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Resilience and Deformability of Fused Textile Systems

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Abstract
The aim of this research was to investigate the resilience properties of textile systems fused with different interlinings by applying the method of pendulum impact loading. For the investigations, four worsted outer fabrics and four interlinings were chosen. For testing, a pendulum impact device was used, the operation of which is based on cyclical strikes of the spherical indentor upon the specimen, taking into account the resilience and deformability of the material. It was defined that resilience properties could be characterised not only by the values of impact β_n *and angles rebound* α_n *but also by the duration of vibration periods* T_n*. It was defined that the decay of pendulum impact* β_n *and rebound angles* α_n *in the period of* $t = 20$ *s can be described by power function* $y = a + bx^c$ *with a high accuracy (*$R^2 = 0.995 - 0.999$*). For the rebound process, better resilience of fabrics and their fused systems is characterized by higher values of power function coefficients a and b and lower values of its coefficient c. For the impact process, lower deformability of the samples tested is characterised by lower values of power function coefficients a and b, but with a more intensive decrease in deformability – by higher values of coefficient c. The degree of the fused system's deformability directly depends upon the thickness and mass per unit area of the interlinings used, i.e. less deformable and more stable systems were obtained with thicker interlinings, the mass per unit area of which was higher.*

Key words: *fused textile system, resilience, pendulum impact device, deformability, impact angle, rebound angle.*

Introduction

The resilience properties of textile systems under impact loading are important in many applications, e.g. pneumatic tyres, off-the-road equipment, and military supply systems. The latter items are armoured clothing and climbing ropes, the adequate performance of which depends upon the ability of the component yarns to withstand the effects of impact loading. However, fabrics in certain garment production processes are compressed dynamically, e.g. by fabric feeding mechanisms in sewing machines, the gripping of single or multiple plies of fabric or by certain fabric ply separation devices [1].

Fabrics in ready-made garments also experience multi-cycle dynamic impact loadings and must not lose their stable shape, e.g. in the zones of elbows or knees, thus maintaining the garment's quality during all the wear period [1].

The ability of textile fabrics to restore their original shape after removing the external load is known as fabric resilience. The resilience of textile systems is one of the main exploitation parameters describing the quality of the garment and its stability during all the wear period. Thus the investigation of resilience properties of textile systems is of great importance [2, 3].

P. M. Taylor and D. M. A. Pollet [4] confirmed the accuracy of a new method based on the pendulum principle. A close relationship was obtained between the parameters, which were defined by a pendulum impact device at low impact and static compression conditions. Furthermore in other research works close dependency was determined between energy absorption capacities and impact loading velocity [5]. Other investigations have shown that the resilience of textile materials can be improved by creating fused systems with an interlining orientated in different directions [6].

The tensile resilience characteristics of textile materials under impact loading were thoroughly analysed in the research works of Y. Termonia [7]. Nowadays it is defined that not only close dependency exists between the strain level of textile materials and their impact energy absorbed[8, 9], but also a linear relationship exists between the impact energy absorbed and tensile resilience characteristics of the same materials [10]. Thus the method of pendulum impact loading can provide all necessary information about the resilience of textile materials investigated, defined in conditions of multi-cycle low energy loading corresponding to the forces acting during real garment wear [11 – 12]. Thus the investigation of textile system resilience presented was performed using a method based on the pendulum principle. It allows to deter-

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mine deformational properties and textile systems resilience under multi-axial deformation conditions at low impact loads.

Important constituent components of garments are fusible interlinings [13], which are invisible because they are usually hidden between the shell fabric and the lining. On the other hand, their properties have a great influence upon the shape, appearance, softness and durability of garments. If the outer fabric is the component that directly influences the appearance of the garment, then the interlining can be considered as the component that improves its aesthetic and preference properties [13].

Fusible interlinings are used to create and maintain a spatial shape [14]. Careful selection of interlinings can compensate for some of the shortcomings of shell fabrics, and, conversely, the use of a poor or unsuitable interlining can lead to inferior quality garments, even when good quality shell fabrics are used [13].

In our earlier research [15] the effect of interlining orientation (0, 45 and 90 degrees in respect to the outer fabric warp direction) upon a fused textile system's resilience properties was investigated. The highest first rebound angle and smallest first impact angle was obtained for fused textile systems with an interlining in the bias direction (45°), hence resilience of such systems is the highest. Investigation of the resilience properties of fused textile systems was also presented in our second research [16], and the results obtained showed that the rebound angle does not show any significant difference when using various fusible interlinings. However, the meantime impact angles differ significantly. But it should be stated that evaluation of the resilience properties was done on the basis of first impact and first rebound angles without estimation of all the vibration period, which is also very important for characterisation of the resilience properties of textile materials. Thus the aim of this research was to investigate the dependencies of textile system resilience and deformability changes by applying the method of continuous pendulum impact loading. Also the parameters of pendulum vibration process decay mostly affected by the resilience properties of the materials tested were defined.

