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Mechanical Analysis of Woven Fabrics: The State of the Art

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1. Introduction

The automation and integration of processes in the textile industry is dictated by the increasing need to offer specialized products at optimum quality and low cost, satisfying at the same time the fast cycles of fashion trends or in the case of technical applications the delivery of products of high quality and of exact properties. Under these premises, computer engineering tools, such as computer-aided engineering (CAE) and computer-aided design (CAD), have recently gained attention. The revolutionary role of CAE and CAD tools in the textile industry is the guaranty that the final product meets the set specifications, optimizing thus the quality control procedure. Moreover, the prediction of the properties and the aesthetic features of the product before the actual fabrication can essentially benefit the textile research community [Hu and Teng, 1996]. Especially nowadays that textile materials can be used for the production of a wide range of technical products, such as reinforcements in composites for aerospace or marine applications or textiles for medical applications, the prediction of the end-product's mechanical properties is of major importance. Furthermore, the textile raw materials are processed under low-stress conditions and it is thus reasonable to assume that the knowledge of the possible modifications introduced via the manufacturing process is necessary for the final product realization (Hu, 2004).

Textiles are flexible, anisotropic, inhomogeneous, porous materials with distinct viscoelastic properties. These unique characteristics makes textile structures to behave essentially different compared with other engineering materials. Moreover, textiles are characterized by an increased structural complexity. Their properties mainly depend on a complicated combination of their structural units and their interactions. The complicated nature of the textiles' mechanics makes them ideal candidates for a mechanical analysis using computer-based methods.

This paper focuses on the investigation of the modeling attempts of woven fabrics. The woven fabrics' weave patterns as well as the deformation mechanisms of their consistent yarns make these structures modelling extremely challenging (Parsons et al., 2010). An extended literature review of the computational models for the deformation of woven fabrics is presented. Based on these models, the difficulties towards a comprehensive model for textile structures are highlighted. Taking into account the existent literature, the perspective of developing a widely accepted integrated CAE environment for textiles (Hearle, 2006), is also extensively discussed.

2. Textile structures and their mechanical behavior

Since this study focuses on the investigation of the existent woven fabrics' simulation techniques, some introductory remarks concerning the basic structural units of these unique substrates, are thought to be extremely useful. Textile fabrics are made of interlaced yarns which consist of the basic element of every textile product, the fibres. Fabrics are classified according to their manufacture process as knitted, woven and non-woven.

The computational representation of textiles is hindered by the geometrical complexity of the textiles' basic structural units (fibres and yarns) as well as of the fabrics' weaving and knitting patents. The aforementioned characteristics of the textiles woven fabrics result in complicated deformations even in cases of simple loading. For example, the tensile deformation of a spun yarn corresponds to the superposition of bending, tensile and compression of the constituent helically arranged fibres. Furthermore, contact phenomena, as sticking and sliding interaction, should be also taken into account in the mechanical deformation analysis increasing thus further the complexity of the mechanical study.

Fabric mechanics study often leads to the introduction of models with simplifying assumptions. The yarn, which is usually assumed as a homogeneous material, is considered as the basic structural unit of the fabrics. The elastic properties of the homogeneous yarn result from the elastic properties of the fibres and include the non-linear structural synergy of them within the yarn body. Even if the yarns are assumed as homogeneous materials, the contact phenomena dominate the deformation procedure of the fabrics. Actually, the friction effects support the stability of the textile structures. The contact phenomena have also a great significance for the stress and strain distribution in a fabric subjected to deformation. The friction energy losses appear during the load transferring along threads. Thus, very often, uneven load distribution appears within the textile structures.

