International Journal of Solids and Structures 96 (2016) 81–91

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

A multiscale micromechanical model of needlepunched nonwoven fabrics

F. Martínez-Hergueta[a], A. Ridruejo[b,*], C. González[a,b], J. LLorca[a,b]

[a] IMDEA Materials Institute, C/ Eric Kandel 2, 28906, Getafe, Madrid, Spain
[b] Department of Materials Science, Polytechnic University of Madrid, E. T. S. de Ingenieros de Caminos, 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 19 March 2016
Revised 6 May 2016
Available online 15 June 2016

Keywords:
Nonwoven fabrics
Damage
Constitutive models
Multiscale modeling

ABSTRACT

A constitutive model for the mechanical behavior of a mechanically-entangled nonwoven fiber network is presented. The model is built upon a detailed characterization of the dominant deformation and failure mechanisms at different length scales (fiber, bundle, network) (Martínez-Hergueta et al., 2015) and accounts for the effects of non-affine deformation, anisotropic connectivity induced by the entanglement points, fiber uncurling and re-orientation as well as fiber disentanglement and pull-out from the knots. The model provides the constitutive response for a mesodomain of the fabric corresponding to the volume associated to a finite element and is divided in two blocks. The first one is the network model which establishes the relationship between the macroscopic deformation gradient **F** and the microscopic response obtained by integrating the response of the fibers in the mesodomain. The second one is the fiber model, which takes into account the deformation features of each set of fibers in the mesodomain, including non-affinity, uncurling, pull-out and disentanglement. As far as possible, a clear physical meaning is given to the model parameters, so they can be identified by means of independent tests. The numerical simulations based on the model were in very good agreement with the experimental results of the tensile deformation of a commercial needle-punched nonwoven fabric along two perpendicular orientations in terms of the nominal stress–strain curve (including the large anisotropy in stiffness and strength), the specimen shape and the evolution of the fiber orientation distribution function with the applied strain.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Nonwoven fabrics are a class of textile materials used in many different applications (including thermal insulation, geotextiles, fireproof layers, filtration and water absorption, ballistic impact, etc.) because of their low processing cost and the possibility to tailor the properties by manipulating the fiber nature, the pore size or the interfiber bond (Russell, 2007). Moreover, carbon nanotubes, as well as other high performance fibers manufactured by electrospinning, cannot be weaved and have to be used in the form of nonwoven fabrics (Dzenis, 2004; Yue et al., 2015). From the viewpoint of the mechanical performance, nonwoven fabrics present lower stiffness and strength than the woven counterparts but much higher ductility and energy-absorption capability (Russell, 2007). Deformation of nonwoven fabrics involves a number of different mechanisms, including fiber straightening, bond failure and fiber reorientation as well as fiber sliding and fracture. The sequence of activation of these processes and their interaction depend on a number of factors, such as the nature of the fibers and of the interfiber bonds (Jubera et al., 2014; Kulachenko and Uesaka, 2012; Ridruejo et al., 2010; 2015). The analysis of the failure mechanisms is further complicated by the disordered microstructure of the nonwoven and by the development in some cases of non-affine deformation i.e. the macroscopic strain is not homogeneously transferred to the fiber network leading to the formation of loading paths that percolate the network (Picu and Subramanian, 2011).

Experimental studies to analyze the dominant deformation and failure micromechanisms were initially focused on paper (Bronkhorst, 2003; Hägglund and Isaksson, 2006; Isaksson et al., 2006; 2004) and have been recently extended to other nonwoven fabrics with brittle interfiber bonds created by chemical forces, polymeric binders or local fusion (Farukh et al., 2013; Jubera et al., 2014; Ridruejo et al., 2010; 2011; 2015; Silberstein et al., 2012). These investigations were fundamental to establish the relationship between the microstructure and the mechanical properties and also to develop microstructure-based constitutive equations, as

* Corresponding author. Tel.: +34 915493422; fax: +34 915503047.
E-mail address: javier.llorca@upm.es (J. LLorca).

http://dx.doi.org/10.1016/j.ijsolstr.2016.06.020
0020-7683/© 2016 Elsevier Ltd. All rights reserved.

opposed to phenomenological ones, to be used in structural analysis (Demirci et al., 2012; Farukh et al., 2013; Onck et al., 2005; Raina and Linder, 2015; Ridruejo et al., 2012a; Sabuncuoglu et al., 2012; Silberstein et al., 2012; Wilbrink et al., 2013). Nevertheless, the brittle interfiber bonds in these nonwoven fabrics limit the mechanical properties and it is well established that enhanced properties can be obtained by means of the mechanical entanglement of the fibers (Chocron et al., 2008; Jearanaisilawong, 2008; Raval et al., 2013). In fact, mechanically-entangled polyethylene nonwoven fabrics have demonstrated an excellent performance for balistic protection (Cheeseman, Bogetti, 2003; Chocron et al., 2008; Ipson and Wittrock, 1966; Russell et al., 2005; Thomas, 2008; Thomas et al., 2003) but multiscale experimental analysis to determine the dominant deformation and failure mechanisms in these complex materials have only appeared recently (Martínez-Hergueta et al., 2016; 2015). In the absence of this information, it was not possible to develop physically-based models of the mechanical behavior of mechanically-entangled nonwoven fabrics and this is the objective of the present investigation.

