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Mathematical Simulation of Elongation at Break after Fatigue Loading of Fabrics Containing Fancy Yarns

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Abstract
The aim of this research was to investigate the mechanical indices of fabrics with fancy yarns before and after fatigue loading and develop a mathematical simulation of the elongation at break of the fabrics investigated. For this purpose fancy yarns were produced in one process using hollow spindles and these yarns were used to weave fabrics. In this research we analyzed and forecasted the breaking force and elongation at break of fabrics with fancy yarns in their structure. It was also noted that the relationships obtained give a possibility to design fabrics with fancy yarns characterised by the best particular properties. It was estimated that fatigue loading significantly influenced the structure of the fancy yarns and consequently changed the mechanical indices of the fabrics containing these yarns. The elongation at break in the weft direction after fatigue increased in almost all fabric variants investigated. Moreover the biggest increase was observed for fabrics containing fancy yarns with waves and a spiral structure, as well as for fabrics containing fancy yarns with a non-periodically located open and closed loop structure.

Key words: *fancy yarns, mechanical indices, mathematical model, elongation at break.*

Introduction

An especially pressing and important problem of today is creating high quality new textile products and analysing their properties and usage possibilities. Modern–day fashion and the popularity of woven, knitted and nonwoven fabrics made from fancy yarns, as well as the importance of functional and usage properties requires the designing of new fancy yarns and analysis of their mechanical and end-use properties [1, 2].

The materials for textile and apparel products undergo multiplex cyclic deformation during wear. Due to creases of the upper material in packets, the uncovering of threads very frequently appears [3]. It is known that the cyclic loading stress limit is less than the static stress capability [4]. Dynamic failure is a very serious problem because materials fail at stress levels much lower than under static loading [5]. Parameters, such as environment temperature, stress amplitude, mean stress level, frequency etc., have a great influence on the cyclic lifetime behaviour of polymers [6]. Various elements of clothing during wear are affected by cyclic compression, flexing, stretching, and even scooping [7]. The bending resistance is an important property for very different goods with or made from textile - from carpets to tire cords [8, 9]. According to J. W. S. Hearle and M. Miraftab, the study of the flex fatigue of fibres is important for three reasons. Firstly, it is of practical relevance to the failure of textile materials in use, whether in traditional applications such as clothing or in new engineering uses. Secondly, it involves some interesting features of the mechanics of deformation, with a combination of stresses which can lead to different modes of rupture. Thirdly, the response of the material at the microstructural level is a challenging problem in polymer physics. The authors noticed that the flex fatigue of polyamide and polyester fibres is highly dependent on temperature and humidity. A fibre which lasts for a long time under one set of conditions might fail in a fraction of the time under other conditions [10]. L. Nkiwane and S. K. Mukhopadhyay investigated the flex fatigue of nylon 6.6 tire yarns and cords at different stress levels. Their results showed that twisting and dipping the cord in RFL resin has a significant effect on the fatigue life. SEM observations showed that all specimens experienced more than one kind of mechanisms leading to failure [9].

In resistance researches of flexing, the effort to imitate real material fatigue is seen during exploitation, which is why the constant developing of new experimentation can be of great importance [11, 12]. A novel method was employed to assess and compare the bending properties of three types of hybrid yarns embedded with superelastic shape memory alloy wires that had been developed. The hybrid yarns were embedded in a woven structure, and it was found that they significantly contributed to an increase in the crease recover angle of the flaxed fabrics [11]. In a study of Chinese scientists, new bending fatigue test apparatus was used and the effects of pre-tension, bending angles and temperatures on the bending fatigue of high performance polyethylene fibres were analysed to provide guidance for using high performance polyethylene fibres [12].

In this study, double creases in apparel flexing zones during wear were generated repeatedly in specimens by means of a suitable apparatus until the test pieces survived a specified number of flexure cycles. This method has already been used for investigation of the flexing fatigue influence on the properties of microporous breathable leather laminates for clothing [3, 7]. It was determined that the environment temperature of flexing fatigue has a significant influence on the laminated leather strength and waterproof properties. The decreasing of the environment temperature decreased the strength of flex fatigue of the laminated leather [3]. Water penetration starts when the environment temperature of flexing falls to ≤ -10 °C. Laminated leather stayed impermeable after flexing at the highest temperatures [7].

Most of the literature published regarding this has focused on the study of the fatigue properties of synthetic polymers, knitted and woven fabrics, laminates, carpets, and cords [3, 7 - 12], but there have not been investigations conducted on fabrics with fancy yarns in their structure.

The aim of this research was to investigate the mechanical indices of fabrics with fancy yarns before and after fatigue loading and to mathematical simulate the

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Table 1. Code and real independent variables of manufacturing fancy yarns.

Variant number	Code independent variables			Real independent variables			Linear density, tex
	X_1	X_2	X_3	X_1, m/min	X_2, m/min	X_3, min^{-1}	
1	-	-	-	40	30	14,000	171.5
2	+	-	-	80	30	14,000	178.0
3	-	+	-	40	50	14,000	261.4
4	+	+	-	80	50	14,000	144.9
5	-	-	+	40	30	20,000	187.7
6	+	-	+	80	30	20,000	189.5
7	-	+	+	40	50	20,000	159.4
8	+	+	+	80	50	20,000	253.3
9	-	0	0	40	40	17,000	154.3
10	+	0	0	80	40	17,000	212.9
11	0	-	0	60	30	17,000	147.4
12	0	+	0	60	50	17,000	223.6
13	0	0	-	60	40	14,000	212.9
14	0	0	+	60	40	20,000	168.9

elongation at break of the fabrics investigated.