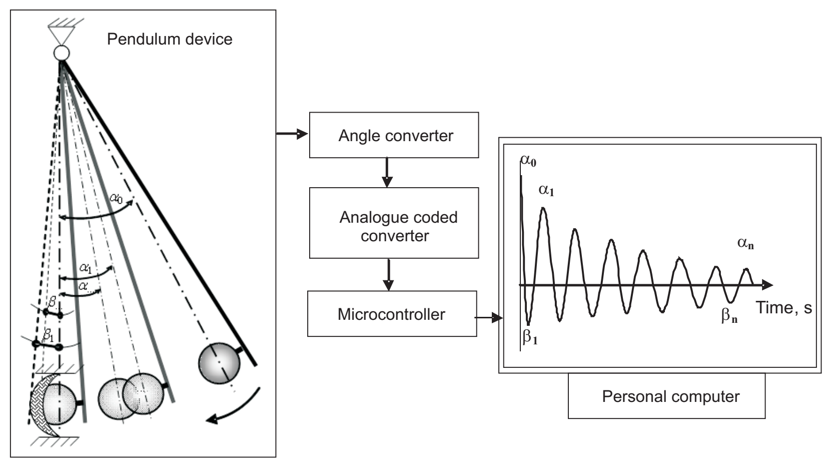


Figure 1. *Pendulum impact device and registration of its vibration process (α_0 – initial deflection angle of the pendulum, α_n – amplitudes of rebound angles, β_n – amplitudes of impact angles) [15].*

Table 1. *Characteristics of woven outer fabrics;* Wa – warp direction; We – weft direction; **SD – standard deviation.*

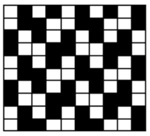
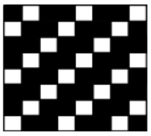
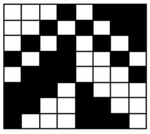
Weave □ – warp, ■ – weft	Broken twill 2/2 				Twill 2/1 		Broken twill negative 	
Code	M1	SD**	M2	SD	M3	SD	M4	SD
Mass per unit area, g/m^2	305	2.00	341	1.53	330	2.52	236	1.00
Thickness, mm	1.59	0.025	1.04	0.015	1.63	0.025	1.72	0.035
Density Wa/We*, 1/cm	10.0/9.2	0.58/0.10	10.6/9.6	0.06/0.10	15.0/12.0	0.66/0.76	10.4/9.8	0.10/0.05
Linear density Wa/We, tex	120/120	1.53/0.58	105/105	1.04/1.26	130/138	1.28/0.29	108/112	0.76/0.50

Table 2. *Characteristics of interlinings investigated.*

Type	Nonwoven		Nonvoven with polyester thread in longitudinal direction	Woven
Code	A	B	C	D
Adhesive, dots/cm^2	118		72	
Mass per unit area, g/m^2	40	27	46	100
Thickness, mm	0.03	0.01	0.11	0.21

Materials and methods

For the investigations, four woven outer fabrics (AB Liteksas, Lithuania), (***Table 1***) and four interlinings (Kufner, Germany), the composition of which was 100 PES, were applied (***Table 2***). A and B are thermo-bond nonwoven fusible interlinings. Bilayer textile systems were prepared by fusing the outer fabrics with the interlining for 15 seconds at a temperature of 145 °C while maintaining a pressure of 40 kPa.

The mass per unit area of textile materials was determined in accordance with the LST ISO 3801:1998 standard, the thickness of the fabrics and interlinings investigated measured at a pressure of 0.049 kPa, and fabric warp and weft density was established in accordance with the LST EN 1049-2:1998 standard. A pendulum impact device (***Figure 1***) was applied for investigations of fused textile system's resilience properties [15].

The principle of the pendulum impact device's operation is based on cyclical strikes of the spherical indentor upon the vertically clamped specimen, taking into account the resilience of its material. For the research, samples of 140 × 140 mm size were used, fixed in circular clamps with a diameter of 50 mm.

