Research of Material Properties for the Purposes of Modeling the Fabric Destruction Process

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Abstract. The need to diversify the sources of raw materials used in industry has resulted in the increasing popularity of recycled materials. This situation is also observed in the clothing industry, which shows a growing interest in using recycled down and feathers from old jackets. Because the recovery process was being carried out manually, it is necessary to automate the process. Designing a suitable device requires testing to allow the modeling of the process to be carried out by the machine. The article presents the results of experimental tests whose purpose was to determine the material properties necessary to carry out numerical simulations of the destruction process of polyester fabrics. The article further presents the research methodology together with the research stand and discusses the results obtained..

1 Introduction

With the growing importance of sustainability and recycling, the current research effort leads to the development of numerous new constructions and technological solutions [1-9] or modernization of existing solutions; the intention is to limit the usage of natural resources. This trend for sustainability is observed in practically all the industry branches, even the down and feather industry recycles used down jackets in order to reuse the material. Recycled feather down material is utilized to cut down on the breeding of poultry and the use of fodder.

Materials suitable for reuse include both the down from jackets as well as other textile industry produce, e.g. duvets, pillows, etc. Down feathers in such products are typically employed to provide sufficient thermal insulation which can only be achieved if the down feathers are distributed uniformly. To prevent its displacement, the so called quilting is used, which often also serves an aesthetic and artistic purpose.

Down material in processed clothing is therefore enclosed in a relatively small space of the jacket. It is necessary to separate the fabric in order to extract the desired material. It is therefore evident that the process of separating the fabric must not cause destruction of the down. After consultations with employees of a down feather shop handling down jacket recycling and after observation of their work processes, it was noticed that the currently employed process of material extraction involves manual tearing open of each enclosed area of the jacket by the employee. This process is very time consuming and hardly

economical; therefore, a machine construction concept was developed to improve the economic efficiency of the down material recycling process. The principle of operation of such a device would be based on the process of tearing the textile material used in the clothing article [10]. This necessitates the development of a model to describe the characteristics of the fabric so as to apply it for modeling the process of fabric destruction to be carried out in the machine in question.
The present work discusses the procedure to determine some of the material parameters for selected synthetic fabrics. The results of static shear and tensile testing were presented to model the material in the Abaqus/CAE software. Next, the simulated results were compared with the results from the experiments.

2 Static shear test using PFT frame

The PFT frame is a rhombus-shaped device with variable internal angles with grips attached to the sockets of the strength machine. The sample of the examined material, shaped as indicated in Fig. 1b, is placed in the frame and clamped down along all its sides so that the material does not move relatively to the frame [11]. Next, the strength machineis operated. As the upper gripper of the strength machinemoves, the internal angles of the frame change and the material is subject to pure shear. The aim of this procedure is the determination of the material shear modulus G as well as the shear resistance of the material.

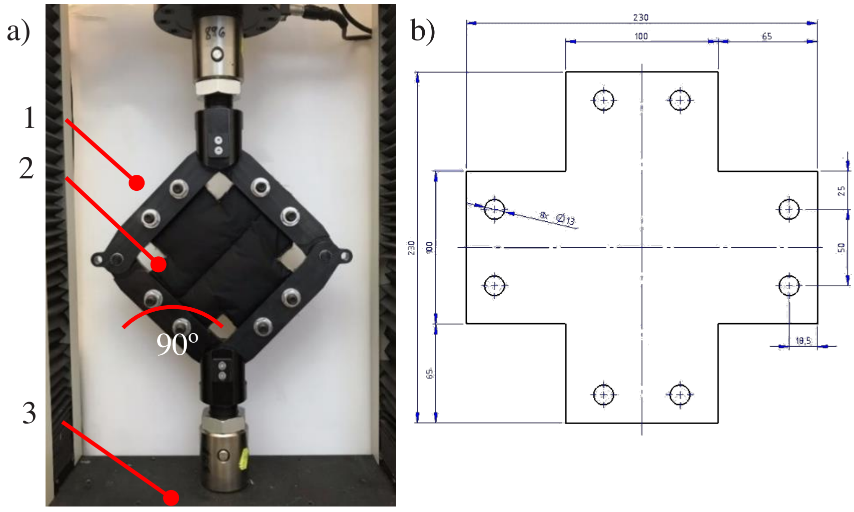

Fig. 1. Testing station: a) static shear test: 1 – Picture/Shear Test Frame, 2 – examined synthetic fabric material sample, 3 – mounting of the test frame in the strength machine; b) sample dimensions for static shear test.

