Mechanical modelling of textiles

*Literature Survey*

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1 Introduction

A textile is a flexible material consisting of a network of natural or synthetic threads or yarns. Textiles form a part of everyday life. They are used in many applications such as clothing, bedding, towels, furniture, etc. Textiles are used in such a wide range of applications for their characteristic properties, such as flexibility. Textiles are also used for instance in the aerospace industry in combination with resins or other matrix materials. Characteristic of textiles, such as the stiffness of the individual yarns or the flexibility of the structure, are combined with characteristics of the matrix.

At the moment the use of electronics in combination with textiles is an upcoming trend. The integration of functional yarns and components in clothes and furniture is widely studied. Research is required to tackle the new challenges the integration of electronics introduces. Reliability is one such challenges, as mechanical failure may occur due to the high strains that are being reached during usage. As a first step towards predictive mechanical models of electronic textiles, the mechanical behavior of plain textiles is examined in this report.

As mentioned, textiles are networks (or structures) of yarns. Different kinds of configurations are used; woven, non-woven and knitted structures are the three main categories, which have their own characteristic features. Figure 1 shows examples of these structures. The major difference between woven and non-woven structures is the orientation of the yarns. In woven structures the different yarn directions are orthogonal whereas in non-woven structures the directions are non-orthogonal. Knitted textiles have a more entangled structure.

To understand and model the particular mechanical behavior of textiles, numerous studies were performed in the past decades. These studies on the mechanical behavior of textiles can be subdivided in three categories based on the typical length scale at which textile is
investigated.

Microscale analyses focus on the mechanical behavior of single yarns (< $10^{-3}$m). The internal structure of a yarn consisting of a bundle of fibers ($10^{-6}$m), as shown in figure 2, is examined to predict single yarn behaviour and interactions between individual yarns. For example, the interactions between different fibers are examined to describe yarn-compression.

Figure 2: Yarn consisting of a bundle of fibers.

Mesoscale analyses provide insight in the behavior of a small piece of fabric which covers one or more representative volume elements (RVEs) of the examined structure. Single yarn interactions are also taken into account in analyses on the mesoscale. Representative cells between $10^{-3}$ and $10^{-2}$m characterize the mesoscale.

Macroscale analyses focus on the characterization of fabric behavior without explicitly modelling the geometric structure of the textile. Usually the fabric is modeled as a homogeneous continuum which obeys a certain constitutive relation. The typical length scale of macroscopic analyses is $>10^{-2}$m.

Analyses on the micro- and mesoscales, and the results of performed experiments can provide the input for macroscopic models. Such a hierarchical chain of models is called a multiscale model.

In the following chapters examples of different types of modelling are described and afterwards compared. Chapter 2 contains the microscale analyses, chapter 3 the mesoscale analyses, chapter 4 the macroscale analyses and in chapter 5 the multiscale analyses are discussed.
2 Microscale analysis

Both continuous and discrete models have been developed to examine the textile behavior on the microscale. The aim when analyzing textile on the microscale is to obtain the properties of a single yarn with a certain length. A difficulty is that a yarn is not a uniform continuum, but it consists of numerous fibers which interact in a complex network. Two examples of analyses are described below. First, the digital-element approach of Wang & Sun [5] and Zhou et al. [6] is explained. Secondly, a homogenization approach proposed by Lim [28] is explained.

2.1 Digital-element approach


Wang and Sun [5] represent a yarn by a pin-connected digital-rod-element chain, i.e. a set of short cylindrical trusses which are connected to each other by frictionless pins, as shown in Figure 3. The single elements in this model are assumed rigid. The relative rotations of the frictionless pins mimic the flexible nature. As the element length approaches zero, the chain becomes fully flexible, mimicking the properties of a yarn/fiber. This analysis was developed to obtain detailed information on the deformation during manufacturing processes, where the conventional mathematical and experimental methods did not provide the required detailed information.

Figure 3: Discretization of the yarn [5].

Because yarn elongation can be neglected in reality, the stiffness matrix of the digital elements, K, can be described using a penalty factor with a large positive value. With this stiffness matrix, the equilibrium state of the system was stated as

\[ [K]\{U\} + \frac{1}{2} A\sigma_0\{e\} = \{F\} \]  (1)
where the stiffness matrix \( [K] \) is a 6x6 matrix with the penalty stiffness at \( K_{11}, K_{14}, K_{41} \) and \( K_{44} \) and zero elsewhere, \( \{U\} \) the nodal displacements, \( A \) the area of the cross-section, \( \sigma_0 \) is the initial tension, \( \{e\} \) the vector of the initial tension and \( \{F\} \) the nodal forces.

Subsequently the yarn contacts are analyzed. Contact between two yarns is represented by a contact of two nodes, when the distance of two nodes becomes as small as the fiber diameter. In the case of contact, a contact element is added between the two nodes. The \( x \)-axis is determined as the direction of this contact element and the \( y \)- and \( z \)-axes are perpendicular to the contact element. The yarns stick when

\[
\mu |\vec{F}_{xi}| > |\vec{F}_{yi} + \vec{F}_{zi}|
\]

where \( \mu \) is the friction coefficient and \( \vec{F}_{xi}, \vec{F}_{yi} \) and \( \vec{F}_{zi} \) are nodal forces. Sliding occurs when

\[
\mu |\vec{F}_{xi}| \leq |\vec{F}_{yi} + \vec{F}_{zi}|
\] (3)

Wang and Sun [5] proposed a rigid contact, where the displacements of the two constrained nodes are the same. Again a large positive penalty value is used in the stiffness matrix to avoid deformation in the yarn’s cross-section. In reality the assumption of rigid yarns is incorrect. Zhou et al. [6] proposed a multi-chain digital element approach. Instead of representing a yarn by a single digital chain, the yarn is modeled by an assembly of digital chains, representing the fibers in the yarn. This multiple-chain digital element approach does not only capture yarn movement, but also cross-sectional deformation.

Figure 4 illustrates a simple example of the analysis. As shown in figure 4, the modeled yarn consists of several dozens of fibers. A real yarn is composed of hundreds or thousands of fibers. Computing power limited the amount of chains that could be used. According to Zhou et al. [6] in most cases 19-50 digital chains are sufficient.
2.2 Homogenization approach

Lim [28] proposed that a fiber bundle, representing the yarn, can be mechanically modeled as a stack of densely packed fiber filaments. The aim was to determine the mechanical properties of a composite fiber bundle, which consists of matrix material with densely packed fiber filaments. The performed analysis can form a basis for larger-scale analyses, where an elemental length of the composite fiber bundle can be represented by a representative volume element (RVE) in a finite element (FE) model. Figure 5 shows an example of a bundle of fibers.