Materials

Fancy yarns were produced by the one-process method using a fancy yarn twisting machine - "Jantra PrKV-12" ("Jantra", Bulgaria) equipped with hollow spindles of the type FAG (Germany), according to "Prenomit" technology. The object of the subsequent research were fancy yarns with structure effects like loops, waves, knots, spirals and combined effects. The components of the fancy yarns were the core and effect components – twisted, bulk PAN yarns, each of 31 tex × 2, and the binder component – multifilament PA yarn, 5.0 tex.

A second order composite model with experimental points on the hypercube was chosen, with the following design characteristics: number of levels and number of variables – 3, the number of factor level combinations – 14, i. e. $N = 2^k + 2k$. This composite model was developed, taking the D-optimality criterion rather than orthogonality or rotatability criteria. It has no central run. This design was highly suitable for the study because of its obvious advantages: the corner points can be successively investigated, enabling to study the larger part of the space. The number of factor value combinations is small.

The independent variables chosen were:

- speed of supply of effect yarn X_1: 40 – 80 m/min (0.67– 1 .33 m/s),
- delivery speed of fancy yarn X_2: 30 – 50 m/min (0.50 – 0.83 m/s),
- rotational rate of hollow spindle X_3: 14000 – 20000 min^{-1} (233.3 – 333.3 s^{-1}).

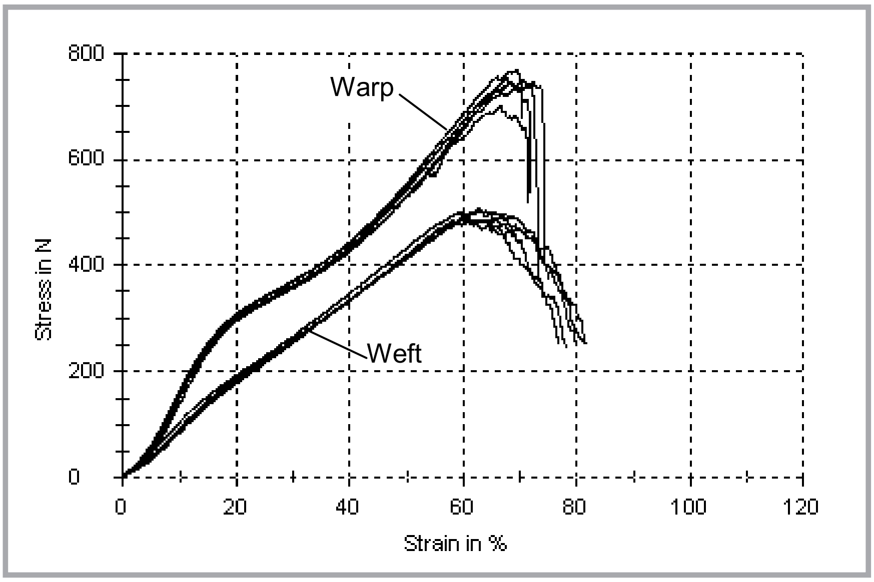

Figure 1. Stress-strain curves of 5 tensile tests before fatigue of the 7th variant of fabric.

The code and real independent variables of manufacturing the fancy yarns are presented in ***Table 1***.

Thus fancy yarns were produced at 14 different factor value combinations and such fancy yarns can be used for woven and knitted fabrics designated for clothing, as well as for home, decorative and technical textiles.

The fabrics predestined for this research were woven on a STB-2-180 gripper loom with blended yarn of 18 tex × 2 (55% wool fibre and 45% PES fibre) as the warp and the same yarns together with fancy yarns in the weft. Fancy yarns in the weft of woven fabrics had been used with the following repeat: one fancy yarn and one blended yarn. The weave of the fabrics investigated was chosen as twill 1/3, the warp setting 240 dm^{-1}, and the weft setting 140 dm^{-1}.

Test methods

In this research we analysed and forecasted (and the basis for designing was created) the breaking force F and elongation at break ε of fabrics containing fancy yarns. The fabrics were tested on standard test equipment using standard test methods.

The mechanical indices were tested with a Strength Tester Zwick/Z005 („Zwick/Roell", Germany). The experiments were performed as specified in Standard ISO 13934-1. The experimental length of the fabrics was 200 mm, the initial stress – 2 N and the clamp movement speed – 100 mm/min. The number of tests of the fabrics before fatigue was 5, after fatigue – 3. The stress-strain curves of five tensile tests are shown in ***Figure 1***.

All indices were analysed before and after fatigue. Double creases in the apparel flexing zones during wear were generated repeatedly in the specimens by means of suitable apparatus until the test pieces survived a specified number of flexure cycles. ***Figures 2.a*** and ***2.b*** present the fixation of the samples in the flexing machine. The test was performed using methodology in accordance with Standard ISO 5423:1992. The fatigue was carried out on a "VAMP"testing flexing

