabric with a sign in the shape of a rectangle of 50 mm width and length, equal to the spacing between clamps before stretching (100 mm).

The stretching directions for the particular kinds of fabrics are presented in Figure 1.

The stretching process was filmed together with a mark indicating loading, in the form of a light signal emitted at every 100 N of the stretching force. The photos were analysed, and the dimensions *X* and *Y* between the vertical and horizontal control lines were determined in pixels (Figure 2).

The perpendicular deformation of the woven fabrics while stretched one-directionally is characterised by the shape coefficient *KP*:

$$KP = X/P \qquad (1)$$

where:

X – the transversal dimension of the sample, i.e. vertical to the stretching direction,

Y – the longitudinal dimension of the

***Table 2.** Shape coefficients KP, transversal deformability Δ_i, and standard deviations of the three-axial woven fabric with area mass comparable to the area mass of the 3rd reference woven fabric.*

Stretching direction	Shape coefficients, transversal deformability, and standard deviations under stretching force P_i						
A	KP_0 δ_{n-1}	KP_{100} δ_{n-1}	Δ_{100}, %	KP_{300} δ_{n-1}	Δ_{300}, %	KP_{Fmax} δ_{n-1}	ΔP_{max}, %
0º *) warp O_S	**0.497** *0.004*	**0.430** *0.009*	13.5	**0.383** *0.005*	22.9	**0.303** *0.021*	39.0
15º	**0.501** *0.003*	**0.392** *0.014*	21.8	**0.330** *0.014*	34.1	**0.250** *0.015*	50.1
30º	**0.493** *0.003*	**0.357** *0.030*	27.6	**0.298** *0.008*	39.7	**0.196** *0.008*	60.2
45º	**0.501** *0.005*	**0.369** *0.009*	26.3	**0.317** *0.003*	36.7	**0.236** *0.016*	52.8
60º *) warp O_Z	**0.501** *0.007*	**0.433** *0.013*	13.6	**0.403** *0.009*	19.6	**0.334** *0.018*	33.3
120º *) weft	**0.504** *0.009*	**0.430** *0.029*	14.7	**0386** *0.030*	23.4	**0.280** *0.026*	44.4

***Table 3.** Shape coefficients KP, transversal deformability Δ_i, and standard deviations of the 3rd reference woven fabric.*

Stretching direction	Shape coefficients, transversal deformability, and standard deviations under stretching force P_i						
A	KP_0 δ_{n-1}	KP_{100} δ_{n-1}	Δ_{100}, %	KP_{300} δ_{n-1}	$-\Delta_{300}$, %	KP_{Pmax} δ_{n-1}	ΔP_{max}, %
0º warp *)	**0.511** *0.006*	**0.420** *0.001*	17.8	**0.389** *0.002*	23.8	**0.329** *0.007*	35.6
30º	**0.513** *0.001*	**0.318** *0.008*	38.0	**0.244** *0.016*	52.4	**0.164** *0.009*	68.0
45º	**0.512** *0.003*	**0.273** *0.015*	46.7	**0.207** *0.014*	59.6	**0.132** *0.011*	74.2
60º	**0.505** *0.006*	**0.291** *0.008*	42.3	**0.213** *0.006*	57.8	**0.157** *0.006*	68.9
90º weft *)	**0.498** *0.004*	**0.407** *0.004*	18.3	**0.383** *0.004*	23.1	**0.321** *0.004*	35.5

***Table 5.** Shape coefficients KP, transversal deformability Δ_i, and standard deviations of the four-axial woven fabric with inhomogeneous net, and with area mass comparable to the area mass of the 2nd reference woven fabric.*

Stretching direction	Shape coefficients, transversal deformability, and standard deviations under stretching force P_i						
B	KP_0 δ_{n-1}	KP_{100} δ_{n-1}	Δ_{100}, %	KP_{300} δ_{n-1}	Δ_{300}, %	KP_{Pmx} δ_{n-1}	ΔP_{mx}, %
0º *) warp	**0.508** *0.007*	**0.403** *0.006*	20.7	**0.364** *0.010*	28.3	**0.311** *0.008*	38.8
15º	**0.506** *0.006*	**0.390** *0.003*	22.9	**0.330** *0.006*	34.8	**0.264** *0.003*	47.8
22.5º	**0.503** *0.009*	**0.318** *0.040*	36.8	**0.259** *0.013*	48.5	**0.198** *0.006*	60.6
30º	**0.504** *0.008*	**0.347** *0.004*	31.2	**0.285** *0.060*	43.5	**0.231** *0.006*	54.2
45º *) warp O_Z	**0.511** *0.002*	**0.289** *0.015*	43.4	**0.235** *0.050*	54.0	**0.156** *0.006*	69.5
90º *) weft	**0.504** *0.005*	**0.415** *0.003*	17.7	**0.389** *0.012*	22.8	**0.328** *0.005*	34.9
-45º *) warp O_S	**0.499** *0.009*	**0.274** *0.007*	45.1	**0.217** *0.004*	56.5	**0.217** *0.004*	56.5