When the pendulum is released, its spherical indentor strikes the specimen at the lowest point of the swing. After impact, the indentor rebounds from the specimen and continues swinging until it reaches the rebound angle, which is $\alpha_1<\alpha_0$. Thus the descending vibrations are obtained (***Figure 2***), which can be characterised by the duration of the vibration period T_n and by changes in the rebound angle $\Delta\alpha$. The testing conditions were as follows: initial deflection angle of the pendulum α_0 = 5°, radius of the spherical indentor r_1 = 30 mm, the pendulum length l = 1.5 m. The descending vibrations of the pendulum were recorded for 20 s.

When the pendulum is released, part of its energy is lost during the deformation of the fabric. Hence when the pendulum is on its backward swing, it will not be able to reach the same angle as it started from. The difference between the starting angle is proportional to the energy lost in deforming the fabric, i.e. the energy which was absorbed during plastic deformation of the specimen. It is known that the fibre properties, fabric structure and mass per unit area are the major factors of textile energy absorption. Besides this, the interactions between fabric layers and friction between yarns and between the yarns and the pendulum indentor are also important factors in the impact energy absorption. A physical phenomenon of the pendulum impact vibration process is also described in our previous research [1, 2].

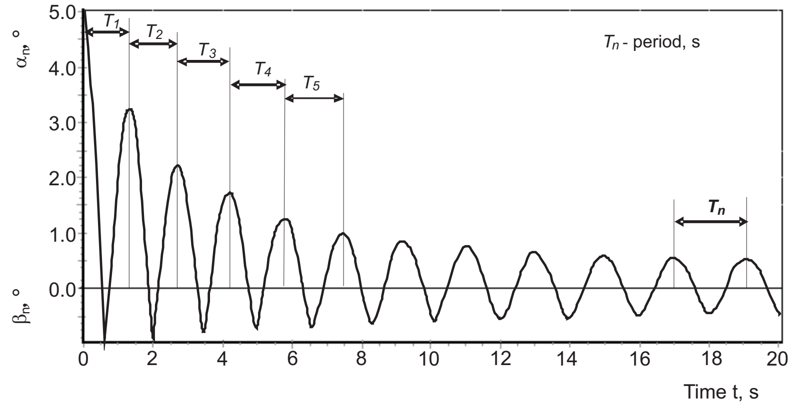


Figure 2. *Scheme of the pendulum impact vibration process.*

During testing, the material is deformed by overcoming its resistance due to the kinetic energy of the pendulum. When the spherical indentor of the pendulum is released from the highest point of the swing, its potential energy transforms into kinetic energy. Energy loss during one swing related to air resistance and friction in the pendulum's bearings is not taken into account in this research because it is considered to be negligible. Thus the main energy loss is obtained when the spherical indentor of the pendulum deforms the specimen during impact, describing the deformation properties, i.e. resilience of the sample tested.

The initial pendulum deflection angle α_0, rebound angles α_n, impact angles β_n and the whole pendulum vibration process were registered for evaluation of the textile materials and their fused system behaviour under impact loading. Thus it was possible to evaluate the deformation behaviour of the samples tested in each swing and after each contact on the basis of impact β_n and rebound angles α_n. Also the duration of pendulum vibration periods T_n and changes in rebound angles $\Delta\alpha$ were applied for evaluation of the fused textile system's resilience characterisation.

Curves of descending vibrations were obtained by registering the sequences of values α_n and β_n (***Figure 1***). The intensity of the descent can be described by the vibration cycle number n and values of impact and rebound angles. It can be seen that the vibration curve is not symmetrical in respect to the vibration duration on the X axis, i.e. the curve above the X axis describes the elastic behaviour, while that below describes the deformability of the material tested. Power functions $y = a + bx^c$ were applied to describe the dependencies between characteristics mentioned above and the resilience of the materials tested and their systems. Six specimens were used for each sample investigated. Coefficients of variation v did not exceed 6%.

Results and discussion

In our earlier investigations [16], the resilience properties of fused textile systems and their deformability were analysed taking into account only the first impact β_1 and first rebound angles α_1. The results of textile systems fused with

