AUTEX Research Journal, Vol. 23, No 2, June 2023, DOI 10.2478/aut-2022-0002

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MODELING OF MATERIAL CHARACTERISTICS OF CONVENTIONAL SYNTHETIC FABRICS

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Abstract:

This article presents a method for modeling the material characteristics of synthetic fabrics based on static tensile test results with consideration of material orthotropy. Material characteristics were determined for fabrics under load at three different angles in relation to their orthotropy. The fabrics examined were the following: polyester fabrics Bratex and Ortalion, cotton fabric with nylon and elastin fabric (poplin), and Gore-Tex membrane fabric. Considering the material mechanical characteristics, the differences were in grammage, maximum strain, and tensile strength. The study allowed us to determine the nonlinear elastic dependency between strain and stress. Test results were implemented within the Abaqus/Explicit framework for the purpose of performance of verification simulations. The correlation between simulated and experimental results was established. A high degree of similarity allows us to classify the obtained material model as usable in simulation work.

Keywords:

polyester fabrics; down, feathers; fluff; picture frame test; static shear test; numerical simulation; materials modeling

1. Introduction

Manufacturing of synthetic fabrics, mostly polyester and viscose-based, has been on the increase in previous years. This was brought about by the growing demand from the textile market, but also environmental limitations imposed on the manufacturing of cotton and other natural fabrics [24]. Currently, synthetic fabrics constitute nearly 76% of all fabrics produced worldwide; in 2015, the global total for manufactured fabrics was approximately 68.9 million tons [1]. Polyester fabrics are the most widely used fabrics in the world. In 2018, polyester fabrics constituted nearly 52% of all the manufactured fabrics, which at that time amounted to 52 million tons of polyester [2, 3]; cotton comes second, at slightly above 24% of total manufacturing, followed by polyamide fabrics 5% and other fabrics (including synthetic) at approximately 19%. Growing production increases the amount of waste generated [4]. In 2008, recycled strands amounted for 8% of total production, whereas in 2018, it rises to 13% [2, 3]. As evident from Figure 1, the growing share of recycled fabrics in global manufacturing is lower than the general increase in the demand for fabrics. At present, an effort is being made to reverse this trend and increase the usage of recycled materials in the global textile manufacture [3]. Consumer awareness of product recycling continues to increase as well [7]. These efforts are aided by, among others, the Directive of the European Parliament and Council (EU) of May 30, 2018, applicable for the entire European Economic Area (EEA), which requires the EU member states to encourage their citizens to recycle products and establish systems to promote the reuse, in particular, of electronics, textiles, furniture, packaging, and construction materials and products. The same directive requires that member states enact selective waste collection for textiles from January 1, 2025, similar to the selective collection process currently in place for paper, metal, glass, and plastics [26].

Recycled polyester fabrics are typically made of plastic PET bottles but can also use other end-of-lifetime products such as jackets, pillows, duvets, clothing, weaving scraps and other textile products [5, 6]. The most popular approach to reuse textile products is with mechanical recycling which entails detangling, separation, or fragmentation of waste material. The disadvantage of mechanical recycling is the increase of fabric

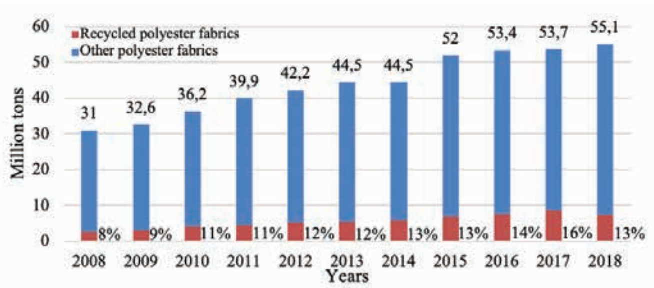

Figure 1. Global polyester production (own elaboration, based on [3]).

twist and the increase in the number of short monofilaments [8]. The development of this process aims to increase the average strand length as well as to increase the number of monofilament yield per weight unit of recycled waste [8, 9]. Development works on mechanical recycling methods are implemented slowly, focusing on the modification of existing systems or introducing new methods of work [8, 9].