Due to the large deflection effects and the nonlinearity of the textile structures' deformation phenomena, the fabrics mechanics study requires special attention. The relative large deformation of the fabrics arises from the flexibility of the textile fibres and yarns as well as from the structural details and the way of the load application. The yarns present high deformability which results from the low values of packing factor (the ratio of the fibres volume to the total volume of the yarn). The air trapped between the fibres is easily removed during the axial loading imposing the reduction of the apparent yarn cross sections and thus the high deformation of the yarns which is obviously transferred to the fabrics. Moreover the pattern of the fabrics itself and especially the structure of the fabrics, supports the development of high deformations. From the structural point of view the fabric pattern can be considered as a multi-body system of yarns. The tensile deformation of the fabric corresponds to the synthesis of two processes, the bent yarns' straightening and their subsequent elongation. The first process dominates in the lower loading stage and the second process appears upon the increase of the load. Thus the load-deflection curves of a textile structure subjected to tensile deformation is strongly nonlinear. The nonlinearity is also supported from the change of the contact status between the yarns, the large deflection effects observed even within the unit cell of the fabric and finally the material nonlinearities

2.1 Technical applications of textiles

Although conventional textiles are primarily used for clothing, the use of a variety of raw materials as well as the development of new manufacturing processes led to a considerable expansion of their possible applications. The importance of aesthetic and decorative

characteristics of textiles has been decreased by the new materials' performance and functionality. The growing recognition of the textiles potentials led to revolutionary new technical applications which according to Techtextiles (the international Trade exhibition for technical textiles) are (Horrocks, 2000):

Agrotech: agricultural (nonwoven for wind protection)

Buildtech: building and construction (awning, concrete reinforcements)

Clothtech: clothing (garments)

Homotech: household (curtains, wall covering)

Indutech: industrial applications textiles (filters)

Medtech: medical (bandages, sutures)

Mobitech: mobility (ropes, seat covers)

Oekotech: eco-friendly textiles (recyclable composites)

Packtech: packaging (nets, wrappings)

Protech: protection (bullet-proof jackets, uniforms)

Sportech: sports and leisure (carbon-fibre composites for racquet frames)

Geotech: geotextiles (nonwovens for drainage, reinforcement)

Over the last decades there is also an intensive need for high-tech materials with "life functions". Consequently, research interest has been moved towards the development of textile-based structures which change their properties in response to an external stimulus, offering products with increased functionalities. The so called "intelligent", "smart" textiles in conjunction with the wearable electronics usually consisting of electronic modules incorporated into textiles, support activities in military, telemedicine or rehabilitation (Rossi et al. 2006; Tang, 2007; Cho et al., 2009). Textiles' flexibility, indicative of the wearer's comfort, makes them ideal candidates for interfaces in contact with the human skin. Based on these assumptions, a large number of wearable electronic systems have been developed (Dunne et al., 2005; Xu et al., 2008; Tognetti et al., 2006). Smart textiles development requires the synergistic action of different disciplines such as textile science and engineering, natural sciences, material science, mechanical engineering, electrical and computer engineering and informatics, making this promising research area extremely challenging. Furthermore, the attention attracted by this dynamic sector of textile research is thought to make a contribution towards a cost effective commercialization of innovative textile-based products aiming in the improvement of people's quality of life.

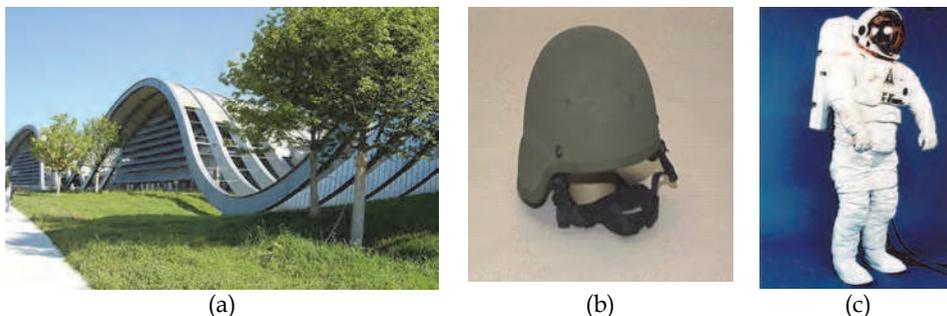


Fig. 1. Technical applications of textiles (a) Fabric for solar protection used in the Paul Klee museum, (soltis-textiles, 2011), (b) DuPont's Kevlar® XP™ developed for hard armor applications, (DuPont, 2011), (c) Space suit developed by ILD Dover (ilddover, 2011)



Fig. 2. Smart textiles (a) Interactive Led dance shoe by Moritz Waldemeyer (waldemeyer, 2011) (b) Luminate textiles by Phillips (smarteconomy, 2006), (c) Led Dress by Cute Circuit (crunchwear, 2010)

