Analysis of yielding during the tensioning of fabrics in plain and four-wire twill weave

DOI: 10.35530/IT.076.03.2024144

JOVANA STEPANOVIĆ PROFIROVIĆ
TATJANA ŠARAC
JOVAN STEPANOVIĆ

ABSTRACT – REZUMAT

Analysis of yielding during the tensioning of fabrics in plain and four-wire twill weave

The deformation properties of woven textile materials depend on several factors. The main factors are the physical and mechanical properties of the yarn, the weave of the fabric and the density of the warp and weft in the fabric. The paper analysed the parameters at the yield point during tensioning of fabrics with different densities of weft wires, different weft yarns, with applied plain weave and four-wire twill weave. A special problem for predicting the deformation characteristics of textile materials is their anisotropic properties, so the results were analysed in the direction of the warp, in the direction of the weft and the diagonal direction.

A comparative analysis of the parameters at the yield point of fabrics in plain weave and four-wire twill weave, produced on the same basis in the weaving process, is given. Based on the obtained results, dependencies were proposed that can be used to predict the yielding of the corresponding fabrics in plain weave and four-wire twill weave, when the fabric is stretched in the direction of the warp, in the direction of the weft and at an angle of 45°.

Keywords: *fabric, plain weave, twill weave, force, elongation, yielding of material*

Analiza elasticității țesăturilor cu legătură pânză și legătură diagonal în patru fire

Proprietățile de deformare ale materialelor textile țesute depind de mai mulți factori. Principalii factori sunt proprietățile fizice și mecanice ale firului, legătura țesăturii și densitatea firelor de urzeală și de bătătură în țesătură. Lucrarea a analizat parametrii la punctul de elasticitate în timpul întinderii țesăturilor cu densități diferite ale firelor de urzeală, fire de urzeală diferite, cu legătură pânză și legătură diagonal în patru fire. O problemă specială pentru prezicerea caracteristicilor de deformare ale materialelor textile o reprezintă proprietățile lor anizotrope, astfel încât rezultatele au fost analizate în direcția urzelii, în direcția bătăturii și în direcția diagonală.

Este prezentată o analiză comparativă a parametrilor la punctul de elasticitate a țesăturilor cu legătură pânză și legătură diagonal în patru fire, produse pe aceeași bază în procesul de țesere. Pe baza rezultatelor obținute, au fost propuse dependențe care pot fi utilizate pentru a prezice elasticitatea țesăturilor corespunzătoare cu legătură pânză și legătură diagonal în patru fire, atunci când țesătura este întinsă în direcția urzelii, în direcția bătăturii și la un unghi de 45°.

Cuvinte-cheie*: țesătură, legătură pânză, legătură diagonal, forță, alungire, elasticitatea materialului*

INTRODUCTION

Mechanical characteristics represent a complex of properties that determine the ability of woven materials to resist the action of various external forces that can cause various types of deformation (shearing, compression, tension, twisting, bending, etc.).

Changes in the shape of woven materials occur as a result of the action of external forces. Deformation of the material depends on the type, direction, intensity, time of force action and relaxation time. Changes in the shape of textile material cause disruption of the structure of woven materials [1–3]. More significant changes in the structure of woven materials occur at the moment when the tension force in intensity exceeds the value of the force at the yield point [4].

Woven textile materials are characterised by anisotropic properties, which represent a special problem when predicting their mechanical characteristics [5, 6]. New methods and devices have been developed for measuring the mechanical characteristics of fabrics [7–9] to explain the changes in the shape of the woven material during use. The effect of changing the weft density on the fabric thickness during stretching was analysed in paper [10].

In addition, methods have been developed for predicting the breaking forces of fabrics and changes in sample dimensions until breaking [11, 12]. In the paper [13], a mechanical model was developed using which can calculate Poisson's ratio through the stress-strain curve of the fabric.

Also, the influence of the anisotropy was analysed of the fabrics in the plain weave on the constants of elasticity in different directions [14]. Also, some papers investigate the tensile behaviour of fabrics with elastane in the stretching process. The deformation of woven materials with different percentages of elastane yarns was analysed [15–17].

However, a review of the literature reveals a lack of data on methods for determining limit loads that can cause significant deformations of fabrics. Therefore, the paper presents a method that can be applied to determine the limit values of the load. The method is based on the analysis of the flow of the force-elongation function and defining the limit up to which the material offers significant resistance to the tensile force, that is, until the moment when the material begins to yield.

In practice, a conclusion is often made about the quality of a fabric (mechanical properties) only based on its breaking characteristics, which is not enough to obtain real information about the material. The values of force and elongation at the yield point of fabrics give a true picture of the permissible loads to which textile materials can be subjected without being significantly deformed.