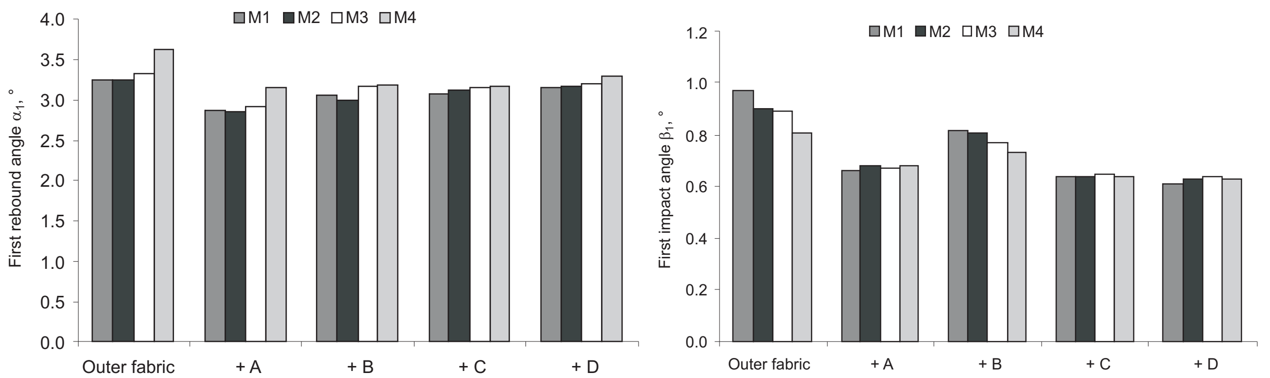


Figure 3. Values of *the first rebound (a_1) and first impact (b_1) angles of outer fabrics tested and their fused textile systems.*

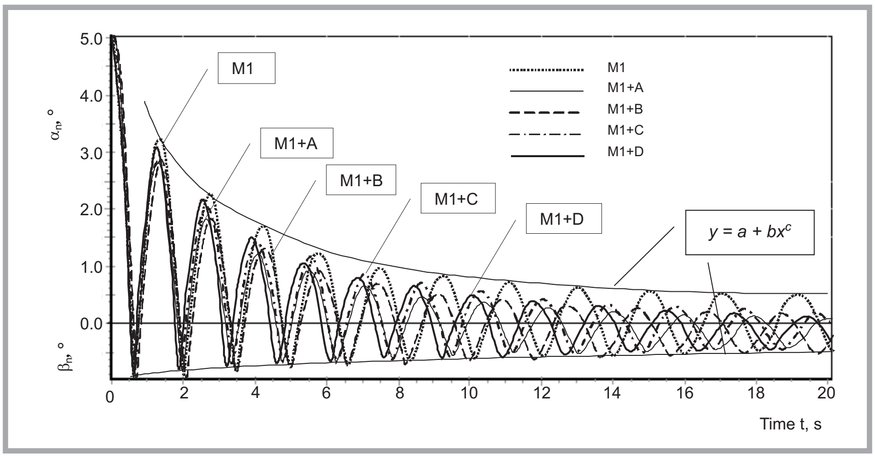


Figure 4. Pendulum vibration curves of fabric M1 and its systems fused with interlinings A, B, C and D.

different interlinings A, B, C and D are presented in ***Figure 3***.

It was obtained that both the first rebound angles α_1 and first impact angles β_1 of separate textile materials were higher compared to their corresponding fused systems (***Figure 3***). Thus the assumption was made that during impact, separate fabrics transmit more energy to the pendulum then to fused systems, i.e. the pendulum expends less kinetic energy on fabric deformation. Analysis of the fused systems showed that after fusing, the values of the first impact angle b_1 decreased by even 10 – 37 percent, i.e. the systems became less deformable. Values of the first rebound angle α_1 decreased in the range of 0.92 – 16 percent, i.e. the resilience of the systems decreased (***Figure 3***, ***Figure 4***). It was also noticed that values of the first impact angles β_1 of the fused systems with interlining D, which had the highest thickness and mass per unit area (***Table 2***), were the lowest, but the first rebound angles α_1 were the highest. Thus fused systems with interlining D were the least deformable and could be considered to have the best resilience properties. However, analysis of all pendulum vibration process (***Figures 4*** and ***5***) showed that the fused system with interlining D (M1 + D) up till the fourth rebound had the highest rebound angles α_1, but later the fused system with interlining C (M1 + C) had the highest rebound angle values up till the end of the 20 second vibration process [16].

Thus the aim of this research was to investigate the resilience properties of textile systems fused with different interlinings through all the process of pendulum vibration decay. The example of the whole pendulum vibration process with fabric M1 and its fused systems is presented in ***Figure 4***. It was stated that the decay of impact β_n and rebound angles α_n in the period of $t = 20$ s can be described by the same power function $y = a + bx^c$ with a high accuracy ($R^2 = 0.995 - 0.999$).

Certain power functions which describe the dependence of impact and rebound angle value changes upon the duration of vibration t for fabrics M1, M2, M3, M4 and their fused systems are presented in ***Figure 5***.