3. Mechanical modelling of the textile structures

3.1 Classification of the modelling approaches

During the last decades, several methods were adopted for the mechanical modelling and analysis of the textile structures. A basic classification, according to the modelling method used, divides them into the analytical and numerical or computational approaches. The dominant engineering design culture played important role for the development and the succession of these approaches. Classical modelling methods find in textiles an attractive application field. Another essential classification of the modelling of the textile structures is made according to the scale of the model. There is micromechanical, mesomechanical and the macromechanical modelling. The micromechanical modelling stage focuses on the study of the yarns, tows even fabrics taking into account the structure, orientation and mechanical properties of the constituent fibres. The mesomechanical modelling, on the other side, studies the mechanical characteristics of the fabric unit cell considering the yarns as homogenous structures. Finally the macromechanical modelling stage is referred to the prediction of mechanical performance of the fabric in complex deformations, as drape, studying the fabric as a continuum material.

Although the mentioned modelling stages were developed as distinct analysis approaches, their integration in a compound modelling approach was directly rised. Thus the textile society implemented a modelling hierarchy (Takano et al., 1999; Lomov et al. 2004; Bogdanovich, 2006) based on three modelling scales: the micromechanical modelling of yarns, the mesomechanical modelling of the fabric unit cell and the macromechanical modelling of the fabric sheet (Figure 3).

According to the integrated textile modelling concept, the only inputs in the total design procedure are the fibre properties, the yarn structure and the fabric structure. In the first modelling stage, the fibre properties and the yarn structure (yarn type, number of fibres, orientation) are introduced as input parameters for the mechanical analysis of the yarn and the calculation of the yarn properties. Then the yarn properties are transferred in the second

modelling stage. The selection of the required yarn properties and their attribution in the modelled yarns corresponds to a homogenization procedure that connects the two individual stages. Moreover the woven fabric structure is introduced in the mesomechanical modelling stage. At the current stage the yarns are represented as continuum structures and the analysis is limited on the study of the fabric unit cell. Then a second homogenization stage is required for the connection of the second and the third modelling stage, defining the required properties of the unit cell and their attribution in the continuum fabric models. Finally the macromechanical modelling stage based on the generation of simplified structure (usually continuum material) predicts the mechanical performance of extended fabric pieces in complex deformations. Each individual modelling procedure such as their interface presents significant obstacles.

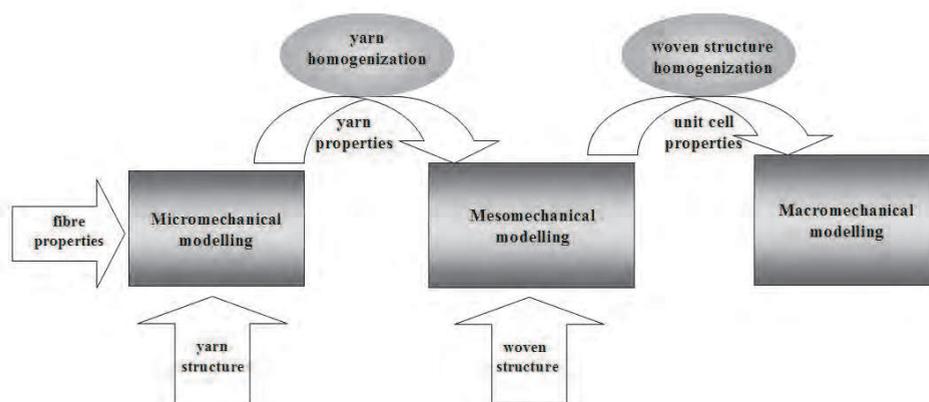


Fig. 3. Integrated textile modelling.