MATERIALS AND METHODS

The mechanical properties of 40 different fabrics were analysed, 20 in plain weave (Plain 1/1) and 20 in four-wire twill (Twill 3/1). The fabrics are produced in industrial conditions, on a weaving machine with electronic regulation of the weaving process, using yarns from a mixture of PES/Co 50/50% fibres.

All 40 fabrics were produced on the same warp, linear density 25×2 tex (break – 1157 cN; elongation – 8.5%; twist – 600 m^{-1}), with a warp density of 27 cm^{-1}. For the weft are used yarns with a linear density of 25x2 tex (break – 1157 cN; elongation – 8.5 %; twist – 600 m^{-1}), 50 tex (break – 1033 cN; elongation – 9.3 %; twist – 520 m^{-1}), 41.67 tex (break – 807 cN; elongation – 8.8 %; twist – 551 m^{-1}) and 29.41 tex (break – 609 cN; elongation – 6.9 %; twist – 630 m^{-1}), with densities for each weft; 14 cm^{-1}, 16 cm^{-1}, 18 cm^{-1}, 20 cm^{-1} and 22 cm^{-1}.

The breaking characteristics of the fabrics were measured on a dynamometer, MesdanLab Strength Tester, Standard ISO 13934/1 [18]. The speed of stretching until the break of the fabric sample is 100 mm/min. In addition, data were recorded based on which force-elongation dependences were obtained for all analysed fabrics in the direction of the warp, in the direction of the weft and the direction of the diagonal and approximated in the corresponding functions of polynomials of the 9th degree.

Based on the analysis of the flow of the force-elongation function, the yield limit was defined for all 40 fabrics in the direction of the warp, in the direction of the weft and the direction of the diagonal. The maximum of the first derivative of the force-elongation function (the second derivative of the function equal to zero) defines the yield limit [4]. At a given maximum of the first derivative of the function, the data for force and elongation at the yield point were recorded.

RESULTS AND DISCUSSION

When the fabric is loaded, there are changes in its structure that are conditioned by the intensity, direction and time of the force, as well as the fabric's construction solution. Changes in fabric structure at low loads occur as a result of mastering and redistribution of warp and weft crimp. By further increasing the tension force, resistance to stretching is provided by the fibres in the yarn, which elongate in the direction of the force until the moment when the resistance of the frictional force between the fibres is overcome, i.e. when slippage between the fibres occurs and the material loosens. By further increasing the tensioning force, resistance is provided by the yarns that stretch and at the same time bear the pressure of the other yarn system, until they break. The transition from one phase to phase does not mean that the deformations from the previous phase stop. The straightening of the wires in the direction of the force, as well as the sliding between the fibres, continues until the break. Dislocations of the wires occur in the diagonal direction during the stretching of the samples, which is especially expressed in fabrics with a lower density of weft wires [4].

To objectively observe the influence of the change in weft density on the force at the yield point of the analysed fabric samples, all other constructional and structural parameters must be equal (raw material composition, linear density of warp and weft, weave, warp density). Therefore, all analysed fabrics were made on the same warp. Based on the obtained test results, histograms were created, which show the influence of the density of weft wires on the values of force and elongation of fabrics at the yield point in the three observed directions. The results for fabrics are grouped on the histograms, so that the influence of the density of the weft wires, as well as the influence of the applied weave on the deformation properties of the fabrics, with other parameters being equal, can be seen. The corresponding colours indicate the type of weft yarn, and the influence of the applied weft yarn on the force and elongation values at the yield point of the analysed fabrics can be seen.

Figure 1 shows the influence of weft density on the values of force and elongation at the yield point of fabrics in the direction of the warp for 20 fabrics with applied plain weave and for 20 fabrics with applied four-wire twill weave of the warp effect.

Based on the obtained results, it is not possible to see a clear influence of the density of the weft wires on the force values at the yield point of fabrics with applied plain and four-wire twill weave. If the influence of the wave is observed, with other parameters being unchanged, in the majority of cases, fabrics with applied plain weave have higher force values at the yield point in the direction of the warp (figure 1, *a*). The elongation at the yield point in the direction of the warp increases with the increase in the density of the warp wires (figure 1, *b*). This statement applies to all analysed fabrics. Also, it can be noted that the elongation at the yield point in the direction of the warp in fabrics with applied plain weave is greater than in fabrics with applied four-wire twill weave, other parameters being unchanged. By analysing the obtained results, it can be observed that the linear density of the weft has an influence on the value of

