Mechanics of Electronic Textiles
"Literature Study"

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Abstract

Electronic textiles incorporate flexibility as a feature to functional applications such as electronically addressed LED matrices. The robustness of such a device is essential to its success when introduced into the market. The textile substrate’s material behavior has to be readily understood in order to improve robustness. Modeling of the substrate is crucial in order to predict material behavior. An extensive literature study categorizes modeling and experimental possibilities, which are subsequently presented and discussed.
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Chapter 1

Introduction

The applicability and marketability of electronic (e.g. photonic) textiles seems extremely promising [1]. Not surprisingly, significant investments are made in research and start-up companies to anticipate a future demand of applications within this field of technology. Applications embrace a multitude of sectors, e.g. healthcare and lifestyle. Before customers are willing to spend their money on electronic textile products, quality, lifetime and flexibility must be drastically improved. In order to predict failure modes and optimize product design, a profound understanding of the mechanics behind this technology is of primary importance. The demands on the flexibility of the products imply application of large strains. The material behavior subject to these strains and consequent stresses has to be readily understood in order to solve design and quality issues.

Textile mechanics research is a relatively old field of research, where the first publications go back to the early twentieth century. Our main interest lies in the mechanics of the textiles and ultimately the mechanical effect of stiff islands on the compliant textile substrates. Since the mechanics of textiles have been of interest for many years, important work has already been performed on analytical solutions to simple textile structures, subject to mechanical loading. During the past few years, due to the increased computing power available, multiscale modeling has matured as a method with great possibilities. Through the use of unit cells or RVE’s (representative volume elements) a coupling can be made between mechanics at different scales of spatial resolution.

In the following chapter some general thoughts on photonic or electronic textiles are presented, in order to justify and introduce the mechanical aspects. The next three chapters describe possible mechanical analyses on three different levels, macroscopic [2-5], mesoscopic and microscopic, where the former contains the least detail on material structure, assuming homogeneity, and the latter takes the heterogeneous properties of the fibres into account.
Chapter 2

Vision on electronic textiles

Electronic textiles have an important application within the field of the wearable electronics and photonics. Numerous examples exist, e.g. information and communication, healthcare and medical applications, fashion/leisure and home applications, as well as military and industrial applications [1]. As stated in the introduction, applicability and marketability seem promising. As can be concluded from Table 2.1, estimations are promising and investments should be made by companies interested in taking their market share. As always time-to-market will be of vital importance to success in gaining market share. Maturing this technology, i.e. improving lifetime and robustness, is essential for a successful market introduction.

Table 2.1: Market estimation for smart fabrics and intelligent clothing (Venture Development Corporation, 2003)

<table>
<thead>
<tr>
<th>Market</th>
<th>$US x 1000</th>
<th>Annual increase rate (%)</th>
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<tbody>
<tr>
<td></td>
<td>2003</td>
<td>2008</td>
</tr>
<tr>
<td>Consumer sector</td>
<td>122 205</td>
<td>251 691</td>
</tr>
<tr>
<td>Professional/Industrial sector</td>
<td>150 884</td>
<td>388 086</td>
</tr>
<tr>
<td>Government</td>
<td>30 751</td>
<td>80 223</td>
</tr>
<tr>
<td>Total</td>
<td>303 840</td>
<td>720 000</td>
</tr>
</tbody>
</table>

2.1 Overall background

Several fields of expertise come together within the technology of electronic textiles. In order to create "wannahaves" the designers play an important role in the design stage, whereas electrical engineers should work closely together with computer scientists and system architects. However, without a profound understanding of the mechanics within these textiles, the robustness cannot be optimized.

Within Philips (LumaLive) [2], the first generation of electronic textiles has already been launched, displaying the possibilities and impact of this technology. In this generation some degree of flexibility has been introduced, which is still far from the flexibility desired in a
fashion, leisure or commercial application, Fig. 2.1. However, progress within Philips Research shows promising results with LED-packages attached to fully flexible plain weave cloth, interlaced with conductive yarns. Robustness is an important issue, which has not yet been solved. Fig. 2.1 clearly shows some fashion and leisure applications, however flexibility of these examples is still limited unfortunately.