In this microscopic analysis only linear elastic behaviour of the RVE was examined. The fibers were represented by Young’s moduli \( E_{f1} \) and shear moduli \( G_{f12} \), where \( E_{f2} = E_{f3} \) and \( G_{f31} = G_{f12} \) for transversly isotropic fibers. The matrix material was assumed to be isotropic and to have only one Young’s modulus \( E_m \) and shear modulus \( G_m \). With these material properties, the effective moduli \( E_{fb1}, E_{fb2}, E_{fb3}, G_{fb12}, G_{fb13}, G_{fb23} \) and the poisson’s ratios in different directions) of the RVE were determined for the composite fiber bundle using the volume fraction of fibers, \( V_y f \), and a simple rule-of-mixture (e.g. \( E_{fb1} = E_{f1} V_y f + E_m (1 - V_y f) \)).

Lim [28] experimentally determined the volume fraction of fibers using figure 6. The fiber volume fraction in the fiber bundle was obtained by the line method as shown in figure 6b.

Based on the microscopic RVE, initially a mesoscale model and subsequently a macroscopic model were developed to describe the draping behavior of a knitted fabric composite.

2.3 Discussion

The applications considered by Lim [28] and Wang & Sun [5] are different; Lim used the homogenization approach for a composite material and Wang & Sun used their approach for plain weave material. As result, Lim [28] cannot easily be used for plain weave material and Wang & Sun[5] can definitely not be used for composite materials.
Whereas Wang & Sun explicitly modeled friction between the fibers, the disadvantage of the model proposed by Lim [28] is that the friction between yarns was neglected. The difficulty when modeling friction in composites is whether the yarns are in contact with other fibers or with matrix material.

In general when examining textile on the microscale, the single yarn behavior is obtained. An advantage of the analysis on this scale is that it is not restricted to one type of textile; it can be applied for all structures. A possibility for future work on this scale can be failure. For example, locally reducing the amount of fibers per yarn can be a start of a failure analysis.

Figure 6: (a) Fiber bundle cross-section and (b) enlarged view of the fiber bundle showing fiber filaments [28].
3 Mesoscale analysis

In contrast to microscale analysis, in mesoscale analysis the focus lies on the internal structure of a fabric. The general aim of mesoscale analysis is characterizing the material’s behavior by examining a small network of yarns. As the type of structure is important in the mesoscale analysis to decide which approach is used to model the structure, a distinction will be made between woven and knitted structures; in §3.1 models of woven structures will be discussed and in §3.2 knitted structures. Independent of the structure, in the mesoscale analysis a wide diversion of choices have to be made about which phenomena (e.g. friction or yarn compression) are taken into account and which are not.

3.1 Woven structures

Similar as in microscale analysis, a classification can be made for the different types of modelling; a discrete spring model is proposed by Ben Boubaker et al. [7, 8, 9], a finite element model is proposed by D’amato [11], a 2D truss network is proposed by Sharma & Sutcliffe [16] and finally a 3D cross-over model is proposed by a Kawatbata et al. [41, 42, 43].

3.1.1 Spring models

Ben Boubaker et al. [7, 8, 9] proposed a discrete model for a woven structure. The woven structure was considered as being organized in two sets of intertwined yarns, the warp yarns $\Omega_{wa}$ and the weft yarns $\Omega_{we}$ as shown in figure 7. Each subsystem is considered as a sum of $n$ single yarns. One single yarn is discretized and consists of a set of point masses mutually connected by extensional springs (figure 8). Each node (point mass) is provided with rotational stiffness.

![Figure 7: Discrete model of the woven structure [7].](image)

The kinematics of the model as sketched in figure 8 are described by the vertical displacements, $w_i$, and the rotations, $\psi_i$, of the nodes. The contact forces $R_{we/wa}$ are composed of
several contributions. Initially a contact force was proposed using the Timoshenko beam theory for the transverse yarns (see figure 8). This contact force is expressed as

$$R_{we/wa} = \frac{\pi}{4} \frac{EI_{we}}{(L_{we})^3} \left( 1 + \frac{\alpha_{we}}{N_{wa}^2} \right) \tilde{w}_{we}$$

(4)

where $L_{we}$ is the length of half a period, $\alpha_{we}$ the ratio between $P_{we}$ (traction in weft direction) and $P_{we}^{cr}$ (the beam’s critical compressive load), $N_{wa}$ the number of half periods and $\tilde{w}_{we} = A_{we}$ the amplitude of the weft yarns within the woven structure. A similar relation applies for $R_{wa/we}$. Under the effect of the loads $P_{wa}$ and $P_{we}$, a lateral compressive deformation of the yarns and an undulation transfer due to the yarn-yarn interaction occur, resulting in a description of the amplitude

$$\tilde{w}_{we} = w_{j,k}^{j,k} + w_{s-wa}^{j,k} - w_{s-so-we}^{j,k} - (-1)^j \left( \delta_{c,k}^{wa} + C_2 \left[ 1 - \left( 1 - \frac{\delta_{c,k}^{wa}}{C_1} \right) \frac{K_2 L_{wa}}{L_{c,k}^{wa}} \right] \right)$$

(5)

where $w_{j,k}^{j,k}$ and $w_{s-so-we}^{j,k}$ are the initial displacements of the weft and warp summits, $w_{s-so-wa}^{j,k}$ the displacement of the warp summits, $\delta_{c,k}^{wa}$ the vertical displacement of the warp under compression, and $C_1$ and $K_1$ parameters for the warp and $C_2$ and $K_2$ for the weft yarns.