Recycling does not apply exclusively to fabric. Feathers and down used as fillings are other valuable resources for recycling. This has caused a new area of development to emerge in the down manufacturing and clothing industry, which entails a reuse of down and feathers from end-of-life jackets, duvets, and pillows [10]. The shell of these products, as mentioned earlier, is primarily made of polyester fabrics [5, 6]. Therefore, the industry recycles not just the fabric used to manufacture the jackets, pillows, and duvets, but also the filling, i.e., the down and feathers. This new trend for reusing recycled down strives to limit the otherwise necessary breeding of geese and ducks used for this purpose, limiting the use of fodder and the amount of waste generated [10,11,12]. The down is characterized by low self-weight and offers good airflow insulation, therefore being highly suitable for use in winter jackets, duvets, pillows, etc. [13]. Only 30 grams of down can be harvested from a single goose [14]. Whereas, for example, a winter duvet contains from 0.7 kilogram to up to 2.5 kilograms of down. In the latter case, it requires 84 geese to manufacture such an article. Furthermore, each year globally we observe a growing demand for products containing down. The feather and down industry worldwide in 2017 was worth $5.9 billion, in 2020 the worth was estimated at $6.7 billion, and it is expected to reach $10.25 billion by 2025 [15]. It therefore appears to be the right approach to recycle down for this purpose. Clothing industry and down industry employs detergent to clean the recovered down so that a high product quality can be produced that is suitable for reuse. The process of collection of end-of-life products to recover down begins with the customer [10]. To replace or dispose of a used down-containing product, the customer gives the product away to clothing bins, second hand stores, or recycling facilities directly. At the down works, employees cut open the casing of the duvet, pillow, jacket, etc., and the down is then removed from the articles and vacuumed into bags. In the next stage, the recovered product is placed in a washing machine. Cleaning of this type of filling materials should follow the relevant OHS regulations as well as the EN 12935:2001 standard detailing the obligatory requirements for feather and/or down cleaning and hygiene that is to be used as filling material; this allows the mixing of the recovered down with fresh material. After reprocessing and verification that the relevant standards are met, the recovered down can be reused as filling material [10]. The down to be recycled is confined within a relatively small space in articles of clothing. It is therefore required to destroy the fabric to recover the desired filling material. It is evident that the process that destroys the casing (fabric) must not affect the actual down. The process recovers not only the down, but also fabrics that are the byproducts thereof. The manual process of recovery is time consuming and inefficient. Improving the speed and economic efficiency of the recovery of down and fabric from textile products would call for employing industrial-grade automation and mechanical solutions. The operating principle of the device based on these solutions would be based on tearing the textile material used for casing for jackets, pillows, etc. This necessitates the development of a model to describe the characteristics of the fabric so that it can be used to model the process of destroying the fabric in the above-mentioned device.

This work presents the results of a static tensile test. The examination was carried out along the main orthotropic directions within the material, in line with the direction of strands forming the weft and warp as well as for samples cut at a 45° angle to the assumed arrangement. The materials examined differ with respect to strength, grammage, composition, and application. The aim of the experimentation was to determine the material characteristics that allow the development and description of the process of decomposition of synthetic fabrics in the course of future works.

2. Materials and methods

2.1. Materials

The fabrics are made of weft and warp. The purpose of the warp is to absorb and transfer loads as well as to maintain the dimensional stability of the product. The purpose of the weft is not to transfer loads within the fabric, so it doesn’t need to be as strong. The perpendicular threading of the weft through the warp forms the textile. The directions of weft and warp treads constitute the main (orthotropic) directions within the fabric. When designing textile materials, we require information both on the strength of the material that we want to use as well as on how the material’s strength varies, e.g., under prestress [27, 28]. The base materials for obtaining yarn, thread, and fabric are fibers. These are typically anisotropic. This follows from their composition in which the structural components (macromolecules) align more or less in an ordered manner with the main axis of the fiber. The fiber tears as a result of chemical bonds being broken, the breaking of the much weaker molecular bonds and through lateral displacement of structural components in relation to one another. Fibers—in particular, polymer—demonstrate a clearly indicated dependence between their strength and the conditions of examination, e.g., the velocity with which the load is applied [27, 28]. The presence of structural defects in fibers causes a localized concentration of stress and facilitates its tearing [27, 28]. The materials used in the study are four different synthetic fabrics available on the market. One of them is Gore-Tex, which consists of a thin layer of Teflon (PTFE), ~50 μm thick, which, together with the upper nylon fabric and polyurethane bottom layer, forms a water barrier. At the same time, this fabric is classified as vapor-permeable [16]. Gore-Tex is used to make clothing such as jackets. The second material used in the study is Bratex. Bratex polyester fabric is also classified as vapor-permeable and is a laminated woven product used as a shell. It is characterized as wind-proof and highly hydrophobic. Its main application is in making hunting jackets. The remaining materials used in the study are conventional fabrics. One of these materials is Ortalion (100% polyester fabric) with grammage of 65 g/m^2;

another is Poplin, with 82% cotton, 15% nylon, and 3% elastin content and grammage of 105 g/m^2.