3.2 Classification of the deformations

The substantial difficulty arising in textile mechanics consists in the calculation of the superposed deformations in the microscopic scale. Even a simple deformation of the woven fabric, for example a tensile deformation, incurs a complex deformation mechanism of straightening, tensile, compression and sliding of yarns in the mesoscopic scale and respective deformations of fibres in the microscopic scale. Moreover the percentage of the deformation increases when it is referred to the microscopic scale since the subjected structures are smaller. For example, a 5 % shear deformation of a fabric could impose a huge displacement of the constituent fibres. Thus a simple deformation in the macroscopic scale corresponds to complex deformations in the microscopic scale. However the classification of the deformations is based on the macroscopic level. Thus the tensile, shear, bending and compression of the fabric sheet are considered simple deformations. The complex deformation of fabrics is mainly referred to the drape test. The performance of a fabric in drape is very interesting for the aesthetic effects and the dynamic functionality. The fabrics have the ability to undergo large, recoverable draping deformations by bending in single and double curvature providing a sense of fullness and a graceful appearance. Especially when the fabrics are used as reinforcement materials for the construction of composites, drape is very important since it determines the formability of the fabric in the matrix. The

drapeability of the fabric reinforcement offers the advantage of bending around double-curvature mould producing complex shaped composite parts.

4. Analytical modeling

The first mechanical modelling and analysis attempts of the textile structures started about a hundred years ago. The earliest publication probably is from R. Haas in the report of the National Advisor Committee for Aeronautics in 1918 (Haas, 1918). It is worth to mention that NACA is the early form of the today's NASA of the US. This publication is the translation from the German of the original article dated back on 1913 appeared in a German Journal. The work of Haas is of great importance. Although it is the first known, it is characterized by its integrated character. It brings together the theoretical and practical aspects up to the testing and application topics. However the work of Haas remained unknown for a long period while the work of Peirce (Peirce, 1937) was considered as the starting reference for the analytical mechanical modelling of the textile structures. The researchers focused on the application of the existent analytical methods already used in other sectors of engineering. The main characteristic is the balance between the simplifications introduced and the precision of the modelling. The energy methods and the elastica theory are dominating in these attempts.

4.1 Micromechanical modelling of simple deformations

In the field of the analytical modelling of the textile yarns, several investigations focused on multi-filament twisted yarns. Purpose of these investigations was the prediction of the response of a twisted yarn when subjected to a certain deformation. It was supposed that the mechanical parameters such as the load-elongation curve of the constituent fibres, the twist density, the initial specific volume etc are given. The analysis focused on the correlation of the macroscopic distortion of the yarn with the microscopic response of the constituent fibres. A basic challenge in the modelling of the yarns is the balance between the realistic formulation and the idealization required for a theoretically treatable model. In the most cases the yarn was considered as being made of continuous filaments of circular cross-sections and constant linear density along their length. All the fibres were assumed to have identical properties and to be perfectly elastic. The cylindrical-helix model of Hearle et al. (Hearle et al., 1959), the conical-helix model of Önder and Başer (Önder & Bacer, 1996) and the statistical model of Komori (Komori, 2001) approached the yarn mechanical modelling from different points of view, depending on the considered alignment of the fibres. The tensile, bending and torsional behaviour of the yarns were approached using the force, the stress-analysis and the energy methods (Backer, 1952; Platt et al., 1959; Freeston & Schoppee, 1975; Choi & Tandon, 2006; Park & Oh, 2006).

4.2 Mesomechanical modelling of simple deformations

Starting point for the analytical modelling of woven fabrics was the uniaxial/biaxial deformation of the plain woven structure. The proposed approaches were based on three principal underlying geometrical models of plain weave (Dastoor et al., 1994). The "flexible thread" model of Peirce (Peirce, 1937) assumed the yarns infinitely flexible, incompressible and inextensible, without bending rigidity and having circular cross-sections (Figure 4, Figure 5). The analytical transcendental equations proposed by Peirce for the systematic

description of his model cannot easily give a solution. Thus graphical and nomographic tools were presented in order to support the users. Peirce's model has been modified later towards a better representation of the real fabric structure. Thus the assumptions of the race-track (Figure 6) or elliptical (Figure 7) yarn cross-sections (Kemp, 1958; Olofsson, 1964b) were adopted for the fabric modelling. The concept of the elastica model (Peirce, 1937), in continue, introduced the yarn bending rigidity in the analysis. According to this model the shape of yarn axis can be obtained by treating the yarns as elastic slender rods subjected to transverse point forces, equidistant but alternating in direction. In general, the mentioned models and their later modifications used the equilibrium, energy or elastica method for the mechanical analysis.