This method is often employed for materials made of thermoplastic composites, fiber-reinforced composites, fabric with mono-directional and bi-directional strands relative to the main axis of the sample.
During the test, the force applied along the device axis is measured together with the displacement of the main gripper. Each sample was prepared so that the fabric strands are parallel to its axis.

Before examining the samples, tests were carried out to measure the frame resistance force value mounted on the strength machine(without the sample). The obtained functions of force and displacement after testing were within the measurement error of the instrumentation. On this basis, the possibility of significant measurement errors during actual testing was therefore excluded.

6 different material samples were subject to shear testing, as provided in Table 1. The samples are marked with symbols K and M. The letter M denotes new materials used for jacket manufacturing, whereas samples cut out from jackets are designated with the letter K. The letter S denotes that the sample was subject to shearing with strands parallel to the sample axis. The samples designated with K3_S, are sewn together from 2 fabric layers, forming the pocket to be filled with down feathers.

Table 1. Designations and data for materials used in the examination.

Designation	Material	Average material thickness [mm]
M1_S	Bratex	0.098
M2_S	Liper	0.280
M3_S	Goretex	0.412
K1_S	65% Polyester 35% Cotton	0.194
K2_S	Polyester	0.136
K3_S	Nylon	0.352

When determining the shear modulus, the gripper displacement velocity should be v=5 mm/min [11].

The stress values are calculated with the formula [12]:

$$\tau = \left(\frac{FL_0}{v_0}\right)\sin\left(\frac{\psi}{2}\right) \tag{1}$$

where:

τ – shear stress value, [MPa]
F – stretching force (force applied along the axis of the gripper) [N]
L_0 – length of the working side of the sample before testing [mm]
v_0 – working volume of the sample before testing [mm^3]
ψ – angle between sample sides [°].
ψ_0 =90° for sample without load (F = 0 N)

During the test, the displacement of the fastening system (grippers) of the strength machine was registered. Afterwards, the material strain angle was calculated from the equation [12]:

$$\gamma = \psi_0 - \psi \tag{2}$$

where:

γ – shear strain angle in radians [rad]
ψ_0 – the angle between the side edges of a sample with no load applied, [rad].
ψ – the angle between the side edges of the sample, [rad]

The resultant strain and stress values were used to calculate the value of the shear modulus [11]:

$$G = \frac{\tau_2 - \tau_1}{\gamma_2 - \gamma_1} \qquad (3)$$

where:
G – shear modulus [MPa]
τ_1 – stress measured at strain value γ_1= 0,001, [MPa]
τ_2 – stress measured at strain value γ_2= 0,005, [MPa

The experimental data were used to prepare graphs to present the function of stress and strain values for individual samples. 3 test were carried out for each material. The shear strain angle was calculated according to [13]:

$$\gamma = \frac{\pi}{2} - 2\arccos\left[\frac{L\sqrt{2}+d}{2L}\right] \qquad (4)$$

where:
γ – shear strain angle in radians [rad]
L –PFT frame side length [mm]
d – PFT frame gripper displacement [mm]

3 Static tensile test

The subsequent examination to be carried out involved a static tensile test. This allowed to determine the tensile characteristics of the fabric. Fig. 2 presents an example of a fabric sample subject to tensile testing on the MTS Insight strength machine. In order to eliminate the influence of gripper jaws of the place of separation of the sample, plastic pads were used. The examination was carried out at the velocity of 5mm/s.

Six different material samples provided in Table 2 were subject to the examination. Two out of six samples were selected to be modeled in the numerical analysis software. Samples taken from new materials to be used for jacket manufacturing were designated with the letter M (M1_P, M1_W, M2_P etc.), whereas samples extracted from jackets were designated with the letter K (K1_P, K1_W, K2_P etc.). The letter P denotes the horizontal orientation of the strands, whereas the letter W denotes longitudinal orientation. Samples with designation K3_P and K3_W are sewn together from two layers of fabric. This means that down feathers were not removed from the K3 samples and the two sides of the jacket: internal and external were sewn together. The K3 shaped samples were prepared for comparison.