2.2. Methods

In order to determine the characteristics of tensile stress and strain, the fabrics Gore-Tex, Bratex, Ortalion, and Poplin underwent tensile stress testing along the direction of the weft and warp. Shear strength testing was also carried out through the use of a picture frame fixture, in order to determine the characteristics of shear stress depending on the displacement angle. All the tests were carried out using the MTS Insight 50 kN strength machine. The results obtained were employed to develop a material model in the Abaqus software framework. The model developed was used to carry out simulations of material stretching at a 45° angle to the direction of the weft and warp strands. Additional testing of fabric stretching was carried out at a 45° angle to the orthotropic directions, which allowed us to verify the numerical model.

2.2.1. Picture/Shear frame test

The purpose of the picture frame test is to gain information on the mechanical behavior of the woven material under shear forces, along the plane of the material [18, 19, 20]. The picture frame fixture is a rhomboid-shaped device with variable integral angles [29]. The upper and lower frame grips are attached to the strength machine. The sample is affixed in the picture frame by fastening the four side grippers (Figure 2b), securing it in place and preventing motion along all its sides. The upper gripper of the fixture moves upwards at a constant velocity; subsequently, the displacement enacts a rotating motion at the frame arm joints, changing the inner angles of the device. In order to minimize the motion resistance, the nodes of the frame designed were fitted with needle bearings. Consequently, the friction associated with the momentary rotation at the joint of the frame arms are reduced and are within the range of the measurement error rating of the strength machine.

During the examination, the force of reaction at the upper grip and the displacement of this grip are measured. These data are necessary to determine the function between the shear stress and the displacement angle. The formulas employed for the calculation of shear stress and displacement angle are as in [18, 19, 20, 21]:

The shear stress is calculated with the formulas below:

$$\tau = \frac{F_{sh}}{L_0 b} \tag{1.1}$$

$$F_{sh} = \frac{F_n}{2\cos\alpha} \tag{1.2}$$

where:

τ – the shear stress value [MPa],

F_{sh} – the shear force [N],

L_0 – length of the working side of the sample before the examination [mm],

b – average sample thickness [mm],

F_n – force applied along the gripper axis [N],

2α – angle between the sides of the frame [radians].

From the experiment data graphs were prepared to represent the function of shear strain in relation to shear angle for each sample. The shear angle was calculated according to [18, 19, 20, 21]:

$$\gamma = \frac{\pi}{2} - 2\arccos\left[\frac{L\sqrt{2}+d}{2L}\right] \tag{1.3}$$

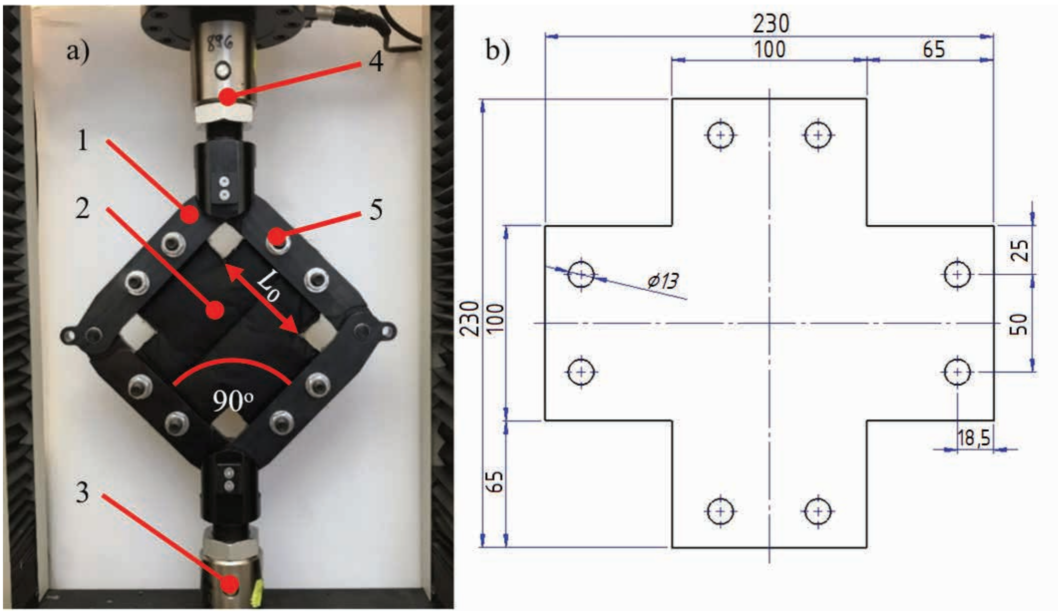

Figure 2. Testing station a static shear test: (1) Picture/Shear Test Frame, (2) examined synthetic fabric material sample, (3) and (4) mounting of the test frame in the strength machine, and (5) side safety handle; b sample dimensions for static shear test.

where:

γ – shear strain angle [radians],

L – PFT frame side length [mm],

d – PFT frame gripper displacement [mm].

