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Time-dependent Mechanical Behaviour of Heterogeneous Textile Fabric Systems

Abstract
We have studied the time-dependent mechanical behaviour of binary textile compound systems of textile fabrics assembled or fused together, including stress-strain relations, creep and creep recovery, as well as the redistribution of tension on single components under a constant total load. The fabrics and systems discussed in this study are characteristic for the manufacture of garments. A relaxometer with digital specimen tension and elongation meters was developed with the purpose of more precisely defining the starting points of creep and creep recovery processes of fabric systems, and to measure the tension of single components within the fabric system. We have also studied the influence of the adhesive interconnection of the components in fusion on the stress-strain relations and creep recovery behaviour of the fabric systems. It is shown that at constant total load on assembled textile fabric systems, the single components of the system undergo very different partial tensions - the greater tension falls on the component possessing the higher modulus. It is further shown that tensions on the single components are redistributed over time.

Key words: *textile fabric, binary textile compound systems, fusing, creep, recovery, tension.*

Introduction

Most garments include details composed of two or more fabric layers which differ in fibre constitution as well as in structural composition, and possess very different deformation characteristics. The garment's appearance, dimensional stability and other functional properties greatly depend on the differences in the mechanical characteristics of the fabrics used as the components of such a heterogeneous textile system. As these fabrics differing in dimensional stability are interlinked together, puckers, buckles or bubbles in the face fabric may appear during wear and after laundering or dry cleaning procedures, so impairing the garment appearance. The garment designer and manufacturing technologist is always forced to look for rational compositions in various aspects. Nowadays the details of fused face fabrics and interlinings are used [1-5] almost everywhere in suit or overcoat manufacture. The dimensions of fused clothing details are more stable in sewing, and so the risk of their inter-displacement is less. The properties of such heterogeneous composition depend not only on the properties of constitutive fabrics, but also on the properties of the fusing resin.

It has been previously shown [6,7] that deformation characteristics such as creep, recovery, and the residual deformation of loaded heterogeneous textile systems inevitably depend on the characteristics of single components. It has also been observed [8,9] that tensions on single components of a loaded heterogeneous textile system vary in time, redistributing among themselves. Nevertheless, the features of this redistribution are as yet insufficiently considered. In this research, the features of creep and creep recovery are analysed for systems composed of fused and simply assembled textile fabrics used as component layers for making garments. Attempts have also been made to reveal the character of the redistribution of tension on single components of the loaded fabric system.

Materials for Investigation

Six woven and knitted fabrics of different fibre constitution and structure were taken for the investigation. The actual structural characteristics of the fabrics are presented in Tables 1-3. Three of the fabrics, coded respectively as T1, T2 and K1, are used as the face fabrics of a garment; one fabric, coded as I1, is a lining, and two warp-knitted fabrics, coded as I2 and I3, are the fusible interlinings. A number of fabric systems have also been investigated. The systems coded as T2+I2 and K1+I3 are the specific units for making suits. They are compound of fabrics fused together lengthwise on the Stirovap fusing device. The behaviour of these systems has also been compared with the T2/I2 and K1/I3 systems, where the fabrics are assembled together simply without any interconnection. The system coded as T1/I1 is a specific unit for making jackets, and is a compound of the components which are assembled lengthwise but are not interconnected.

Stress-Strain Behaviour

The main tensile properties of the fabrics and of fabric systems were established on a CRE tensile testing machine according to standard EN ISO 13934-1. The gauge length was 100 mm. In each case, eight specimens were extended in each of the principal directions, lengthwise and crosswise. From each family of the eight force-elongation curves, the characteristic curve was selected by the principles of the method proposed in [10]. These characteristic force-elongation curves are presented in Figure 1(a-f). The average indexes of stress-strain behaviour of the samples tested are presented in Table 4. At a confidence level of 95%, the confidence limits of breaking force were within the range

Table 1. Structural characteristics of woven fabrics.