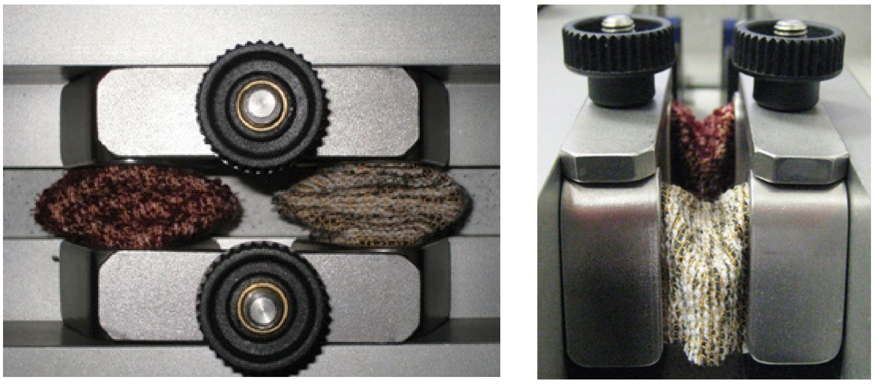

Figure 2. *Fixation of samples in "VAMP" flexing machine.*

machine ("Pegasil/ZIPOR", Portugal). The "VAMP" flexing machine comprises 12 test stations, each unit of which has a fixed clamp and a movable clamp which moves forwards and backwards with constant speed. The apparatus consists of pairs of V-shaped clamps suitably mounted so that the axes of each pair are in the same straight line. One clamp of each pair is capable of reciprocating at a frequency of 1.5 ± 0.2 Hz. Both clamps are spaced apart by 28.5 ± 1.0 mm when open and by 9.5 ± 1.0 mm in the closed position, which makes a stroke of 19 ± 1.5 mm, repeated at 90 ± 9 cycles/minute. The test equipment was mounted inside a cold chamber so that it was possible to adjust the test temperature down to – 25 °C.

Before testing, all specimens were conditioned at standard atmospheric conditions of 20 ± 2 °C and relative humidity 65 ± 4% for at least 48 h. Fatigue testing was carried out at a temperature of T = –20 °C ± 2 °C during a number of cycles N_C = 1,000,000 (more than 7 days of non-stop fatigue).

The kind of fancy effect of the yarns was tested organoleptically before and after the fatigue test with the use of an optical microscope.

Results and discussions

Preliminary research showed that the structural and mechanical indices of the fancy yarns depend on their manufacturing parameters [2]. It was proved the structural indices of fancy yarns primarily depend on overfeed. Overfeed shows the excess of the effect component, i.e. how many times the effect component is longer in relation to the core component. With an increase in this factor, the values of such indices of fancy yarns as the linear density, the height and width of the effects, and the number of effects per unit length also rise, and in this case the distance between effects decreases. At a minimal overfeed, spiral effects were formed in the majority of places along the yarn. With an increase in overfeed, the structure of fancy yarns changes, i. e. open & closed loops, knots, and slubs, among others, are formed. It was repeatedly estimated that the structure of fancy yarns influences the end-use properties of fabrics manufactured with the use of fancy yarns, for example if the dimensions of effects are higher (slubs) e.g. the abrasion resistance of the fabric is lower, whereas fabrics including fancy yarns with effects of smaller dimensions e.g. spiral effects, are more resistant to abrasion. Also air permeability depends on the kind of effects of fancy yarn in the fabric and on the regularity of their distribution [13].

Therefore it seemed reasonable to devote the next investigation to analysing the mechanical indices of fabrics with fancy yarns and estimate the influence of fatigue loads on these indices. Test equipment such as the "VAMP" flexing machine is popular to evaluate the occurrence of cracking in the area of greater flexion. Woven and/or knitted fabrics with fancy yarns are often used for technical textiles, including car seat covers. That was the reason why in this investigation fatigue testing was carried out at the extreme low temperature of T = -20 °C. The mechanical indices of fabrics with fancy yarns in the warp and weft direction before and after fatigue obtained by our investigation are presented in ***Figures 3*** and ***4***, where the dark columns show the values of mechanical indices before fatigue, and light columns – after fatigue.

It is evident from ***Figure 3.a*** that the breaking force of fabrics in the warp direction after fatigue is almost the same as it was before fatigue. The extreme exceptions are fabric variants 1 and 4, whose value of the breaking force before fatigue is approximately 40% bigger than after fatigue. This index also decreased after fatigue by about 10% for 2 other fabric variants. These tendencies are stated for fabrics with fancy yarns in which bosses and arcs as well as open-and closed loops are formed, and in some places knots occur.

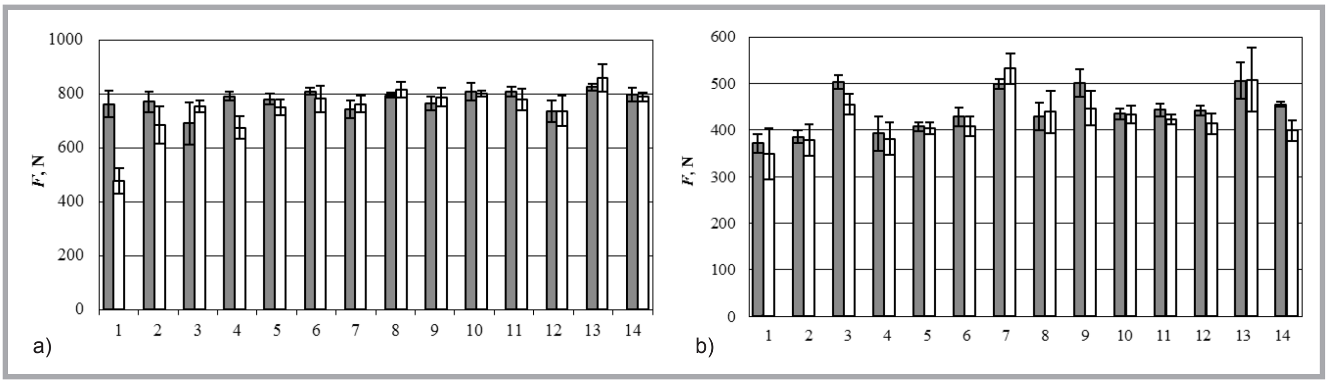

Figure 3. *Breaking force of fabrics in the warp (a) and weft (b) direction before and after fatigue.*