2.2.2. Static tensile test

Standard fabric stretch testing are carried out separately along the direction of the weft and warp of the material. Fabrics are flat products; however, the thickness of the fabric may differ depending on the weave and point of measurement [17]. Therefore, the standard examination of textile materials does not account for thickness and does not determine maximum stress. The examination determines the maximum tensile force along the direction of the weft/warp and relative elongation at maximum force expressed as a percentage. However, for the purposes of the assumed method of modeling, it is necessary to determine the characteristics of shear stress σ in relation to the displacement ε for the direction of the warp and weft. In the present case, for a flat rectangular sample, the tensile stress is determined to be the tensile force for the cross-section area. The cross-section area of the fitting affected by the tensile force depends on the sample width and its thickness. In order to determine the characteristic of the tensile stress $\sigma_1(\varepsilon_1)$ in the direction of the fabric warp as well as the characteristic of the tensile stress $\sigma_2(\varepsilon_2)$ in the direction of the weft, the average thickness of the fabrics examined was determined, as provided in Table 1.5, and measurements of sample thickness were taken for each material. The measurement was carried out with a micrometer with accuracy of up to 0.001 mm.

The ideal description of the thickness parameter of a woven material (depending on the strand material, weave, and point of measurement) is included only in cases necessitating a very accurate representation or description of material reaction to bending as well as when the material examined is made up of multiple layers of the fabric [19, 21, 22]. The present work does not entail the examination of fabric bending or examining multilayered fabric samples.

The static elongation testing was carried out on the MTS Insight strength machine. The samples were examined with a constant movement speed of 2 mm/s. The four materials provided in Table 1 were subjected to examination. Rectangular samples with nominal dimensions of 250 × 25 mm were prepared according to EN ISO 527-4.

Table 1. Synthetic textiles prepared for the examination

Material	Average material thickness [mm]
Bratex	0.098
Gore-Tex	0.412
Ortalion	0.1
Poplin	0.182

Grippers were used to mount the samples for the static tensile test. They were connected to the strength machine in a way that aligns the main axis of the fitting with the direction of the applied force and in line with the gripper axis. The sample for testing in the machine was secured with polyurethane foam pads to immobilize the sample in the gripper. During the examination, tensile force was applied to the sample until tearing occurred. In the course of the test, both the tensile force and the displacement of the upper gripper of the strength machine.

3. Numerical model

There are several methods for modeling fabrics in a simulated environment. The modeling of fabric's mechanical characteristics in the macro scale as proposed by Xiaoping Gao and Liping Wang [30] is based on the classical theory of composite materials. This approach assumes that the fabric is an orthotropic material consisting of three layers with assigned different material constants. despite utilizing a simplified model [30], the study achieved a high degree of convergence between the simulated and actual results. Per the subject literature [21, 22], the nonlinear mechanical characteristics of fabrics result from, among other factors, friction between the strands of the weft and warp, the wrinkling of the fabric, stretching and shearing in directions that are different from the direction of the weft and warp strands. High strength is demonstrated by the fabric only along the direction of the strands (weft and warp), and therefore, in order to model the material characteristics, the data are used from the stretching examination in these directions as well as the behavior of the weft and warp strands under shear forces. The variance in the shear strain of angle γ is defined as the change of the angle between the two directions of the fabric strands. For the purposes of this paper, in order to characterize the fabric model in the macro scale within the Abaqus/Explicit framework, the **FABRIC* material model as described in [22] was used, which was based on experimental

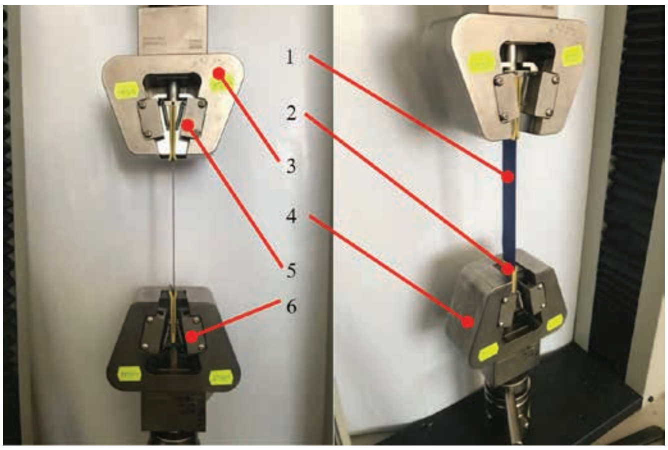

Figure 3. Testing station, static tensile test: (1) examined synthetic fabric sample, (2) polyurethane foam pads, (3) upper grip, (4) lower grip, (5) upper grip jaws, and (6) lower grip jaws.