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	warp - PA weft - cotton	10	22	600	450	8.8	4.4	159	broken twill 2/2
T2	wool	25	25	340	290	2.3	10.8	158	twill 2/1
I1	PES/viscose spun (67:33)	18	21	339	210	0.8	2.5	93	plain

Table 2. Structural characteristics of face-knitted fleecy fabric.

Fabric code	Fibre constitution	Yarn linear density, tex	Area density, g/m²	Number of stitches per dm		Stitch length, mm	Knitting structure
				wale	course		
K1	PES textured (base knit) Wool (fleece)	19 36 × 2	380	64	88	5.7	plain jersey

Table 3. Structural characteristics of warp-knitted fusible interlinings, and the fusing regime.

Fabric code	Fibre constitution	Warp-knitting structure	Resin dots	Number of resin dots per cm²	Area density, g/m²	Fusing regime		
						Temp., °C	Pressure, kPa	Time, s
I2	PES	combined with weft inlay	PA	21	71	135	25	12
I3	PES	combined with weft inlay	PA	52	75	135	25	12

Table 4. Stress-strain behaviour indexes of fabrics and fabric systems (° - first break of face fabric; × - first break of lining/interlining).

Fabric or system code	Extension lengthwise			Extension crosswise		
	Breaking (maximum) force, N	Elongation at break, %	Secant modulus (at 50 N force), N/cm	Breaking (maximum) force, N	Elongation at break, %	Secant modulus (at 50 N force), N/cm
T1	883	51.6	190	521	12.6	250
T2	340	29.2	250	301	28.2	84
K1	288	76.4	27	152	204.5	15
I1	550	12.4	460	368	24.2	120
I2	172	31.8	92	118	13.3	150
I3	66	23.4	72	199	9.6	420
T1/I1	892 / 722×	53.4 / 13.2×	530	°655 / 395	°12.7 / 26.4	290
T2/I2	°486 / 172	°29.2 / 32.1	290	306 / 183×	28.0 / 14.5×	160
K1/I3	312 / 83×	81.0 / 23.5×	83	153 / 220×	205.0 / 10.6×	510
T2+I2	°501 / 174	°27.3 / 33.5	300	333 / 191×	31.5 / 15.6×	180
K1+I3	365 / 89×	89.0 / 24.5×	88	154 / 252×	207.0 / 10.7×	550

Table 5. Tension on residual component at break of the other component that breaks first in the system (∧ - extension lengthwise; > - extension crosswise. The code of the residual component is shown in brackets).

T1/I1		T2/I2, T2+I2		K1/I3, K1+I3	
∧	>	∧	>	∧	>
174 N (T1)	116 N (I1)	151 N (I2)	72 N (T2)	19 N (K1)	5 N (K1)

3.5 to 6.1% of the mean values, and the confidence limits of elongation at breaking force were within the range of 4.0 to 6.6% of the mean values respectively. The values of the secant modulus (Table 4) are obtained from the characteristic force-elongation curves presented in Figure 1.

As can be seen in Table 4 and in Figure 1, a high anisotropy in stress-strain behaviour is characteristic of most of the studied fabrics. The tensile strength and ultimate extensibility of the fabrics are quite different when extending lengthwise and crosswise. The anisotropy in the stress-strain behaviour of the face fabric T1 is associated both with the different constitution of warp and weft threads and the different amount of crimp of the warp and the weft yarns. When extending the fabric T1 warpwise, the tensile stresses are taken up by more extensible and more crimped multifilament PA yarns. Therefore the fabric elongation at breaking force is about 4 times higher than when extended weftwise, where the stresses were taken up by spun cotton yarns. For the lining I1, both the warp and the weft threads are spun yarns of identical blended fibre constitution and do not differ appreciably in their fineness. The anisotropy of the lining I1 is mainly associated with the specific fabric structure as a result of the different amount of crimp of the warp and the weft yarns (see Table 1).