Coefficients a, b and c of power functions for the rebound process are presented in ***Table 3*** and for the impact process - in ***Table 4***. It can be seen that during the rebound, process coefficient a obtains the highest values for systems fused with interlining C, and a little less – for systems with interlining D. Almost the same can be said about coefficient b, but for coefficient c it is opposite. Coefficients a and b are related with the rebound angles, i.e.

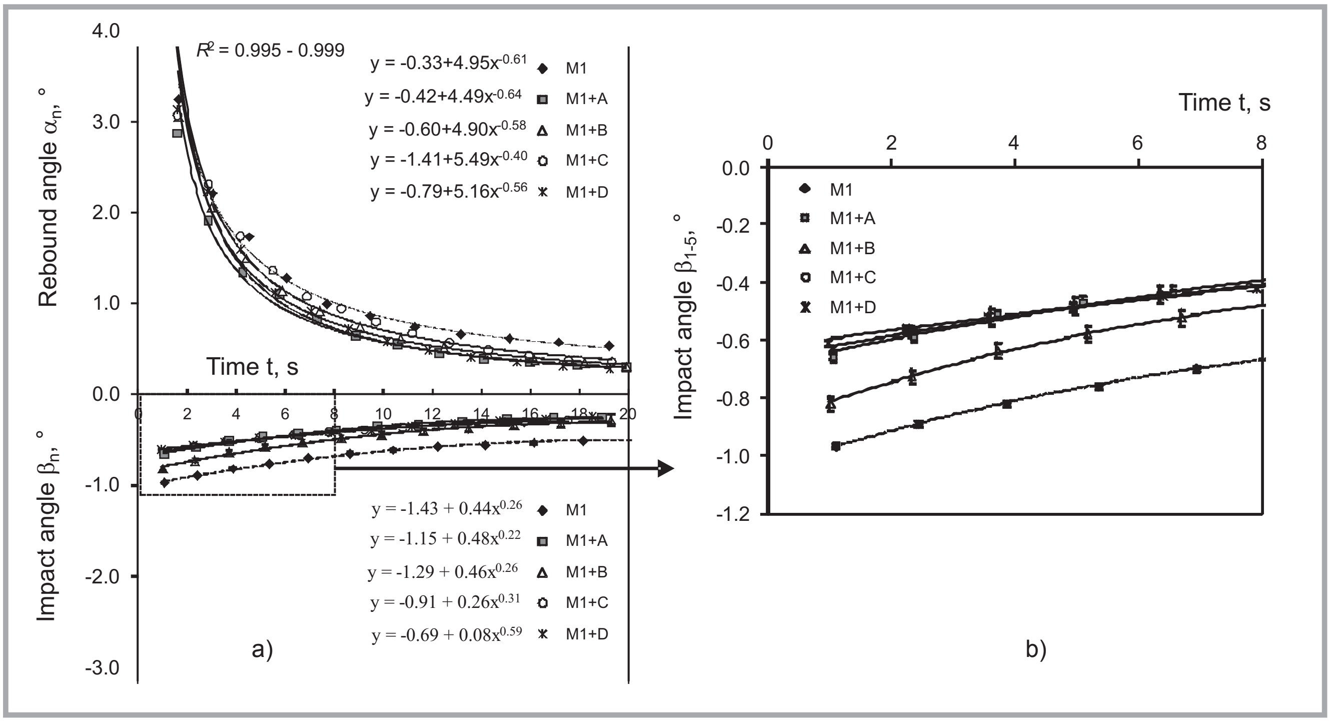


Figure 5. *Processes of pendulum rebound and impact for outer fabric M1 ant its fused systems during all the vibration process (a), and an enlarged view till the 5th impact (b).*

Table 3. *Coefficients of power function* $y = a + bx^c$*, describing the rebound process for fabrics M1 - M4 and their fused systems.*

	M1					M2					M3					M4				
	outer fabric	**+ A**	**+ B**	**+ C**	**+ D**	**outer fabric**	**+ A**	**+ B**	**+ C**	**+ D**	**outer fabric**	**+ A**	**+ B**	**+ C**	**+ D**	**outer fabric**	**+ A**	**+ B**	**+ C**	**+ D**
a	-0.33	-0.42	-0.60	-1.41	-0.79	-0.31	-0.39	-0.24	-0.93	-0.52	-0.66	-0.33	-0.51	-1.16	-0.55	-0.68	-0.36	-0.82	-0.95	-0.90
b	4.95	4.49	4.90	5.49	5.16	5.05	4.73	5.12	5.66	4.50	5.11	5.95	5.80	5.48	5.24	5.34	5.28	5.31	5.69	5.30
c	-0.61	-0.64	-0.58	-0.40	-0.56	-0.63	-0.67	-0.73	-0.50	-0.61	-0.52	-0.78	-0.67	-0.43	-0.63	-0.47	-0.69	-0.51	-0.49	-0.50