Using (4) and (5) an expression for the external work, $W_{ext}^{k}$, was derived. Together with the strain energy, $U_{wa}^{k}$, an expression for the total potential energy was derived as

$$V_{wa}^{k} = U_{wa}^{k} - W_{ext}^{k} = \left( U_f^{k} + U_{ex}^{k} + U_{comp}^{k} \right) - \left( E_{traction}^{k} + W_{gr}^{k} + W_{reaction}^{k} \right)$$

(6)

with $U_f^{k}$, $U_{ex}^{k}$ and $U_{comp}^{k}$ respectively representing the flexional, the extensional and the compressive deformation of the yarn. $W_{traction}^{k}$ is the work of the traction load $P$, $W_{gr}^{k}$ the work of the gravity load and $W_{reaction}^{k}$ the work of the reaction forces at the contact points. The total potential energy of all warp yarns (sub-mechanical system $\Omega_{wa}$) can then be calculated as
\[ V = \sum_{k=1}^{N_{wa}} V_{wa}^k \] \hspace{1cm} (7)

The equilibrium state of the sub-mechanical system \( \Omega_{wa} \) is determined by minimizing the total potential energy \( V \), i.e. by requiring that the first variations of the total potential energy vanish.

Ben Boubaker et al. [8, 9] also examined the incorporation of yarn-yarn friction. Based on Gralen and Lindberg [26] the following empirical relation was proposed:

\[ F_t = \alpha R_{we/wa} + \beta l R \] \hspace{1cm} (8)

with \( \alpha \) and \( \beta \) two material constants, \( l \) the effective contact length between the two yarns and \( R \) the radius of the considered yarn. The friction force is perpendicular to the reaction force and is considered as a point load on only the summit nodes. When analyzing the simulations, the incorporation of the friction force appears to lead to a stiffer response.

Traction forces, undulation, compression and gravity influences have been included by Ben Boubaker et al. [7, 8, 9]. On the other hand, the effective contact area, distribution on the contact zone and accurate friction calculations were not included and still need to be examined.

Using this model for the woven structure, several phenomena were examined. The consideration of the yarn-yarn interactions leads to a stiffer response and thus lower displacements and less undulation. Both uniaxial and biaxial simulations were performed to analyze the effect of the transverse extension load. Increasing the \( P_{we}/P_{wa} \) ratio leads to higher reaction forces, \( R_{we/wa} \), resulting in lower transverse extensions and flexional displacements. Increasing the transverse stiffness (ratio) also resulted in higher reaction forces and lower displacements.

A the major disadvantage of this model is that it cannot predict the shear behavior of the woven structure.

### 3.1.2 Modelling by three dimensional solids

Another structural analysis was performed by D’amato [11]. A tri-axial fabric used in the aerospace industry was examined. The braiding layout is shown in figure 9. A finite element model was made of this fabric. The geometric characteristics were defined by the analysis of images of various through-thickness cross-sections of the fabric. Figure 10 shows the FE model of the elementary cell (unit cell).

In this analysis only small deformations were examined. The linear elastic Young’s modulus of the fabric was predicted by the FE model for several model sizes. Figure 11 shows two of the examined sizes.
Figure 9: Braiding layout of the examined fabric by D’amato [11].

Figure 10: Finite element model of the elementary cell [11].

Figure 11: 12x2 and 12x4 cell structural models [11].
The analyses highlighted the dependence of the predicted stiffness of the material on the model size. The global stiffness can be decomposed as

\[ E_x = E_{0^\circ} + E_{60^\circ} + E_{braiding} \]

where \( E_{0^\circ} \) is the contribution of the longitudinal yarns, \( E_{60^\circ} \) the contribution of the inclined yarns and \( E_{braiding} \) the contribution due to yarn braiding. The first two contributions were discriminated by using the partial FE models shown in figure 12. It was observed that the tensile stiffness of the yarns with a 0° inclination is proportional to the number of yarns. On the contrary, the contributions of the yarns with a ±60° weaving inclination depend on the length/width ratio of the examined structure. The largest contribution to the total stiffness of the examined structures, by more than 50%, is related to the braiding of the structure. Slightly more than 40% of the total stiffness can be attributed to the longitudinal yarn stiffnesses. The remaining 2 - 4% is due to the inclined yarns. As the geometrical arrangement only relied on images, the used geometry was additionally examined by varying the wave shape in the geometry. Variations of about 3% in stiffness were found.

3.1.3 2D truss network

Sharma & Sutcliffe [16] proposed a truss network representation of the textile. A 2D network of two-node 3D truss elements form a small reference unit cell model, as shown in figure 13. This network was used to describe the draping behavior of a dry fabric, which is a textile structure consisting only of yarns which has not yet been embedded in a resin.

The four outer elements in the sketch of figure 13 represent the yarns while the diagonal element endows the cell with shear stiffness. The elements are connected via pin joints. The Green-Lagrange strain definition is used for all elements. The Young’s modulus of the tow elements and the stress-strain response of the shear elements were fitted on the data of a bias extension experiment.

Force-displacement, width-displacement and shear angle-displacement results were given for varying stiffnesses. Comparisons were made between the simulation, the bias extension tests and results from another pin-jointed net model [17]. The tow elements were fitted on the results of the pin-jointed net model and the bias extension tests. Significantly different stiffnesses for the tow elements were needed to fit the data of the pin-joined model \( (E = 15kN/m) \) in comparison with the bias extension experiments \( (E = 150kN/m) \).

The truss element model was used to predict the draping behavior of a dry fabric. During these simulations, the combination of flexibility in the FE approach and speed of computation illustrated how optimization studies could easily be performed with this model. A more sophisticated shear response can be incorporated. For example, viscoelastic terms can be included in the current model while the computing time remains limited.

Another 2D truss network, in combination with a continuum, is proposed by Fonteyn [22]. Fonteyn proposed a similar model compared with Sharma & Sutcliffe [16]. Although,
Figure 12: FE models for evaluation of yarn contributions to the overall stiffness [11].
Fonteyn [22] used a continuum material, instead of a diagonal element, to endow the model with shear stiffness. Fonteyn used linear elastic properties and used large deformation theory. The model was compared with experimental results and both the local and global response were satisfactory. The elastic properties of the model can easily be adapted to stiffer or weaker fabrics.

In both model discussed above stiff components, such as wires for electronics, can be implemented easily by increasing stiffnesses of single elements in a bigger grid.

### 3.1.4 3D cross-over model

Kawabata et al. [41, 42, 43] represented yarns in the woven network by truss elements in the cross-over model as shown in figure 14. Several researchers proposed similar models of the woven fabric for various purposes. For example, references [48, 49, 50] proposed cross-over models, based on the work of Kawabata et al.. Kawabata et al. proposed the cross-over model to describe the biaxial behavior of the woven fabrics [41]. Subsequently, a uniaxial-deformation theory was proposed [42] and finally a shear-deformation theory was presented [43]. King et al. [49] and Ching & Tan [50] used their models to analyze ballistic impact on a woven fabric. A difference between the two can be found in the constitutive relations used for the truss elements. King et al. [49] used a linear elastic relation, whereas Ching & Tan [50] used a viscoelastic model as shown in figure 15. Ching & Tan used three parameters to describe the viscoelastic elements. Viscoelastic elements are more often used in ballistic researches (see [47, 51]). Potluri et al. [48] extended the work of Kawabata et al. to describe not only the model shown in figure 14 but all three possible configurations shown in figure 16.
Figure 14: Cross-over model presented in various references [49].