data obtained from static tensile tests along the direction of the weft and warp, as well as the static shear test carried out with the PFT, providing the nominal fabric stress as a function of nominal strain in the form of a table. This is a simplified method of fabric modeling that facilitates representing actual studies within a simulated environment. The model is intended to be used for single-layer fabrics with different types of structure. The method does not account for parameters such as the distance between strands, the shape of the material cross-section of the strands, orthe weave. The method used to define those characteristics assumes that the responses of the textile material along the direction of the warp, weft, and reaction to shearing action are independent of each other. Therefore, the state of composite stress in the single mesh item of the virtual model depends on the strain of this item. To summarize, the model is based on three independent sets of data related to the functions of tensile stresses and material strain along the warp, with the characteristic of tensile stress and material strain along the weft as well as the functions of shear stress and the displacement angle.

In order to verify the **FABRIC* material model, the study discussed in section 2.2.2 was recreated within the Abaqus virtual framework. The geometric models for 3 flat rectangular samples were created. The first sample was at a 0° angle to the local coordinate system, the second sample was at a 90° angle, and the third sample was at 45° angle. These objects were defined as deformable or planar (shell), and the thickness was defined according to the examined fabric. The geometric models were divided into three parts, two of which were the parts of the sample representing the location of the grippers of the fixture. The third section is the stretched part. The cross-section type of the geometric model was set as a membrane. The mesh item type is M3D4R. All degrees of freedom of movement were disabled for the bottom parts of the samples, using the ENCASTRE edge parameter. Reference points (RP) were created in the middle of the upper edges of the geometric models. By use of the COUPLING function, the model reference points were connected to the upper section of the given sample (Figure 4a). The reference points were assigned a speed of motion along the axis of the given sample equal to 2 mm/s.

Due to the quasi-static nature of the examination, in order to reduce computation time, the simulation employed the Mass Scaling function. This is justified in cases of a negligible influence of inertial forces on the results [22, 24]. During this simulation, the samples were stretched until torn. The data fed into the framework were obtained directly from empirical studies.

4. Results

In order to determine the nominal stress as a function of nominal strain obtained in the course of the simulation, the Field OUTPUT function was used with the time interval setting 0.05 s. This function allowed us to read the reaction force value at the reference points depending on the time of the test *t*. The stress values were calculated with the formula below (4.1):

$$\sigma_n = \frac{F_n}{bh} \tag{4.1}$$

where:

σ_n – tensile stress [MPa],

F_n – tensile force measured during the simulation [N],

b – width of the geometric model (sample), equal to 25 mm,

h – thickness of the geometric model (sample), depending on the used fabric material, from 0.098 mm to 0.412 mm.

Whereas the strain of the geometric models was calculated with (4.2):

