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MODELIZATION OF ADVANCED NONWOVEN FABRICS SUBJECTED TO TENSILE LOADS

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Abstract

The aim of this study is the determination of the deforming micromechanisms of needle-punched felts subjected to tensile loads. A large experimental campaign has been carried out at micro and meso-scale levels to analyze the influence of the fiber and the network structure in the mechanical properties. Pull-out tests and felt tensile tests were performed. A constitutive physically-based model was developed within the context of the finite element method, which provided the constitutive response for a mesodomain including micromechanical aspects as fiber sliding and pull-out. The macroscopic response has been validated with the experimental results, showing a very good agreement.

1. Introduction

In recent years, soft-body amour manufacturers are replacing the traditional protection systems based on ceramic/composite panels in applications such as vehicles or aircrafts armoring. Dry fabrics are promising solutions due to their inherent low density, as for instance, Kevlar or Dyneema barriers [1]. However for small calibers, nonwoven felts show the best ballistic performance. The structural behavior is not only due to the stiffness and strength of the fibers but on the way the fibers interact between each other through physical entanglement points. Regarding the structural properties, nonwovens posses moderate strength and stiffness as compared with their woven counterparts, but they are superior in terms of energy consumption during deformation [2].

Nowadays new nonwovens materials have appeared as a consequence of their low processing cost and its high versatility. The complex mechanical response includes large deformations and rotations, bond and fiber fracture and fiber sliding [3]. The most important factors affecting the mechanical response of felts are not the fiber properties, but the manufacture processes and the web layout which determines the interaction between individual fibers, fiber entanglement and fiber orientation [4,5]. A key aspect for the understanding of the mechanical response of these materials is the development of constitutive models, and a considerable amount of literature has been published. The simplest solution consists of a linear elastic orthotropic model [6]. These models are useful to predict the mechanical response under certain conditions, but most of the parameters used have to be adjusted with experimental test and have no relation with physical material properties. More complex simulations take into account the microstructure by explicitly including the fiber network structure [7]. These models were in very good agreement with the experiments in terms of the macroscopic response and of the microscopic mechanisms. However the computational cost could be extremely high so for large scale problems it is required to use homogenization techniques over a representative volume element approach or by the development of continuum models. Liao and Adanur [8] developed a numerical model for needle-punched felts based on fiber failure, as they considered bonds as indestructible. Silberstein [9] developed a model for electrospinning nonwoven fibrous mats. The microscopic mechanisms included were fiber alignment, fiber bending and network consolidation. For needlepunched nonwoven felts the most important micromechanism is fiber sliding and pull out. These failure processes are well-documented for woven fabrics and multiple numerical models can be found in the literature [10,11]. Pull-out force is dependent on many different parameters such as fabric style, pull-out length, out-of-plane pressure, fiber modulus, fiber diameter, friction and loading state. However the extrapolation of the characterized force for the pull-out of a single yarn to a more complex problem as a tensile test is a laborious task as it has been proved that increasing the number of pull-out yarn increases the pull-out force [12]. Friction between fibers seems to be one of the most relevant parameters [13,14]. A similar approach could be used for the needlepunched felts to obtain the pull-out forces, but in the literature no research has been found for this characterization.

The present study was designed to determine the relevance of the deformation micromechanisms from a physical viewpoint and analyze their influence in the mesoscale level for an un-bonded non-woven material. A commercial polyethylene felt known as Dyneema Fraglight was used for this purpose. An experimental campaign from a mechanical viewpoint was carried out at different length scales (individual fibers and fiber network), so that the properties necessary for modeling were measured rather than assumed. Damage and fracture micromechanisms were studied for different strain rates. The information regarding felt architecture (fiber distribution and orientation, fiber volume fraction, resistance to fiber sliding) was used to build up a finite element model to simulate the mechanical behavior.