High anisotropy is also characteristic of the knitted face fabric K1 and for the fusible interlining I3. The breaking force of the fabric Kl extended lengthwise is 1.9 times higher, and the elongation at breaking force is 2.7 times lower than that of the fabric extended crosswise. Such features are typical of the common response of a plain jersey structure. Conversely, due to straight weft inlays, the breaking force of the interlining I3 extended crosswise is three times higher, and the elongation at breaking force is 2.4 times lower, than of the fabric extended extension. The low extensibility of the interlining I3 is in contrast to the high extensibility of the face fabric K1 when joining both the components into the fabric system. A similar but considerably less pronounced converse is also characteristic of the components of other fabric systems. Such high anisotropy of fabrics is reflected in the pronounced two-peak breaks of the fabric systems in extension (Figure 1 a,c,d,e). At the first break, the system loses its undivided integrity, so

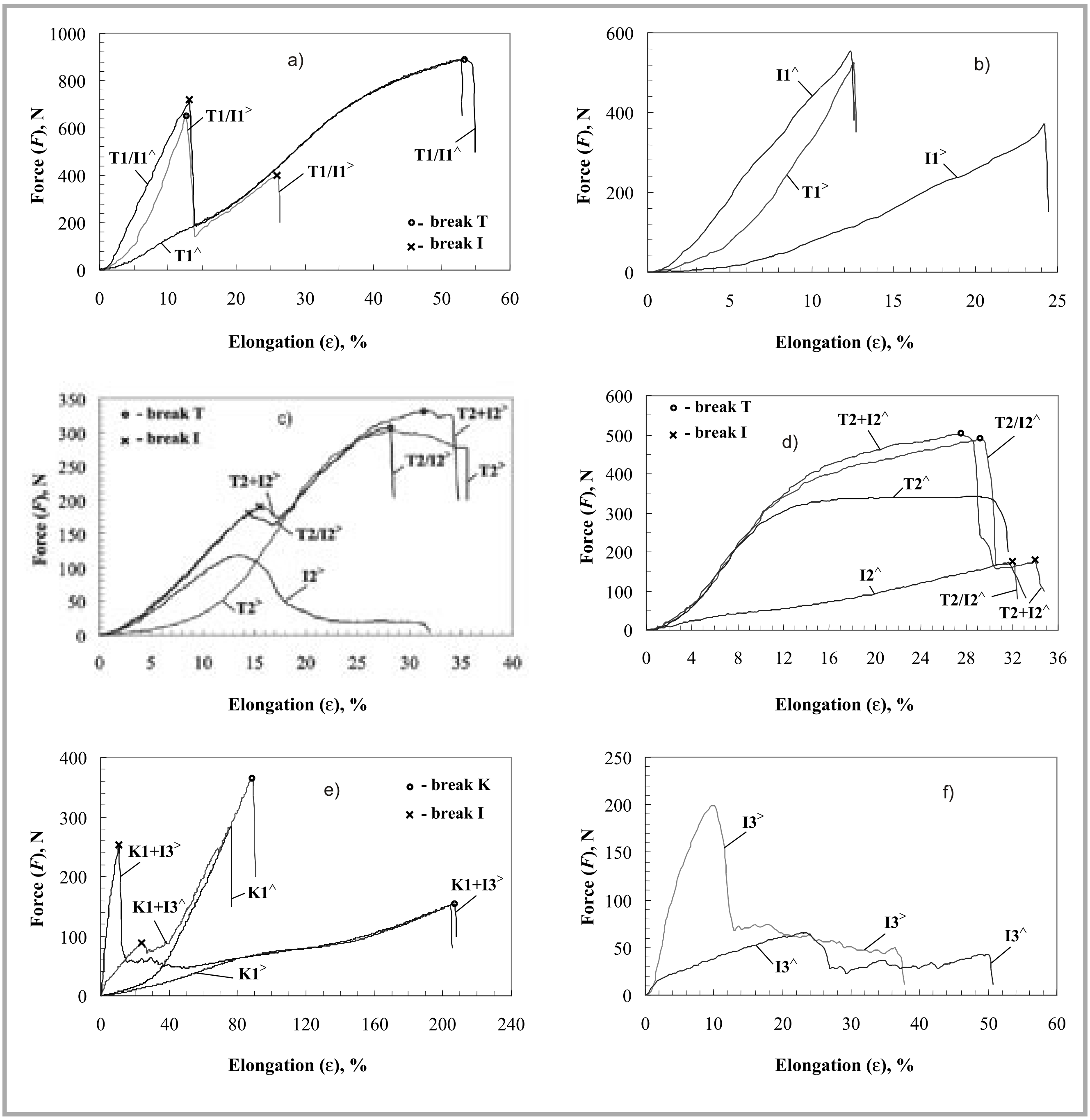

***Figure 1.** Force-elongation curves of fabrics and fabric systems: ^ - extension lengthwise; > - extension crosswise; a) fabric T1 (ext. lengthwise), and system T1/I1 (ext. length- & crosswise), b) fabric T1 (ext. crosswise), and I1 (ext. length- & crosswise), c) fabrics T2 & I2, and systems T2/I2 & T2+I2 (all ext. crosswise), d) fabrics T2 & I2, and systems T2/I2 & T2+I2 (all ext. lengthwise), e) fabric K1, and system K1+I3 (ext. length- & crosswise), f) fabric I3 (ext. length- & crosswise).*

the first break should indicate the ultimate capabilities of the system.