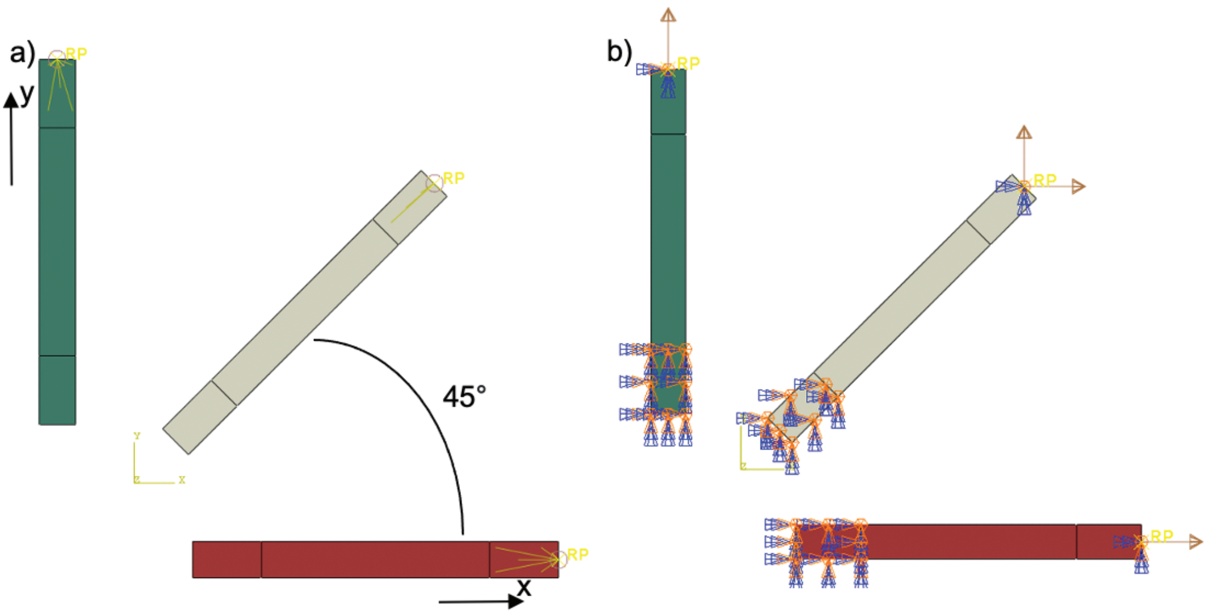

Figure 4. Geometric sample models: (a) reference points and (b) boundary conditions.

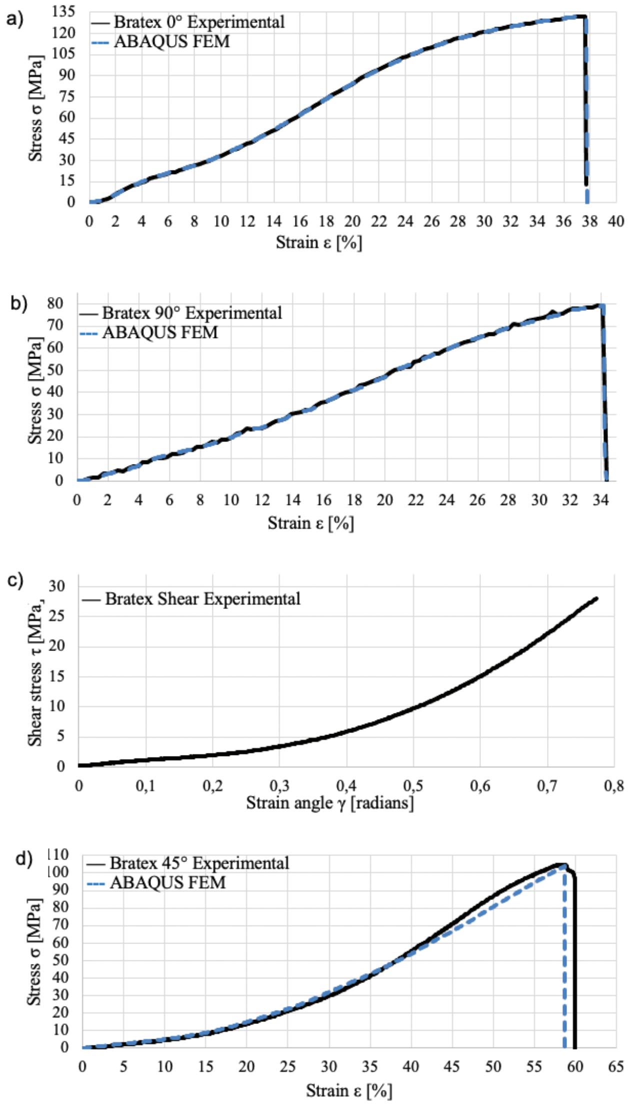

Figure 5. Comparison of the empirical results data and the MES analysis from the static tensile test as well as the results from the static shear test: Bratex (a) 0°, (b) 90°, (c) shear, and (d) 45°.