Figure 15: Three-element viscoelastic model [50].

Figure 16: Three possible yarn configurations [48].
Kawabata et al. initially proposed a geometric description for the cross-over configuration as shown in figure 14. Subsequently, a mechanical model was presented where the tensile properties of the yarns are represented by blocks with mechanical properties. At the contact point also blocks were added to represent the compressive behavior of the yarns as shown in figure 17.

![Figure 17: Mechanical model proposed by Kawabata et al. [41].](image)

Blocks $A_1$ and $A_2$ represent the mechanical properties of the yarns and blocks $B_1$ and $B_2$ represent the compressive properties of the yarns. Empirical relations were used to obtain relations for all blocks. For simplicity reasons, blocks $A_1$ and $A_2$ were assumed elastic (linear and non-linear).

For each yarn a force equilibrium was considered. There are three acting forces from the blocks as shown in figure 18. These forces are caused by stretching of the yarns from points P and Q (for yarn one) or R and S (for yarn two) in $X_1$ or $X_2$ directions by $\lambda_1$ or $\lambda_2$ respectively (with the axes as in figure 18). These forces result in a force $F_r$ acting in the $X_3$ direction. This resulting force depends on the translation $h_i$ (as defined in figure 18).

The resulting forces ($F_{r1}$ and $F_{r2}$) of the two yarns act in opposite directions as shown in figure 19. Equilibrium is reached when $F_{r1} = F_{r2}$. From this condition, $h_1$, $h_2$, $F_1$ and $F_2$ can be determined.

As each combination of values for $\lambda_1$ and $\lambda_2$ has its own solution, the equilibrium was solved for a wide range of combinations. Several biaxial cases were examined and force-strain curves were obtained for these cases.

Using this model Kawabata et al. found fairly good agreement between the theoretical and experimental results; the theoretical and experimental results of examples with spun yarns (such as woolen yarns) show less than 5% difference. When using less compressible yarns
Figure 18: Force equilibrium proposed by Kawabata et al. [41].

Figure 19: Interaction between the yarns as proposed by Kawabata et al. [41].
(such as polyester-fibre yarns) the difference between the theoretical and experimental values becomes significantly larger, but remains below 20%.

The differences between theoretical and experimental results can be attributed to the lack of yarn-bending. The yarns are assumed to be infinitely stiff in bending. The differences caused by this assumption are particularly present at low strains \(0 \leq \epsilon \leq 0.05\), where the curvature of the yarns is at its maximum. At higher strains, the yarns are more straightened and the experimental fabric behaves more alike the model.

The model as presented by Kawabata et al. [41] is used to describe biaxial behavior. Analyzing the uniaxial behavior faces some difficulties using this model. The problem is that there is only one resulting force in \(X_3\) direction because the transverse yarn has no tension (in figure 19, \(F_{r1}\) or \(F_{r2}\) are zero). Kawabata et al. [42] therefore introduced an analytical differential equation representing the shear and bending stiffnesses of the transverse yarn. The introduced shear and bending stiffnesses of the transverse yarn result in the opposing force. The yarn on which the strain is applied, is still assumed to be perfectly flexible.

Similar as in the biaxial model, differences where less than 5% in the force-strain curve. Still, the bending properties of one of the yarns were neglected. This again resulted in differences between the theoretical and experimental results at low strains.

Finally, Kawabata et al. [43] proposed a model for shear behavior, again using the cross-over model. A force required to change the angle between the two yarns around the \(X_3\) axis was introduced as follows

\[
T_i = \pm T_{i0} \pm C_1 F_c \pm C_2 F_c \phi + C_3 \phi + C_4 \phi F_c
\]  

where \(T_i\) is the couple required to change the intersection angle \(\phi\) with a unit element, \(F_c\) the force between the two yarns and \(C_1, C_2, C_3\) and \(C_4\) are constants. Two assumptions were made before using equation (10); the yarns are assumed to be straight both before and after the shear deformation and the weave angles in the other directions \((X_1\) and \(X_2)\) are not changed (i.e. \(h\) is constant for both yarns). The constants \(C_1, C_2, C_3\) and \(C_4\) were determined by experiments. Comparing theoretical and experimental results, good agreement was achieved. Apart from the results between \(0^\circ \leq \phi \leq 2^\circ\), the differences were again less than 5%. In this case it is not very surprising as the constants were fitted on experimental data. The \(0^\circ \leq \phi \leq 2^\circ\) region show larger differences. These are caused by the assumptions made. Particullary the assumption that the yarns remain straight in shear deformation is most likely not satisfied in the experiments. Nevertheless, when accounting for yarn bending during shear, the model will become significantly more complex.

### 3.1.5 Discussion

In sections 3.1.1 - 3.1.4, four classes of models were reviewed. Some considerations on these models are discussed below.
Ben Boubaker et al. and D’amato model the fabric by modelling the structure. A disadvantage is that the computing time is considerable when the behavior of larger sized samples must be predicted. To prevent this, two common methods are available to simplify the models. One method is homogenization of the examined material. Another possibility is to use representative volume elements (RVE’s) to characterize the material behavior. The advantage of using a unit cell representation or using homogenization is that the complexity of the examined fabric is reduced, which results in less computing time.

The model of Ben Boubaker et al. has some similarities with the model proposed by Kawabata et al. Both models are 3D and both models analyze the fabric by considering the forces acting between the warp and weft yarns. Furthermore, both models have a description for yarn compression and the undulation that occurs and both models can describe the uniaxial and biaxial behavior of woven textile.

The major difference between the models is that Ben Boubaker et al. considers the yarn between two contact points as a collection of linear and rotational springs, while Kawabata et al. represents the yarn as one truss element. Considering that both models show a good agreement with experimental data, the less complex model of Kawabata et al. is to be favored above the model of Ben Boubaker et al. when analyzing uniaxial and biaxial behavior.

