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Study into the Redistribution of Tension on the Components of the Loaded Textile Fabric System

Abstract
We have studied the trends in the redistribution of tensions falling on the individual components of bi-component textile fabric systems under a constant load on the system. Using Matukonis' model of a heterogeneous bi-component system, we show the factors predetermining the trends in the change in partial tensions falling on individual components of a system. The creep behaviour of three bi-component textile systems characteristic of outer garment manufacture, composed of face fabric and interlining, is experimentally studied on a relaxometer we have developed, in order to verify the features revealed by the analysis of the model's behaviour. Experimental results proved the theoretical findings. It was established that the trend of change over the time under tension which initially falls on individual components of loaded bi-component textile fabric system is unambiguously predetermined by the difference in creep amount of the entire system and of a single component.

Key words: *textile fabric, bicomponent systems, redistribution of tension, creep, mechanical modelling.*

Introduction

Multilayer systems composed of textile fabrics with different properties are nowadays universally accepted for various types of clothing and technical products. Appropriate selection of the system components, as well as the usage of relevant methods for joining them together, meets the functional and aesthetic requirements of the final product [1-4]. To improve the dimensional stability of a product, e. g. a coat or jacket, the details of both face fabric and interlining, whether they are fused, stitched or simply assembled together, are used almost everywhere [2, 3, 5-9]. It was shown in [9] that the difference in the properties of individual components of heterogeneous fabric systems yields a diversity in behaviour of a fused or stitched fabric system in processing or in usage. This especially concerns the system's time-dependent mechanical behaviour (e. g., creep, relaxation, recovery).

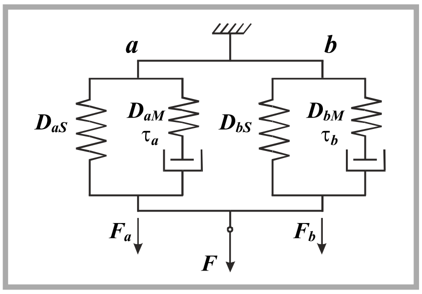

Figure 1. Mechanical model of the bi-component textile system.

In our previous work [10], it has been shown that at a constant load on a system composed of a face fabric and an interlining, the partial tension falling on one individual component of the system may be very different in proportion to another component. The individual component with a higher tensile modulus, and which consequently undergoes the highest partial tension, determines the total elongation of the system. Moreover, the level of partial tensions on the components changes over the time while they redistribute themselves. Phenomena of the same kind have been formerly studied in composite yarns [11, 12].

It was observed in [10] that in some cases the partial load which falls on the more rigid fabric components of a system increased over time, while in other cases it decreased over time. Up to now, unfortunately, there has been insufficient knowledge of factors predetermining the trends in redistributing tension in components . In the present study we have tried to answer this question and to demonstrate how the partial tension distribution trends influence the time-dependent behaviour of both the total fabric system and its individual components.

Model approach

Mechanical modelling is a useful theoretical method of analysing the behaviour of visco-elastic materials. A comprehensive overview of the various mechanical models used for such purposes has been

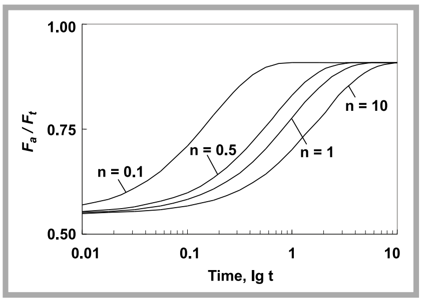

Figure 2. The dependency of change in partial tension (F_a) on the component a ($F_a > F_b$) of the model at constant total load F_t upon the ratio n of relaxation times ($\tau_a = 1$, $k = 0.1$, $m = 0.9$, $p = 10$).