Since the components of the systems T1/I1, T2/I2 and K1/I3 are not interconnected, they behave as two separate units in constant rate extension. As can be seen from Tables 4 and 5, in both directions of extension the breaking force of such bi-unit system is approximately equal to the sum of two forces: the breaking force of the less extensible fabric, and the tension on the residual fabric at the instant when the first component of the system breaks. The differences do not exceed 2.7%. The elongations at breaking forces of the systems also show only marginal differences with the elongations at breaking forces of the corresponding single components.

The adhesive interconnection of the components in fusing does not show a very pronounced influence on the stress-strain behaviour of the fabric systems. The strength of the fused systems is higher by a few percentage points than that of the assembled systems, but no appreciable difference in elongation at breaking force is obtained.

It is seen from Figure 1(f) that in both directions of extension, the break of interlining I3 is very specific. When the rupture starts (the inlay yarns break first when extending crosswise), this is followed by the gradual fragmentation of the interlining's warp-knitted structure. During this fragmentation, however, the interlining elongates under an approximately steady

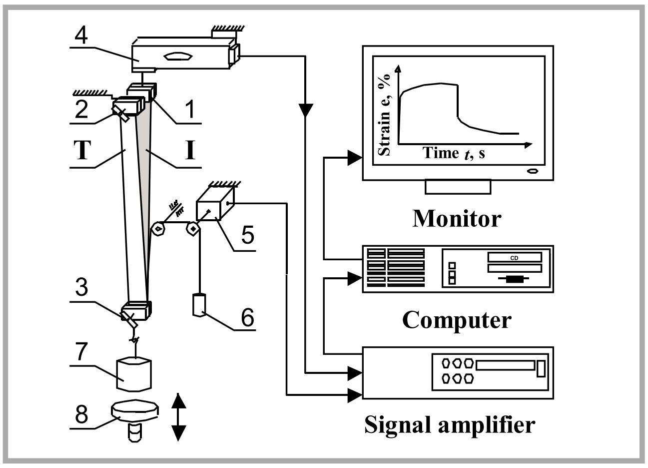

Figure 2. Relaxometer for creep and creep recovery tests of fabric systems: 1, 2 - two upper clamps, 3 - one bottom clamp, 4 - force measuring system, 5 - specimen elongation meter, 6 - weight for counter balance, 7 - weight for constant load, 8 - operated plate, T - specimen.