2. Materials and methods

2.1. Fabric characteristics

The needle-punched non-woven felt studied had the trade name Dyneema Fraglight and was manufactured by DSM. It was made of ultra-high-molecular weight polyethylene fibers (UHMWPE) known as Dyneema. The needle-punched manufacture process consists of fibers mechanically entangled by reciprocating barbed needles through a moving batt of fibers in needleloom. Main properties are shown in Table 1.

Property	Value
Fiber denomination	Dyneema SK75
Fiber Young Modulus	116 GPa
Fiber Strain to failure	3.5%
Fiber Maximum Strength	3.2 GPa
Fiber Diameter	9 µm
Fiber Length	45-55 mm
Fiber Density	970 kg/m^3
Felt Areal Density	200 g/m^2
Felt Thickness	1.5 mm

Table 1. Properties of Fraglight Felt and Dyneema fiber.

2.2. Single fiber tensile tests

Individual bundles were extracted from the felt by carefully pulling with tweezers. Bundles were glued on a cardboard frame with a gage length of 15 mm and fixed to the mechanical testing machine. The cross-head speed was constant and equal to 0.005 mm/s. The fiber diameter was accurately measured for each sample in a scanning electron microscope after each test.

2.2. Felt tensile tests

Tensile tests of the felt with rectangular specimens of 100x100mm2 were carried out at room temperature by using an electromechanical universal testing machine (Instron 3384. The strain was registered with a Digital Image Correlating system (Vic2D). To analyze the anisotropic behavior of the material, quasi-static tests were carried out for three main orientations; roll direction RD, transverse to the roll direction TD and oblique direction 45D. Strain rates from 0.001 to 0.08 s^{-1} were used for the tests.

2.3. Pull-out tests

The objective of the pull-out tests was the characterization of the load-displacement curves of fibers which slide from the net network. With this test a range of maximum strength and dissipated energy for the failure of the felt has been determined. This phenomenon has been considered the most important energy dissipation mechanism. Square specimens of 80 x 80 mm^2 were obtained from the felt. One fiber from each specimen was extracted and glued with cyanoacrylate to an acetate film. The samples were tested using a MTS NanoBionix (MTS Systems Corporation). Three different cross-head speeds, from 0.01mm/s to 1mm/s were used for the tests.

3. Experimental Results

By SEM microscopy it was observed that most of the times filaments were presented in bundles of 2 fibers, see Figure 1.a. The average fiber diameter was 9 µm. This characteristical bundle was considered the basic entity of the felt. In Figure 1.b the mechanical behaviour of the Dyneema fiber is shown and was considered linear elastic up to failure.

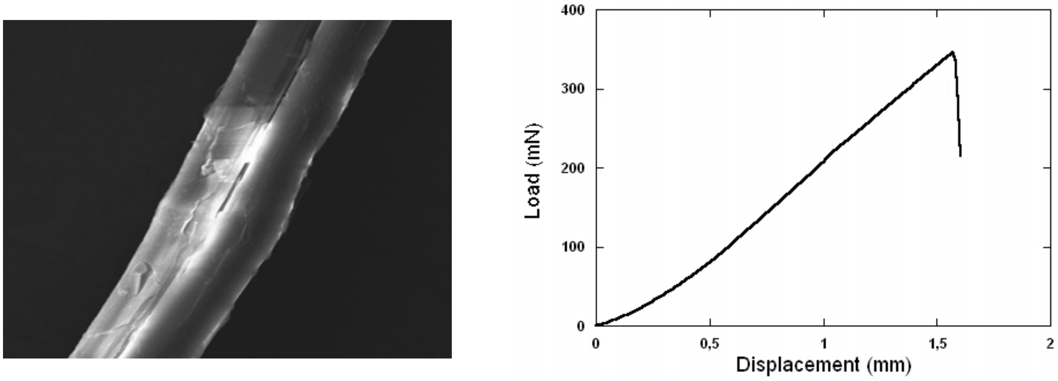

Figure 1. Single fiber characterisation, a) Dyneema bundle composed by 2 fibers and b) Load-displacement curve for a single bundle of Dyneema