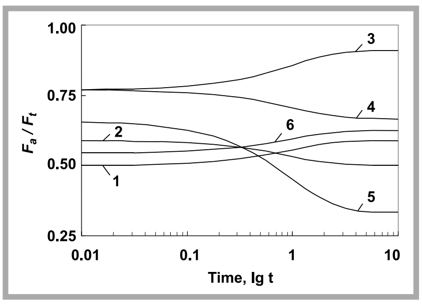

Figure 3. The characteristic curves of change in the partial tension (F_a) on component a ($F_a \geq F_b$) of the model at $F_t = 1$, $D_{aS} = 1$, $\tau_a = 1$, and n = 1: 1) $k = 0.7$ $m = 1.4$, $p = 0.75$; 2) $k = 1$, $m = 0.5$, $p = 1.5$; 3) $k = 0.1$, $m = 0.5$, $p = 1$; 4) $k = 0.5$, $m = 0.1$, $p = 0.1$; 5) $k = 2$, $m = 0.1$, $p = 3.5$; 6) $k = 0.6$, $m = 1$, $p = 1.5$.

presented in [13]. In this study, we took the a-b model (Figure 1) proposed by Matukonis [11] to analyse the time-dependency of tensions fallening on the components of the loaded bicomponent textile system. Each component (a and b) of the model consists of a Maxwell unit and a single spring in parallel. The parameters of the model are the springs' elasticity constants D_{aS}, D_{aM}, D_{bS}, D_{bM}, and the relaxation times τ_a, τ_b of the Maxwell units.

It has been shown in [11], that the interrelation of total load F acting on the model, tension F_a fallen on the *a* component, and the time t is given by the differential Equation (1).

Naturally,

$$F_b = F - F_a \qquad (2)$$

To analyse the changes in the tension on an individual component of the system over time, the following dependencies between the parameters of the model are introduced into Equation (1): $\tau_b = n\tau_a$; $D_{bS} = kD_{aS}$; $D_{bM} = mD_{aM}$; $D_{aM} = pD_{aS}$, where *n*, *k*, *m*, and *p* are constant coefficients, all of them being quantities bigger than zero. This introduction eliminates the particular values of spring constants of the model in Equation (1) which results in Equation (3).

For $F = F_t$ =const, the solution of Equation (3) is:

$$F_a = C_1 \exp(-r_1 t) + C_2 \exp(-r_2 t) + \frac{F_t}{1+k} \qquad (4)$$

where r_1 and r_2 jest opisane Equation (5).

If the total load F_t is applied to the model instantaneously, the initial (at $t = 0$) partial tension on the component a is:

$$F_{a0} = \frac{1+p}{(1+k)+p(1+m)} F_t \qquad (6)$$

while its derivative is described by equation (7).

Putting the expressions (6) and (7) into (4), and differentiating the latter, the constants C_1 and C_2 are obtained expressed by Equation (8) and (9).

To reveal how partial tensions on the model's components are redistributed among themselves over time, as well as how this redistribution is influenced by parameters of the model, we took $F_t = 1$ and $D_{aS} = 1$ in the analysis. Since the relaxation times τ_a and τ_b determine

$$\tau_a\tau_b \frac{D_{aS}+D_{aM}+D_{bS}+D_{bM}}{D_{aS}}\frac{d^2F_a}{dt^2} + \left[\frac{\tau_a(D_{aS}+D_{aM}+D_{bS})+\tau_b(D_{bS}+D_{bM}+D_{aS})}{D_{aS}}\right]\frac{dF_a}{dt} + \frac{D_{aS}+D_{bS}}{D_{aS}}F_a = \tau_a\tau_b\frac{D_{aS}+D_{aM}}{D_{aS}}\frac{d^2F}{dt^2} + \left(\tau_a\frac{D_{aS}+D_{aM}}{D_{aS}}+\tau_b\right)\frac{dF}{dt} + F \qquad (1)$$

$$n\tau_a^2\left[(1+k)+p(1+m)\right]\frac{d^2F_a}{dt^2} + \tau_a\left[(1+k)(1+n)+p(1+mn)\right]\frac{dF_a}{dt} + (1+k)F_a = n\tau_a^2(1+p)\frac{d^2F}{dt^2} + \tau_a(1+n+p)\frac{dF}{dt} + F \qquad (3)$$

$$r_{1,2} = \frac{\left[(1+n)(1+k)+p(1+mn)\right] \pm \sqrt{\left[(1+k+p)-n(1+k+mp)\right]^2 + 4mnp^2}}{2n\tau_a\left[(1+k)+p(1+m)\right]} \qquad (5)$$