Another difference between Ben Boubaker et al. and Kawabata et al. is that Kawabata et al. incorporated shear stiffness in the model, while Ben Boubaker et al. did not. The method proposed by Kawabata et al. in principle can also be applied to the model of Ben Boubaker et al. although this may not be trivial.

Different as in Ben Boubaker et al. and Kawabata et al., Sharma & Sutcliffe proposed a 2D model. Through-thickness phenomena (e.g. yarn compression) are not taken into account. The major advantage of this model is its simplicity. Different material parameters can be easily implemented.

The model presented by D’Amato has the disadvantage that it was developed for small deformations. In practice often large deformations occur. Still this model is interesting as it emphasized the entangling effect occurring in the fabric, which contributes to the materials stiffness. This effect is lower in normal woven fabrics, but it is interesting as it contributes to the non-linear material behavior. Another remark is that all the three other models only have contact points whereas this model has contact surfaces.

Another advantage of the model proposed by D’Amato is that with this model local stress and failure analyses can be more easily performed in comparison with the other models. These analyses can be possibly required in the future to determine failure criteria. Stress analyses were not performed by others than D’amato. On the other hand, the FE model of D’Amato has significantly larger computation times than Sharma & Sutcliffe and Kawabata et al. and is therefore more expensive.
3.2 Knitted structures

For knitted fabrics, which have a structure which is more complex than that of woven fabrics, the modeling poses even more challenges. A general difference between knitted and woven structures is the names give to the principal directions. The directions in knitted fabrics are not called warp and weft, but the course and the wale direction. Choices have to be made weather to adopt simplifying assumptions or to model complex phenomena in detail. Because of the complexity of the knitted structure, various studies have been performed to get a geometrical description of the undeformed structure. Others have proposed mechanical models to obtain the mechanical properties of the structure. Also simplified mechanical models, which do not resemble the knitted structure geometrically, have been proposed to obtain the same mechanical properties.

3.2.1 Mechanical models

Several geometrical models have been proposed in the literature. First, the model of Ramakrishna [29] is elaborated and then other proposed models are compared with it. Ramakrishna [29] proposed a geometrical model of plain weft-knit fabric as shown in figure 20. The so called weft-knit fabric is a commonly used knitted fabric.

Figure 20: Schematic representation of a unit cell of plain-knit fabric [29].

Figure 20 represents an idealized unit cell in which the yarns are assumed to have a circular
cross-section and the projection of the central axis of the yarns on the plane of the fabric is composed of circular arcs. $O$ is the origin of the defined coordinate axe and the $OQ$ loop has its center $C$ with radius $ad$, $OC$ in figure 20, where $a$ is a constant and $d$ the diameter of the yarn. When defining the angle $OCP = \theta$ the coordinates in point $P$ are

$$x = ad(1 - \cos \theta)$$  \hspace{1cm} (11)$$

$$y = ad \sin \theta$$  \hspace{1cm} (12)$$

The function describing the height is then formulated as

$$z = \frac{hd}{2} (1 - \cos \frac{\pi \theta}{\varphi})$$  \hspace{1cm} (13)$$

with $\varphi = OCQ$ and $hd$ the maximum height at point $Q$. The unknowns in (11), (12) and (13) are $a$, $\varphi$ and $h$. Through analytical derivations they are obtained as

$$a = \frac{1}{4Wd \sin \varphi}$$  \hspace{1cm} (14)$$

$$\varphi = \pi + \sin^{-1} \left( \frac{C^2d}{(C^2 + W^2(1-C^2d^2)^2)^{1/2}} \right) - \tan^{-1} \left( \frac{C}{W(1-C^2d^2)} \right)$$  \hspace{1cm} (15)$$

$$h = \left[ \sin \frac{\pi \psi}{\varphi} \sin \frac{\pi \phi}{\varphi} \right]^{-1}$$  \hspace{1cm} (16)$$

where $W$ is the wale density, $C$ the course density and the angle $\phi$ (=HCB) defined by

$$\phi = \cos^{-1} \left( \frac{2a - 1}{2a} \right)$$  \hspace{1cm} (17)$$

The lengths of the loops are determined by

$$L = L_{OQ} = ad \varphi$$  \hspace{1cm} (18)$$

$$L_s = L_{MNOQR} = 4ad \varphi$$  \hspace{1cm} (19)$$

Ramakrishna [29] considered the $OQ$ portion of the loop as an assembly of short straight segments with length $\delta s = ad \delta \theta$. The orientation of each segment is giver by angles $\alpha$, $\beta$ and $\gamma$ with respect to the $x$, $y$ and $z$ axis as

$$\alpha = \cos^{-1} \left( \frac{x_n - x_{n-1}}{\delta s} \right)$$  \hspace{1cm} (20)$$

$$\beta = \cos^{-1} \left( \frac{y_n - y_{n-1}}{\delta s} \right)$$  \hspace{1cm} (21)$$

$$\gamma = \cos^{-1} \left( \frac{z_n - z_{n-1}}{\delta s} \right)$$  \hspace{1cm} (22)$$
Assuming $\gamma = 0$, Ramakrishna [29] proposed the cross-over unit cell model as shown in figure 21. Assuming that the yarns consist of many small segments, the elastic properties of each single segment were obtained as

\[
\frac{1}{E_x(\alpha)} = \left[ \frac{\cos^4 \alpha}{E_{11}} + \left( \frac{1}{G_{12}} - \frac{2\nu_{12}}{E_{11}} \right) \sin^2 \alpha \cos^2 \alpha + \frac{\sin^4 \alpha}{E_{22}} \right] 
\]

(23)

\[
\frac{1}{E_y(\alpha)} = \left[ \frac{\sin^4 \alpha}{E_{11}} + \left( \frac{1}{G_{12}} - \frac{2\nu_{12}}{E_{11}} \right) \sin^2 \alpha \cos^2 \alpha + \frac{\cos^4 \alpha}{E_{22}} \right] 
\]

(24)

\[
\nu_{xy}(\alpha) = E_x(\alpha) \left[ \frac{\nu_{12}}{E_{11}} \left( \sin^4 \alpha + \cos^4 \alpha \right) - \left( \frac{1}{E_{11}} + \frac{1}{E_{22}} - \frac{1}{G_{12}} \right) \sin^2 \alpha \cos^2 \alpha \right] 
\]