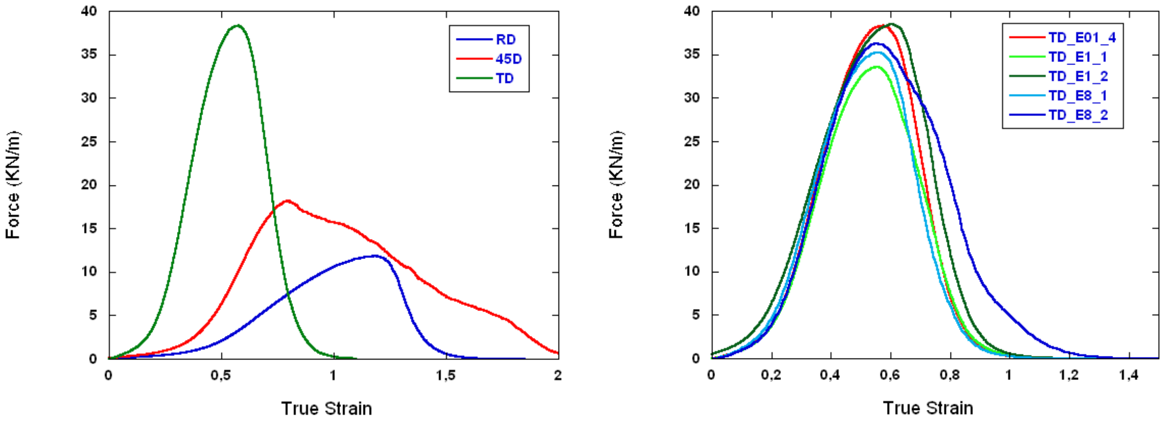

Figure 2. Load-Strain curves, a) Felt orientation dependency and b) Strain-rate dependency for transverse direction to the roll TD.

However the mechanical response of the felt was non-linear non-elastic (Figure 2.a). High anisotropy was also found and the transverse direction to the roll TD was three times stronger and stiffer than for the roll direction RD. The deformation micromechanisms appreciated during the tests could not be explained by a simple stretching of the fibers. The irrecoverable evolution of the fabric texture by fiber sliding accommodated by fiber alignment and rotation was considered the dominating deformation mechanism. In Figure 2.b it is shown the dependency with the strain rate and negligible differences were found for the analyzed range. Uniform deformation with high axial contraction was observed for the first stages of the tests. After a certain deformation level, stresses started to localize in the weakest points and fiber pull-out caused the degradation of the material. Once the maximum load was reached, damage coalescence generated a failure band totally controlled by fiber disentanglement. It is important to notice the difference of the total dissipated energy between each orientation. Specimens oriented in the transverse direction to the roll TD and in oblique direction 45D were able to dissipate twice the energy of their counterparts oriented at the roll direction RD.

Pull-out tests were the most useful experiments to explain the complex response of the felt. Three different mechanical behaviours have been observed during the tests. As an example load versus displacement curves have been plotted in Figure 3.a. The general mechanical behaviour during pull-out tests could be compared with typical pull-out curves for a yarn in a woven fabric. The force vs displacement curve was determined by the contact surfaces and the random entanglement distribution. Increasing the displacement of the fiber increased the load until the resistance for pull-out was reached and the fiber was extracted. Scatter of tests was taken into account for analyzing the results. On the other hand, some of the fibers were extracted of the felt with an insignificant amount of work. This has been called the slippage mechanism. In this case the entanglement with adjacent fibers was assumed to be null. These fibers had a negligible contribution in the felt stiffness. Finally, there was a population of fibers with extremely high junctions where pull-out was inhibited. This was the socalled anchored mechanism because the characterized load did not represent a pull-out process, but a tensile test of the felt. Only fibers near the discrete points where the needles penetrated the felt during the manufacture process had presented this pull-out behaviour. Increasing the load may lead in fiber breakage.