$$\frac{dF_{a0}}{dt} = \frac{mp\left[(1-(kn/m))+p(1-n)\right]}{n\tau_a\left[(1+k)+p(1+m)\right]^2}F_t \qquad (7)$$

$$C_1 = -\frac{F_t}{(r_1-r_2)}\left\{\frac{mp\left[(1-(kn/m))+p(1-n)\right]}{n\tau_a\left[(1+k)+p(1+m)\right]^2} - r_2\frac{mp\left[1-(k/m)\right]}{(1+k)\left[(1+k)+p(1+m)\right]}\right\} \qquad (8)$$

$$C_2 = \frac{F_t}{(r_1-r_2)}\left\{\frac{mp\left[(1-(kn/m))+p(1-n)\right]}{n\tau_a\left[(1+k)+p(1+m)\right]^2} - r_1\frac{mp\left[1-(k/m)\right]}{(1+k)\left[(1+k)+p(1+m)\right]}\right\} \qquad (9)$$

$$\varepsilon_\infty - \varepsilon_0 = \frac{F_t}{D_{aS}+D_{bS}} - \frac{F_t}{D_{aS}+D_{aM}+D_{bS}+D_{bM}} = \frac{p(1+m)}{D_{aS}(1+k)[(1+k)+p(1+m)]}F_t \qquad (13)$$

$$\varepsilon_{a\infty} - \varepsilon_{a0} = \frac{F_{a0}}{D_{aS}} - \frac{F_{a0}}{D_{aS}+D_{aM}} = \frac{p}{D_{aS}(1+p)}F_{a0} \qquad (14)$$

***Equation:** 1, 3, 5, 7, 8, 9, 13 and 14.*

***Table 1.** Values of parameters determining the trend in change of partial tension which initially falls on the component a ($F_{a0} \geq F_{b0}$) of the model at constant total load F_t=1 and D_{aS}=1.*

Variant	Trend of tension's (F_a) change	k	m	p	Corresponding no of curve in Figure 3	ε_∞-ε_0	F_{a0}	$\varepsilon_{a\infty}$-ε_{a0}
1	↑ (m>k)	< 1	>1	≤ (1-k)/(m-1)	1	0.30	0.50	0.21
2		< 1	= 1	> 0	6	0.95	0.54	0.33
3		< 1	< 1	> 0	3	0.79	0.77	0.38
4	↓ (m<k)	< 1	< 1	> 0	4	0.28	0.77	0.38
5		> 1	< 1	> (k-1)/(1-m)	5	0.05	0.66	0.51
6		= 1	< 1	> 0	2	0.13	0.59	0.35

***Note:** When m=k, the initial partial tensions F_{a0} and F_{b0} do not change over time.*

the speed of any change in the partial tensions on the model components which have no influence upon the direction and scale of the run (Figure 2), we took also

$$\tau_a = \tau_b = 1, \text{ i. e. } n = 1.$$

It follows from Equations (4) and (6) that for F_t = const the higher partial tension initially falls on the component a (at $t = 0$, $F_a = F_{a0}$) when

$$\frac{F_{a0}}{F_t} = \frac{1+p}{(1+k)+p(1+m)} > \frac{1}{2} \qquad (10)$$

In any case, the final (at $t = \infty$) tension on the component a becomes equal to

$$F_{a\infty} = \frac{F_t}{1+k} = \frac{F_{b\infty}}{k} \qquad (11)$$

Hence, the initial partial tension F_{a0} will continue to increase if

$$\frac{1+p}{1+p\left(\frac{1+m}{1+k}\right)} < 1 \qquad (12)$$

or if $m > k$. If $m < k$, the initial partial tension F_{a0} will continue to decrease, and if

$m = k$, the partial tensions which initially fall on the components *a* and *b* will not generally change over time.

The eventual values of the model's coefficients coinciding with Equations (10) and (12) are shown in Table 1. The set of curves reflecting the diversity of trends and scales in a change of partial tension F_a at $F_t = const$ is presented in Figure 3. It is seen that the partial tension which initially falls on an individual component of the model, as well as the direction and magnitude of the tension's change in time, are unambiguously determined by the values of the coefficients *k*, *m*, and *p*.