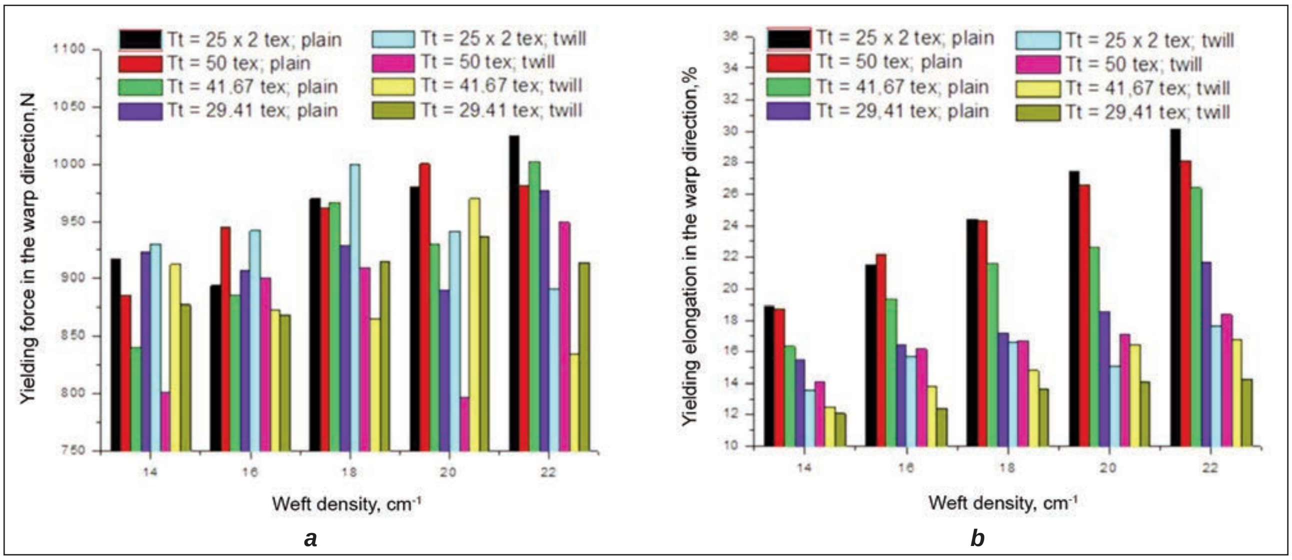

Fig. 1. Influence of weft density and weave on: *a* – force; *b* – elongation at the yield point of the fabric in the direction of the warp

the elongation at the yielding limit of the fabric in the direction of the warp. The crimp of the warp, in addition to other parameters, has a significant influence on the elongation value in the direction of the warp. Raw fabrics with applied plain weave have a higher warp crimp compared to fabrics with applied four-wire twill weave [19]. Also, the crimp of the warp increases with the increase in the density of the weft wires, but also with the use of thicker yarns for the weft, which is one of the reasons for the elongation values obtained in this way at the limit of yielding in the direction of the warp.

The influence of the density of the weft wires and the applied weave on the deformation properties of the fabrics in the direction of the weft is shown in figure 2. The obtained results show that the density of the weft wires has a direct influence on the value of the force at the yield point of fabrics with applied plain and four-wire twill weave (figure 2, *a*). Also, the results show that the force values at the yield point of the fabrics in the direction of the weft are higher in fabrics with applied plain weave compared to fabrics with applied four-wire twill weave. This is the expected result, since the number of changes in wire effects about the pattern repeat is greater in fabrics with applied plain weave [20], and therefore, the contact surface between the warp and weft yarns is larger, which contributes to the strength of the fabric.

Figure 2, *b* shows the influence of the weft density on the elongation value at the yield point of the fabric in the weft direction. The results show an increasing trend of elongation at the yield point in the direction of the weft, with an increase in the density of the weft wires, for all analysed fabrics.

Figure 3 shows the results of the force and elongation values at the yield point of the fabrics in the diagonal direction for all forty samples. A certain trend of increasing force at the yield point is observed