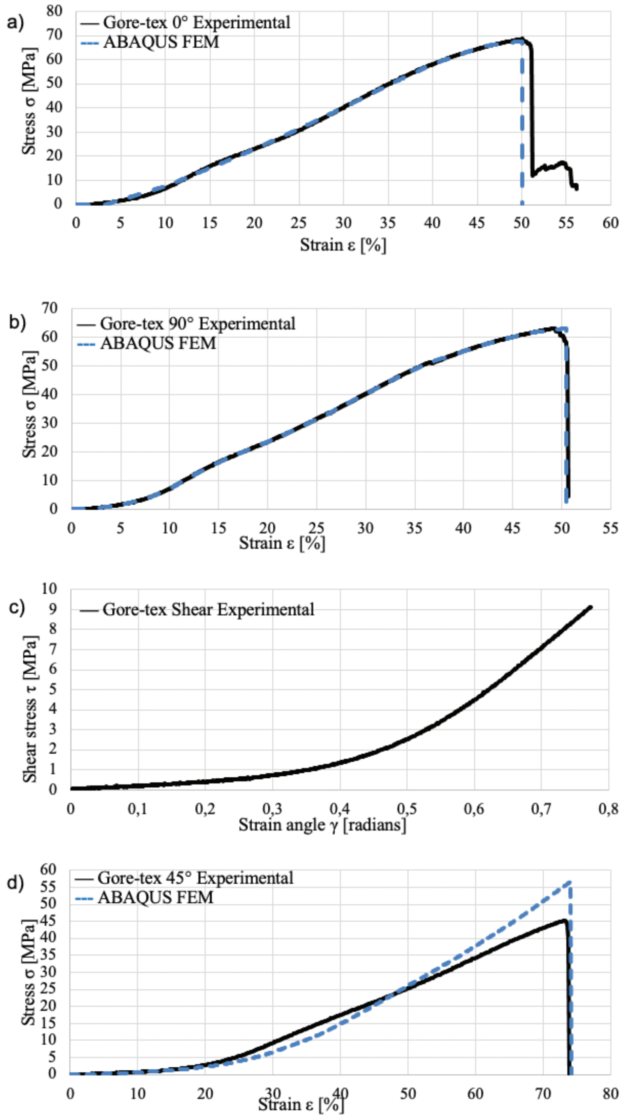

Figure 6. Comparison of the empirical results data and the MES analysis from the static tensile test as well as the results from the static shear test: Gore-Tex (a) 0°, (b) 90°, (c) shear, (d) 45°.

Table 2. Strength characteristics of selected textiles.

	Fiber direction	Bratex		Gore-Tex		Ortalion		Popelina	
		Empirical	FEM	Empirical	FEM	Empirical	FEM	Empirical	FEM
Average of tensile strength Rm [MPa]	0°	128.7	132.3	67.6	67.4	99	109.9	40.1	41.7
	90°	79.9	79.3	62	63.2	38.8	42.5	51.4	53.2
	45°	103.4	103.1	45.5	56.6	70.4	85.3	21.6	23.7
Average of maximum strain ε_{max} [%]	0°	36.4	37.7	48.8	50	19	20.9	66.1	66.5
	90°	31.1	34.2	47.5	50.4	9.7	11.2	7.4	7.3
	45°	59	58.7	73.9	74	59.8	59.9	61.1	63.7

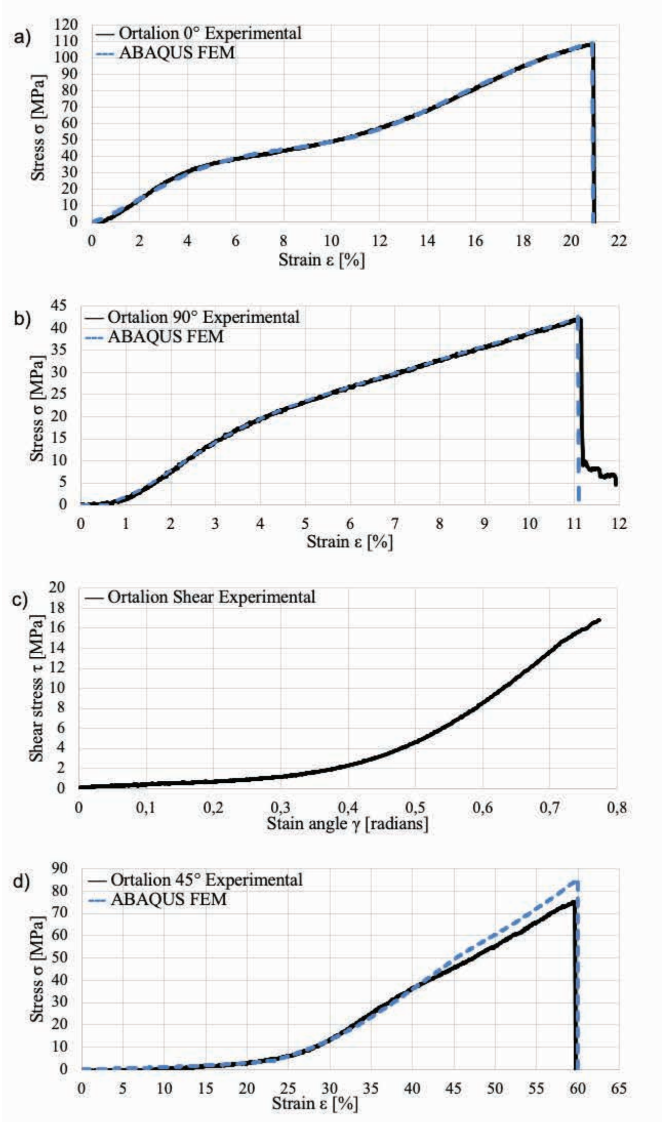

Figure 7. Comparison of the empirical results data and the MES analysis from the static tensile test as well as the results from the static shear test: Ortalion (a) 0°, (b) 90°, (c) shear, and (d) 45°.