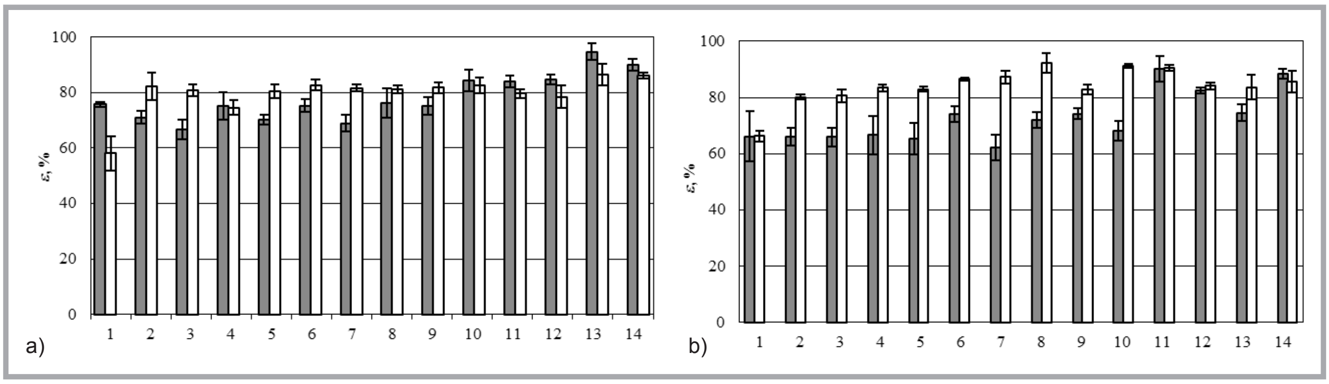

Figure 4. Elongation at break of fabrics in the warp (a) and weft (b) direction before and after fatigue.

Values of the breaking force in the weft direction of the fabric variants researched after fatigue are unchanged or fractionally decreased (see ***Figure 3.b***). This index for variants 14 and 9 of the fabrics investigated decreased by 12.4% and 10.6%, respectively. In the structure of these fancy yarns, spiral effects, arcs and open or closed loops were estimated in some places. Exceptional is the 7th variant of the fabrics because the breaking force after fatigue increased by about 6.3%. This fact can be explained by the structure of the fancy yarns (only with waves and a spiral structure).

The elongation at break of the fabrics in both directions changes differently after fatigue (see ***Figure 4***). In the warp direction this index increased for some variants of fabrics (variants 1 - 3, 5 - 9) and decreased for others (for variants 4, 10 - 14). The biggest increase was noted for fabrics with fancy yarns characterised by waves and a spiral structure, i.e. 18.3% (7th variant), and about 14% (3th and 5th variants). The elongation at break of the fabrics in the weft direction after fatigue increased for almost all fabric variants investigated. Moreover the biggest increase was observed for fabrics with fancy yarns having waves and a spiral structure (7th variant – 40.1%, 5th variant – 26.8%, and 3rd variant – 22.3%) as well as for fabrics with fancy yarns with a non-periodically located open and closed loop structure (10th variant – 34.1%, 8th variant – 28.1%).

It is clearly visible that the structure of fancy yarns in the fabrics as well as the kind of effects and their distribution influence the values of mechanical indices of the fabrics investigated. The interpretations described above and relations between the tensile test results and the structure of fancy yarns were only possible thanks to the organoleptic and microscopic tests performed on the objects investigated before and after fatigue. When examining the fabrics investigated by optical microscope, it was observed that after the fatigue process, fibre distribution in the yarns and yarn structure had changed. At first, after fatigue the fibres in the yarn structure become more crimp, diffuse from the yarn axis, and they twine around each other and around the axis. At the second stage, after the mechanical fatigue the structure of fancy yarns breaks down, the fancy effects change their form, distribution, size etc. It is clear that such changes must have influenced the mechanical indices of the fabrics tested.

We estimated that the stress-strain curves obtained by tensile tests of fabrics containing fancy yarns have similarities depending on their structure and primarily on the overfeed of fancy yarns. Moreover the distribution of values of the mechanical indices presented similar regularity. Thus in this research the fabrics could be grouped into three categories according to their structure: fabrics containing fancy yarns with waves and spirals (variants 3, 7 and 9), fancy yarns with arcs, and in some places open or closed loops (variants 1, 5, 12 – 14), as well as fancy yarns with non-periodically located open and closed loops, knots and slubs (variants 2, 4, 6, 8, 10, and 11). The first group of fancy yarns was made with the smallest overfeed i.e. not greater than 1.00. The core and effect components were switched around. The second group of fabrics made with fancy yarns was produced with a medium large overfeed of 1.0 - 1.5. The third group of fabrics contained fancy yarns - produced with the largest overfeed of 1.6 - 2.67. One fabric from each of the three groups was selected and then the stress-strain curves of the tensile tests were obtained, presented in ***Figure 5***. It was estimated that the character of changes in the curves is very similar (see ***Figure 1***), shown in ***Figure 5*** as average stress-strain curves.

It can be seen from ***Figure 5*** that the behaviour of the fabrics investigated after fatigue is different than before fatigue. It was established that the fatigue changed not only the values of mechanical indices of fabrics in all groups, but also the character of curves, which is especially evident in the initial part of the curves. The behaviour of fabrics with fancy yarns after flexing mechanical loading is comparable to those with air textured yarns. What more, it is completely different than the behaviour of textile materials manufactured with the use of normally spun or multifilament yarns, which can be explained by the nature of the physical phenomena when the textile material is composed of loops, as shown in this research. During the fatigue process, the structure of fancy yarns is destroyed, loops, knots and other fancy effects break and/or self-adjusting of the effects occur. It could be easily understood that such changes in the structure of yarns affect the appearance of textile materials produced with these yarns, and, in particular, their mechanical characteristics. Therefore it was estimated that fatigue significantly influences the structure of fancy yarns and it changed the mechanical indices of fabrics with these yarns.