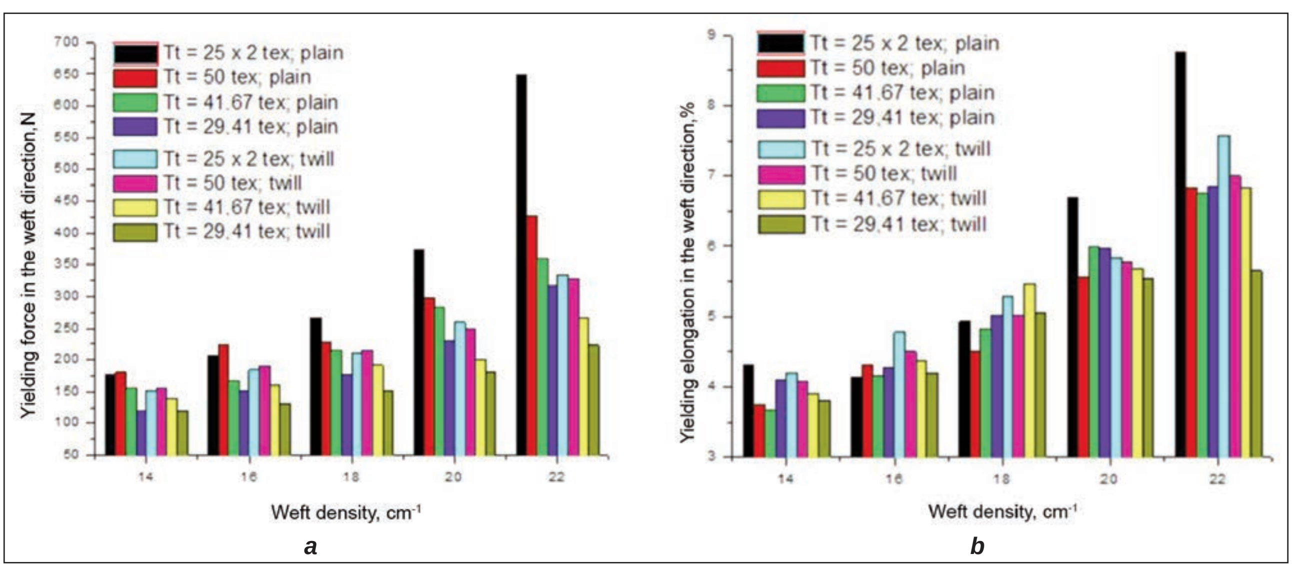

Fig. 2. Influence of weft density and weave on: *a* – force; *b* – elongation at the yield point of the fabric in the direction of the weft

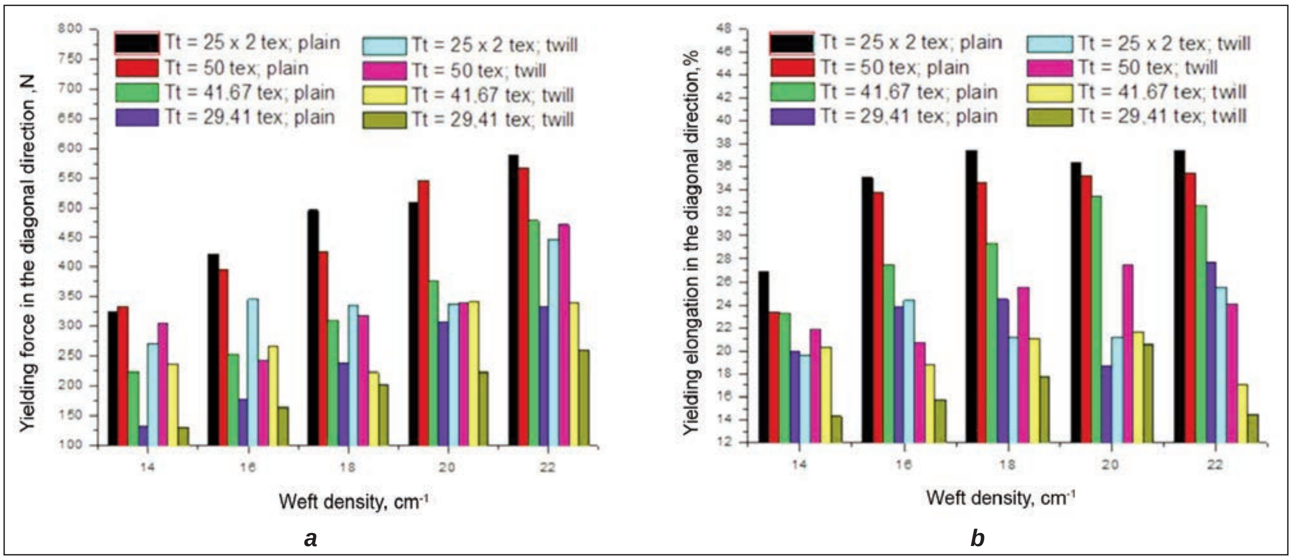

Fig. 3. Influence of weft density and weave on: *a* – force; *b* – elongation at the yield point of the fabric in the diagonal direction

for fabrics with a higher density of weft wires, while no clear influence of weft density on elongation at the yield point of fabrics in the diagonal direction can be observed.

Based on the obtained results, it can be concluded that the fabrics with the applied plain weave have higher force values at the yield point in the diagonal direction. Also, fabrics with applied plain weave have a greater elongation at the yield point in the diagonal direction compared to fabrics with applied four-wire twill, other parameters being unchanged.

The mechanical properties of weft yarns generally have the expected influence on the properties of fabrics at the yield point. Namely, the smallest force values at the yield point in the direction of the weft and in the direction of the diagonal have fabrics with an applied weft of linear density 29.41 tex.

Breaking force and breaking elongation of the fabric are important parameters that characterise the mechanical properties of the material. However, data on these parameters are not sufficient to obtain a true picture of the mechanical properties of the woven material. Textile materials suffer various loads during exploitation. From the point of view of preserving the structure of woven material, it is very important to have data on the limit loads to which a material can be subjected without its properties being impaired. That is why the limit values of load in the direction of the warp, the direction of the weft and in the diagonal direction have been determined for all fabrics. By analysing the flow of the force-elongation function, the yield point was determined, which represents the load limit up to which a material can be loaded without being deformed.