(25)

\[
\frac{1}{G_{xy}(\alpha)} = \left[ 2 \left( \frac{2}{E_{11}} + \frac{2\nu_{12}}{E_{22}} + \frac{4\nu_{12}}{E_{11}} - \frac{1}{G_{12}} \right) \sin^2 \alpha \cos^2 \alpha + \frac{1}{G_{12}} \left( \sin^4 \alpha + \cos^4 \alpha \right) \right] 
\]

(26)

Where $E_x(\alpha)$ and $E_y(\alpha)$ are the Young’s moduli in $x$ and $y$ directions, respectively, $\nu_{xy}(\alpha)$ is the Poisson’s ratio and $G_{xy}(\alpha)$ the in-plane shear modulus of the segment. In these equations $\gamma$ is assumed to be zero and $\beta$ is expressed as a function of $\alpha$. The descriptions for the single segments can be evaluated for the entire length of the curve in the unit cell by integrating the Young’s modulus in $x$—direction as

\[
\overline{E}_x = \frac{1}{L} \int_0^L E_x(\alpha) \, dx
\]

(27)

with $L$ the total length of a yarn in the unit cell. The other elastic parameters, $\overline{E}_y$, $\overline{G}_{xy}$ and $\overline{\nu}_{xy}$ are determined similarly. At this point, the stiffness matrix of one curved yarn in the unit cell, $\overline{Q}_{ij}$ has been derived. The second yarn has a similar description, however with $\alpha$ replaced by $\alpha + \pi$, since the orientation of this yarn is $180^\circ$ rotated compared with the first yarn. Assuming that each curved yarn is subjected to the same strain in $x$—direction the total stiffness matrix is given as

\[
A_{ij} = \sum_{n=1}^{2} L_n \overline{Q}_{ij(n)} \quad (i, j = 1, 2, S)
\]

(28)
The input parameters for this model are $W$, $C$ and $d$. Both $W$ and $C$ were experimentally determined and $d$ was analytically estimated. No results were given using this model. Ramakrishna [29] also analytically determined the tensile strength for single yarns. The analytical model was compared with experimental results to fit the parameters.

Whereas Ramakrishna [29] has only used circular arcs in the geometrical model (which is never in complete agreement with reality), Kurbak & Ekmen [33] have proposed a geometrical description using elliptical integrals. Figure 22 shows a schematic representation of the proposed model by Kurbak & Ekmen.

![Figure 22: (a)schematic drawing of the loop central axis: (b) drawing of the reel loop model [33].](image)

Besides the difference in shape, some of the assumptions made by Kurbak & Ekmen [33] were different than those of Ramakrishna [29]. One of the additional assumptions is that interlocking, i.e. the point/surface where the two inclined loops make contact, occurs at the broadest point of the loop (point B in figure 22b). This assumption slightly simplifies the complex geometrical analysis. However, it implies that friction between yarns is not included, as models with friction included have the interlocking point higher in the loop. The aim of Kurbak & Ekmen [33] was reached though; creating a small diameter tubular technical fabric model. Comparisons with experimental results were satisfactory. The proposed model was a base for analysis of several phenomena in knitted structures, such as fabric spirality [34], purl fabrics [35], miss stitches [36] and tuck stitches [37].

Another way of for describing the properties of knitted structures was proposed by Hepworth & Leaf [32]. Hepworth & Leaf aimed to describe the ‘relaxed’ state of the knitted structure. This is the configuration towards which the fabric tends when there are no external loads, i.e. the ‘minimum-energy’ state of the fabric.

Equilibrium equations were proposed and solved for a yarn using forces, momentum, twisting forces and the corresponding stiffnesses of the yarn. To solve this system some assump-
tions have been made; the yarn is considered inextensible, incompressible and naturally straight, and the cross-section is assumed to remain circular and perpendicular to the yarn’s central axis after bending. Hepworth & Leaf [32] assumed two contact points for one interlocking system instead of one. Due to symmetry assumptions only a quarter-loop was regarded. The proposed system is shown in figure 23.

![Figure 23: The forces acting on a quarter loop. [32]](image)

As a result of this model several loop shapes are obtained for different $d/l$ ratios, where $d$ is the diameter of the yarn and $l$ the length of one loop in the knitted structure. Different fabric thicknesses are obtained by varying this dimensionless quantity. Another aspect that was observed by Hepworth and Leaf [32] is jamming. Jamming occurs when two different loops or loop parts come into contact with each other (apart from the interlocking). With an increasing $d/l$ ratio both course and wale jamming is observed. When the ratio is even more increased, the contact forces also increase.

Jamming is also observed by Shanahan & Postle [31] using a model based on their earlier work. Shanahan & Postle [30] proposed a model which is comparable with the model of Hepworth & Leaf [32]. However, it is based on some what different assumptions, namely that forces and couples only act at the interlocking point and the force is only acting in the course direction, while the couple is acting perpendicular to the tangent to the yarn. Similar as in the study of Hepworth and Leaf [32], the minimum energy state was derived to obtain the solution.

One of the remarks of Shanahan & Postle [30] is that the strain energy, when plotted against the loop configuration, has a fairly shallow minimum. This implies that this state will most likely not be reached in experiments. Simulations and experiments are therefore likely not to match. Another disadvantage of the models of both Shanahan & Postle [30] and Hepworth & Leaf [32] is that the relaxed state of the yarn is assumed to be straight, which is reasonable for stiff yarns (which were used in both studies), but not for compliant textiles. Nevertheless, when deforming knitted structures and releasing the force on the fabric afterwards, most knitted structures tend to return to the original shape, which
implies that some sort of relaxed state exists, even for flexible yarns. This so-called yarn setting has to be further examined according to Shanahan and Postle [30].

Subsequently, Shanahan & Postle [31] have analyzed jamming. Geometrical conditions were derived for course and wale jamming to occur. It was observed that in loosely knitted fabrics it is not likely that jamming occurs and in tight fabric, from $d/l > 0.0625$, jamming in both course and wale direction can occur. When tensile experiments are performed, jamming can occur in the perpendicular direction of the tensile direction. This leads to higher stresses in the stress-strain curve for the fabric. This non-linearity is observed in experiments, for example by Arajo et al. [38].

Following up on Arajo et al. [38], where experimental results and some general considerations on weft-knitted fabrics were discussed, Arajo et al. [39] proposed a geometrical model of the knitted structure, again based on force equilibrium. Similar assumptions were used as in the study of Shanahan & Postle [30]. Simulation results are compared with experimental results and a satisfactory agreement was found. Furthermore, simulation results were compared with those of Shanahan & Postle [30] and showed close agreement.