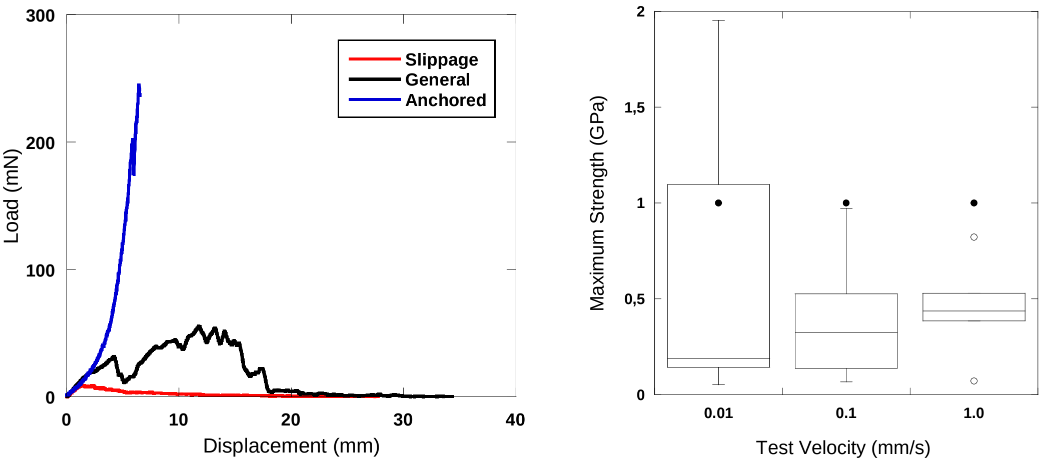

Figure 3. Results for pull-out tests, a) Load vs displacement curve for three different tests. Slippage behavior, offering no-resistance. General behavior, comparable to woven fabrics. Anchored behavior, tensile test of the felt and b) Statistical analysis by means of Box Plot graph. Pull-out maximum stresses sort by test velocity.

During tests it has been found that for medium or high displacement velocities (1mm/s and 0.1mm/s) the predominant pull-out behaviour was the general friction mechanisms. The slippage of fibers was presented for the 20-25% of the cases and no anchored fibers appeared for these tests. However decreasing the displacement velocity of the test (0.01mm/s) increases the scatter in the results. About the 40% of the fibers presented slippage during the pull-out. Some anchored fibers were found for this strain rate, but just due to their proximity to a needle point. All results are resume in Figure 3.b. Stress to pull-out have been obtained with the registered load and the mean bundle section consisted of two fibers of 9µm of diameter.

4. Constitutive Model

The constitutive model used in the present work describes the mechanical response of the network in terms of non-linear elastic texture evolution related to the fiber realignment, rotation and sliding. These microstructural features are included in a tensorial representation which is embedded in a continuum formulation. The constitutive model was based on a previous study perform by Ridruejo et. al [15] and it was implemented in three different blocks; fiber network model, the fiber model and a damage model. For the fiber network it was needed to introduce a function with the entanglement distribution. Preferential connection orientations have been considered to obtain the felt anisotropy and finally a distribution function was implemented by fitting the quasi-static tests with the experimental data. The main deformation mechanisms considered for the fiber model was the fiber sliding. It could be considered that one fiber crossing some fixed junctions was extracted from them while the network was clamped, Figure 4. In a first stage uncurling of the fiber happened without extracting the fiber from the entanglements. Once the fiber was totally uncurled, in the second stage, adjacent fibers were pulled with the rest, increasing the stresses in the bonds. In the last stage, as the bond strength was overtaken, sliding of the fiber took place and fiber disentanglement produced the felt failure.