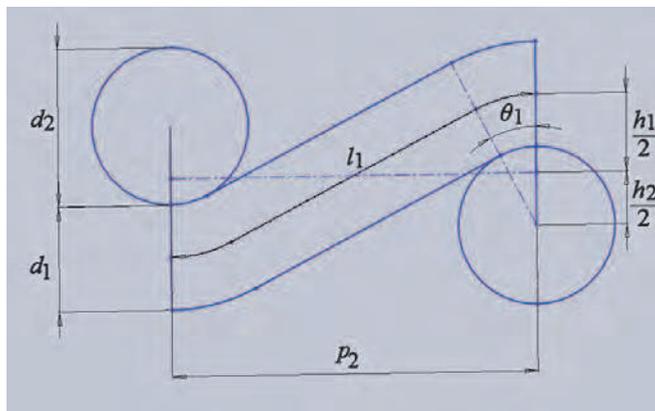


Fig. 4. Plain woven geometry proposed by Peirce.

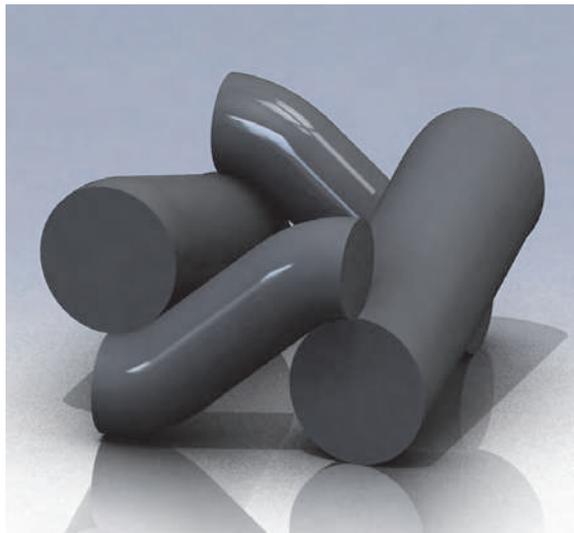


Fig. 5. 3D representation of woven model proposed by Peirce.



Fig. 6. 3D representation of woven model proposed by Kemp.

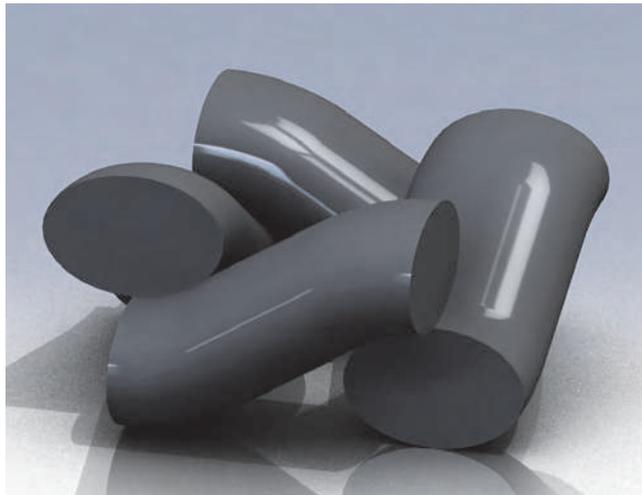


Fig. 7. 3D representation of elliptical model proposed by Olofsson.

An approach including the effect of crimp and yarn extension, based on a flexible thread model was proposed by Freeston et al. (Freeston et al., 1967). The yarns were assumed as homogenous, linear elastic materials with linear work-hardening. An elastica model declining from the assumption of the standard shape yarn cross-section was published by Olofsson (Olofsson, 1964a). The shape of the cross-section of the yarns was considered as a function of the forces acting on them and the degree of set. The mathematical analysis was given on equilibrium conditions, on stress-strain relationships in extension and compression and on energy in bending. The effect of fabric set was included, also, in the work of Grosberg and Kedia (Grosberg & Kedia, 1966; Grosberg, 1966). They adopted an energy method on small deformation for the investigation of the initial load extension modulus of completely relaxed woven fabrics, while the yarns were assumed inextensible and