On the basis of the tests performed, mathematical statistical characteristics were calculated for all the indices investigated. The minimum and maximum values of mechanical indices of fabrics with fancy yarns were determined using the values of factors X_1, X_2 & X_3 in the experimental space, the statistical data of which are presented in ***Table 2***.

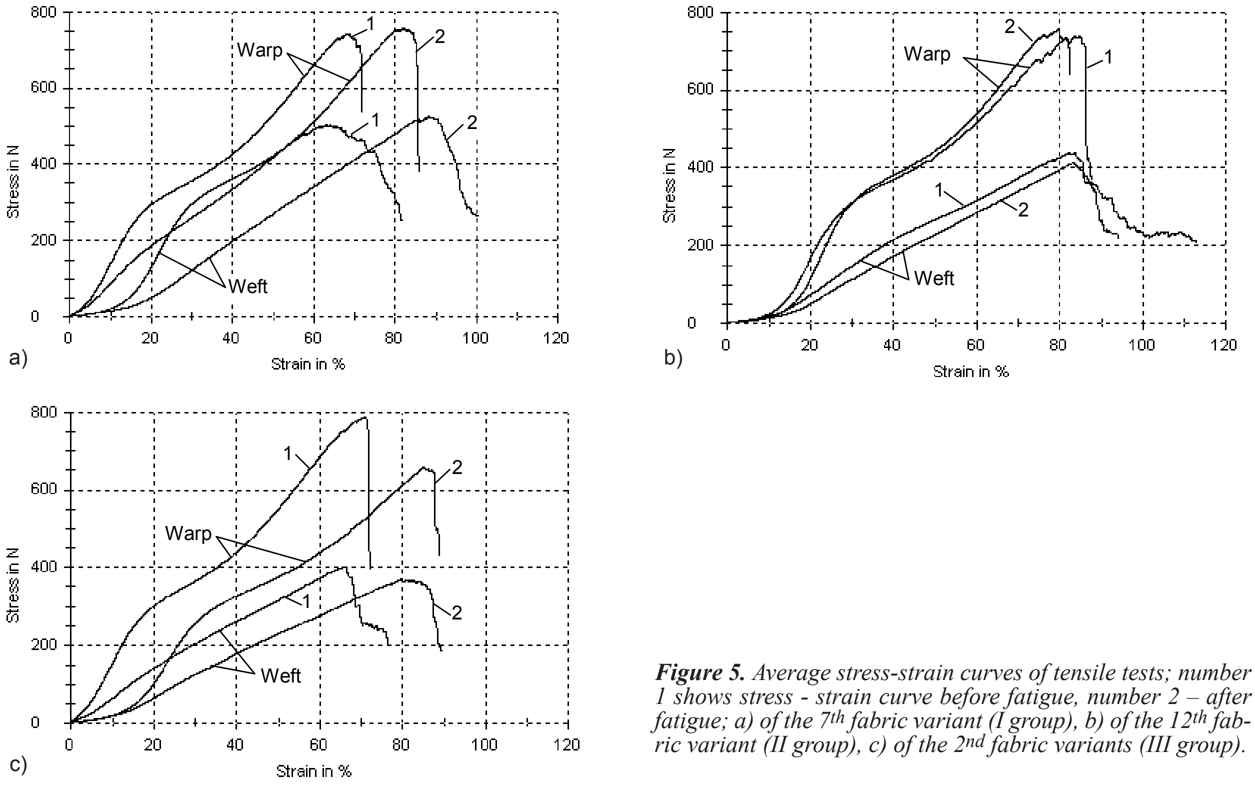

Figure 5. Average stress-strain curves of tensile tests; number 1 shows stress - strain curve before fatigue, number 2 – after fatigue; a) of the 7th fabric variant (I group), b) of the 12th fabric variant (II group), c) of the 2nd fabric variants (III group).

According to these data, one can find the limits of variation of the mechanical indices examined. For example, the variation coefficient of the mechanical indices varied as follows: the breaking force F before fatigue – nearly 5.5% in both directions, the elongation at break ε – 5.5% (in warp direction) and – 9.8% (in weft). It was found that the values of variation in the mechanical indices after fatigue were higher. The variation coefficient of the breaking force F in the warp direction reached 17.9%, and in the weft direction – 14.9%. Similar values of variation were estimated for the elongation at break index in the warp direction.

After achieving the monitored and calculated mechanical indices of fabrics with fancy yarns before and after fatigue, relations were established between such indices of the fabrics as the breaking force F, elongation at break ε and such parameters of fancy yarns manufactured as the supply speed of the effect yarn X_1, the delivery speed of fancy yarn X_2 and the rotational rate of the hollow spindle X_3. The general relation between the response Y (in this case F and ε in the warp and weft direction) and parameters X_1, X_2, X_3 [14] are presented below:

$$\begin{aligned} Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + \\ + B_{12}X_1X_2 + B_{13}X_1X_3 + B_{23}X_2X_3 + \\ + B_{11}X_1^2 + B_{22}X_2^2 + B_{33}X_3^2 \end{aligned} \quad (1)$$

were:

B_0 – constant term;

B_1, B_2, B_3 – coefficients of the main factor effects;

B_{12}, B_{13}, B_{23} – coefficients of the interaction effects;

B_{11}, B_{22}, B_{33} – coefficients of the quadratic effects.

