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Notches in fibrous materials: micro-mechanisms of deformation and damage

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Abstract

Fibrous networks are ubiquitous structures for many natural materials, such as bones and bacterial cellulose, and artificial ones (e.g. polymer-based nonwovens). Mechanical behaviour of these networks are of interest to researchers since it deviates significantly from that of traditional materials treated usually within the framework of continuum mechanics. The main reason for this difference is a discontinuous character of networks with randomly distributed fibres (that can be also curved) resulting in complex scenarios of fibre-to-fibre interactions in the process of their deformation. This also affects a character of load transfer, characterised by spatial non-uniformity and localisation.

A discontinuous nature of fibrous networks results in their non-trivial failure character and, more specifically, evolution of failure caused by notches. In order to investigate these mechanisms, various notches are introduced both into real-life specimens used in experimentation and discontinuous finite-element (FE) models specially developed (Farukh et al., 2014a; Hou et al., 2009, 2011a; Sabuncuoglu et al, 2013) to mimic the microstructure of fibrous networks. The specimens were tested under tensile loading in one of the principal directions, with FE-based simulations emulating this regime. The effect of notch shape on damage mechanisms, effective material toughness and damage patterns was investigated using the obtained experimental and numerical methods. The developed discontinuous model with direct introduction of microstructural features of fibrous networks allowed assessment of strain distribution over selected paths in them in order to obtain strain profiles in the vicinity of notch tips. Additionally, evolution of damage calculated in advanced numerical simulations demonstrated a good agreement with images from experiments.

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1. Introduction

Fibrous networks are omnipresent in many natural materials such as biological tissues, cellulose wood, collagen tissues as well as artificial materials such as nonwovens. Their complex microstructures and interactions between their constituent fibres and/or surrounding matrix complicates characterization and assessment of leading deformation and damage mechanisms. Some existing numerical and analytical models along with experimental results are discussed below.

In our experiments, nonwoven samples were used as one of the types of fibrous networks. In general, nonwoven materials have certain anisotropy in their microstructure due to their manufacture, influencing their mechanical performance in three orthogonal directions: machine direction (MD), cross direction (CD) and thickness direction (MD) (Farukh et al., 2014a). Usually, they exhibit higher stiffness in MD compared to that in CD, and TD. Damage begins with fracture of interfibre bonds in bundles, and this results in a rearrangement of fibres, affecting their orientation distribution in fibre-glass nonwoven materials (Jubera et al., 2014; Ridruejo et al., 2010). Yang et al. (2015) investigated tearing resistance of rabbit skin (another example of fibrous material) and found that four mechanisms decreased the possibility of any tearing in presence of a notch: (i) fibril straightening, (ii) fibre reorientation towards a loading direction, (iii) elastic stretching, and (iv) interfibre sliding.

A research of the effect of fibre orientation distribution on effective elastic properties and strength of fibre networks was conducted, and it was established that elastic behaviour of any kind of fibre distributions could be represented by four set of parallel fibres in various ratios (Cox, 1951). Another theory was presented to predict tensile response of spun-bonded nonwovens in respect to fibre orientation distribution function, elastic modulus - assuming that fibres demonstrate behaviour similar to that of laminate composites (Bais-Singh & Goswami, 1995). A computational model based on an incremental deformation principle – updating a strain level and an effective elastic stiffness tensor due changes in orientation of each fibre with regard to a loading direction – was proposed to predict tensile performance of thermally point-bonded nonwovens (Kim & Pourdeyhimi, 2001). Hägglund and Isaksson (2008) coupled macroscopic material degradation and interfibre bond fracture with a model of a randomly-distributed fibre network, where macroscopic degradation was explained in terms of a fracture parameter, which is linearly related to the inverse of bond density above a certain percolation threshold.

Although a continuous model was not capable of explaining the changes in microstructure (unlike discontinuous models), it was sufficient to analyse the effect of bonding parameters such as bond size and shape. Ridruejo et al. (2010) investigated glass nonwoven felts (employing transversely notched and non-notched samples) using experimental tests and two-dimensional finite-elements models, accounting separately for brittle bond failure and fibre sliding after fracture. Anisotropy coefficients for three orthogonal directions (MD, CD and TD) of fibrous networks might be derived from a fibre orientation distribution (Demirci et al., 2011a), and a tensile response of thermally bonded nonwovens was simulated with a continuous model taking those coefficients into account (Demirci et al., 2011b). Furthermore, for fibres realigned along the loading direction, anisotropy parameters should be updated at every increment of stretching (Raina & Linder, 2014). A lattice-like structure was also used to emulate microstructure of isotropic fibre distributions in nonwoven fibrous mats and constitutive equations were derived to incorporate elastic-plastic response of individual fibres (from RVE in microscale) into a macroscopic model (Silberstein et al., 2012). Discontinuous modelling approach enables to simulate progressive damage evolution by controlling failure of individual fibres (Farukh et al., 2014b).

In this research, the focus is on deformation and fracture mechanisms in presence of various notches in randomly distributed fibre networks. First, virgin samples and samples with various notch shapes were stretched in experiments; second, a feature analysis was conducted to quantify microstructural features such as fibre diameter, fibre orientation distribution, size of bond points. Finally, finite-elements models are generated to quantify changes in microstructure and to obtain strain distribution along notches.

2. Material

The material used in this study is 30 g/m^2 (or gsm) thermally-bonded nonwoven, composed of mono-component polypropylene fibres (manufactured by FiberVisions, USA). Polypropylene is one of the most commonly used