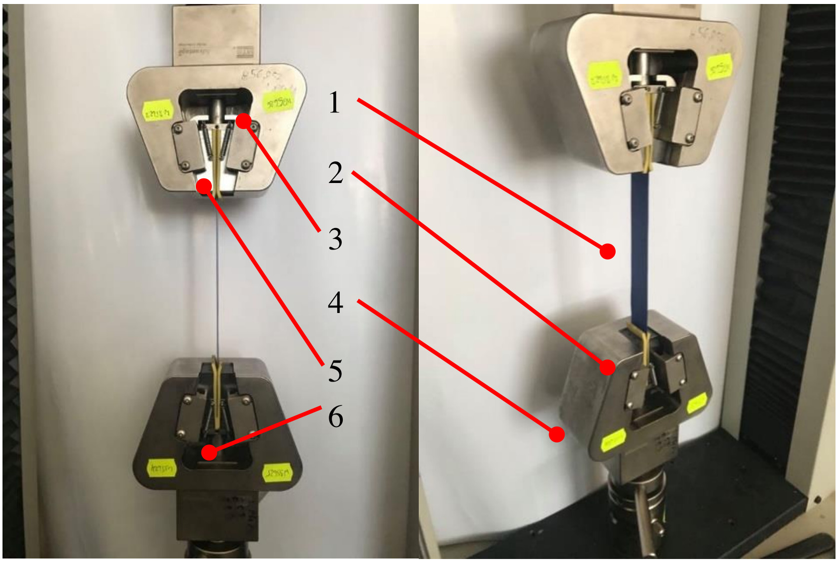

Fig. 2. Testing station – static tensile test: 1 – examined synthetic fabric sample, 2 – polyurethane foam pads, 3 – upper grip, 4 – lower grip, 5 – upper grip jaws, 6 – lower grip jaws.

Table 2. Characteristics and designations of the samples for examination.

Designation	Material	Average material thickness [mm]	Average sample width [mm]	Strand direction 0°/90°
M1_P	Bratex	0.098	24.42	90°
M1_W	Bratex	0.098	24.56	0°
M2_P	Liper	0.280	24.52	90°
M2_W	Liper	0.280	24.57	0°
M3_P	Goretex	0.412	24.11	90°
M3_W	Goretex	0.412	24.25	0°
K1_P	65% Polyester 35% Cotton	0.194	24.76	90°
K1_W	65% Polyester 35% Cotton	0.194	24.56	0°
K2_P	Polyester	0.136	24.96	90°
K2_W	Polyester	0.136	24.83	0°
K3_P	Nylon	0.352	25.11	90°
K3_W	Nylon	0.352	25.06	0°

Five measurement of sample thickness were performed for each material. The measurements were carried out using Silverline micrometer with measurement accuracy of up to 0,001 mm. The width of the cut samples was measured using Limit caliper gauge with measurement accuracy of up to 0,01 mm. 5 width measurement were made for each sample and the average value was provided in the table below.

4 Numerical model

The carried out experimental study was used to develop a numerical model for the analyzed fabrics. Such a model can be successfully employed to carry out different simulations necessary for the design process [14-17]. Based on the determined data from static tensile test, two materials were selected for modeling in the numerical analysis software. The criteria for choice was based on two maximum values, the first being tensile strength and the other being the highest breaking force. The maximum stress value Rm = 132MPa was obtained for the test sample M1_W_3 (Bratex). Whereas in the examination of the sample M3_W_2 (Goretex), the highest breaking force value was observed, equal to F = 860N.
The "*Fabric" material model used in the simulation is based on the test data. It assumes that material reaction under strain are described by 3 independent groups of data: characteristics from longitudinal stretching, from lateral stretching and from shearing. Generally speaking, to define the woven fabric, the macro requires to input the data determined in tensile testing (in both directions) as well as from the examination with the PFT frame. The stress test data can be classified according to the three available types of behavior:
- nonlinear elastic behavior,
- nonlinear elastic behavior with damage,
- nonlinear plastic-elastic behavior with permanent deformation.

