Composites: Part A 48 (2013) 82–92

Contents lists available at SciVerse ScienceDirect

Composites: Part A

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

# Experimental identification of a lattice model for woven fabrics: Application to electronic textile

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ARTICLE INFO

*Article history:*
Received 27 April 2012
Received in revised form 17 December 2012
Accepted 31 December 2012
Available online 20 January 2013

*Keywords:*
A. Fabrics/textiles
C. Computational modelling
C. Micro-mechanics
D. Mechanical testing

ABSTRACT

Lattice models employing trusses and beams are suitable to investigate the mechanical behavior of woven fabrics. The discrete features of the mesostructures of woven fabrics are naturally incorporated by the discrete elements of lattice models. In this paper, a lattice model for woven materials is adopted which consists of a network of trusses in warp and weft direction, which represent the response of the yarns. Additional diagonal trusses are included that provide a resistance against relative rotation of the yarns. The parameters of these families of discrete elements can be separately identified from tensile experiments in three in-plane directions which correspond with the orientations of the discrete elements. The lattice model and the identification approach are applied to electronic textile. This is a fabric in which conductive wires are incorporated to allow the embedment of electronic components such as light-emitting diodes. The model parameters are established based on tensile tests on samples of the electronic textile. A comparison between the experimental results of an out-of-plane punch test and the simulation results shows that the lattice model and its characterization procedure are accurate until extensive biaxial tensile deformation occurs.



## 1. Introduction

Woven materials are frequently used, for instance in clothing, bullet-proof armor and reinforced polymeric and ceramic materials. A relatively new application is electronic textile [7,8,19]. Electronic textiles are textiles which contain electronic components such as light-emitting-diodes, sensors, switches, etcetera. The woven fabric acts as a compliant substrate for the electronic components and conductive wires are woven into it in order to electrically connect the individual electronic components. These conductive wires and the connections of the conductive wires with the electronic components must stay intact during manufacturing and use, since failure of the wires and connections entails a malfunctioning product. Mechanical models can be used to study the mechanical interplay between the different constituents of electronic textile.

To model the mechanical behavior of woven materials different approaches can be used. It can for instance be investigated by performing finite element simulations on a single unit cell in which the yarns are discretized in a detailed manner so that, amongst others, yarn-to-yarn interactions are incorporated [2,16,17,23]. A limitation of these detailed simulations is their computational cost, which prohibits large-scale simulations.

On the other hand, continuum models are often used for large-scale simulations of woven materials [1,14]. They are suitable for large-scale problems because the discrete yarns are not taken into account individually but only in an average sense. A disadvantage of continuum models for woven materials is their inability to capture local (discrete) events such as yarn failure and sliding of yarns. This is an important drawback for the study of electronic textile because the conductive wires are individual, small but relevant features. Other disadvantages are the relatively complex incorporation of large rotations [22] and the occurrence of numerical difficulties such as locking [26].

Lattice models that employ trusses or beams offer a more natural, intermediate description for woven materials. The discrete members of the mesostructure of these materials are represented by discrete elements such as trusses or beams in these models [6,12,25]. An example of a lattice model for a woven fabric is shown in Fig. 1, superimposed on an image of a textile. Individual yarn segments are modeled by a discrete element such as a spring. At the yarn-to-yarn contacts, the discrete elements are connected to each other by nodes. The diagonal elements provide the lattice with shear stiffness. In this way the shear stiffness of the fabric, that comes into play if the yarns rotate relative to each other, can be modeled. Local events such as slip in the member-to-member interaction [6,15] and failure of individual members can be taken into account in a natural manner in lattice models [15], whereas they are complex to include in continuum models. The

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http://dx.doi.org/10.1016/j.compositesa.2012.12.014

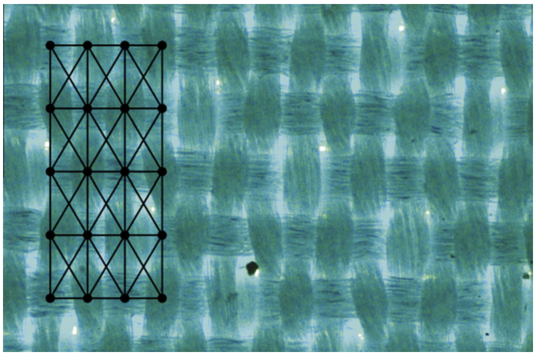

**Fig. 1.** A woven fabric with 12 unit cells of a lattice model superimposed on it. The black lines represent springs or beams which are fixed to each other at the nodes (black dots).

discrete conductive wires in electronic textile can also be modeled individually in lattice models, whereas this is not trivially established in continuum descriptions. Furthermore, the high computational cost of detailed sub-yarn models is avoided. An overview of several lattice models is given by Ostoja-Starzewski [21].