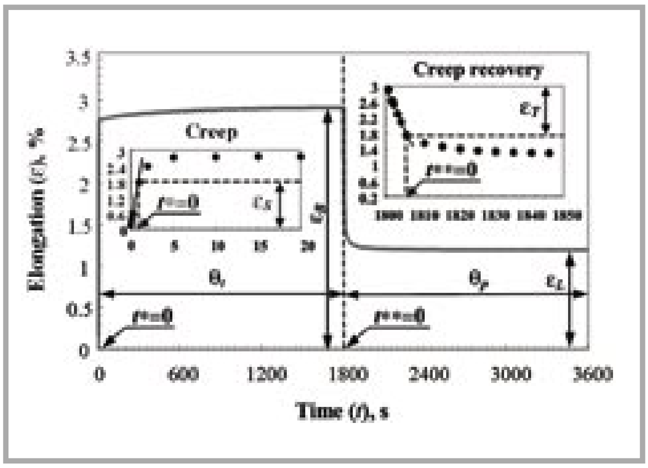

Figure 3. Schematic layout of creep and creep recovery of a specimen; ε_B-total (maximum) creep elongation, ε_T - immediate elastic elongation, ε_L - irrecoverable elongation, θ_t - loading period, θ_p - unloading period, t=0: beginning of time-dependent creep, t**=0: beginnig of the time-dependent creep recovery.*

and quite high level of 'drag' tension (40-60 N). The same gradual fragmentation is also characteristic of the interlining I2 when extending crosswise, going on at a much lower level of 'drag' tension (20-25 N). Due to these 'drag' forces, the after-effect of the first break of fabric system is not a total loss of its resistance to tensile strain, but just a slight decrease in the system tension (Figure 1, c and e).

Creep and Creep Recovery

For studies of the fabric systems regarding creep and creep recovery, as well as for measuring the tension redistribution in the single components of assembled fabric systems, a special tester has been developed - the relaxometer (Figure 2). The relaxometer has two adjacent upper clamps (1 and 2) to mount the upper ends of the component fabrics of the assembled system separately, and one bottom clamp (3) to mount the bottom ends of the assembled system together. Clamp 2 is tightly fixed to the frame of the equipment, while clamp 1 is attached to the force measuring system (4). For testing the fused fabric system, only one upper clamp (1) is needed. The bottom clamp (3) is connected by a flexible rope to a specimen elongation meter (5). Application and removal of a constant load to the specimen is provided by a weight (7) and an operated plate (8). The bottom clamp is counterbalanced by the weight (6), so the specimen is slightly tensioned during a creep recovery by the load of 0.2 N, which is equal to the pre-tension given at the specimen's clamping.

In all tests provided on the relaxometer, the gauge length was 250 mm and the width of specimens was 50 mm. Eight specimens for each fabric system were tested in each principal direction, lengthwise and crosswise. The test cycle consisted of a creep period under the load of 50 N for the time θ_t=30 min, followed by a creep recovery period for the time θ_p=30 min. During the entire test cycle, the changes in specimen length were measured digitally at intervals of 0.11 s.

A schematic layout of fabric specimen creep and creep recovery processes is shown in Figure 3. In theoretical studies of creep and creep recovery processes, it is customary to regard the entirely instantaneous application and removal of a load. In fact, every change in a tension of a specimen takes a finite time. Hence, it is difficult to identify the exact instant of the complete application of a load or the exact instant of a complete load removal, likewise to discern the immediate and the time-dependent response of a specimen to loading and unloading. As the specimen elongation was measured digitally, we had a large quantity of the elongation values at our disposal, whether during the loading and unloading or at the very beginning period of the creep or creep recovery process. This enabled us to define the starting points of the processes more precisely. As seen from the inserted fragments of creep and recovery curves in Figure 3, the sets of the initial points can be approximated by straight lines. The last points of such approximations are regarded as those showing the completion of the load application or of its removal, and also the ending of the immediate response of a specimen to loading or unloading. The instant at which the immediate response ends and the time-dependent creep begins is notified in this paper as t^*=0, and the specimen elongation at t^*=0 is conventionally regarded as instantaneous elongation (ε_S) (see Figure 3). Elongation at the end of a loading period (at $t^*=\theta_t$) is a total, or maximum creep elongation (ε_B). The instant at which the specimen unloading ends and a time-dependent creep recovery begins is notified as t^{**}=0. An elongation that recovers during specimen unloading is conventionally regarded as an immediate elastic elongation (ε_T), and an elongation at the end of the entire test cycle (at $t^{**}=\theta_p$) as an irrecoverable elongation (ε_L). Hence, the specimen elongation

$$\varepsilon_G = \varepsilon_B - \varepsilon_L$$

should be regarded as recoverable elongation, and the elongation

$$\varepsilon_E = \varepsilon_B - \varepsilon_T - \varepsilon_L$$

as delayed elastic elongation.