For materials Goretex and Bratex, it was assumed that lengthwise and crosswise elongation data will be entered with defined damage, whereas shear data will be provided as nonlinear elastic [12].
The numerical simulation was used to reproduce the results of the static tensile test and the static shear test. This allowed to verify the developed model for the analyzed material.
The model of the sample cutout for use in the static tensile test was represented as a deformable object (shell/planar). The model is divided into three parts. Two parts represent the sample areas placed in the strength machine grippers. The third part is used for transferring stress. The cross-section type was defined as "membrane" with thickness identical to a given sample.
All degrees of freedom were removed for the bottom part of the sample, using the ENCASTRE edge condition. The reference point was created at the center of the upper side of the cutout, and the upper section of the sample was bound to it with the COUPLING function. For the reference point RP, the boundary condition was used to assign the velocity equal to 5mm/s in the direction parallel to the side edge of the sample, at the same time preventing its motion in other directions.
Owing to the quasi-static character of the examination, the Mass Scaling function was used in order to reduce the time of computation. This is justified in cases where inertial forces do not influence the results [14].
The mesh component size is 10% of sample width (2,5mm), the generated element type was set to quad.
In the simulation of the shearing process, the sample was also modeled as a deformable object (shell/planar). Its cross-section was defined as "membrane", with thickness corresponding to the given sample. The model of the sample was divided into five parts. Four of these parts were fastened in the frame where 4 reference points were created in the middle of the area of sample fastening, as provided in Fig. 3.

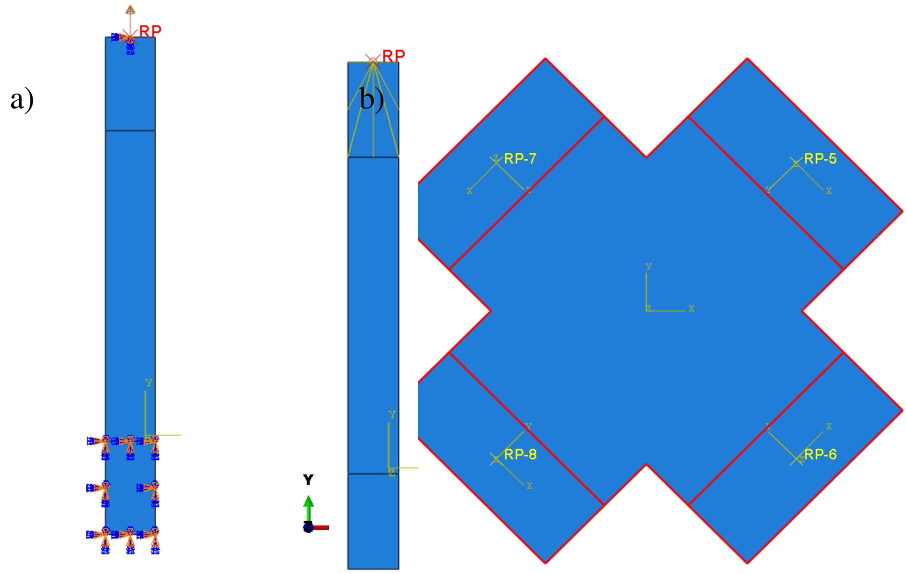

Fig. 3. Numerical models of samples used in testing;a) boundary conditions for the cutout used in the static tensile test;b) for static shear test.

In each reference point, the origin point of a local coordinate system was placed. The axes X are parallel to the sides of the PFT frame, the Z axes are perpendicular to the sample surface. The fastening areas of the sample were bound to the reference points RP using the COUPLING function, the instantaneous velocities of the reference points were determined in the SOLIDWORKS Motion environment. In order to reduce the time of computation, the Mass Scaling function was used. Element size was set to 2mm and generated element type was set to quad.

5 Results

Fig. 4 shows a comparison of tensile forces in the transverse and longitudinal direction, in relation to the measured displacement during sample examination. As shown on these graphs, the examination of samples K1, K2 and M1 indicate that the breaking force for these samples are similar for transverse and longitudinal directions. For the transverse direction, the breaking force in these samples did not exceed 200 N. Whereas in the longitudinal direction, the breaking force value is in the range of 350-400N. The K1 samples are destroyed more quickly than samples K2 and M1. This may be caused by the inclusion of cotton in the material. M1 samples are made of Bratex, the strands of this material are additionally laminated during manufacturing [18] which may have caused a higher elongation during tensile test and a similar breaking strength regardless of the lowest thickness among these three materials.
The samples designated as M2 exhibited the most elongation during the examination, at the same time achieving the highest breaking force in both the transverse and longitudinal direction. In this material, the direction of elongation has the most effect on the resultant displacement. The examination carried out in the transverse direction achieved

a displacement of 254 mm at breaking force of 79 N. Whereas stretching in the longitudinal direction achieved a displacement of 140 mm at 198 N force value.