We have assumed that the redistribution of tensions on the system's components over time is in close conjunction with the creep amount in the entire system as well as of the individual components at certain applied loads. The maximum creep amount of the model *a-b* at constant load F_t is expressed by Equetion (13).

The maximum creep amount of the component *a* at a constant load equal to the tension F_{a0} which initially falls on it when the load F_t is applied to the entire model is expressed by Equation (14).

The values of maximum creep amounts obtained by Equations (13) and (14) are shown in Table 1. It is seen that if the creep of component a is at load $F_{a0} = const$ less pronounced than the creep of the entire system, the tension on this component at $F_t = const$ continues to increase. If the creep of the component is more pronounced than that of the entire system, the initial tension on the component continues to decrease.

Experimental

It has already been demonstrated [10] that the tensions which initially fall on the individual components when the fabric system is loaded depend entirely on the difference in the modulus of the components: the higher tension falls on the more rigid components. To verify the other regularities revealed by the analysis of the model's behaviour for the investigation, we experimentally investigated the creep behaviour of three bi-component systems of the textile fabrics characteristic of outer garment manufacture. Each of the systems considered was composed of a face fabric and of a fusible interlining, both of which were assembled lengthwise together into a sandwich without fusing. The actual structural characteristics of the face fabrics are presented in Table 2, while those of the interlinings are given in Table 3.

The experiments were conducted on a relaxometer [10] designed and developed at the Department of Apparel and Polymer Product Technology, Kaunas University of Technology. The force measuring system of the relaxometer enables the operator to measure the tension on an individual component of the bi-component sandwich-like textile fabric system over time under a constant total tensile load applied to the system. The relaxometer is also suitable for measuring the elongation of a fabric system or of an individual fabric in creep and creep recovery studies. The tension and elongation are measured digitally at 0.11 s intervals during the entire test period.

In all the tests conducted on the relaxometer, the gauge length was 250 mm, and the width of specimens was 50 mm. Eight specimens for every fabric system were tested in each principal direction, lengthwise and crosswise. For the tension redistribution test, a fabric system was loaded by the total load of 50 N for the time $\theta_t = 1800$ s, and the tension of the face fabric was measured during this entire period of time. The tension on the interlining was obtained as the difference between the total load on the system and the tension on the face fabric.

In experimental tests, the complete application of a load to a specimen cannot always be entirely instantaneous, as is customarily assumed in theoretical studies. In our experiments, the real time needed to apply the assigned load to a specimen took a few seconds. To avoid misunderstanding, for every real specimen the time notified as t^* was accounted from the instant at which the specimen began to creep at the assigned constant load.

The values of the tensions on the face fabric and the interlining measured at $t^*=0$ (see Table 4) were afterwards used as the constant loads in the creep tests of these individual components.

Results and discussion

It was found experimentally that the tension on a single component of a loaded bi-component textile fabric system differs in magnitude as well as in the trend of its change over time, in proportion to the properties of the second component of the bi-component system. For example, when the T1/I1 system is loaded lengthwise, the higher tension initially falls on the T1 component, and continues to increase. Conversely, when the T1/I1 system is loaded crosswise, the lower tension initially falls on the T1 component, and it continues to decrease

Table 2. *Structural characteristics of woven face fabric.*

Fabric code	Fibre constitution	Yarn linear density, tex		Number of threads per dm		Yarn crimp, %		Area density, g/m²	Weave
		warp	weft	warp	weft	warp	weft		
T1	Wool	88	96	150	140	2.7	6.8	284	Combined
T2	Wool	25	25	340	290	2.3	10.8	158	Twill 2/1

Table 3. *Structural characteristics of interlinings;* ***Note:*** ** with weft inlay.*

Fabric code	Fibre constitution	Warp-knitting structure	Resin dots	Number of resin dots per cm²	Area density, g/m²	Recommendable fusing regime		
						temp., °C	pressure, kPa	time, s
I1	PET	Combined*	PA	21	71	135	25	12
I2	PET	Closed pillar stitch*	PA	52	60	127	25	15