### 3.2.2 Simplified mechanical models

All previously mentioned studies aimed to geometrically resolve the knitted structure. Arajo et al. [40] have proposed a simplified mechanical model to represent the knitted structure. This simplified representation can be favorable since the simulations with the models as mentioned before can lead to very long simulation times for large or complex shaped structures.

![Figure 24](image.png)

Figure 24: (a) Plain weft-knitted fabric structure and (b) the corresponding mechanical model [40].

Figure 24 gives a schematic representation of the simplified model. Figure 25 additionally shows the smallest unit cell of this structure. The lengths as well as the mechanical properties of the elements have been determined by experiments. The following non-linear
relations were used for the element behavior:

\[ F_1 = M_1 \epsilon_1^{n_1} \]
\[ F_2 = M_2 \epsilon_2^{n_2} \]

where \( F_1 \) and \( F_2 \) are tensile forces, \( \epsilon_1 \) and \( \epsilon_2 \) the axial elongations and \( M_1, M_2, n_1 \) and \( n_2 \) the experimentally determined parameters of the different sections. Simulation results of this model were compared with experimental results and showed good agreement. The model was used to predict the draping behavior of the knitted fabric.

Another simplified model is the model proposed by Lim [28]. Lim has proposed a simplified discrete unit cell model of plain weft-knitted fabric. The model is based on the assumptions that no friction and slip occurs between the yarns. The model as shown in figure 26 neglects several significant phenomena. Lim [28] has only proposed the structure as in figure 26 and no further comments were made.

### 3.2.3 Discussion

The first aspect that can be noted is that the simplified mechanical model is much simpler compared with the geometrical and (non-simplified) mechanical models.

The question arises whether the simplified model is sufficient for describing the complex knitted structure. For the overall material response this may be the case. Nevertheless, when certain particular phenomena are to be examined this model does not suffice. For example when the wear on threads, due to the friction, is of interest, no relevant information can be extracted from this model, whereas in the detailed models, quantities of friction can be derived.

In the detailed models assumptions were made as well. In all models the yarns are assumed as a continuum, which neglect a significant part of energy loss in the system. The major
difference between the geometrical and mechanical model is that the mechanical model assumes the single yarns to be straight when released. In practice this is usually not the case. Possibly a combination of the two models can approach reality, i.e. when the yarns are assumed to be relaxed at a certain curvature. By including this in the existing model, the relaxed state of the model and that in experiment might be closer.

Regrettably, no simulation results were shown of the geometrical model of Ramakrishna [29]. This was perhaps left out because a more detailed analysis is still necessary to assess the full applicability of this method. In its present version, the diameter of the yarns is considered to be constant, which implies no influence of compression, and yarn interactions (friction) were not analyzed.
4 Macroscale analysis

In macroscale analysis not the meso structure, but the global response as result of this structure is the most important aspect. When analyzing on a macroscale, significantly larger specimens can be considered e.g. $10^{-2} - 10^{2} m$.

In this chapter three different types of models are discussed: a discrete model, a continuum model and a semi discrete model.

4.1 Discrete model

Ben Boubaker et al. [10] proposed a discrete model of woven textile in which the basic pattern is represented by stretching springs, connected at nodes where a rotational stiffness is added by flexional springs. Shear springs and torsional springs are implemented as shown in figure 27.

This combination of different types of springs provides a model that can describe many deformation modes such as torsion, stretching, shear and bending. Although this model can describe these deformations, it is not able to describe buckling and post-buckling; this is an aspect that needs further development.

4.2 Continuum model

An example of a continuum model for fabrics is the model of Lim [28]. As with most continuum models, Lim uses a standard mechanical approach for the developed continuum model. The material is assumed to be homogeneous isotropic and linear elastic. The
material properties are based on a material property database, obtained from mesoscale modeling.

On the other hand, Ng et al. [52] recognized that the warp behavior of a woven fabric is rarely identical to the weft behavior, even in the case of plane weave fabric of identical yarns in both directions. This is caused by the manufacturing process. For this reason Ng et al. [52] have proposed an anisotropic material model. The Young’s modulus is built up from two parts. The first part describes the response within the elastic limits and the second part beyond the elastic limit. Due to the anisotropy the response depends on the angle of orientation. Both parts can be written as:

$$E(\theta) = \sum_{i=0}^{in} \{a_i \cos^{2i}(\theta)\}$$

(31)

where $a_i$ are constants and $in = 2$. Both functions (within and beyond the elastic limits) were fitted on experimental results and verified for different angles. The stress strain curve is defined as

$$\sigma = \epsilon E_s(\theta), \epsilon \leq \epsilon_y(\theta)$$

(32)

$$\sigma = \sigma_y(\theta) + [\epsilon - \epsilon_y(\theta)] E_{sl}(\theta), \epsilon > \epsilon_y(\theta)$$

(33)

where $\sigma$ and $\epsilon$ are the stress and strain respectively, $\sigma_y(\theta)$ and $\epsilon_y(\theta)$ are the elastic stress and strain limits of the fabric, $E_s(\theta)$ the modulus below the elastic limit and $E_{sl}(\theta)$ the modulus above the elastic limit.

Another example of a continuum model that is used is Feron [25]. Feron used a combined experimental-numerical approach to characterize and validate electronic textile substrate behaviour. In order to model the textile substrate, an elasto-plastic continuum model is applied, which regards the textile substrate as a sheet in a plane stress state.

To be able to model the textile substrate with this continuum several assumptions were made: the initial yield stress is chosen low, i.e. the ”complete” loading curve is a combination of elastic and inelastic behavior. Feron [25] fitted the elastic parameters on the unloading behaviour, whereas the inelastic parameters were based on the inelastic loading behaviour. This combination of elasticity and inelasticity is physically interpreted as bending of yarns and slipping of yarns. Secondly, power law hardening is used with a power $n \geq 1$, as opposed to the usual application to metals where $n \leq 1$. Lastly, the Hill yield criterion is applied to account for anisotropy in the yield stress.

4.3 Semi-discrete model

A more innovative approach was presented by Hamila & Boisse [20]. They have proposed a semi-discrete approach using a new semi-discrete three node finite element, shown in
figure 28. The three-node element is made up of warp and weft yarns of which the tension and shear energy are considered. The directions of the warp and weft yarns are arbitrary with regard to the element edges, which is important in the case of simultaneous multiple draping simulations and including remeshing. The material data used in the simulations was obtained from straightforward tensile tests. Bending of the elements is neglected. The semi-discrete approach avoids difficulties that occur in the experimental characterization of a continuum model at large strains for a fibrous material.