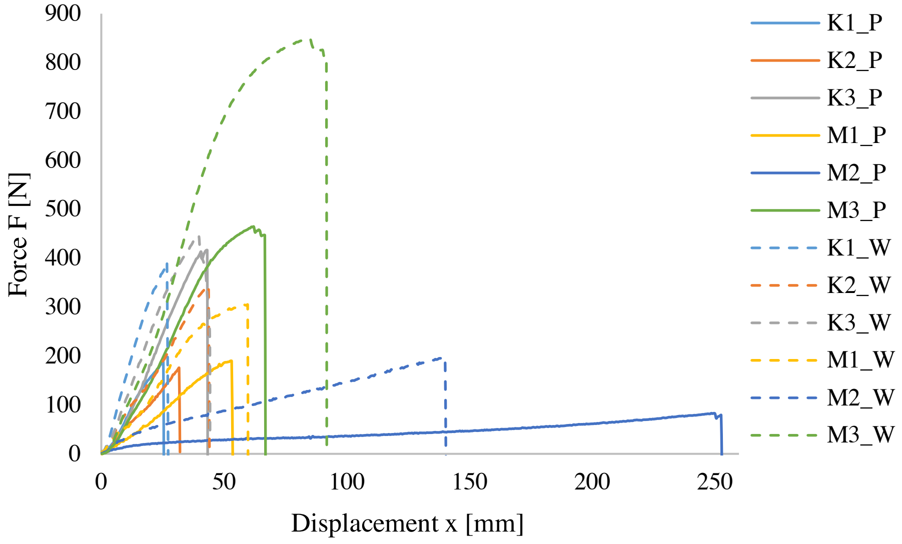

Fig. 4. The function of tensile force and the displacement of fabrics used for the manufacturing of jackets in the transverse and longitudinal direction.

The K3 samples exhibit very similar mechanical characteristics, regardless of direction. The breaking force in both cases was approx. 430 N with displacement of 40 mm. After one layer of material (external) was destroyed, the second layer of material (internal) was also immediately destroyed, this is visible on fig. 4 as a slight decrease of force, followed by a quick increase and separation.
The highest breaking force in the transverse and longitudinal direction was identified in the material designated with M3 (Goretex). This material also has the highest thickness. According to manufacturer data [19], Goretex is a fabric with much higher strength in comparison to other materials used for manufacturing clothing. This fabric is waterproof and such clothes are intended for elevated levels of physical activity under difficult weather conditions (e.g. climbing, sailing, military). This fabric is made of several layers of Teflon-based materials [20]. Due to its strength requirements, the forced required for separation is over 2 times larger than in other fabrics used for manufacturing jackets.
Based on the carried out examinations, the basic mechanical parameters were identified for the studied materials. The Young's Modulus E, tensile strength R_m, and maximum elongation ε_{max} . These parameters for the transverse direction were marked with the index value 1, whereas for the longitudinal direction they were marked with the index value 2. The additional index „s" denotes average value from three attempts. All the determined values are provided in Table 3.

Table 3. Material parameters of fabrics obtained during static tensile test and static shear test.