***Table 6**. Shape coefficients KP, transversal deformability Δ_i, and standard deviations of the 2nd reference woven fabric.*

Stretching direction	Shape coefficients, transversal deformability, and standard deviations under stretching force P_i						
B	KP_0 δ_{n-1}	KP_{100} δ_{n-1}	Δ_{100}, %	KP_{300} δ_{n-1}	Δ_{300}, %	KP_{Pmax} δ_{n-1}	ΔP_{max}, %
0º –warp *)	**0.511** *0.007*	**0.403** *0.005*	21.1	**0.377** *0.006*	26.2	**0.338** *0.010*	33.9
30º	**0.514** *0.013*	**0.269** *0.010*	47.7	**0.196** *0.004*	61.9	**0.148** *0.004*	71.2
45º	**0.502** *0.008*	**0.232** *0.010*	53.8	**0.173** *0.009*	65.5	**0.118** *0.006*	76.5
60º	**0.496** *0.003*	**0.240** *0.023*	51.6	**0.193** *0.005*	61.1	**0.155** *0.005*	68.8
90º –weft *)	**0.495** *0.006*	**0.387** *0.015*	21.8	**0.374** *0.009*	24.4	**0.332** *0.009*	32.9

sample under action of the stretching force P.

A decrease in KP means that while the sample is stretched in the given direction Y, the transversal dimension X decreases more intensively in relation to the increase in its dimension in the direction of stretching (Y).

The sample's susceptibility to deformation, i.e. the transversal deformability, can be expressed by the relation:

$$\Delta_i = 100\% - KP_i / KP_0 \, 100\% = (1 - KP_i / KP_0) \times 100\% \quad (2)$$

where:

KP_i – the shape coefficient during stretching with force P_i, in N, where the index i indicates the value of force P in N,

KP_0 – the shape coefficient before stretching,

Δ_i – determines the decrease in percent of the sample's width during stretching with the given force P_i.

Three measurements of the parameters X and Y were carried out for each kind of the woven fabrics, each under the following three values of force i: P_1 = 100 N, P_2 = 300 N, and $P_3 = P_{max}$ The average values of the coefficients KP and the calculated transversal deformability Δ_i, in percent are listed together with their standard deviations in Tables 2, 3, 5, 6, 8, 9, and 11, the resalts of statistic calculations in Tables 4, 7, 10, and 12, whereas the changes in Δ_i for the particular stretching directions are presented by diagrams in Figures 3 – 9.

*__Remark:__ The designations in all tables are the same, and so they are only explained below; *) indicates stretching in the direction of the thread axis of the particular system, stretching directions at variance with the thread directions we referred to as intermediate; P_{max} – breaking strength, δ_{n-1} – standard deviation. 1) F-significance test for the difference of two variances: hypothesis Ho : $\delta_1^2 = \delta_2^2$, where δ_1^2 and δ_2^2 are variants of the first and second sample test; if $F_\alpha > F_{calc}$ then a ground exists for rejecting the hypothesis Ho. 2) T-Student significance test for the difference of two normal average values: Ho : $a_1 = a_2$; where a_1 and a_2 are average values of the sample tests; if $t_\alpha > t_{calc}$ then no ground exists for rejecting the hypothesis Ho; if $t_{calc} > t_\alpha$, then the hypothesis Ho is rejected, and we conclude that there is a significant difference between the average values of the sample tests at a significance level α= 0.05.*

Table 4. *Statistic calculations for the three-axial and reference fabrics (sample size: $n_1 = n_2 = 3$).*