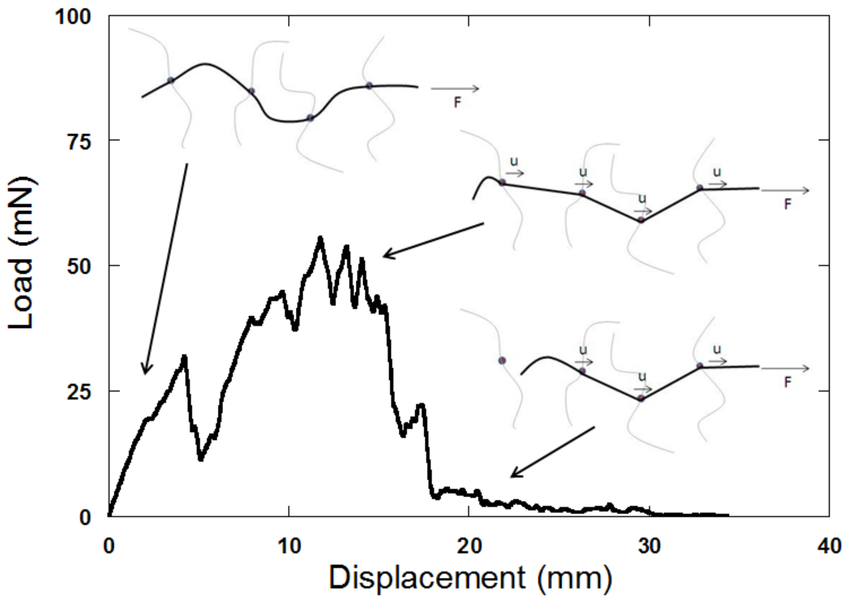

Figure 4. Deforming micromechanisms represented on a typical load-displacement pull-out curve. Stage 1, fiber uncurling. Stage 2, pulling of adjacent fibers. Stage 3, disentanglement.

To obtain such mechanical behaviour the stress-stretch function for a single fiber was computed as function of the pull-out length and of the fiber orientation respect a privileged direction θ, see equation 2. With this formulation the resistance to fiber sliding was increased for higher deformations. Disoriented fibers perpendicular to the loading direction will be easily extracted from the felt by the slippage pull-out mechanical behaviour.

$$s_f = s_f^{po} \tag{1}$$

$$s_f^{po} = E_{po}(e_{po},\theta)\cdot e_{po}\,; \qquad E_{po} = K\cdot e_{po}^2\cdot\left(1-\sin^4\theta\right) \tag{2}$$

For the damage model, maximum strength to pull-out of the fibers was a random value inside an interval given by the experimental pull-out test. The maximum pull-out strength for each set of fibers in the mesodomains was implemented with a Monte Carlo lottery method. With this method it was represented the random nature of fiber connectivity and junctions.

The model was implemented as a VUMAT subroutine in Abaqus/Explicit and all the results correlated quite well with the experimental results. Due to the random nature of the mode, repeating the same analysis never led in the same result. In Figure 5 two consecutive analysis for a similar input file are compared. Although cracks appeared in different regions of the felt the force-strain curves for both simulations were similar. A parametric study of the element size was also performed to ensure the mesh independence of the constitutive model.

5. Conclusions

This paper has given an account of the deforming micromechanisms of needlepunched nonwoven felt subjected to tensile and impact loads. A large experimental campaign has been carried out to fully characterized the mechanical response. Deforming micromechanisms were detailed analyzed, and a physically-based continuum model was developed. Three different mechanical behaviours for a pull-out process had been identified. The relevance of fiber sliding and pull-out in the energy absorption capacity of the material is clearly supported by the current findings.