Large-scale lattice computations may still be computationally costly. To overcome this, unit cells of lattice models often represent several unit cells of the woven material, i.e. one truss or beam represents several parallel yarns [25]. In some studies [4,5,10] the response of the lattice model is translated to the response of a finite element that is also used to represent a number of unit cells. Local events such as element failure can no longer be incorporated in these approaches, but they can still easily deal with large rotations [25] and locking [10,25]. Also a number of multiscale approaches can be used to increase the efficiency of large-scale computations [3,9,20].

Identification approaches to establish the parameters of the different discrete elements in lattice models can be complex since the discrete elements are all mechanically connected. Consequently, they influence each other during the experimental parameter identification. Identification approaches can therefore be somewhat elaborate [5,24,25]. In this paper a rather general two-dimensional lattice model for woven materials is proposed that can be characterized in a straightforward manner. From three types of in-plane tensile tests that are performed in the orientations of the three families of discrete elements, the parameters of the discrete elements are individually established. In this way no (complex) inverse problem has to be solved to establish the material parameters.

In order to separately identify the discrete elements, the mutual influence must be negligible. To this end, the compressive responses of all elements in the lattice model proposed in this paper vanish. The lattice model and its identification procedure are applied to a woven electronic textile including conductive wires, but it can be used for any woven material that is characterized by a compliant rotational stiffness relative to the axial stiffness, such as e.g. metal grids to reinforce concrete [11].

The outline of this paper is as follows. First the electronic textile is described and the in-plane experiments on the electronic textile are discussed. Also the fabric strains at which the conductive wires fail are identified. Subsequently, the lattice model is detailed and the identification procedure is discussed. In Section 5 the lattice model including the identification procedure is validated by a three-dimensional punch test. Overall experimental and predicted deformations are compared as well as the experimental and predicted punch force–punch displacement curves; failure of the conductive wires is also evaluated. Finally, conclusions are presented.

## 2. In-plane experiments

The fabric considered here is an electronic textile produced by TiTV (www.titv-greiz.de). It is a densely woven fabric with embedded conductive wires (see Fig. 2). The conductive wires are predominantly oriented in warp direction and on average one wire is present on 65 warp yarns. In weft direction an insignificant number of conductive wires are present. The conductive wires consist of a number of copper filaments (see Fig. 2). At regular intervals they have some clearance with respect to the textile to allow the mounting of electronic components (see Fig. 2). The textile yarns of the fabric contain different fibers of dtex 76. The yarns in warp direction are turned 600 times per meter and those in weft direction are turned 120 times per meter. The density of the warp and weft yarns is 11,000 $m^{-1}$ and 8900 $m^{-1}$ respectively. The warp and weft yarns are woven in a three layer pattern.

### 2.1. Methodology

Tensile test samples of the electronic textile (including the conductive wires) of $100 \times 29\ mm^2$ are taken in three directions; in warp and weft direction and at an angle of 45° with respect to the warp direction. The tensile tests in the latter direction correspond to the bias extension test [22,24]. The nominal thickness of the samples is measured as 0.35 mm, although this thickness is somewhat arbitrary since the samples are highly heterogeneous. The samples are fixed in between two clamps with a rough surface together with one piece of double-sided tape to increase the fixation. The gauge length of all samples is approximately 60 mm. The used tensile tester (Instrom 5566) has a load cell of 500 N. The strain rate in the experiments in warp and weft direction is $1.67 \times 10^{-3}\ s^{-1}$ and in diagonal direction $3.33 \times 10^{-3}\ s^{-1}$, in order to keep the strain rates of the individual yarns as similar as possible. No influence of time on the material response is investigated.

During the experiments, images of the strained samples are recorded, to which an optical strain measurement technique is applied to determine the local strains. Undesired effects such as slip in the clamps and deformation of the load cell are therefore circumvented in the strain measurement. Furthermore, in the tensile test in diagonal direction (bias extension test), the pure shear strains that only occur in region C in Fig. 3, as is well described in literature [22,24,26], can be established without any influence of the constraining influence of the clamps (in regions A and B). To determine the engineering stress of the samples the measured cell force and the original nominal cross-sectional area are used.

To investigate the failure of the conductive wires within the fabric, X-ray images are made (Phoenix PCB analyzer, using 60 kV and 20 μm) after the tensile tests in warp direction. Although these images are not direct input for the experimental identification, they are used in Section 5 to evaluate the lattice model and the identification procedure.

### 2.2. In-plane stress–strain responses

The engineering-stress/engineering-strain responses of the in-plane tensile experiments are shown in Fig. 4. The engineering stress and engineering strain are used here to obtain a first impression of the textile behavior in the different directions. In Section 4 however, the true stress and true strain of the individual truss elements are determined based on the engineering stress and engineering strain of the textile, since the software in which the lattice model has been implemented uses the true-stress/true-strain constitutive relations. To calculate the engineering stress and engineering strain shown in Fig. 4, the force measured by the load cell is divided by the nominal cross-sectional area and