The relations between calculated coefficients of the mechanical indices of fabrics with fancy yarns before and after fatigue are presented in ***Table 3***. In these tables are presented regression models of mechanical indices in the warp and weft directions. Some coefficients obtained are not significant, and the values of which are shown in brackets in the tables.

The regression models obtained were tested taking into account their informativeness. For mathematical simulation these regression models were used, which supplied inequality:

$$Fa > Ft \quad (2)$$

Table 2. *Minimum and maximum values of mechanical indices of fabrics defined by the values of factors X_1, X_2 & X_3 in the experimental space.*

Test results	Directions	Indices	Coded values of factors			Calculated value, min/max
			X_1	X_2	X_3	
before fatigue	Warp	F, N	-	+	-	690.3 ± 70,0/ 824.7 ± 11.4
			0	0	-	
		ε, %	-	+	+	69.0 ± 2.7/ 94.7 ± 2.7
			0	0	-	
	Weft	F, N	-	-	-	371.3 ± 16.0/ 506.0 ± 33.7
			-	0	0	
		ε, %	-	+	+	62.3 ± 4.5/ 90.2 ± 4.5
			+	0	0	
after fatigue	Warp	F, N	+	+	-	615.8 ± 110.2/ 857.9 ± 55.7
			0	0	-	
		ε, %	+	+	-	69.2 ± 12.1/ 86.4 ± 5.4
			0	0	-	
	Weft	F, N	-	-	-	348.5 ± 56.1/ 531.6 ± 33.9
			-	+	+	
		ε, %	-	-	-	66.2 ± 2.3/ 92.2 ± 4.4
			+	+	+	

Table 3. *Coefficients of relations obtained of mechanical indices of fabrics with fancy yarns before and after fatigue.*

Coefficient	**Before fatigue**				**After fatigue**			
	Breaking force F, N		**Elongation at break ε, %**		**Breaking force F, N**		**Elongation at break ε, %**	
	Warp	**Weft**	**Warp**	**Weft**	**Warp**	**Weft**	**Warp**	**Weft**
B_0	801.81	483.69	67.98	63.41	834.13	443.0	78.02	86.72
B_1	20.30	-17.20	-2.63	-1.11	16.80	(-3.61)	-1.41	2.80
B_2	-14.10	23.90	(0.52)	1.04	20.91	(7.89)	(0.62)	2.17
B_3	11.80	9.40	2.72	4.16	50.60	(8.90)	1.33	2.04
B_{12}	18.38	-28.13	-1.04	-7.79	-40.50	-23.0	(0.41)	-2.74
B_{13}	(0.88)	(1.63)	-3.59	(-0.51)	(1.50)	-19.48	-2.31	-2.76
B_{23}	(-4.13)	-7.13	-4.46	-3.04	-20.75	30.0	(0.08)	-4.36
B_{11}	-16.81	-16.19	5.12	2.49	-41.13	(-2.99)	-3.02	-4.67
B_{22}	-30.81	-41.69	4.77	6.34	-77.63	29.45	3.53	-2.02
B_{33}	(8.69)	(-3.19)	4.57	3.74	(-11.13)	(10.51)	3.38	3.03

Here:

F_A – criterion of informativeness of regression models;

F_T – table criterion of informativeness.

Values of table criterion F_T of informativeness of the regression models were calculated using the mathematical program EKSPLA, which was developed at the Department of Textile Technology of Kaunas University of Technology.

It is known that the value of table criterion F_T of informativeness depends on the degrees of freedom for the numerator v_1 and degrees of freedom for the denominator v_2 [14, 15]. In this research these degrees were determined by the following formulas [14]:

$$v_1 = (N \times m) - 1 \qquad (3)$$

$$v_2 = N - N_{sig} - 1 \qquad (4)$$

where:

N - the number of factor level combinations (in this case 14);

m - the number of investigation series (in this case 5);

N_{sig} - the number of significant coefficients.

The number of significant coefficients can be calculated using known methodology [14 - 16]. Significant and not significant coefficients of regression models are shown in ***Table 3.***

Using criterion F, it was established that the regression models of the dependencies of the elongation at break of fabrics in the weft direction before fatigue (F_A = 6.70; F_T = 5.69) and of the elongation at break after fatigue (F_A = 23.02; F_T = 8.57) upon the independent variables of manufacturing fancy yarns X_1, X_2, X_3 are suitable for further interpretation. Regression models of other mechanical indices of the fabrics with fancy yarns investigated before/after fatigue are not informative and not useful for interpretation.

Therefore mathematical simulation was made with the following models:

$$\varepsilon_1 = 63.41 - 1.11X_1 + 1.04X_2 + 4.16X_3 + - 7.79X_1X_2 - 3.04X_2X_3 + + 2.49X_1^2 + 6.34X_2^2 + 3.74X_3^2$$

$$\varepsilon_2 = 86.72 + 2.80X_1 + 2.17X_2 + 2.04X_3 + - 2.74X_1X_2 - 2.76X_2X_3 - 4.36X_1X_3 + - 4.67X_1^2 + 2.02X_2^2 + 3.03X_3^2$$

The influence of the speed of supply of the effect yarn X_1, the delivery speed of fancy yarn X_2 and the rotational rate of the hollow spindle X_3 are significant for the elongation at break of fabrics before and after fatigue. The three-dimensional response surface figure shows the influence of X_1, X_2 & X_3 on this index (see ***Figure 6 – 8***). In these figures the third factor has a stationary point and the code independent variable value is equal to zero.