Characteristic creep and creep recovery curves of the assembled and fused fabric systems, selected from the families of curves in a similar way as for the force-elongation curves [10], are shown in Figure 4. The average indexes of creep and creep recovery behaviour are presented in Table 6. At a confidence level of 95%, the confidence limits of the mean elongation ε_B were within the range of 3.4 to 6.7% of the mean values.

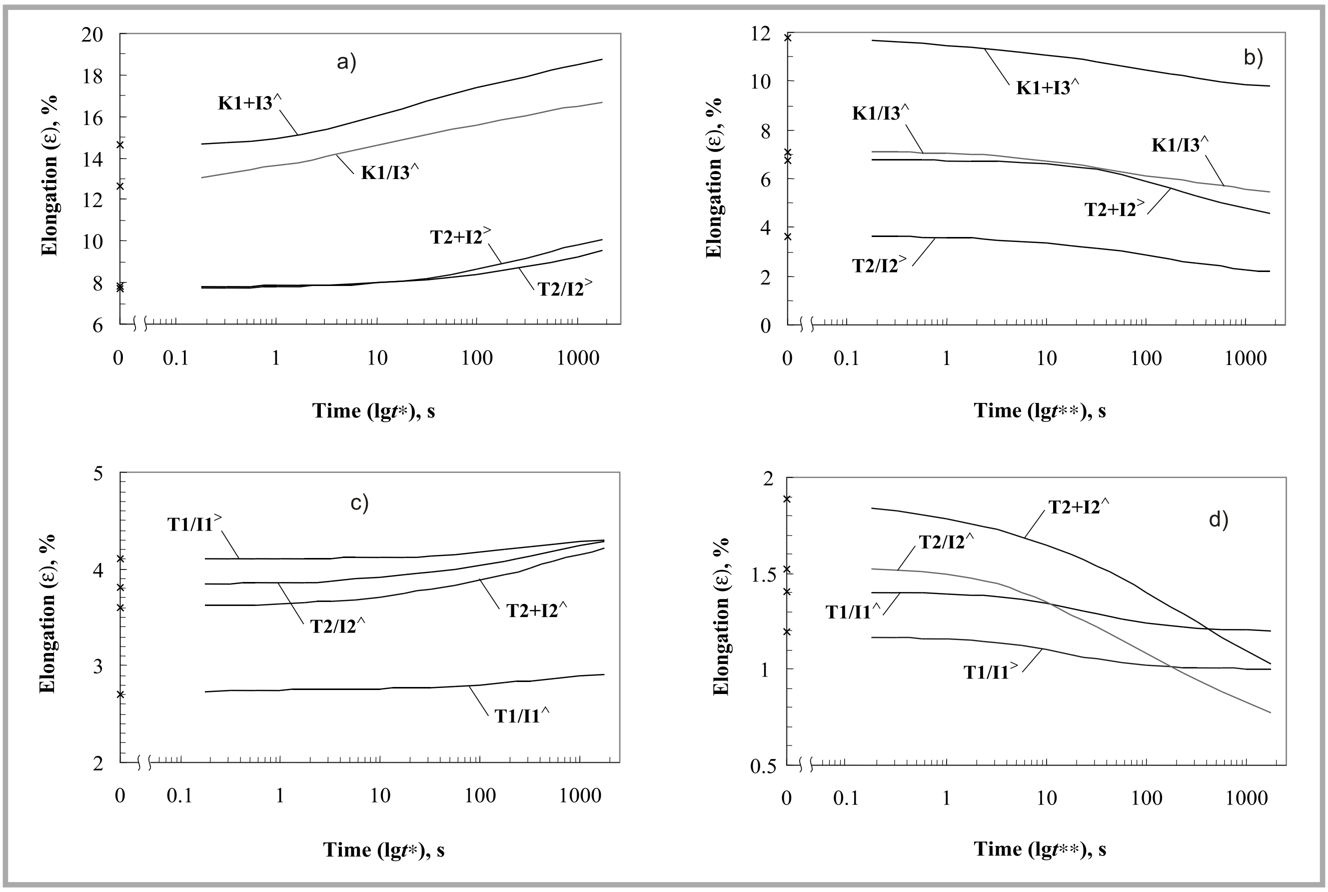

Figure 4. *Creep (a,c) and creep recovery (b,d) curves of fabric systems: ^ - loading lengthwise; > - loading crosswise; a,c) systems T2/I2 & T2+I2 (loading crosswise) and K1/I3 & K1+I3 (loading lengthwise), b,d) systems T1/I1, (loading lengthwise) and T2/I3 & T2+I2 (loading crosswise).*

The instantaneous elongation of the systems developed straight after the load application (Table 6) coincides with the data on the secant modulus (Table 4) of the systems, and it comprises the dominant part of the total (maximum creep) elongation. Creep curves (Figure 4, a and c) ascend upwards against the logarithmic-time axis for all the fabric systems. The curve slope, and hence the maximum creep elongation, is higher for those systems with lower values of tensile modulus. However, no special regularity is noticed for the quite small differences in creep behaviour between assembled and fused systems.

It is evident in Figure 4 (b and d) that creep recovery of the fabric systems does not come to an end during the entire observation period θ_p, especially for the T2/I2 and T2+I2 systems. Consequently, the values of irreversible elongations are in fact lower than those residual elongations of the systems at $t^{**}=\theta_p$, as they are presented in Table 6.