Woven fabric (stretching direction) (A)	Smallest value KP for intermediate directions under P = 300, N; (δ_{n-1})	F-significance test for the difference of two variances 1)	t-Student significance test for the difference of two average values 2)
three-axial, (30°)	0.298 (0.008)	F_{obl} =3.0625 F_α = 19.0; dla α = 0.005 difference statistical insignificant	t_{obl} = 7.98 t_α = 2.776 dla α= 0.05 difference statistical significant
3rd reference fabric, (45˚)	0.207 (0.014)		

Table 7. *Statistical calculations for the four-axial with inhomogeneous net and the reference fabrics (sample size: $n_1 = n_2 = 3$).*

Woven fabric (stretching direction (B)	Smallest value KP for intermediate directions under P = 300, N ; (δ_{n-1})	F-significance test for the difference of two variants 1)	t-Student significance test for the difference of two average values 2)
Four-axial fabric with inhomogeneous net (22.5°)	0.259 (0.013)	F_{obl} = 2.086 F_α = 19.0 dla α = 0.05 difference statistically insignificant	t_{obl} = 7.692 t_α = 2.776 dla α = 0.05 difference statistically significant
2nd reference fabric (45°)	0.173 (0.009)		

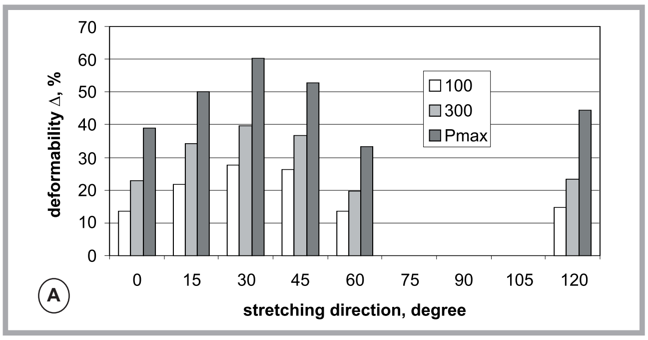

Figure 3. *The ransversal deformability of a three-axial woven fabric.*

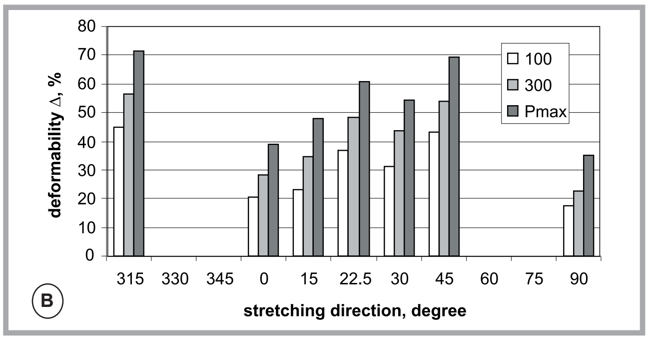

Figure 5. *The transversal deformability of a four-axial woven fabric with inhomogeneous net.*

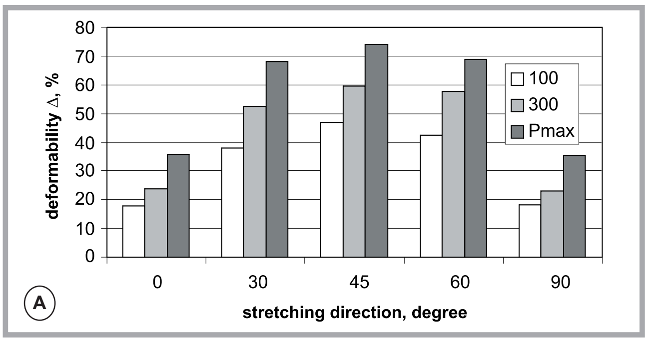

Figure 4. *The transversal deformability of the 3rd reference woven fabric.*

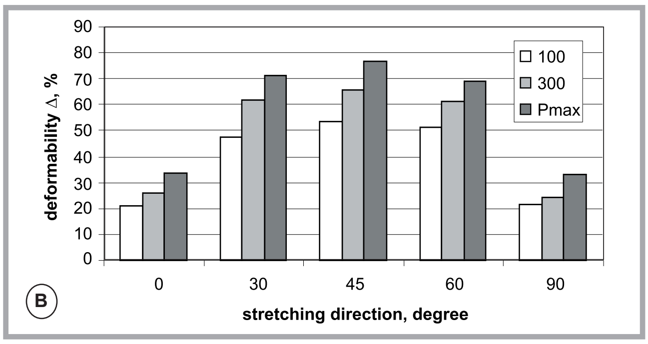

Figure 6. *The transversal deformability of the 2nd reference woven fabric.*

Table 8. *Shape coefficients KP, transversal deformability Δ_i, and standard deviations of the four-axial woven fabric with homogeneous net, and with area mass comparable to the area mass of the 1st reference woven fabric.*