	Material name					
	K1 65% Polyester 35% Cotton	K2 Polyester	K3 Nylon	M1 Bratex	M2 Liper	M3 Goretex
E_l [MPa]	122.6 – 150.8	183.1 – 227.4	34.6 – 84.5	167.7 – 209.5	22.5 – 23.5	44.6 – 99.5
E_{ls} [MPa]	138.2	201	51	188.6	23	70.6
Rm_l [MPa]	25.7 – 34.5	50.7 – 56.3	46.5 – 50.1	79.3 – 81.2	11.5	45.8 – 47.3
Rm_{ls} [MPa]	29.6	53.8	48.1	80.1	11.5	46.3
ε_{maxl} [%]	13.6 – 16.2	17.7 – 20.3	26.4 – 27.7	29 – 34.1	162	39 – 42.8
ε_{maxls} [%]	14.6	19.7	27	31.3	162	41.3
E_2 [MPa]	66.6 – 75	224 – 285	94 – 164.4	474.3 – 586	58.4 – 60.8	173.4 – 203.4
E_{2s} [MPa]	69.6	255.6	127	525.3	59.9	185.6
Rm_2 [MPa]	81.1 – 88.8	101.9 – 109.2	47.7 – 55.1	126.8 – 132	28.8 – 29.6	78.9 – 85
Rm_{2s} [MPa]	83.2	105.2	48,5	128.7	29.2	82.7
ε_{max2} [%]	17.5 – 20	26.2 – 28	22.6 – 25.5	33.5 – 38.3	89.9 – 92.7	54.7 – 60.5
ε_{max2s} [%]	18.7	27.1	24.4	36.4	91.4	58
G_{sh} [MPa]	3.23 – 4.29	1.76 – 3.61	2.90 – 5.18	7.02 – 12.05	5.39 – 7.73	0.81 – 1.70
G_{shs}[MPa]	3.59	2.67	4.04	9.32	6.59	1,29
G_{lc}[MPa]	28.45 – 30.85	29.67 – 30.42	12.41 – 14.36	33.41 – 43.08	-	16.25 – 21.66
G_{lcs} [MPa]	29.64	30.7	13.39	37.60	-	18.14
γ_{lc} [°]	14.92 – 17.24	14.08 – 17.64	6.27 – 6.63	23.17 – 23.59	-	17.77 – 18.95
γ_{lcs} [°]	16.08	15.66	6.45	23.40	-	18.26

The fig. 5 presents the results of tests carried out utilizing the PFT frame. Example characteristics were presented for each type of examined material. The materials K1, K2 and M1 were torn during the examination. Single strands after a certain force value was exceeded, began to lose cohesion, and a subsequent increase of distance between the frame grips caused further damage to develop in the neighboring strands. In the discussed graph, the process can be seen in the jagged line. After breaking the strand in which the stress was exceeded, the force decreased. Next, the force increased once again until further strands were broken. In the sample M3_S Goretex, single strands of material were also broken; however, this did not cause such a clear change in material characteristics as in the case of sample K1_S which was made of polyester-cotton fabric. Regarding the sample K3_S used in the comparison, the strands forming the down feather pockets were broken; consequently, one can see an unexpected decrease of forces in some parts of the graph. Moreover, in the two-layered sample (K3), the force increased faster with slower displacement in comparison to the materials discussed earlier. The characteristics of sample M2_S is significantly different from the other samples. The relation of force and displacement increases more proportionally, this being a feature of composite materials, or composite fiber-reinforced materials, describe in part in [11]. Therefore, this material should not be included among woven materials. The data obtained for other materials show a certain similarity – after a certain angle value is exceeded, the force increases exponentially, this being a feature of textile materials [21].

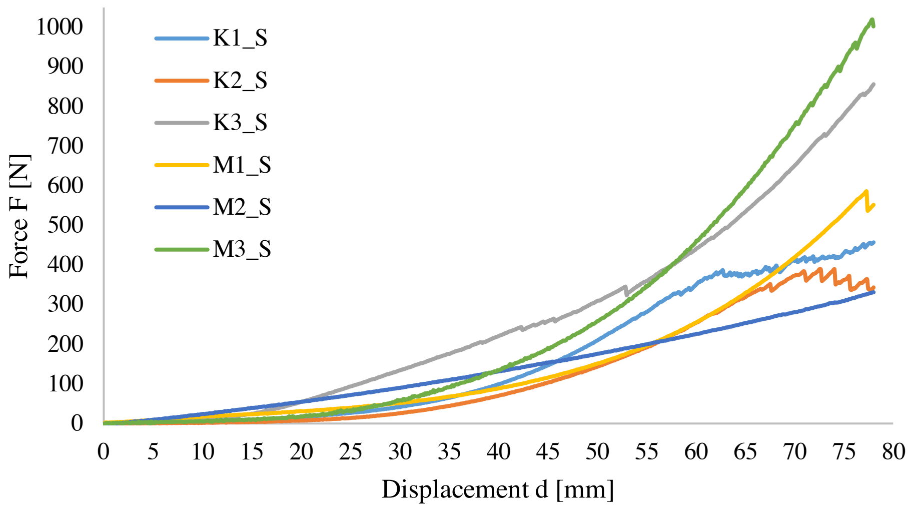

Fig. 5. Dependence of the shear force and displacement of the frame grip.