4.4 Discussion

The major difference between discrete and continuum models is that the discrete (or discontinuous) models describe the fabric with various connected components, while continuum models describe the fabric as a uniform material with homogenized fabric properties. Note that this latter this does not imply that the discrete models cannot have a homogeneous response.

The mechanical properties of the continuum and discrete approaches can be obtained from meso/micro-scale analysis as performed by Peng and Cao [18], where a continuum model is proposed. For discrete models it is difficult to obtain parameters for the different discrete elements from analyses on meso/micro-scale. The discrete models are mostly fitted on the results of experiments.

An advantage of continuous models is the versatility with respect to various types of structures, accounting for the existing material nonlinearities and anisotropy. Moreover, continuous models allow computationally efficient large-scale simulations.
An advantage of the discrete models is that they can be used to predict the structural behavior of a fabric in advance before it is manufactured. On the other hand, large-scale application is difficult as it needs high computing power due to the large amount of degrees of freedom.

Compared with the discrete approach, the semi-discrete approach reduces the amount of degrees of freedom significantly, and thereby the computing power required.

The disadvantage of all macroscopic approaches is that none of these models include yarn compression or undulations. Although the influence of these phenomena is generally relatively small, it can increase for instance when fatigue occurs.
5 Multiscale analysis

In some studies analyses are performed on two or three scales. Results obtained on one scale provide material properties for the next. In this chapter two multiscale analyses are discussed.

5.1 FE homogenization approach using shell elements

Peng and Cao [18] have used two methods to perform analyses on different scales and combined them into a final model. Figure 29 shows the performed steps. An assembly of microscopic unit cells, representing fibers in the yarn (2), were assumed to describe the single yarn behavior (see figure 30). To obtain the mechanical behavior of one unit cell, a detailed finite element model is developed to model the unidirectional E-glass/epoxy (white/gray in figure 30 respectively) composite unit cell (1). Homogenization was employed on the unit cell to obtain the overall elastic constants. Comparisons were made with other approaches (for example Halpin-Tsai's equation [27]) to evaluate the homogenization. Good agreement in axial, transverse and shear deformation have been observed. Subsequently, as depicted in figure 29, a mesoscale unit cell finite element model was developed (3). This model consisted of elements with elastic constants obtained from the homogenized microscale unit cell (1). Extension tests were performed to characterize the force-displacement behavior of this mesoscale unit cell model using finite element analysis. Finally, a shell element (4) with the same mechanical behavior was obtained from simula-

Figure 29: Multiscale material approach og Peng & Cao [18].
tions with the mesoscale unit cell (3). This shell element was used to predict draping of the fabric (5).

5.2 Fibrous vs. Continuum yarn

Another author that proposed a multiscale model is Durville [44]. The aim of this study was to understand and identify phenomena involved at different scales in fibrous materials. The fibers were modeled by three dimensional beam elements based on an enriched kinematic model which describes the fibers by three vector fields; one translation of the centroid of the fiber and two to represent the planar and linear deformations of the cross-section of the fiber. For contact between fibers, a Coulomb’s law was used which included a small reversible elastic displacement before sliding occurs [45]. The numerical detection of contact points can be inefficient even for small models. Durville [46] has proposed an efficient method to solve this problem however.

Using the properties of the fibers, a mesoscale structure was developed by using numerical simulations. A 6x6 yarn structure consisting of 408 fibers (≈80000 contact points) was constructed. Also a mesoscale model, where each separate yarn was modeled as a continuum was employed (as shown in figure 31). Both the fibrous and the continuum model were provided with similar mechanical properties. The purpose of the continuum model is to provide a detailed analysis of the strain localization. In the continuum model, Green-Lagrange strain tensor has been used.

Results of simulations of the continuum model have shown strong inhomogeneities in the single yarns in all simulations. This was not the case in the fibrous model. This raises the question if it is valid to model a yarn as a uniform material.
5.3 Discussion

An advantage of the analyses on different scales is that they can easily be applied for other textiles. On the other hand, a disadvantage of the multiscale analyses is that they contain a series of time consuming steps and numerical simulations.

The two methods described in this chapter are quite different and cannot easily be compared. The reason for the difference in methods is that the aim of the two studies was different: Peng & Cao [18] aimed to describe the draping of a piece of fabric, while Durville [44] particularly aimed to identify phenomena on the micro- and mesoscale.
6 Concluding remarks

Models on three different scale have been described. Most of the proposed models have been strongly influenced by the purposes for which they were developed. Each of the researchers aimed to propose a model that is as simple as possible and still able to describe those aspects of the material behavior that were required. It is thus important to know the purpose of the model before developing one. Two important aspects are the accuracy and the computing time of the model.

Each of the two aspects mentioned above are limiting the other. If the accuracy increases, the computing power necessary will probably increase as well and vice versa. In each study a compromise has to be made between these two aspects. This consideration will influence on which scale the analysis will take place: the smaller the scale, the more details can be accounted for.

The mechanical behaviour of textiles is characterized by the flexibility caused by its structure. Only in mesoscale analyses the structure of the textiles is actually incorporated. Microscale analyses are performed on smaller scales than the structure and are thus independent of any structure influence. On the macroscale, the structure is not explicitly examined, but it nevertheless governs the material behaviour.

The mesoscale is the scale in which the most analyses are performed on textiles. The reason for that is that mesoscale analysis can provide insight in the characteristic behaviour of textiles. Several phenomenon can be examined which cause this characteristic flexible behaviour. Mesoscale models differ a lot. Both the choice of regarding specific phenomena and the difference in structure are the cause of that.

The macroscale analyses are performed by continuum, semi-discrete and discrete models. In all of the models material parameter are implemented into the model to provide the mechanical behaviour of the material. As these parameters are mostly extracted from experiments, the mechanical behaviour of these macroscale models will be similar to the real behaviour. The disadvantage of models on the macroscale is that it does not provide any information about how this mechanical behaviour is established. Localities such as fatigue and yarn compression cannot be examined by macroscale models.

Multiscale analyses can be performed to eliminate some disadvantages from analysis on one of the scales. The major disadvantage of multiscale analysis is that it is time consuming.
References


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