**Figure 2.1:** Examples of current electronic textile prototypes and first generation products. Courtesy of (LumaLive) [6].

For 'smart textiles' integrated functions are present within the textile environment, preferably embedded within the textile itself, [7]. Depending on the complexity of the product, the system configuration may look like Fig. 2.2.

![Diagram](image)

**Figure 2.2:** General system configuration for a wearable electronics or photonics product [1].

Accordingly, not only the "interface", e.g. LED matrix is interesting as a flexible component. However, the other components are not within the scope of this research.

### 2.2 Mechanical background

Many classes of textiles can be distinguished, but most important are:

- Woven textiles
- Non-woven textiles
- Knitted textiles

In the present study, only woven structures are considered.
The mechanical properties of woven textiles have been studied extensively, and numerical approximations as well as analytical solutions to stress states within textiles are readily available. Effective models should include the anisotropy, which is inherently connected to this class of materials, differing significantly from the traditional two-dimensionally reinforced laminates. Reference [2] provides a comprehensive overview of the necessary anisotropic elastic theory to support the modeling phase.

The number of weave structures that can be produced is practically unlimited. Typically, two main classes of weave techniques can be distinguished, namely orthogonally and non-orthogonally woven structures. In current research within the Photonic Textiles group, orthogonally woven structures have the main focus. The plain weave structure represents the simplest orthogonal example, which is depicted in Fig. 2.3(a), while Fig. 2.3(b) shows a non-orthogonal fibre configuration, i.e. a braided structure [8–12]. The plain weave structure is produced by alternatively lifting and lowering one warp thread across one weft thread.

![Figure 2.3: Two examples of woven structures, where the dashed areas represent an arbitrary Representative Volume Element (RVE) and the weft and warp direction are indicated.](image)

When regarding textiles as a material with a specific material behavior, one can imagine that the material behavior is determined by

- Structure of weaving (e.g. plain weave, braided weave)
- Yarn properties
- Settings of the weaving process (e.g. tension in weft and warp direction)
- Textile treatment (e.g. resin addition)
- Environment
• Material history (e.g. pre-loads)

Several possible approaches exist in textile composite mechanics. These approaches differ in accuracy, but most importantly, also in complexity.
Chapter 3

Continuum macroscopic approach

The continuum macroscopic approach regards the textile composite, schematically represented in Fig. 3.1 at a continuum level [13-15]. In other words, the fact that this specific type of solid is made of fibres and that it has a heterogeneous microstructure is ignored and it is instead regarded as a uniform material, which has the homogenized fabric properties. For small stresses or strains, problems can already be described with the simplest form of continuum behavior, namely linear elastic behavior.

Figure 3.1: Schematic representation of a textile structure interpreted as a continuum

3.1 Elastic behavior

The simplest behavior to be assumed is fully elastic behavior, which can be completely described by 21 independent parameters for a generally anisotropic material.

If textile is taken to be a woven structure, a given strain in one direction will result in a certain stress in at least that direction. However, this effect or constitutive response is not necessarily similar in all directions, i.e. anisotropy. A composite material shows anisotropic behavior, where anisotropy refers to the directional dependency of the material properties, as opposed to isotropic material properties. Due to the anisotropic behavior, the Young’s modulus is not the same in all directions, i.e. $E_x \neq E_y$. From a textile point of view this is
readily understood.

Simplifications can be made systematically in order to account for material symmetries, reducing the number of independent material parameters significantly. A special case of anisotropic behavior is orthotropic behavior. An orthotropic material has two mutually orthogonal symmetry planes so that the mechanical properties are, in general, different along the directions of each of these axes.