In the fused fabric systems, the resin adhesive evidently acts as a certain 'brake' for creep recovery of the fabric systems: the recovery curves of fused fabric systems are located more highly, the immediate elastic elongations of fused fabric systems are smaller, and the irreversible elongations are larger than those of assembled fabric systems. It should be noticed that delayed elastic elongation is not the prevailing component of the total elongation of the fabric systems, but its values are higher for fused fabric systems.

It follows from the results obtained that there is a possibility to predict the mechanical response of a fused fabric system to loading as a first approach by testing the system of simply assembled fabrics.

Redistribution of Tensions on the Components of Loaded Fabric Systems

A load on a fabric system composed of components assembled in parallel is a sum of partial tensions on each individu-

Table 6. *The indexes of creep and creep recovery behaviour of fabric systems (∧ - loading lengthwise; > - loading crosswise. The symbols of elongations are related to Figure 4 and to the text above).*

Fabric system code	Instantaneous elongation (ε_S), %		Total (maximum creep) elongation (ε_B), %		Reversible elongation (ε_G), %: Immediate elastic elongation (ε_T), %		Reversible elongation (ε_G), %: Delayed elastic elongation (ε_E), %		Irreversible elongation (ε_L), %	
	∧	>	∧	>	∧	>	∧	>	∧	>
T1/I1	2.7	4.1	2.9	4.3	1.5	3.1	0.2	0.2	1.2	1.0
T2/I2	3.8	7.8	4.3	9.5	2.8	5.8	0.7	1.5	0.8	2.2
K1/I3	12.7	3.6	16.7	4.7	9.6	1.0	1.7	0.1	5.4	3.6
T2+I2	3.6	7.8	4.2	10.1	2.3	3.3	0.9	2.2	1.0	4.6
K1+I3	14.6	2.6	18.8	4.4	6.9	0.7	2.1	0.2	9.8	3.5