Figure 4 shows the values of the force participation at the yield point about the breaking force of the fabric. The percentage of participation of the force at the yield point in the breaking force in the direction of the warp in fabrics with applied plain weave is in the range of 62.5–71.5 %, while in fabrics with applied four-wire twill weave, it is 57.9–75.7 %. The increase in the density of the weft wires in the fabric contributes to the increase in the percentage of the force at the yield point in the breaking force in the direction of the weft, in the range of 25.2–51.8 % for plain weave, while for four-wire twill it is 23.5–40.4 %, and this growth is especially pronounced when the values are analysed in the diagonal direction, where the range of results for plain weave is 37.5–84.4 %, and for four-wire twill 57.6–85.1 %. An increase in the density of the weft wires contributes to an increase in friction between the warp and weft wires, due to a greater number of connecting points of the warp and weft per unit area, so the material provides greater resistance to wire slippage when the fabric is tensioned and stretched. In addition, if the influence of the applied weave on the percentage of force participation at the yield point in the breaking force is analysed, it is observed that these results are higher for fabrics with applied plain weave in the direction of the weft, with other parameters being unchanged.

Figures 5, 6 and 7 show graphs of the relationship between elongation at break and elongation at yield point in warp direction, weft direction and diagonal direction for all analysed fabrics.

The relationship between elongation at the yield point (the maximum of the first derivative of the force-elongation function) and breaking elongation (data measured on a dynamometer) is shown by an equation of the form $y = a + bx$.

Table 1 shows the correlation dependence parameters for all three directions for the analysed fabrics with applied plain and four-wire twill weave.

By applying the obtained data, it is possible to determine the elongation limit values of the corresponding woven materials with the applied plain and four-wire twill weave from the 50% PES/50% Co fibre mixture. As the force-elongation dependence is defined for

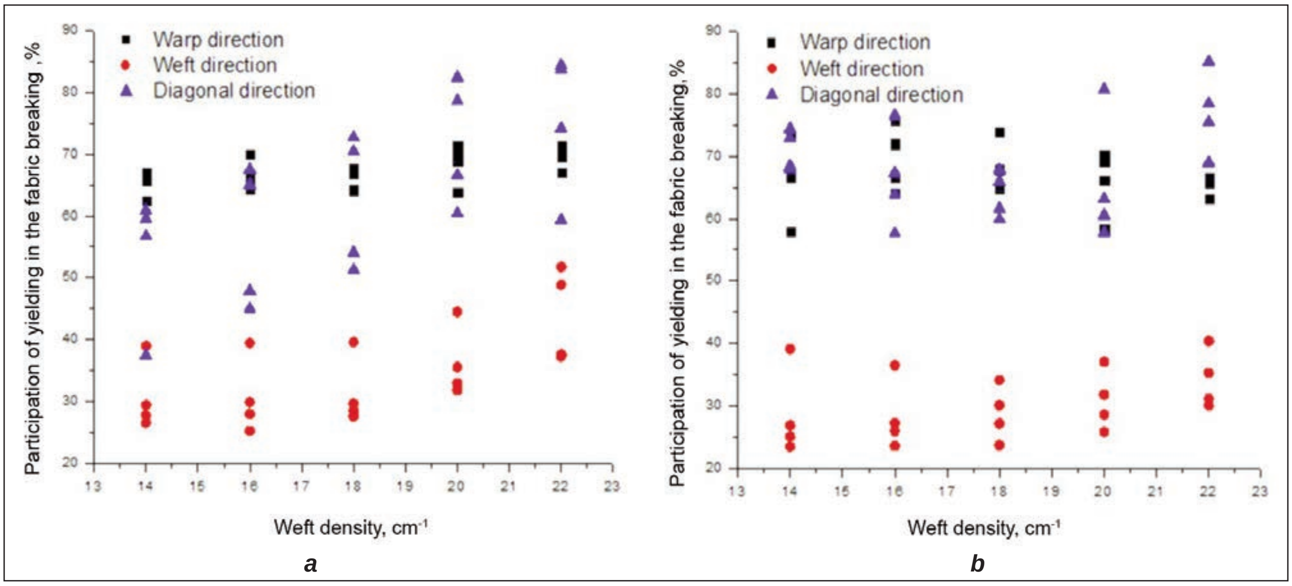

Fig. 4. The percentage of the force at the yield point in the breaking force of the fabric with the applied:
a – plain; *b* – four-thread twill weave