Fig. 6-11 shows a comparison of experimental data and data from digital simulation (dotted line). One can observe a high degree of convergence of the results both for the static shear test and static tensile test. In the case of static shear test, the shear strength is formed by means of three phenomena: the friction at the contact point of strands perpendicular to one another, the contact between neighboring strands and lateral compression; therefore, the SFABRIC function was employed to read the shear stress value, allowing to determine the fabric shear stress only from the middle part of the sample.

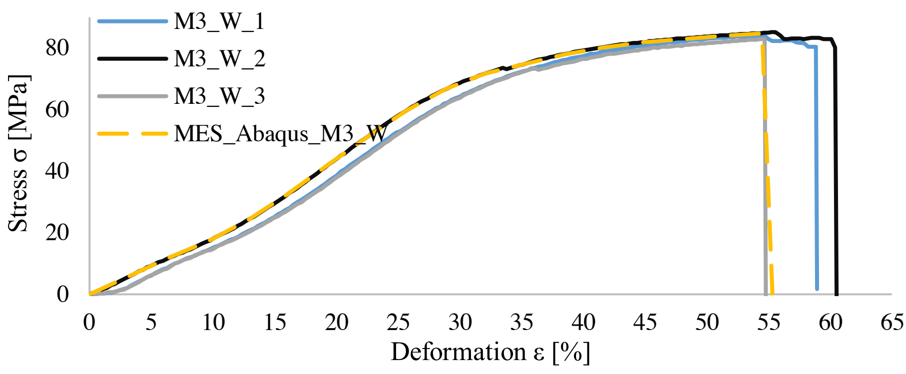

Fig. 6. Comparison of the dependence between the stress and deformation – M3_W Goretex.

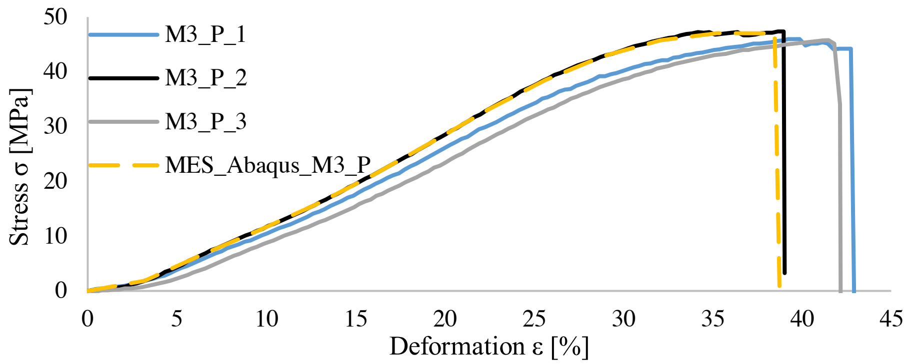

Fig. 7. Comparison of the dependence of stress and displacement – M3_P Goretex.

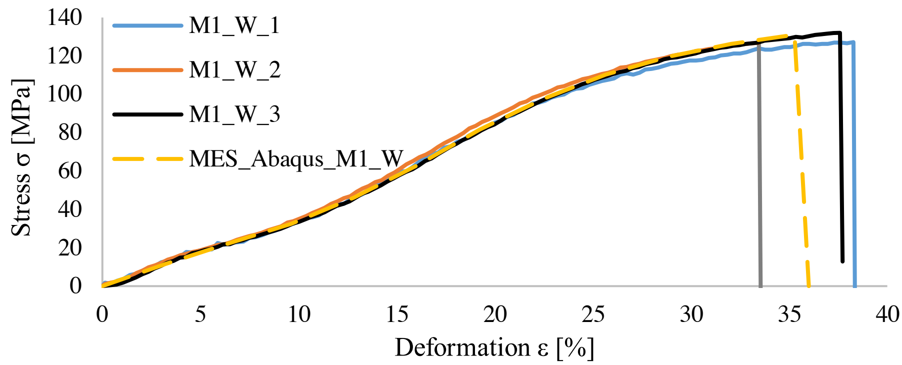

Fig. 8. Comparison of the dependence of stress and displacement – M1_W Bratex.