Table 4. *Tension on the component fabrics under a total load of 50 N on the system.*

System/ component		T1/I1 at t*=				T1/I2 at t*=				T2/I1 at t*=			
		0		1800 s		0		1800 s		0		1800 s	
		T1	I1	T1	I1	T1	I2	T1	I2	T2	I1	T2	I1
Tension, N	∧	31.4	18.6	35.6	14.4	16.4	33.6	21.8	28.2	41.1	8.9	43.6	6.4
	>	9.9	40.1	9.5	40.5	21.4	28.6	17.3	32.7	6.8	43.2	11.6	38.4

Notes: ∧ – *loading lengthwise;* > – *loading crosswise.*

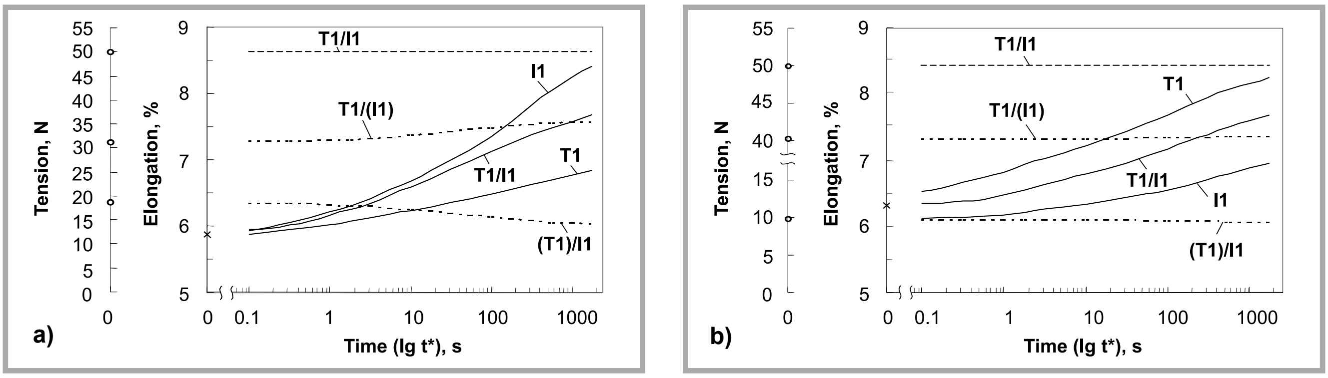

Figure 4. Creep (——) and tension (- - - -) curves of the fabric system T1/I1, of its individual components T1 and I1, and of the components T1/(I1) and (T1)/I1 when behaving within the system: a –loading lengthwise, b – loading crosswise.

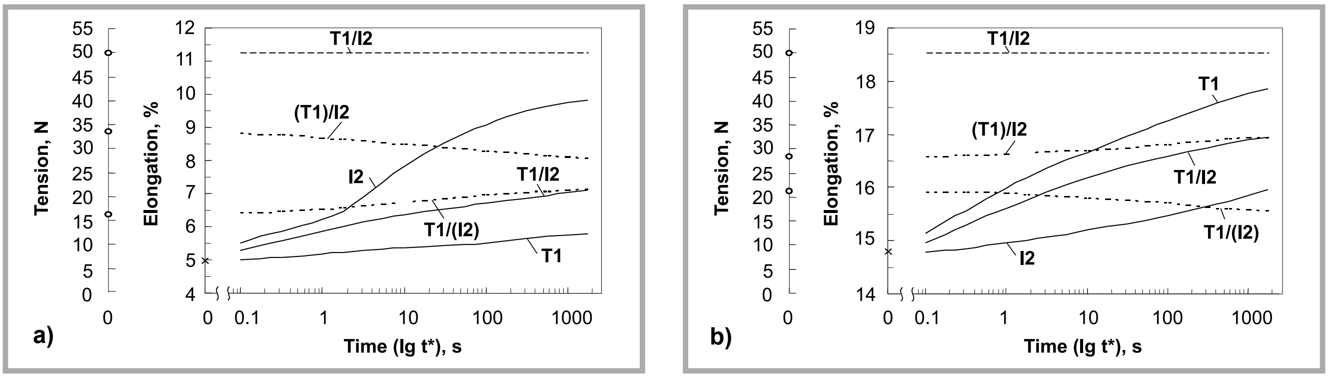

Figure 5. Creep (——) and tension (- - - -) curves of the fabric system T1/I2, of its individual components T1 and I2, and of the components T1/(I2) and (T1)/I2 when behaving within the system: a –loading lengthwise, b – loading crosswise.