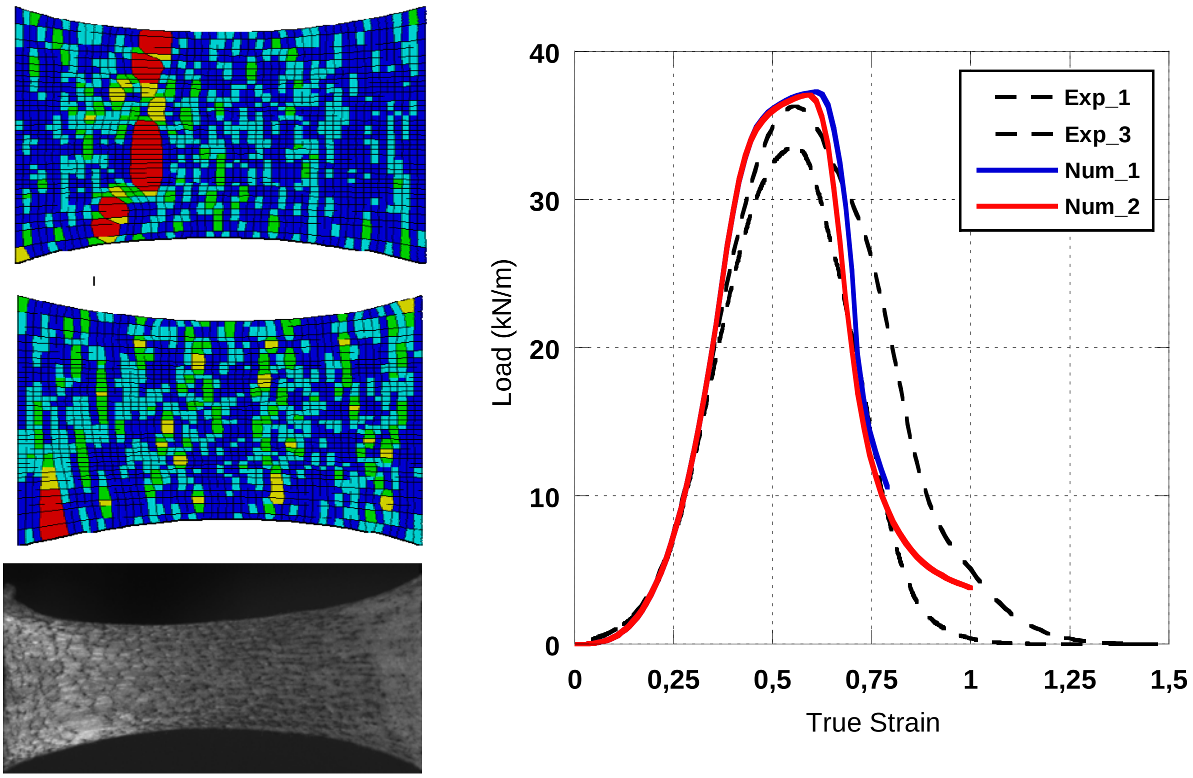

Figure 5. Correlation between numerical predictions obtained by the implemented constitutive model and the experimental test. In left column it is shown the pull-out damage for two consecutive analyses for the simulation of the same specimen subjected to tensile loading and the comparison with the experimental test. Damage pattern was different for each analysis due to the random computation of the maximum pull-out strength. In the right column a comparison between the experimental and the numerical scattering for the force-strain curves is presented

The constitutive model provides the behaviour of the felt at the mesodomain level and has been implemented as a material subroutine within the framework of the finite element methods. The mechanical response of each bundle was described in terms of fiber sliding and disentanglement. These findings suggested that in general the mechanical response of the felt depended on the fiber network rather than in fiber properties. Numerical predictions of the tensile test and impact tests were obtained with and Abaqus/Explicit implementation of the constitutive model. Most of the fiber parameters were obtained from the previous experimental characterization. The force-strain curve for tensile test were reproduced accurately, as well as the main deformation and fracture micromechanisms, including the transition from homogeneous deformation to the localization of damage and the final fracture. The results showed the potential of this physically-base model to reproduce the complex deformation and fracture micromechanisms of nonwoven needle-punched fabrics.

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