The fully elastic constitutive relation, with twelve elastic engineering constants or material parameters, is given by

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{yz} \\
\gamma_{xz} \\
\gamma_{xy}
\end{bmatrix} =
\begin{bmatrix}
1 & -\nu_{yx} & -\nu_{xz} & 0 & 0 & 0 \\
-\nu_{xy} & 1 & -\nu_{yz} & 0 & 0 & 0 \\
-\nu_{xz} & -\nu_{zy} & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{yz} \\
\tau_{xz} \\
\tau_{xy}
\end{bmatrix}
\] (3.1)

Because the following relation holds for orthotropic materials, only nine of the constants are independent:

\[
\frac{\nu_{yx}}{E_y} = \frac{\nu_{xy}}{E_x}, \quad \frac{\nu_{xz}}{E_z} = \frac{\nu_{zx}}{E_x}, \quad \frac{\nu_{yz}}{E_z} = \frac{\nu_{zy}}{E_y}
\] (3.2)

Where \(E_i\) is the Young’s modulus along axis \(i\), and \(\nu_{jk}\) is Poisson’s ratio in plane \(jk\), where \(i, j, k\) can be \(x, y,\) and \(z\). In this case the properties can be described by the nine elastic engineering constants \((E_x, E_y, E_z, \nu_{xy}, \nu_{yz}, \nu_{xz}, G_{xy}, G_{yz}, G_{xz})\), with \(E\) Young’s modulus, \(\nu\) Poisson’s ratio, and \(G\) shear modulus. However, for some commonly woven structures more simplifications can be made.

Symmetric lay-ups of orthogonal balanced woven fabric composites are depicted in Fig. 2.3(a). The assumption is made that the directional dependency of the material behavior (e.g. on manufacturing process) is chosen in such a way, that the behavior is simplified. The equivalence between the ‘\(x\)’ and ‘\(y\)’ direction leads to three identity relations, \(E_x = E_y\), \(\nu_{xz} = \nu_{yz}\), \(G_{xz} = G_{yz}\). The three-dimensional constitutive model takes the form

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{yz} \\
\gamma_{xz} \\
\gamma_{xy}
\end{bmatrix} =
\begin{bmatrix}
1 & -\nu_{yx} & -\nu_{xz} & 0 & 0 & 0 \\
-\nu_{xy} & 1 & -\nu_{yz} & 0 & 0 & 0 \\
-\nu_{xz} & -\nu_{zy} & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{yz} \\
\tau_{xz} \\
\tau_{xy}
\end{bmatrix}
\] (3.3)

\subsection{3.2 Plane stress}

If one of the problem dimensions is significantly smaller than the other two, the stress in this direction can be neglected, resulting in a planar stress state. This stress state is known as
plane stress, because of the fact that the normal stress $\sigma_z$ as well as the two shear stresses $\sigma_{xz}$ and $\sigma_{yz}$ vanish. This assumption is only valid in the macroscopic approach as large pieces of cloth are examined. The out of plane stresses are negligible because the stresses are not able to develop within the small material thickness and are therefore small compared to the in-plane stresses.

The column representation of the stress state as shown in (3.1) takes the form

$$\sigma = \begin{bmatrix} \sigma_x & \sigma_y & 0 & 0 & \sigma_{xy} \end{bmatrix}^T$$

(3.4)

Accordingly, the strain state is of the form

$$\varepsilon = \begin{bmatrix} \varepsilon_x & \varepsilon_y & \varepsilon_z & 0 & \gamma_{xy} \end{bmatrix}^T$$

(3.5)

Now, only four of the initial nine engineering constants are needed to describe the elastic properties. This is concluded from substituting the plane stress condition in (3.1) and assuming orthotropic behavior. The strain component in the out-of-plane direction, $\varepsilon_z$, can be excluded from the system of equations and solved separately. For in-plane elastic orthotropic material behavior the following holds.

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\nu_{xy} & 0 \\ -\nu_{xy} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{bmatrix}$$

(3.6)

### 3.3 Experimental identification

Experimental determination of the material properties of the textile is essential in the case of the macroscopic approach, simply because the model should respond in the same way as the ‘real’ material. This can be achieved without modeling the substructures, responsible for the mechanical behavior. Four parameters are determined: two Young’s moduli, one Poisson’s ratio, and a shear modulus.