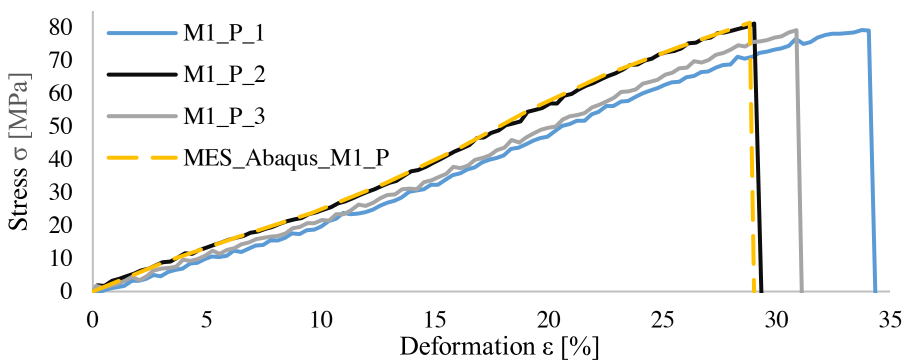

Fig. 9. Comparison of the dependence of stress and displacement – M1_P Bratex.

Based on the results of the examination and MES analysis provided in this work, it is possible to conclude that the developed material models for the tensile characteristics of fabrics are suitable to represent the parameters of actual woven materials such as Goretex andBratexwith a high degree of accuracy.

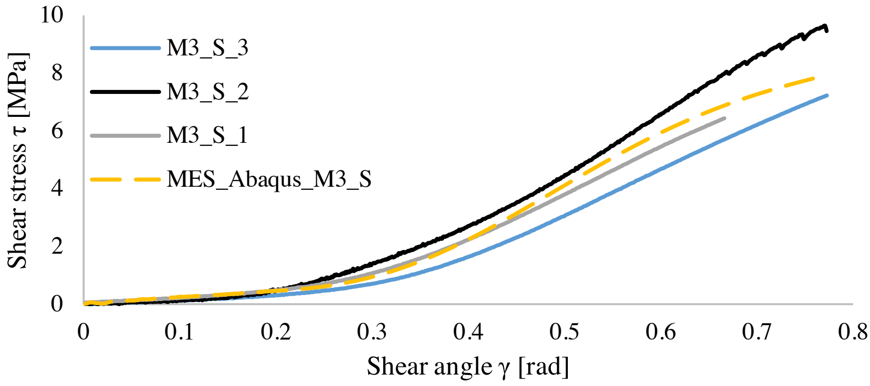

Fig. 10. Comparison of functions of shear stress and shear angle – M3_S Goretex

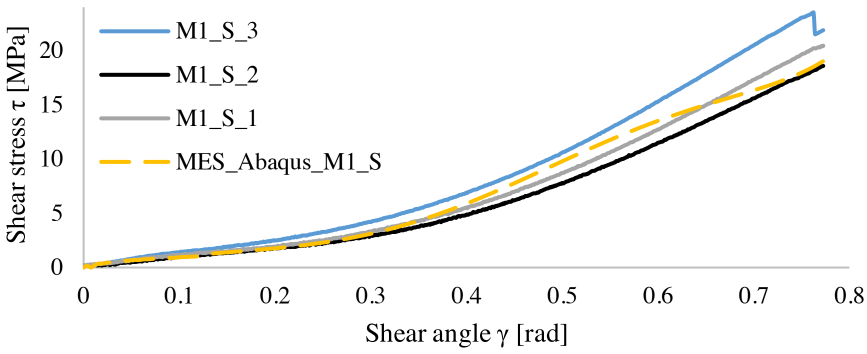

Fig. 11. Comparison of functions of shear stress and shear angle – M1_S Bratex.

6 Summary

Based on the comparison of experimental data and data from MES analyses, one can conclude that the results are convergent, and therefore the developed models allows an approximate representation of the mechanical characteristics of fabrics Bratex and Goretex. Therefore, such models become usable in simulation analysis of material behavior under applied forces.

The numerical solutions in MES analyses call for a correct selection of material model and input of parameters. Incorrect model selection and parameter input may lead to faulty results and interpretations. It is therefore recommended to carry out tests to verify if the assumed model is correct and if the boundary and initial conditions are valid. The most effective method to verify this correctness is to simultaneously carry out the numerical and experimental study of the topic of choice and compare the results thereof.

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