The paper is divided in five sections. After the introduction, the material under study and the dominant deformation and damage mechanisms reported previously are briefly summarized. Based on these findings, a micromechanical model for the mechanical behavior of a entangled nonwoven fiber network is developed in Section 3, which accounts for the fiber uncurling and reorientation during deformation, the degree of affinity in different orientations, the anisotropic connectivity induced by the entanglement points as well as fiber disentanglement and pull-out from the knots. The numerical implementation of the model within the framework of the finite element method is presented in Section 4, while the parameter identification by means of independent experiments is presented in Section 5 together with the comparison with experimental results of the in-plane mechanical response. The main features of the model and the results are summarized in the conclusions section.

2. Material and experimental deformation mechanisms

The constitutive model developed in this paper is based on a detailed experimental characterization of the deformation and failure micromechanisms of a commercial needle-punched nonwoven fabric denominated Fraglight NW201 (DSM). The main microstructural features of the nonwoven fabric as well as the dominant deformation and failure processes were detailed in Martínez-Hergueta et al. (2015) and are briefly recalled here for the sake of completion.

The Fraglight NW201 fabric was manufactured by the deposition of single filaments of Dyneema SK75 ultrahigh molecular weight polyethylene, of approximately 60 mm in length, on a moving bed surface, forming a batt. The nominal fiber diameter was 11 μm, although bundles composed by two fibers were predominant in the microstructure of the material and can be understood as the basic structural unit of the fabric. The batt is needlefelted with the aid of the oscillatory application of barbed needles producing fiber loops and mechanical entanglements among fibers leading to a punch density of ≈13–14 cm^{-2} (Russell, 2007).

The nominal areal density, ρ, and the thickness of the fabric, t, as given by the manufacturer, were ≈190-220 g/m^2 and ≈1.5 mm, respectively. The manufacturing process introduced two principal material directions known as machine (MD) and transverse (TD) which followed the bed displacement and its orthogonal, respectively.

The fiber orientation distribution function (ODF) was analyzed in detail by means of 3D X-ray computed tomography (XCT) and 2D wide angle X-ray diffraction (WAXD) and it was found to be isotropic (Martínez-Hergueta et al., 2015). Fibers were initially curved and load was transferred within the fabric through the random and isotropic network of knots created by needlepunching, leading to the formation of an active fiber network. Uncurling and stretching of the active fibers was followed by fiber sliding and pull-out from the entanglement points. Most of the strength and energy dissipation was provided by the extraction of the active fibers from the knots and final fracture occurred by the total disentanglement of the fiber network in a given section at which the macroscopic deformation was localized. However, the mechanical properties were highly anisotropic: the stiffness, strength and energy dissipated per unit volume upon tensile deformation in the TD were 2–3 times higher than those along MD, while the strain at maximum load along TD was only one half of that along MD.

As the fiber ODF at the reference configuration was isotropic, the anisotropy during deformation was attributed to the fiber entanglements introduced in the network during needle-punched consolidation. Micromechanical pull-out tests indicated that the structure of the knots connected more fibers along TD than along MD and the better fiber interconnection led to a larger active fiber length along TD. The nonwoven fabric deformed along MD behaved as a sparse fiber network, which was not efficient to transfer the macroscopic strain to the fiber network, leading to non-affine behavior. Pull-out tests of multiple fibers (from 14 to 50 fibers) along TD presented twice the stiffness that those carried out along MD and this indicated that the structure of the knots connected more fibers along TD than along MD. The higher active fiber length along TD led to the denser active fiber skeleton, enhancing the mechanical response. The nonwoven fabric deformed along MD behaved as a sparse fiber network, which was not efficient to transfer the macroscopic strain to the fiber network, leading to non-affine behavior. As a result, fabrics deformed along TD essentially displayed affine deformation –i.e. the macroscopic strain was directly transferred to the fibers by the surrounding fabric–, while MD-deformed fabrics underwent non-affine deformation, and most of the macroscopic strain was not transferred to the fibers. The differences in affinity and connectivity along TD and MD had a direct impact on the microstructure evolution as function of the applied strain, leading to higher fiber alignment and straightening when stretching along TD and to a delayed response when stretching along MD. More details can be found in Martínez-Hergueta et al. (2015).

3. Constitutive model of a mechanically-entangled nonwoven fiber network

The model presented in this section describes the mechanical response of a nonwoven fiber network including the effect of non-affine deformation, anisotropic connectivity, fiber uncurling and reorientation as well as fiber disentanglement and pull-out from the knots. The model is intended to be used within the framework of the finite element method and provides the constitutive response for a mesodomain of the fabric corresponding to the volume associated to a finite element. As far as possible, a clear physical meaning is given to the model parameters, so they can be identified by means of independent tests. The model is divided in two blocks. The first one is the network model which establishes the relationship between the macroscopic deformation gradient $\mathbf{F}$ and the microscopic response obtained by integrating the response of the fibers in the domain under study within a rigorous continuum tensorial formulation. The second one is the fiber model, which takes into account the deformation features of each set of fibers, including non-affinity, uncurling, rotation, pull-out and disentanglement.

Download English Version:

https://daneshyari.com/en/article/277064

Download Persian Version:

https://daneshyari.com/article/277064

Daneshyari.com