The determination of the Young’s modulus is readily understood and common practice with support of tensile testing equipment. Adding imaging techniques yields a possibility to measure the Poisson’s ratio. An elaboration is presented in a note on the experimental setup [16].

Textile fabrics can shear up to 50°. Three main methods for measuring shear properties of fabrics can be distinguished. All are depicted in Fig. 3.2. In the biaxial shear test, the fabric sample is held between a fixed clamp and a movable clamp. Shear force and shear angle are measured, while maintaining a constant normal force. More background can be found in [3, 15, 17]. The Bias extension test is addressed in the work of Potluri and Zhu [11, 18]. The picture frame test has been performed by different groups [10, 15].
Figure 3.2: Three shear deformation test methods are depicted. From left to right: Biaxial shear test, Bias extension test, Picture frame test (hinges at the corners), where the gray areas represent rigid bodies.
Chapter 4

Continuum mesoscopic approach

Mesoscopic analyses consider repetitive units of homogenized fibre bundles. This type of analysis identifies and analyzes ‘repetitive unit cells’ or ‘representative volume elements’ on a mesoscopic level, i.e. at the level of a few interacting fibres. The first models were developed relating geometrical and mechanical equilibrium between the yarns [19][22]. A schematic representation is depicted in Fig. 4.1.

Figure 4.1: Peirce model; Schematic orthogonal unit cell showing interlacing geometry for plain weaving structure [1] [19]
4.1 Geometrical and mechanical coupling

The Peirce geometrical model, for circular cross-sectional yarns, assumes a uniform structure and isotropic yarn properties. An orthogonal interlace cell consisting of straight and circular portions has been selected to undergo both geometrical and mechanical analyses, where the model and the corresponding parameters of the unit cell are shown in Fig. 4.1.

The analytical background can be found in [19]. The model is designed to obtain a force equilibrium within the woven structure and accordingly derives geometric parameters. Newton-Raphson is used as a numerical solution algorithm. Eventually, bending forces and crimp can be calculated.

Crimp, or waviness of a yarn in a fabric, is caused during weaving and may be modified in finishing. It is due to the yarns being forced to bend around each other during the weaving process. Crimp is measured by the relation between the length of the fabric sample and the corresponding length of the yarn, when it has been straightened after being removed from the textile structure [8].

4.2 WiseTex

One tool from the group of Lomov et al. [23], called WiseTex, deserves extra attention. This tool is a model of the internal geometry of textiles and takes full advantage of the hierarchical principle of textile modeling. The simulation algorithm uses extensively the minimum energy principle, calculating the equilibrium of yarn interactions. The models cover wide range of textile structures, either relaxed or after compression (out-of-plane), shear or tensile deformation. As input the tool takes yarn properties, e.g. geometry of the cross-section, compression, bending, frictional and tensile behavior. It is even possible to account for fibrous content, therefore WiseTex can even be considered as a micromechanics tool [5]. A graphical editor is provided to virtually create the topology of the yarn interlacing pattern within the fabric repeat. A graphical representation of the yarn interlacing geometry is presented by Fig. 4.2.

Figure 4.2: A graphical representation of interlaced yarns with different properties, WiseTex
Unit cell dimensions, areal density, average porosity/fibrous content and yarn lengths in the unit cell are direct outcome of the energetic analysis. For any point within the unit cell, the fibrous content, the average orientation and an identification of the fibre material in the vicinity of the point are obtained. Furthermore, yarn path, position and size of the yarn cross-sections are obtained as well as fibre density and orientation distribution over the yarn cross-section.

However, this model has not yet been validated for multilayered structures. Applicability to multilayered textile might therefore still be limited in the near future.

4.3 Alternative mesoscopic models

Instead of an analytical approach, more complex models map the geometric description of the textile meso-structure into a 3D grid of finite elements. These models are discussed in Refs. \[24–32\].