incompressible. Another approach based on the elastica theory including linear extensibility of the yarns was given by Dastoor et al. (Dastoor et al., 1994). They assumed the yarns to be homogeneous, weightless slender rods, frictionless and undeformed by shear forces. In addition the yarns were considered as having circular section which does not deform under external forces. A computational implementation was adopted for the solution of the equilibrium equations. The large biaxial deformation of partially and completely set plain woven fabrics was presented by Huang (Huang, 1979b; Huang, 1979a). His approach was based on the elastica model of yarns in the undeformed fabric and the combined action of extension and bending was considered for the fabric deformation. The introduction of bilinear moment-curvature relation (due to the sliding of the fibres within the yarn) in combination to the contact deformation of the yarns increases the reliability of the study. The "sawtooth" geometrical model was proposed by Kawabata *et al.* (Kawabata et al., 1973). The mechanical analysis was based on the force equilibrium and the displacement of the warp and weft yarns in the thickness direction of the fabrics at the contact point of the crossing threads. Although the geometrical representation of the unit cell was approximant, the deformation effect at the cross-over points was taken into account. Most of the models described assume an unrealistic invariable cross-sectional yarn shape along the yarn path, where Gong et al. (Gong et al. 2010), in a recent study moves towards a more realistic representation of woven yarns, suggesting an ellipse model with a variable yarn cross-sectional shape based on the various parameters, including fibre type, yarn count, yarn twist factor and cover factor. An alternative geometric model of woven fabric, based on the yarns' packing density as well as general fabric data, has been suggested by Dolatabadi and Kovař (Dolatabadi & Kovař, 2009).

4.3 Mesomechanical modelling of complex deformations

The concept of the complex deformations on a mesomechanical scale is extremely marginal. It is almost impossible to simulate on the scale of the unit cell the effects occurring during the drape of a fabric. The so called mesomechanical models for the complex deformation of the fabrics mainly refer to the bending behaviour of the fabrics. The first study in complex deformations of fabrics was conducted by Peirce (Peirce, 1937). He proposed an energy method for the analysis of 2D fabric bending. The analysis was based on the calculation of the change of the strain energy of the unit cell after the bending deformation. For the analysis the yarns were assumed to be of circular cross-section and incompressible and distributed forces were considered at the cross-sections of the yarns. Many researchers (Behre, 1961; Dahlberg, 1961; Lindberg et al., 1961; Abbott et al., 1971; Abbott et al., 1973) studied and reported the nonlinear nature of bending and shear properties. The approach adopted by Grosberg (Grosberg, 1966) incorporated the effects of friction into the strip 2D bending analysis. Many relative research actions were carried out in continue contributing to the understanding of drape to some extent. But the 2D drape assessment cannot fully reflect the more complex 3D double curvature deformations of drape (Lo et al., 2002). Shanahan et al. (Shanahan et al., 1978) accented the necessity of the complete drape treatment based on the structural mechanics shell theory. They also defended the consideration of anisotropic constitutive laws for the fabric sheet. Amirbayat and Hearle (Amirbayat & Hearle, 1989) used aspects of the shell theory in their theoretical investigation of the complex buckling. They correlated the drape shape with the bending, membrane and potential energies. From their investigation they concluded that drape is also influenced by other parameters such as the full set of anisotropic in-plane membrane, out-of-plane bending, cross term elastic constants, and the nonlinearity of the materials behaviour.

4.4 Macromechanical modelling of complex deformations

Many publications appeared in the past dealing with the macromechanical modelling of the complex deformations of the fabrics. For many years this specific area has concentrated the interest of many very important researchers. The most representative of them are referenced below.

An approach of the elastica theory for the analysis of complex deformations of fibres and fibre assemblies has been proposed by Konopasek (Konopasek, 1980a, 1980b, 1980c). It was based on the concept of planar and spatial elastica as developed respectively by Euler and Kirchhoff. Phenomena corresponding to the nonlinear behaviour of material, friction-elasticity, elastic-plasticity, and visco-elasticity were introduced in the analysis. The planar elastica theory was applied for the analysis of the large deflections of a yarn in a plane and the cylindrical bending of a fabric treated as sheet material. The spatial elastica was applied in the analysis of fibre buckling and crimp. The solution of the system of the resulted nonlinear differential equations was supported by computational tools.