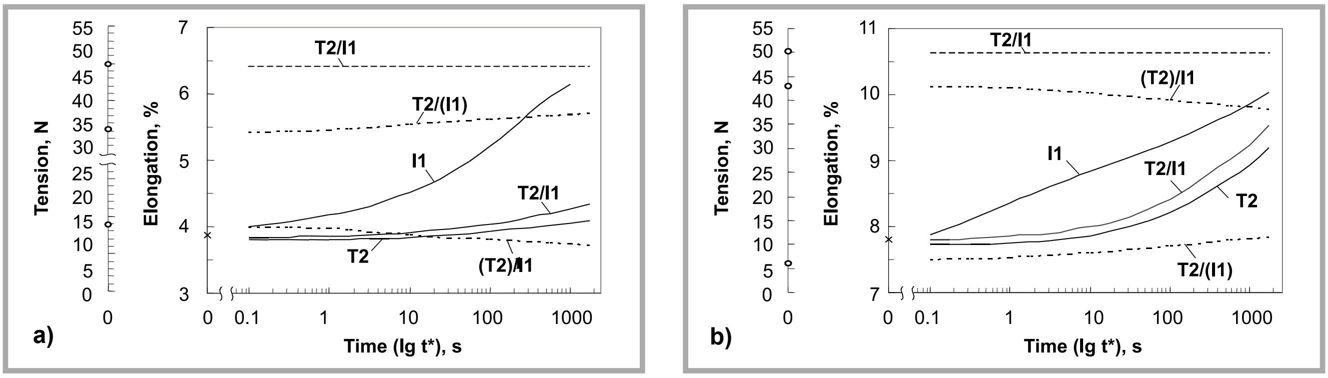

Figure 6. Creep (——) and tension (- - - -) curves of the fabric system T2/I1, of its individual components T2 and I1, and of the components T2/(I1) and (T2)/I1 when behaving within the system: a –loading lengthwise, b – loading crosswise.

(Figure 4). Replacing the I1 interlining in the system by the I2 interlining results in quite different behaviour: when loading lengthwise, the lower tension falls on the T1 component and continues to increase. When loading the system crosswise, the lower tension which had initially fallen on the T1 component continues to decrease (Figure 5). The components of the T2/I1 system behave in yet a different manner: when loading lengthwise, the higher tension which had initially fallen on the T2 face fabric continues to increase; when loading crosswise, the initial tension on the face fabric is lower than on the interlining, but it continues to increase (Figure 6).

The experiments demonstrated the theoretical findings that the onward change and redistribution of the tensions on the loaded system's components are in close conjunction with the creep amount in the entire system, as well as in the individual components. This is testified by creep experiments with the single components at constant loads equal to the tensions which initially fell on them at t*=0, i. e. at the very beginning of the system's creep (see Table 4 for the values of tensions). In such loading conditions, if the creep of the component was less intensive than that of the loaded system, the tension on this component continued to increase irrespective of whether it was higher initially (I2 in the system T1/I2$^{>}$, T1 in T1/I1$^{\wedge}$, I1 in T1/I1$^{>}$, and T2 in T2/I1$^{\wedge}$) or lower initially (T1 in the system T1/I2$^{\wedge}$, and T2 in T2/I1$^{>}$) than the tension on the other component of the loaded system.