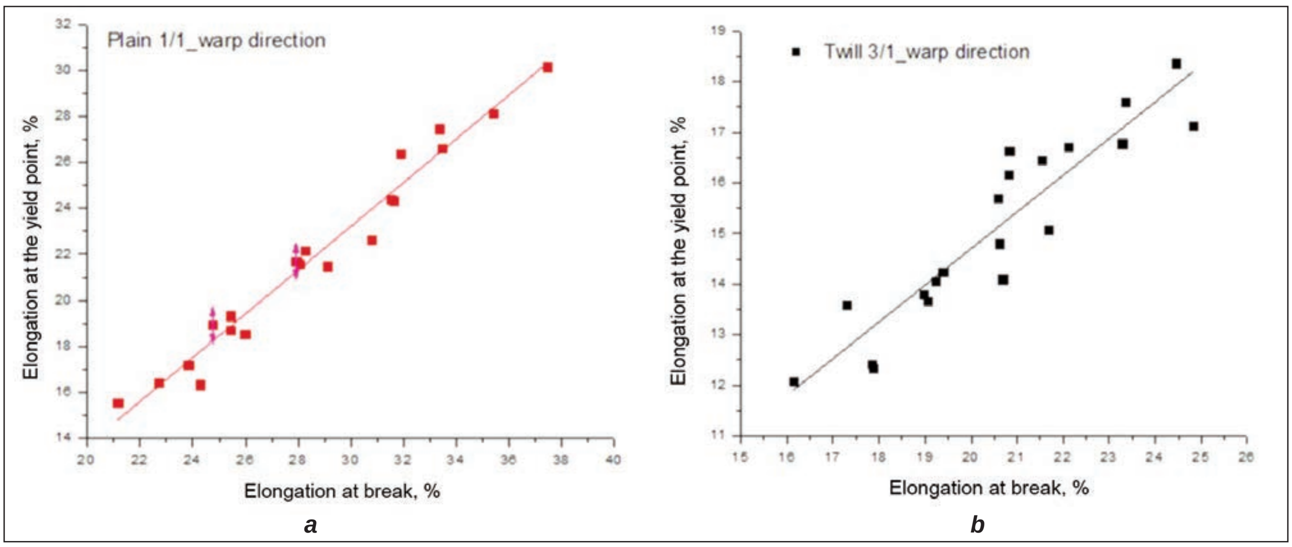

Fig. 5. Relationship between elongation at the yield point and breaking in the warp direction, fabric in:
a – plain weave; *b* – twill weavee

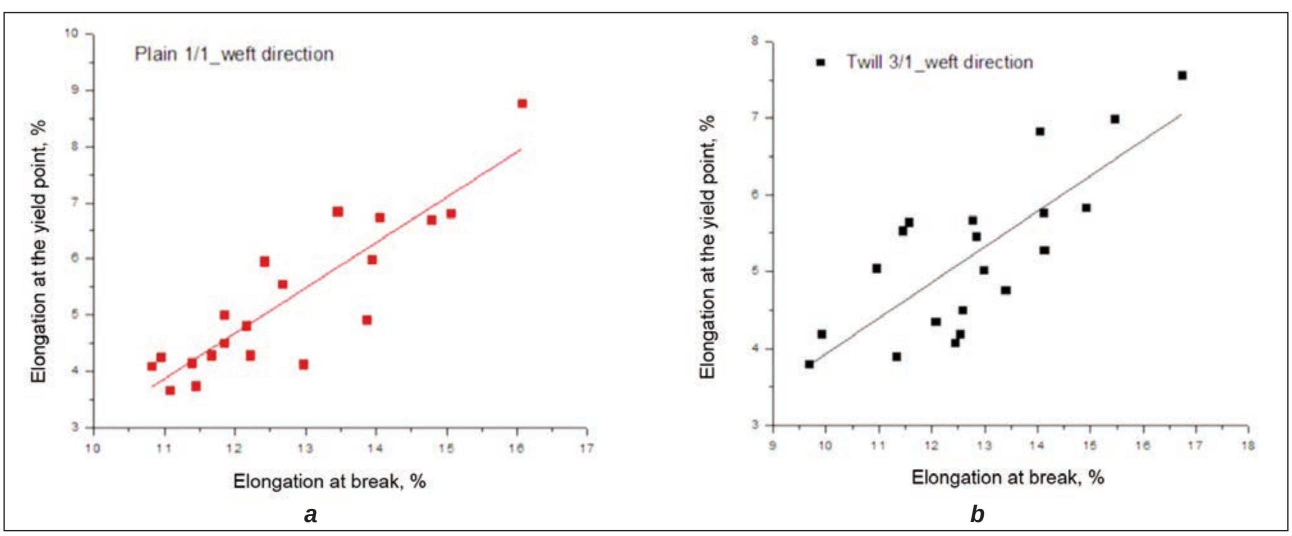

Fig. 6. Relationship between elongation at the yield point and breaking in the direction of the weft direction, fabric in:
a – plain weave; *b* – twill weave