It is known that a possibility exists of calculating the overfeed η and fancy yarn twist K. By evaluating the parameters of fancy yarns manufactured, they can be determined by the formulas:

$$\eta = \frac{X_1}{X_2} \qquad (5)$$

$$K = \frac{X_3}{X_2} \qquad (6)$$

The following data were received according to formulas 2 and 3. It was estimated that by increasing the twist, the elongation at break of fabrics before fatigue is initially decreased and then starts to increase (see ***Figure 6.a***). The elongation at break after fatigue varies, contrary to after the fatigue (see ***Figure 6.b***).

It can be seen from ***Figure 7.a*** that when the delivery speed of fancy yarn has a stationary point and its real independent variable value is equal to 40 m/min, the elongation at break before fatigue varies in the same kind of interval as other factors. At first the parameters of optimisation are decreased (when X_3 = 14750 - 15500 min^{-1}). Later by increasing the rotational rate of the hollow spindle and speed of supply of the effect yarn, the elongation at break also increased. These tendencies are similar for fabrics after fatigue (see ***Figure 7.b***), but the moment of rise is different in relation to the value of the speed of supply of the effect yarn.

It can be seen from ***Figure 8*** that the elongation at break before and after fatigue changed very similarly. With increasing the overfeed, when the rotational rate of the hollow spindle has a stationary point, the parameters of optimisation decrease and then start to increase.

It was estimated that the maximum values of the elongation at break before fatigue were achieved at the same technological parameters, i.e. when the overfeed was about 1.2 and the twist about 400 m^{-1}, the index investigated reached 79.65% (see ***Figure 6.a***), 75.36% (see ***Figure 7.a***), 82.63% (see ***Figure 8.a***). When the overfeed η was 1.2 - 1.3, then the different effects of fancy yarns (bosses, arcs, open loops) were formed. Minimum values before the fatigue of the elongation at break were achieved at the same overfeed. Values of 61.96 - 63.27% of the index investigated were estimated when the overfeed was about η = 1.65. But in these cases the twist was different, i.e. 500 m^{-1} (see ***Figure 6.a***), 388 m^{-1} (see ***Figure 7.a***) and 400 m^{-1} (see ***Figure 8.a***). When the overfeed was at an average of η = 1.5 - 1.6 and the twist of fancy yarns K was changed in the interval mentioned, then bosses, and open and close loops were formed in the fancy yarns, and in some places knots occurred. After fatigue, maximum and minimum values of the elongation at break were obtained at different technological parameters (see ***Figures 6.b, 7.b*** & ***8.b***). It was estimated that the elongation at break after fatigue reached 87.37%, 91.79% & 92.38% when the overfeed and twist were 1.41 and 418 m^{-1}, 1.5 and 500 m^{-1}, 1.0 and 340 m^{-1}, respectively. Minimum values of the index researched (72.32%,

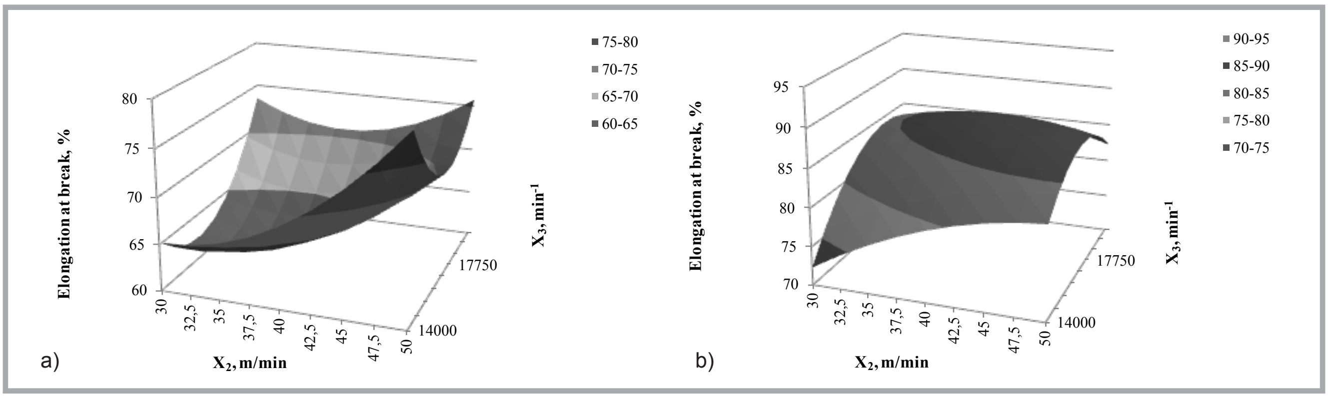

Figure 6. *Dependence of the elongation at break of fabrics in the weft direction before (a) and after (b) fatigue upon the delivery speed of fancy yarns X_2 (m/min) and the rotational speed of the hollow spindle X_3 (min^{-1}) when X_1 = 60 m/min.*