Stretching direction (C)	Shape coefficients, transversal deformability, and standard deviations under stretching force P_i						
	KP_0 δ_{n-1}	KP_{100} δ_{n-1}	Δ_{100} [%]	KP_{300} δ_{n-1}	Δ_{300} [%]	KP_{Fmx} δ_{n-1}	ΔP_{mx} [%]
0° warp *)	**0.462** *0.004*	**0.360** *0.007*	22.1	**0.300** *0.002*	35.1	**0.276** *0.008*	40.3
15°	**0.495** *0.003*	**0.346** *0.006*	30.2	**0.289** *0.003*	41.5	**0.202** *0.007*	49.0
22.5°	**0.496** *0.001*	**0.347** *0.003*	30.0	**0.282** *0.003*	43.0	**0.233** *0.009*	53.0
30°	**0.484** *0.002*	**0.348** *0.005*	28.0	**0.290** *0.006*	40.0	**0.245** *0.008*	49.3
45° warp O_Z *)	**0.504** *0.002*	**0.360** *0.004*	28.6	**0.325** *0.008*	35.5	**0.284** *0.005*	43.7
90° weft *)	**0.487** *0.001*	**0.380** *0.009*	22.0	**0.296** *0.009*	39.2	**0.288** *0.012*	40.9
-45° warp O_S *)	**0.488** *0.002*	**0.346** *0.008*	29.1	**0.297** *0.011*	39.1	**0.264** *0.014*	45.9

Table 9. *Shape coefficients KP, transversal deformability Δ_i, and standard deviations of the 2nd reference woven fabric.*

Stretching direction (C)	Shape coefficients, transversal deformability, and standard deviations under stretching force P_i						
	KP_0 δ_{n-1}	KP_{100} δ_{n-1}	$-\Delta_{100}$ [%]	KP_{300} δ_{n-1}	$-\Delta_{300}$ [%]	KP_{Pmax} δ_{n-1}	$-\Delta P_{max}$ [%]
0° – warp *)	**0.516** *0.006*	**0.399** *0.012*	22.7	**0.386** *0.024*	25.2	**0.376** *0.010*	27.1
30°	**0.496** *0.001*	**0.215** *0.001*	56.7	**0.170** *0.001*	65.7	**0.144** *0.012*	71.0
45°	**0.503** *0.001*	**0.177** *0.008*	64.8	**0.180** *0.002*	64.2	**0.107** *0.007*	78.7
60°	**0.521** *0.003*	**0.238** *0.029*	54.3	**0.176** *0.024*	66.2	**0.139** *0.019*	73.3
90° –weft *)	**0.508** *0.001*	**0.385** *0.010*	24.2	**0.394** *0.014*	22.4	**0.379** *0.032*	25.4

Table 10. *Statistical calculations for the four-axial with homogeneous net and the reference fabrics (sample size: $n_1 = n_2 = 3$).*

Woven fabric (stretching direction (C)	Smallest value KP for intermediate directions under P = 300, N; (δ_{n-1})	F-significance test for the difference of two variances 1)	t-Student significance test for the difference of two average values 2)
Four-axial fabric with homogeneous net (22.5°)	0.282 (0.003)	F_{obl} = 11.4, F_α = 19.0, dla α = 0.05, difference statistically insignificant	t_{obl} = 15.135, tα = 2.776, dla α = 0.05, difference statistically significant
1st reference fabric (30°)	0.170 (0.001)		

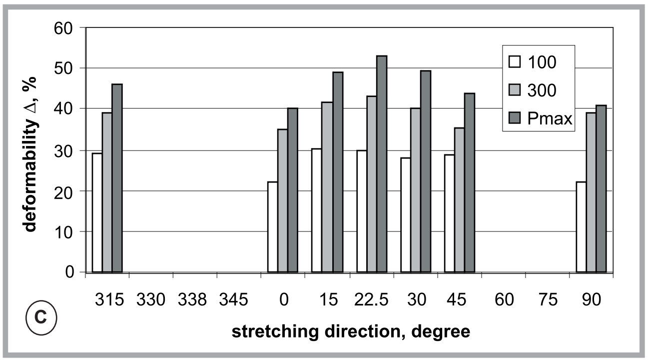

Figure 7. *The transversal deformability of a four-axial woven fabric with homogeneous net.*