Another approach to approximate homogenization of elastic properties on meso-level exploits averaging of properties of differently oriented yarns in the reinforcement, based on expressions for transformation of the stiffness tensor with the reference coordinate system \[2\]. This approach allows calculations for complex 3D braided, woven and knitted composites, \[33–42\]. The inclusion-based model \[43–45\] can be considered as a generalization of this approach.

Table 4.1 below groups the different meso-level analysis methods into several categories and represents a literature overview on meso-level analysis. It should be noted that some of the literature references focus on textile composites, where a resin and a textile are combined. However, in essence this does not change the methods applied and hence they are incorporated in this overview.

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<td>Meso-FE modeling of textile composites in the elastic deformation regime and with damage</td>
</tr>
<tr>
<td>Multi-scale modeling</td>
</tr>
<tr>
<td>Geometrical modeling and meshing of the unit cell structure of textile fabrics</td>
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Chapter 5

Microscopic approach

The microscopic approach takes into account the heterogeneities at the fibre level in order to predict material behavior. This approach is also referred to as the micromechanics approach [5].

A major advantage this technique has, is the great level of detail and the ability to analyze structures at a small scale. However, this advantage already implies that it is numerically costly. The decision on whether to use this method should strongly depend on the purpose of the analysis.

5.1 Micromechanics analysis

Techniques of this kind typically start from a geometric model of a relaxed fibre geometry, which may be based on energy considerations. Bundle properties are predicted using classical micromechanics equations such as a composite cylinder assemblage model [86], with the fibre content and the constituent properties as the input parameters. These bundle properties are transformed to the properties in a laminate coordinate system by the appropriate rotation matrices, according to the undulation of the bundles. Finally, the fabric composite properties are found by averaging the properties of the separate bundle, for instance by assuming a uniform state of strain in all regions. Various software applications are currently available on the internet, such as [17] [87, 88].

5.2 Multi-chain digital element analysis

Another microscopic approach, founded by Wang and Sun [89], is described by Zhou [9]. This multi-chain digital element method models each separate yarn in a bundle as a frictionless pin-connected truss element chain. These truss elements are modeled as “digital elements” and contact is modeled by contact elements. Zhou tackles the original weakness of the unchanged cross-section by carefully conforming to fibre, yarn and fabric physics.

In multi-chain digital element analysis, each fibre, rather than each yarn in the mesoscopic approach, is modeled as a flexible one-dimensional physical entity with a circular cross-section. Each yarn is modeled as an assembly of fibres, simulating both yarn movement and cross-section deformation during fabric deformation. Figs. 5.1 and 5.2 depict illustrations of this
Figure 5.1: Yarn under single side compression, results of the multi-chain digital element method by (Zhou, 2004, [9])

microscopic approach.

Figure 5.2: woven fabric generated by the multi-chain digital element model by (Zhou, 2004, [9])
Chapter 6

Conclusions

Plain textiles have been subject to an extensive period of research, leading to a solid mechanical background. Analytical studies coupling geometrical properties with mechanical behavior cover the most important woven textile structures, where mechanical models present solutions to more complicated problems or whenever simplification is desired.

A literature overview is presented and acts as a guideline for mechanical analysis of textile woven structures. Characteristics are discussed and a potential direction is presented on how to continue mechanical research of photonic textiles within Philips Research.

Analyses can be split into three main categories: Macroscopic, mesoscopic and microscopic analyses. Each of these analysis levels has specific advantages and disadvantages, where advantages generally refer to applicational difficulty, level of detail, accuracy, whereas the disadvantages predominantly refer to computational cost or difficulty concerning material characterization.

The research intention lies within the field of textile characterization and modeling in order to predict and improve material behavior. A continuum macroscopic approach is to be used as the observation scope of a first generation solution.

Ultimately, the research goal is to describe the effect of stiff islands mounted, either chemically or mechanically, on the textile substrate. A first generation model will act as a tool to predict product robustness and quality [90].
References