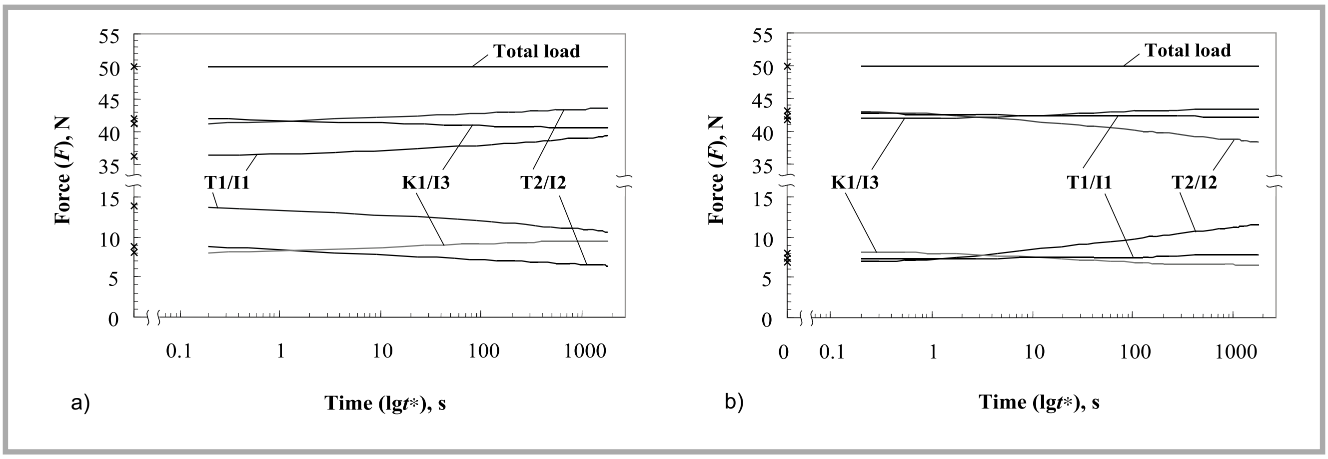

Figure 5. *Redistribution of tension on the components (T1, T2, I1, I2, I3, and K1) of fabric systems (T1/I1, T2/I2, and K1/I3) under a constant total load: a - loading lengthwise; b - loading crosswise.*

al component. If the tensile moduli of the system's components differ significantly, tensions on single components will also differ significantly. In order to reveal how the constant load applied to the fabric system is proportioned to the single fabrics of the system, the assembled fabric systems were studied under a constant total load of 50 N. It was verified that the tensions on single fabrics of each system redistribute over time. The characteristic tension development curves are shown in Figure 5. As seen, just after the application of constant load on the fabric system, its components undergo very different tensions, depending on the difference in their modulus - the higher tension falls on the more rigid component. For example, for the system T2/I2 loaded lengthwise, the higher tension falls on the more rigid face fabric T2. Just after the load application on the system, the tension on the fabric T2 amounts to 82% of the total load, and at the end of the loading period it increases up to 87% of the total load. Correspondingly, the tension on the interlining I2amounts to 18% of the total load initially, and decreases to 13% at the end of the loading period . This means that the longer the loading time, the more tension falls on the fabric T2. If the load is applied to the system T2/I2 crosswise, the higher tension falls on the more rigid interlining I2. Initially it amounts to 86% of the total load on the system, and at the end of loading it decreases to 77%. Any detailed analysis of the regularities in component tension changes, especially including a theoretical analysis of the process trends, exceeds the limits of the present research.

Summary and Conclusions

The high anisotropy of face fabrics and linings or interlinings joint into a textile system, and the different extensibility of the system's components is reflected in the pronounced two-peak break of a fabric system when extended in the principal directions. The adhesive interconnection of the components in fusing does not show a very pronounced influence on the stress-strain and creep behaviour of the fabric systems. The strength of the fused systems is higher by a few percentage points than that of the assembled systems, but no appreciable difference in elongation at breaking force is obtained.

A relaxometer with a digital specimen tension and elongation meters has been developed. It allows the starting points of the creep and the creep recovery processes of fabric systems to be defined more precisely, and to measure the tension on single components of a fabric system.

In the fused fabric system, the resin adhesive acts as a certain kind of 'brake' on the fabric system's creep recovery. Nevertheless, it is evidently possible to predict the mechanical response of a fused fabric system to tensile loads as a first approach by testing the system of simply assembled fabrics.

It has been verified that at a constant total load on an assembled textile fabric system, the single components of the system undergo very different partial tensions: the higher tension falls on the component possessing the higher modulus. The tensions on the single components are redistributed over time.

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