To obtain model constants from the experimental data for every fabric system, the following procedure is used. As the main component of the system, the face

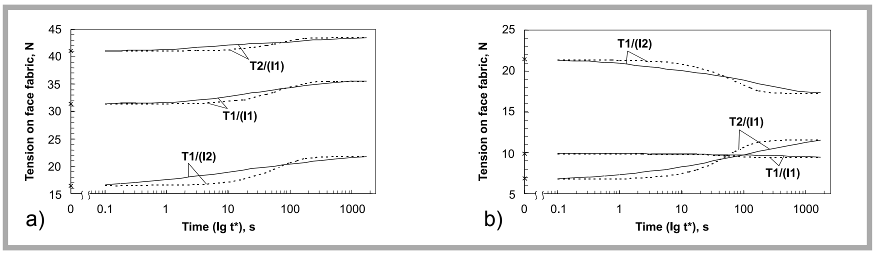

Figure 7. *Experimental (——) and theoretic (- - - -) curves of partial tension fallen on face fabric (T1 or T2) at constant total load F_t=50 N on the fabric system (the values τ_a = 60 s, τ_b = 120 s are taken for the system's model): a – loading lengthwise, b – loading crosswise.*

fabric (T1 or T2) is considered as component a of the model, and the interlining (I1 or I2) is considered as component b. At a constant total load of F_t = 50 N on the system, the experimental values of initial (at t^* = 0) tensions F_{a0} and F_{b0} which fell on the components and the corresponding final (at t^* = 0) tensions F_{a0} and F_{b0} are assumed to be equal to the corresponding tensions of the model at t = 0 and $t = \infty$. Adapting the experimental values of tensions on the individual fabrics to Equations (4) and (6), the values of coefficients k = F_{b0} / F_{a0} and

$$q = \frac{k + pm}{1 + p} = \frac{F_{b\infty}}{F_{a\infty}} \qquad (15)$$

are obtained. Next, the value of the coefficient m is chosen in accordance with the data in Table 1 and the experimental value of q: i) $m > q$ at $m > k$; ii) $m < q$ at $m < k$; iii) $m = q = k$. Finally, the value of the coefficient p is obtained from Equation (15). The relaxation times τ_a and τ_b may be arbitrarily chosen, depending on the experimental timescale of loading.

The calculated parameters of the models for every tested fabric system are shown in Table 5, and the curves of change in tension on the face fabrics of the loaded systems over time are shown in Figure 7. It is seen that the model *a-b* well represents the distribution of tensions on the individual components of loaded bi-component textile fabric systems. This can serve as a reliable medium in attempts to predict the trend of changes in tension on the individual components of a loaded textile system.

Conclusions

The two-component model *a-b* used in the study well represents the redistribution of tensions on single components of a loaded bi-component textile fabric system. The model is able to predict the redistribution trends determined by the model's constants D_{aS}, D_{bS}, D_{aM}, D_{bM} or the ratios m, k, and p. The model's relaxation times determine the speed of change in the tensions on the components, but they do not influence the initial or final values of the tensions.

It has been theoretically and experimentally established that the tension which initially falls on the individual component of the loaded bi-component textile fabric system continues to increase if the creep of the system is more intensive than that of the single component at a constant load corresponding to the tension which initially fell on it at the beginning of the system's creep. If in similar conditions the system creep is less intensive than that of the single component, the tension which initially fell on the single component will continue to decrease.

Table 5. *Parameters of the model for the fabric systems.*

System code	Parameters of the model at selected relaxation times τ_a = 60 s and τ_b = 120 s							
	k	q	m	p	D_{aS}	D_{aM}	D_{bS}	D_{bM}
↑T1/I1 ^	0.404	0.592	0.8	0.905	35.6	32.2	14.4	25.8
↓T1/I1 >	4.263	4.051	2.1	0.109	9.5	1.1	40.5	2.2
↑T1/I2 ^	1.294	2.049	3.1	0.718	21.8	15.7	28.2	48.5
↓T1/I2 >	1.890	1.336	1.1	2.342	17.3	40.5	32.7	44.6
↑T2/I1 ^	0.147	0.217	0.4	0.380	43.6	16.6	6.4	6.6
↑T2/I1 >	3.310	6.353	11.0	1.847	11.6	7.6	38.4	83.5

Notes: *∧ – loading lengthwise; > – loading crosswise; ↑↓ – increase and decrease in the tension which initially fell on the face fabric.*

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