Table 11. *Shape coefficients KP, transversal deformability Δ_i, and standard deviations of the six-axial woven fabric with inhomogeneous net, and with area mass comparable to the area mass of the 1st reference woven fabric.*

Stretching direction (D)	Shape coefficients, transversal deformability, and standard deviations under stretching force P_i						
	KP_0 δ_{n-1}	KP_{100} δ_{n-1}	Δ_{100} [%]	KP_{300} δ_{n-1}	Δ_{300} [%]	KP_{Fmax} δ_{n-1}	Δ_{Fmax} [%]
O° *) warp	**0.496** *0.007*	**0.368** *0.009*	25.8	**0.252** *0.002*	49.2	**0.195** *0.006*	60.1
15°	**0.492** *0.006*	**0.312** *0.002*	36.6	**0.251** *0.007*	49.0	**0.235** *0.003*	52.2
30° *) weft, w_{120}	**0.494** *0.010*	**0.324** *0.009*	34.4	**0.280** *0.010*	43.3	**0.261** *0.026*	47.1
60° *) warp, O_{60}	**0.503** *0.006*	**0.354** *0.007*	29.6	**0.230** *0.029*	54.3	**0.191** *0.012*	62.0
90° *) weft	**0.490** *0.002*	**0.361** *0.009*	26.3	**0.289** *0.003*	41.0	**0.231** *0.021*	52.8
120° *) warp, O_{120}	**0.495** *0.009*	**0.351** *0.007*	29.1	**0.270** *0.005*	45.4	**0.206** *0.021*	58.3
150° *) weft, w_{60}	**0.492** *0.001*	**0.365** *0.012*	25.8	**0.281** *0.018*	42.9	**0.237** *0.023*	51.8

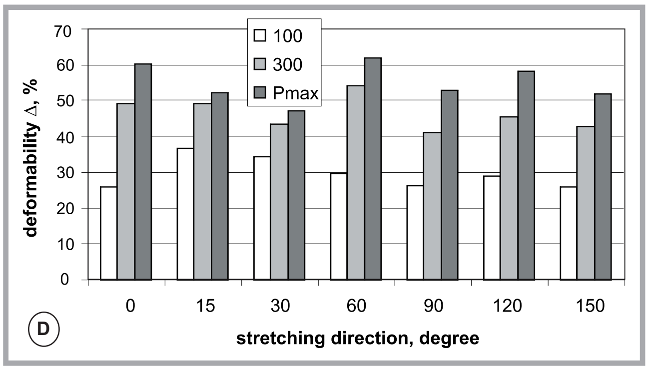

Figure 9. *The transversal deformability of a six-axial woven fabric.*

Table 12. *Statistical calculations for the six-axial woven fabric and the reference fabric (sample size: $n_1 = n_2 = 3$).*

Woven fabric (stretching direction (D)	Smallest value KP for intermediate directions under P = 300, N ; (δ_{n-1})	F-significance test for the difference of two variances 1)	t-Student significance test for the difference of two average values 2)
warp O_{60} (60°)	0.230 (0.029)	F_{obl} = 17.16, F_α = 19.0, α = 0.05, difference statistically insignificant	t_{obl} = 0.996, t_α = 2.776, α = 0.05, difference statistically insignificant
intermediate direction (15°)	0.285 (0.007)		

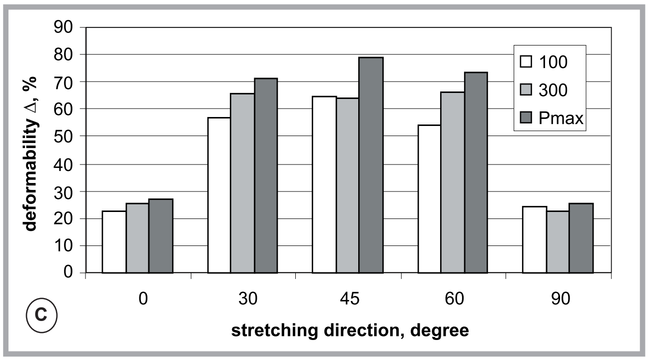

Figure 8. *Thr transversal deformability of the 1st reference woven fabric.*

Test results of the three-axial woven fabric

The results are presented in Tables 2, 3, & 4, and Figures 3 & 4, marked (A).