Table 4. *Coefficients in power function* $y = a + bx^c$*, describing the impact process for fabrics M1 - M4 and their fused systems.*

	M1					M2					M3					M4				
	outer fabric	**+ A**	**+ B**	**+ C**	**+ D**	**outer fabric**	**+ A**	**+ B**	**+ C**	**+ D**	**outer fabric**	**+ A**	**+ B**	**+ C**	**+ D**	**outer fabric**	**+ A**	**+ B**	**+ C**	**+ D**
a	-1.43	-1.15	-1.29	-0.91	-0.69	-1.13	-1.60	-1.39	-0.89	-0.71	-1.07	-1.23	-1.18	-0.82	-0.71	-0.91	-1.02	-0.96	-0.80	-0.72
b	0.44	0.48	0.46	0.26	0.08	0.20	0.91	0.54	0.22	0.07	0.17	0.51	0.37	0.16	0.06	0.09	0.33	0.21	0.15	0.09
c	0.26	0.22	0.26	0.31	0.59	0.40	0.12	0.21	0.32	0.58	0.45	0.22	0.30	0.41	0.67	0.52	0.25	0.34	0.37	0.47

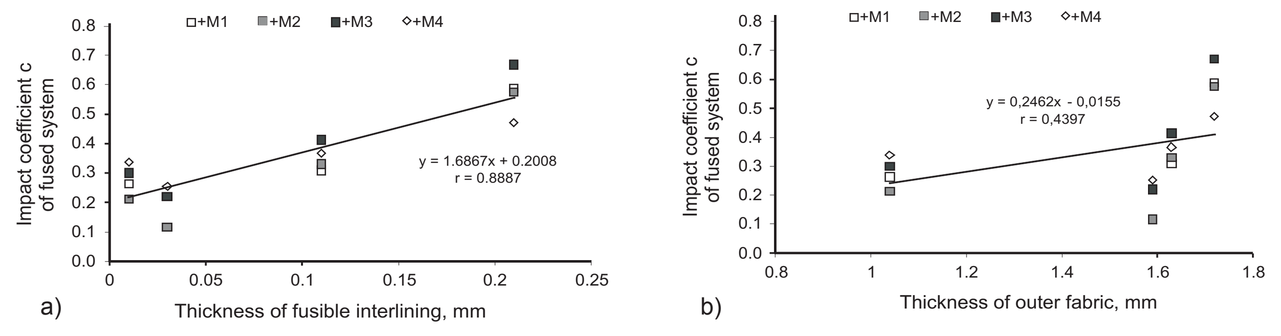


Figure 6. *Dependencies between the coefficients c of impact power functions, interlinings tested, and also fabric thickness.*

their higher values indicate higher rebounds. At the same time, coefficient c is related with the intensity of the rebound angle decrease, i.e. its lower value shows a slower decay process. All this leads to the assumption that better resilience of samples tested is characterised by higher values of rebound power function coefficients a and b and lower values of its coefficient c.

Table 4 shows that during the impact process, coefficients a and b obtain the lowest values for fused systems with interlining D, and a little higher for fused systems with interlining C. The values of coefficient c – conversely – are the highest for these systems. The assumption can be made that lower deformability of samples tested is characterised by lower values of impact power function coefficients a and b, while a more intensive decrease in deformability – by higher values of coefficient c.

Later the dependencies between coefficients a, b & c of impact power functions and such characteristics of fabrics M1 – M4 and interlinings A – D tested as the thickness and mass per unit area were established (***Figure 6***). It can be seen from ***Table 5*** that evident dependencies were obtained for separate interlinings A – D - higher are their thickness and mass per unit area, lower are coefficients a and b of impact power functions, which indicates lower deformability of the fused systems. It must be noted that the relation between these coefficients and interlining thickness is strong, but the same relation for separate fabrics is much weaker. Also the relation between coefficients and the interlining's mass per unit area is strong, but for separate fabrics it is weaker and even opposite. Whereas no meaningful dependencies between the coefficients of rebound power functions and characteristics of the separate fabrics and interlinings tested were defined.