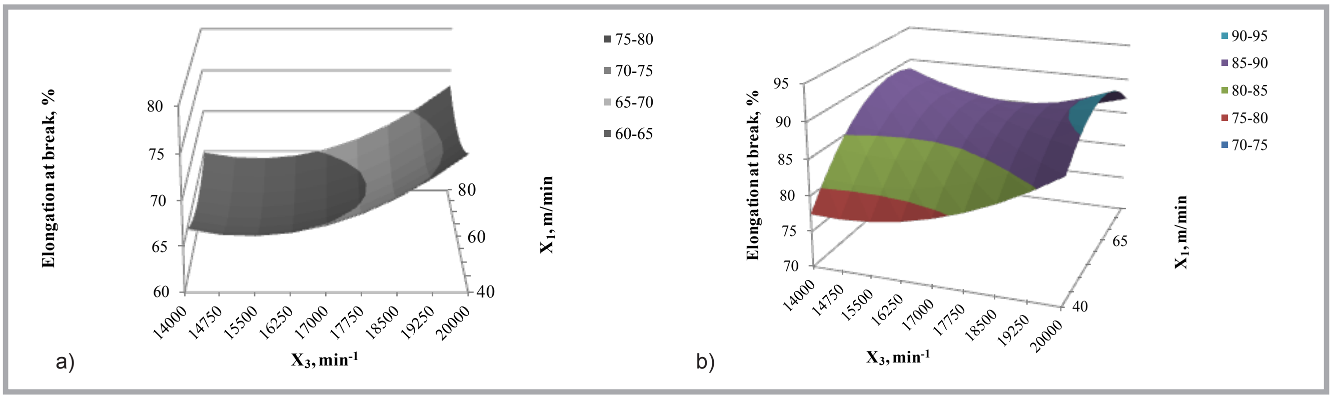

Figure 7. *Dependence of the elongation at break of fabrics in the weft direction before (a) and after (b) fatigue upon the rotational speed of the hollow spindle X_3 (min-1) and the speed of supply of the effect component X_1 (m/min) when X_2 = 40 m/min.*

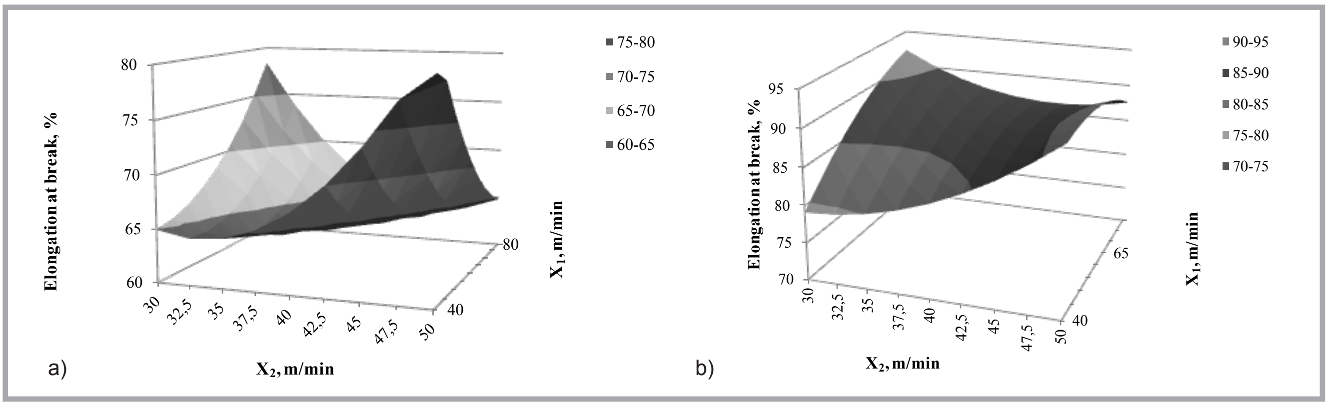

Figure 8. *Dependence of the elongation at break of fabrics in the weft direction before (a) and after (b)fatigue upon the delivery speed of fancy yarns X_2 (m/min) and the speed of supply of the effect component X_1 (m/min) when X_3 = 17000 min^{-1}.*

77.35% and 79.16%) were obtained when η was 2.0, 1.0 and 1.3 and twist 467 m^{-1}, 350 m^{-1} and 567 m^{-1}, respectively.

The reason for changes in the mechanical indices of fabrics with fancy yarns is cyclic compressing, flexing and stretching. Hence, in view of the tendencies to change the elongation at break mentioned, possibilities arise to design fabrics with fancy yarns with the best resistance to flexing.

Conclusions

- It was estimated that the fatigue significantly influences the structure of fancy yarns and consequently changes the mechanical indices of fabrics containing these fancy yarns, where, the elongation at break of the fabrics flexed was especially changed.
- The behaviour of the fabrics investigated after fatigue is different to that before fatigue. It was established that fatigue changed not only the values of the mechanical indices of the fabrics but also the character of the stress-strain curves.
- The breaking force of fabrics in both directions (warp and weft) after fatigue is almost the same as it was before. In the warp direction an exception was noted for the 1st and 4th fabric variants, where the value of the breaking force before fatigue was approximately 40% bigger than afterwards. This index decreased by about

10% after fatigue for fabrics with fancy yarns with bosses as well as when arcs, and open and closed loops are formed, with knots occurring in some places.

- The elongation at break of fabrics in the warp direction increased for some variants of fabrics (variants 1 - 3, 5 - 9) and decreases for others (variants 4, 10 - 14). The biggest increase is estimated for fabrics with fancy yarns having waves and spiral structures. The elongation at break of fabrics in the weft direction after fatigue increased for almost all fabric variants investigated.
- It was estimated that the stress-strain curves of tensile tests of the fabrics with fancy yarns investigated have similarities dependent on their structure, which is primarily caused by the overfeed. Moreover in the distribution of values of mechanical indices, similar regularities were established.
- Using criterion *F,* it was established that the mathematical models of the dependencies of the elongation at break of fabrics in the weft direction before and after fatigue upon the independent variables of manufacturing fancy yarns were suitable for further interpretation.
- The elongation at break before and after fatigue changed very similarly. With increasing the overfeed, when the rotational rate of the hollow spindle has a stationary point, the parameters of optimisation decrease and then start to increase.
- The tendencies to change the elongation at break established by us can help to design fabrics containing fancy yarns with the best resistance to flexing.

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