We defined the following features for the three-axial and two-axial comparable woven fabrics (Tables 2 and 3):

- a smaller transversal deformability, when the fabric was stretched in directions in accordance with the thread axes than when stretched in the intermediate directions;
- the differences between the transversal deformability in the directions of the tread axes and the intermediate directions were higher in the case of the two-axial fabric.

The significance of the differences was confirmed by the t-Student test (Table 4).

Summarising the results obtained, we can state that the deformabilities of a three-axial woven fabric in the direction vertical to the direction of stretching are smaller than those of a classical woven fabric with comparable area mass.

Test results of the four-axial woven fabric with inhomogeneous net

The results are presented in Tables 5, 6, & 7, and Figures 5 & 6, marked (B).

The relatively small values of KP_i, which means high transversal deformability Δ when stretching a four-axial woven fabric with an inhomogeneous net in the directions *Os* and *Oz*, are probably the result of the high working-in values of these systems. This situation is not correct; in fact it results from the interlacing of the woven fabric by hand, which does not allow an identical preliminary tension of all thread systems to be maintained.

The four-axial woven fabric with inhomogeneous net is less susceptible to transversal deformations than a two-axial fabric. As in the case of the three-axial fabric, for the four- and two-axial woven fabrics the smallest values of *KP* under stretching force of $P = 300$ N were compared for the intermediate directions. These differences are statistically significant (Table 7).

Test results of the four-axial woven fabric with homogeneous net

The results are presented in Tables 8, 9, & 10, and Figures 7 & 8, marked (C).

The average values of the coefficients KP and Δ are listed in Tables 8 and 9 (for the reference fabric), and presented as diagrams in Figures 7 and 8 (for the reference fabric). The values of the transversal deformability Δ when stretching the woven fabric in the directions of the thread axis are significantly more uniform than those of the fabric with the inhomogeneous net. The results indicate explicitly that the structure of the woven fabric with the homogeneous net secure a more uniform transversal deformability (compared with a two-axial fabric) for the stretching directions in accordance with the thread axes and the intermediate directions.

As for the pairs of woven fabrics previously compared, it was next determined for the four- axial woven fabric and its two-axial reference item that the differences (under $P = 300$ N) between the smallest values of KP for intermediate directions are statistically significant (Table 10). This means that this four-axial fabric is also less susceptible to transversal deformations than the two-axial fabric.

Test results of the six-axial woven fabric

The results are presented in Tables 11 & 12, and Figures 9, marked (D).

The average values of the coefficients *KP* and Δ are listed in Tables 11 and 9 (for the reference fabric), and presented as diagrams in Figure 9. The result of the statistic difference estimation is presented in Table 12.

The six-axial woven fabric is characterised by high uniformity of the deformability while stretching in the directions of all thread systems (Table 11) With the increase in the stretching force, the differences between the transversal deformability Δ in the directions of the thread axes and the intermediate direction of 15 degree decrease. At the highest deformation, which occurs under the force value of $P = 300$ N, the difference between the smallest KP value longitudinal to the thread system, and the value for the intermediate direction, resulted as statistically insignificant. This indicates a relatively high uniformity of the six-axial woven fabric's deformability while compared with fabrics with a smaller number of axes.

Summary

The research results obtained allow us to formulate the following statements:

- The differences in the deformability of multi-axial woven fabrics along the main and the intermediate directions, within the range of stretching forces investigated, are smaller than for the two-axial reference fabrics.
- For the three-axial woven fabric, these differences, although distinct, are statistically insignificant (for $\alpha = 0.05$).
- For the four-axial woven fabrics, these differences are statistically significant.
- In the case of the six-axial woven fabric, the statistical test was not used, as only one intermediate stretching direction was accepted; but the level of the deformability differences is definitively the smallest among all the woven fabrics tested.

To summarise the considerations described above, on the basis of the experiments carried out we can state that the degree of the transversal deformability of multi-axial woven fabrics stretched one-directionally in the directions of the thread axes, as well as in the intermediate directions, is smaller than for two-axial woven fabrics with comparable area masses.

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