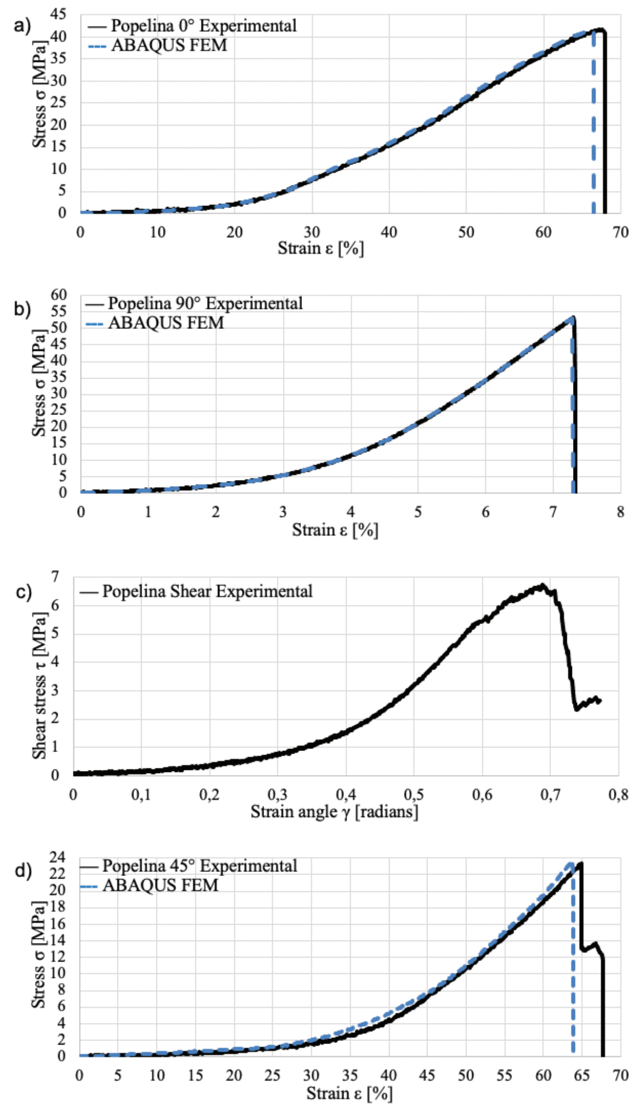

Figure 8. Comparison of the empirical results data and the MES analysis from the static tensile test as well as the results from the static shear test: Poplin (a) 0°, (b) 90°, (c) shear, (d) 45°.

$$\varepsilon_n = \frac{vt}{L_0} \cdot 100\% \tag{4.2}$$

where:

ε_n – strain of the geometric model [%],

v – constant speed of motion of the reference points equal to 2 $\frac{\mathrm{mm}}{\mathrm{s}}$,

t – time limit (simulation) [s],

L_0 – initial length of the stretched area [mm].

After determining the characteristic of stress as a function of strain, the virtual framework data for the four materials discussed were used to juxtapose the results obtained in the simulation with the empirical results (Figures 5–8). Table 2 provides the selected strength characteristics of the examined fabrics that were obtained after processing the results of the examination and the numerical analyses.

Given the test results and MES analysis results provided in this paper, one can conclude that the developed material models for stretching at the angle of 0°, 90° and 45° are able to represent the parameters of actual woven materials such as Bratex, Gore-tex, Ortalion, and Poplin.

5. Summary

This paper presents the results of an experimental study and modeling of the characteristics of synthetic fibers used in the manufacture of down jackets.

In order to carry out numerical analyses for woven materials in the Abaqus/Explicit simulation framework, the nonlinear characteristics of these materials are to be defined. These dependencies are arrived at through experimental data. The testing was limited to straightforward, uniaxial tensile tests and uniaxial shear test employing the PFT fixture.

The results of each numerical simulation were juxtaposed with the results obtained via experimentation. This allowed us to verify the numerical model. The juxtaposition of actual and simulated characteristics for stretching and shearing indicate that the results obtained in the MES analysis are convergent with the actual results. Consequently, the designed material models are suitable for employment in the simulated framework.

Following the appropriate calibration, the material model can be used to simulate the decomposition process of synthetic fabrics for the purpose of designing shredding machines. The development of this aspect in mechanical engineering may serve to improve the usability of waste textile material and increase the efficiency of recovery of products such as feather and down.

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