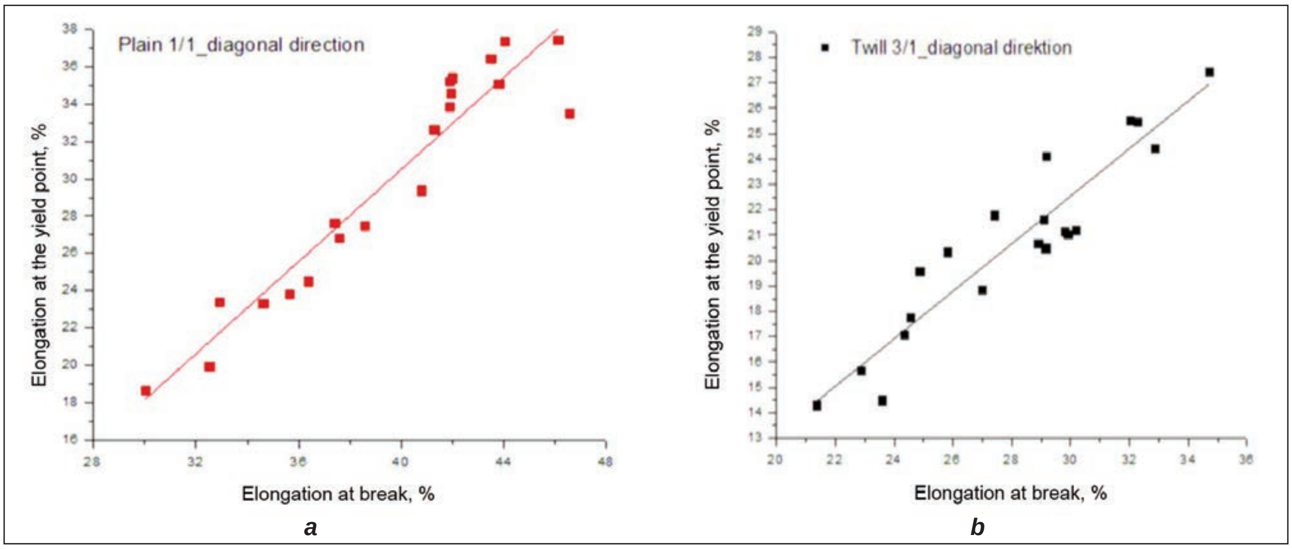

Fig. 7. Relationship between elongation at the yield point and breaking in the diagonal direction, fabric in: *a* – plain weave; *b* – twill weave

Table 1

CORRELATION DEPENDENCE PARAMETERS					
Function	$y = a + bx$				
	Plain weave				
Parameters	a	St.error	b	St.error	r^2
Warp direction	–5.352	1.138	0.953	0.039	0.967
Weft direction	–4.991	1.273	0.806	0.099	0.773
Diagonal direction	–18.826	3.668	1.233	0.092	0.903
	Twill weave 3/1				
Parameters	a	St.error	b	St.error	r^2
Warp direction	0.200	1.433	0.725	0.069	0.851
Weft direction	–0.696	1.127	0.463	0.087	0.588
Diagonal direction	–5.581	2.314	0.937	0.082	0.872

each sample in the form of a ninth-degree polynomial, it is easy to determine the value of the force at the yield point at the corresponding elongation.

CONCLUSIONS

By increasing the density of the weft wires in the fabric, the force at the yield point of the fabric increases in the weft direction and has a growing trend in the diagonal direction. Also, elongation at the yield point increases in the direction of the warp and the direction of the weft.

Fabrics with applied plain interlacing have higher values of elongation at the yield point in the direction of the warp and in the diagonal direction, and generally higher values of force at the yield point compared to fabrics with applied four-wire twill weave.

The deformations of woven materials depend on their structure, construction, and the intensity and direction of the load. Defining the parameters of fabrics at the yield point and relating them to breaking characteristics can serve to develop a method for predicting the behaviour of fabrics during exploitation. Also, the obtained data can be useful for optimising the structure and construction of woven materials according to their future purpose.

ACKNOLEDGEMENTS

Republic of Serbia – Ministry of Education, Science and Technological Development, Program for financing scientific research work, number 451-03-65/2024-03/ 200133.

REFERENCES

[1] Dolatabadi, K.M., Kovar, R., Linka, A., *Geometry of plain weave fabric under shear deformation. Part I: measurement of exterior positions of yarns*, In: Journal of Textile Institute, 2009, 100, 4, 368–380, https://doi.org/10.1080/00405000701830474

[2] Dolatabadi, K.M., Kovar R., *Geometry of plain weave fabric under shear deformation. Part II: 3D model of plain weave fabric before deformation and III: 3D model of plain weave fabric under shear deformation*, In: Journal of Textile Institute, 2009, 100, 5, 381–300, https://doi.org/10.1080/00405000701830631

[3] Mousazadegan, F, Ezazshahabi, N., *Contribution of constituent yarns of the worsted woven fabrics in various directions during the tensile loading*, In: Journal of Engineered Fibers and Fabrics. 2019, 14, 1–10, https://doi.org/10.1177/1558925019846694