The results have shown that although the deformational behaviour of the separate materials tested under low stress pendulum impact loading was different, because of their structure and mass per unit area, after fusing it became similar. The difference in the fused system's deformational behaviour was dependent only on the interlining applied, because its adhesive dots during fusing lock the movement of fabric yarns and make the whole system less deformable. On the other hand, the number of fabric layers also plays a significant role upon the total deformational behaviour of the textile system, because the interaction between yarns from different layers becomes more complex. All this leads to lower residual plastic deformation of the whole system. Thus less deformable and more stable systems were obtained with thicker interlinings, the mass per unit area of which was higher.

At the second stage of the investigations, changes in pendulum vibration periods T_n during all the vibration process for

Table 5. *Correlation r between impact power function coefficients, thickness, and also mass per unit area of separate interlinings and fabrics.*

For separate interlinings	*a*	*b*	*c*	**For separate fabrics**	*a*	*b*	*c*
thickness	**-0.8234**	**-0.7434**	**0.8870**	**thickness**	-0.5409	-0.3546	0.4373
mass per unit area	**-0.7150**	-0.6336	**0.8643**	**mass per unit area**	0.5483	0.4547	**-0.7423**

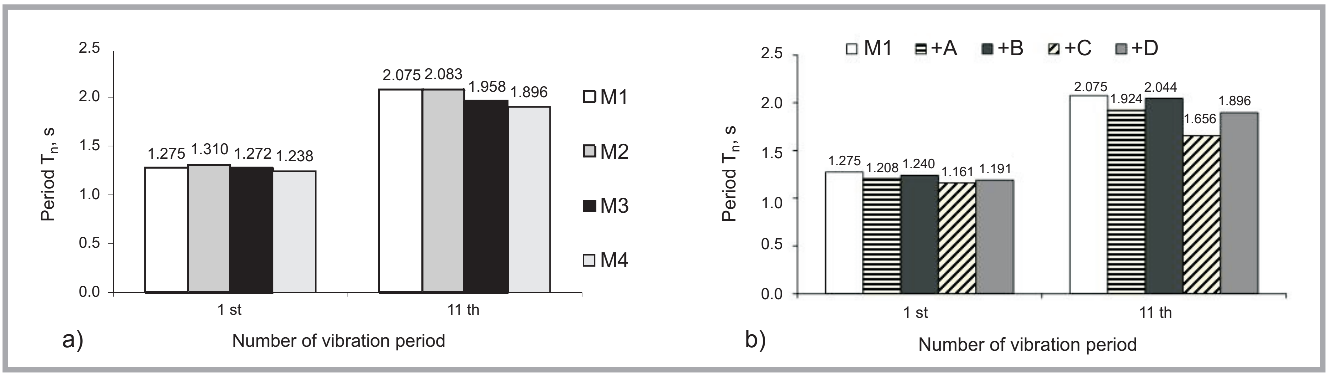


Figure 7. Changes in the first and last pendulum vibration periods T_n for separate fabrics (a) and fused systems of fabric M1 (b).

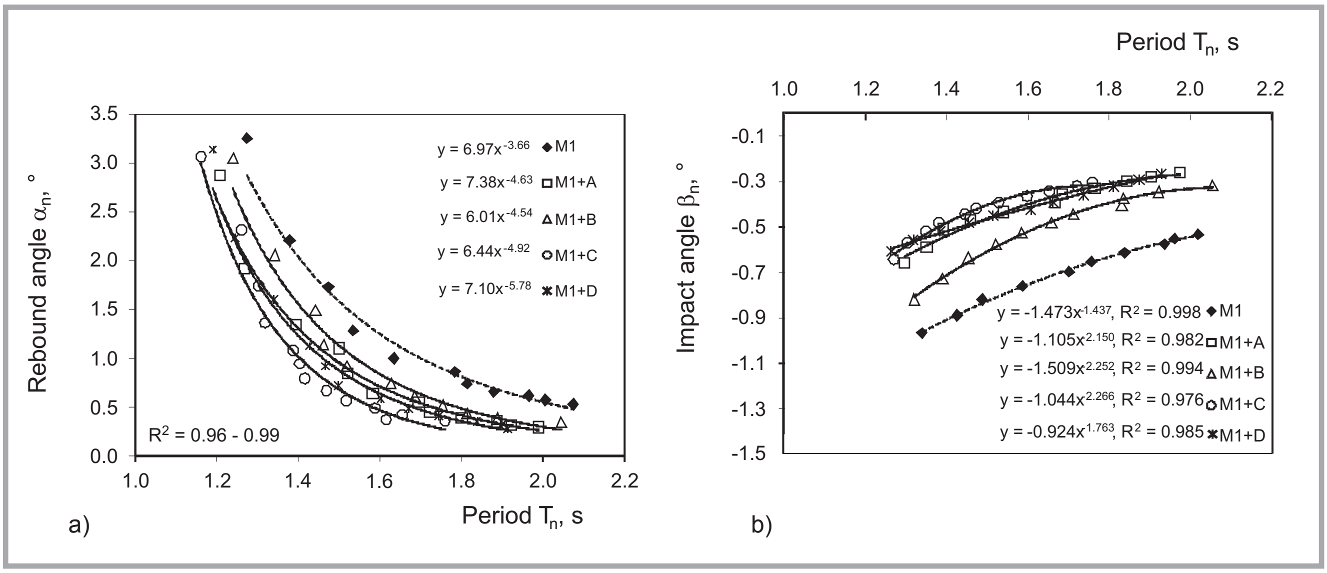


Figure 8. Dependencies between the duration of the pendulum vibration period T_n, values of rebound angles α_n (a), and those of impact angles β_n (b) for fused textile systems.

separate fabrics and their fused systems were analysed. This phenomenon can be described by linear dependency ($R^2 > 0.98$). ***Figure 7*** presents a comparison between the durations of the first and last vibrations. It can be stated that a shorter vibration period T_n is characteristic of fabrics and fused systems of higher resilience. During the investigations, the longest vibration periods were obtained for separate fabric M1, the resilience of which is the worst. This coincides with the results presented in ***Figure 3***: the first rebound angle α_1 for fabric M1 was the smallest, whereas the first impact angle β_1 was the highest, and with the results of power function coefficients (***Table 4***). The shortest vibration periods were obtained for fused systems with nonwoven interlining C, of polyester thread in the longitudinal direction. The number of vibrations during 20 s for these systems is the highest, i.e. average 12 - 13. Changes in the first and last pendulum vibration periods T_n for separate fabrics is between 53 and 63%. For fused systems of fabric M1, changes in the first and last period T_n depends upon the interlining, and are between 43% (with interlining C) and 65% (with B).

The dependency between the duration of pendulum vibration period T_n and the values of corresponding rebound angles α_n was defined (***Figure 8.a***), which showed their opposite relationship. ***Figure 8.a*** illustrates that the duration of pendulum vibration periods of separate fabric M1 for the same rebound angles is longer compared to that of its fused systems, thus its resilience is lower as well. Also we can see that the fused system with interlining C has the best resilience properties, which coincides with the results of power function coefficients for the rebound process.

The duration of pendulum vibration period T_n is related with the values of impact angles β_n (***Figure 8.b***). The dependencies presented in ***Figure 8.b*** show that the value of impact angle β_n for the same duration of vibration period T_n is higher for separate materials compared to their fused systems. Thus separate fabrics lose energy during each impact more than fused systems, hence their resilience properties are characterised as worse.

Conclusions

The results of the investigation performed show that pendulum impact testing can be successfully applied for the characterisation of textile materials and their systems' behaviour under continuous impact loading. They provide additional information to research performed earlier, where it was stated that the first impact β_n and first rebound angles α_n of the pendulum are indicators which can be used to describe fabric resilience. At the same time, the results of this investigation reveal that the whole pendulum vibration process is very important for the prediction of textile resilience changes during a certain period of cyclic loading. It was stated that the decay of pendulum impact β_n and rebound angles α_n in the period of t = 20 s can be described by power function $y = a + bx^c$ with a high accuracy ($R^2 = 0.995 - 0.999$) The higher resilience of fabrics and their fused systems during the pendulum rebound is characterised by higher values of power functions coefficients *a* and *b* and lower values of its coefficient *c*. Hence lower deformability of samples tested during pendulum impact is characterised by lower values of coefficients *a* and *b,* while a more intensive decrease in deformability – by higher values of coefficient *c*.

The application of the continuous pendulum impact loading method for textile systems with different fusing interlinings has proved that the most deformable are separate fabrics; but their fused systems become less deformed and their first impact angle β_1 decreases from 15.5% to 24.7%. The degree of fused system deformability depends directly upon the thickness and mass per unit area of interlinings used, i.e. less deformable and more stable systems were obtained with thicker interlinings, the mass per unit area of which was higher. Also it was stated that the vibration period T_n closely depends on both the impact and rebound angles. After fusing, the rebound and impact angles decrease; but the resilience properties of fused systems become better in respect to separate outer fabrics, because the duration of pendulum vibration periods becomes shorter, and at the same time the number of its vibrations becomes higher.

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