[4] Stepanović, J., Ćirković, N, Sadiković, A., Stepanović, J., *Analysis of the deformation characteristics of woven textile materials in plain weave,* In: Advanced Technologies, 2024, 13, 1, 50–56, https://doi.org/10.5937/savteh2401050S

[5] Dai, X., Li, Y., Zhang, X., *Simulating Anisotropic Woven Fabric Deformation with a New Particle Model,* In: Textile Research Journal, 2003, 73, 12, 1091–1099, https://doi.org/10.1177/004051750307301211

[6] Klevaitytė, R., Masteikaitė, V., *Anisthropy of Woven Fabric Deformation after Stretching,* In: Fibres & Textiles in Eastern Europe, 2008, 69, 4, 52–56

[7] Du, Z., Yu, W., *Analysis of shearing properties of woven fabrics based on bias extension,* In: Journal of Textile Institute, 2008, 99, 4, 385–392, https://doi.org/10.1080/00405000701584345

[8] Kovar, R., Gupta, B.S., *Study of the Anisotropic Nature of the Rupture Properties of a Woven Fabric,* In: Textile Research Journal, 2009, 79, 6, 506–506

[9] Zheng, J., Takatera, M., Shimizu, Y., Inui, S., *Measuring technology of the Anisotropy Tensile Properties of Woven Fabrics,* In: Textile Research Journal, 2008, 78, 12, 1116–1123, https://doi.org/10.1177/0040517507083437

[10] Penava, Ž., Penava, D.Š., Knezić, Ž., *Determination of the Impact of Weft Density on Fabric Dynamic Thickness under Tensile Forces,* In: Fibres & Textiles in Eastern Europe, 2019, 27, 6, 46–53, https://doi.org/10.5604/01.3001.0013.446

[11] Shahabi, N.E., Saharkhiz, S., Varkiyani, S., M.H., *Effect of fabric structure and weft density on the Poisson's ratio of worsted fabric,* In: Journal of Engineered Fibers and Fabrics, 2013, 8, 2, 63–71, https://doi.org/10.1177/155892501300800208

[12] Zulfiqar, A.M., Mumtaz, H.M., Tanveer, H., Farooq, A., Phil, M., *Development of Models to Predict Tensile Strength of Cotton Woven Fabrics,* In: Journal of Engineered Fibers and Fabrics, 2011, 6, 4, 46–53, https://doi.org/10.1177/155892501100600407

[13] Brnada, S., Šomođi, Ž., Kovačević, S., *A new method for determination of Poisson's ratio of woven fabric at higher stresses,* In: Journal of Engineered Fibers and Fabrics, 2019, 14, 1–13, https://doi.org/10.1177/1558925019856225

[14] Penava, Ž., Šimić, D., Knezić, Ž., *Determination of the Elastic Constants of Plain Woven Fabrics by a Tensile Test in Various Directions,* In: Fibres & Textiles in Eastern Europe, 2014, 22, 2, 57–63

[15] Gorjanc, D.S., Bizjak, M., *The Influence of Constructional Parameters on Deformability of Elastic Cotton Fabrics,* In: Journal of Engineered Fibers and Fabrics, 2014, 9, 1, https://doi.org/10.1177/155892501400900106

[16] Siddiqa, F., Haque, M., Smriti, S.A., Farzana, N., Abu, N.Md., Haque, A., *Effect of Elastane and Thread Density on Mechanical Attributes of Stretch Woven Fabric,* In: AATCC Journal of Research, 2020, 7, 1, 21–30, https://doi.org/10.14504/ajr.7.1.3

[17] Jiang, L., Zulifqar, A., Hai, A.M., et al. *Effect of using alternate elastic and non-elastic yarns in warp on shrinkage and stretch behavior of bi-stretch woven fabrics*, In: Journal of Engineered Fibers and Fabrics, 2023, 18, 1–9, https://doi.org/10.1177/15589250221137897

[18] European standard EN ISO 13934-1. *Determination of maximum force and elongation at maximum force using the strip method*

[19] Stepanović, J., Ćirković, N., Radivojevic, D., Reljić, M., *Defining the warp length required for weaving process*, In: Industria Textila, 2012, 63, 5, 227–231

[20] Stepanovic, J., Milutinovic, Z., Petrovic, V., Pavlovic, M., *Influence of relative density on deformation characteristics of fabrics in plain weave*, In: Indian Journal of Fibre & Textile Research, 2009, 34, 1, 69–75

Authors:

JOVANA STEPANOVIĆ PROFIROVIĆ, TATJANA ŠARAC, JOVAN STEPANOVIĆ

University of Nis, Faculty of Technology in Leskovac, Department of Textile Sciences,
Bulevar oslobodjenja 124, 16000, Leskovac, Serbia

Corresponding author:

JOVAN STEPANOVIĆ
e-mail: jovan.stepanovic@ni.ac.rs