An alternative approach to the theoretical mechanics of static drape of fabrics based on the differential geometry of surfaces was published by Lloyd et al. (Lloyd et al., 1996). They developed a computationally convenient implementation of the theoretical mechanics of fabrics. The fabrics themselves were treated as 2D continua represented by a surface without considerable thickness embedded in the 3D Euclidean space. The mechanical properties of the fabric were assigned to the model. The shape of the surface was described for both the deformed and the undeformed state by the means of the differential geometry of the surface. The strain values were deduced from the differences in the differential geometry expressions for the two extreme states. The strain values were correlated to the applied forces by the constitutive equations that express the mechanical properties of the material.

The differential geometry of surfaces for the dynamical modelling of fabric deformations was used for the approach of the problem by J. and R. Postle (Postle & Postle, 1996). The surface was considered as a series of twisted curves generated into the 3D Euclidean space. The differential geometry parameters incorporated the mechanical properties of the material (fabric) relating these mechanical properties to the changes in curvature as the surface was transformed into another surface. The deformation of the surface from the initial state to the final was mathematically modelled using the concept of homotopy. Bäcklund transformations were chosen for the solution of the nonlinear partial differential equations of the dynamic system.

Trying to combine the theoretical study to the experimental knowledge, Stump and Fraser (Stump & Fraser, 1996) analyzed the drape of a circular fabric sample over the circular disk of the drapemeter. They proposed an elastic ring-theory model of the draped fabric and used an energy analysis associated with the various large post-buckled deformations of the ring. Aim of their investigation was the study of the ability of the fabrics to present different configurations when they are draped under exactly the same conditions. The explanation of this ability was based on the calculation of the energy that corresponds to the various symmetric configurations.

4.5 Evaluation of the analytical approaches

The review of the literature of the analytical methods for the mechanical analysis of textile structures demonstrates the absence of a successful globally accepted technique suitable for the textile design. The basic drawbacks of the analytical methods result from the simplifying assumptions implemented in order to generate a low-complexity geometry and mechanical

problem. Thus the two-dimensional approach for the mesomechanical modelling, the attribution of isotropic elastic properties in the yarn models, the assumption of linear and isotropic properties in the macromechanical model introduces significant inaccuracies in the textile modelling. However the basic disadvantage of analytical approaches is the difficulty in handling in respect to the time consumption, the application field in terms of structures and materials, and the integration of the individual stages (micro, meso, macro). On the other side the analytical approaches accentuated the modelling difficulties of textile mechanics, the basic considerations and roadmap for an integrated design procedure.

5. Numerical modeling

The enormous computational power arose from the development of the computer systems and the expansion of advanced commercial software codes for the analysis of mechanical problems was guiding the textile design towards the numerical approaches. Mainly the Finite Element (FEM) and Boundary Element Method (BEM) were used for the mechanical modelling of the textile structures (Hu & Teng, 1996).

5.1 Micro- and mesomechanical modelling of simple deformations

The first attempts in the computer based mesomechanics of textiles dealt with the 2D and 3D representation of the plain woven structure. The geometry proposed by Haas and then by Peirce was the starting point for the solid geometrical modelling since the numerical techniques succeed the solution of the complex system of equations. Keefe et al. (Keefe et al., 1992) based on Peirce's geometry presented the solid model of the plain woven fabric. They also extended the model for various compactions and fabric angles. Later comparative studies examined the accuracy of the geometrical models for use in the numerical modelling of fabrics (Provatidis & Vassiliadis, 2002, 2004, Provatidis et al., 2005).

The first studies in mechanical analysis of textiles focused on the tensile deformation of the plain woven unit cells. The initial use of computational methods in textile mechanics was oriented towards the numerical solution of the complex analytical expressions. The use of numerical methods, as FEM, BEM etc, for the achievement of a rigorous approach for the textile micro- and mesomechanical analysis appeared in a later stage. Obstacles for the successful use of numerical methods were mainly the large displacement effects and the nonlinearity related with the deformations of textiles and the convergence problems arose. Munro et al. (Munro et al., 1997a) proposed a new approach for the application of FEM to the aligned fibre assembly problem. Three dimensional 8-node elements with cuboid shape in the neutral configuration and 6 degrees of freedom (DOF) per node employed for the investigation. The approach attempted to separate the various energy contributions to the element stiffness, allowing the user to specify their properties individually. This technique was successful in the easy introduction of nonlinear material properties in the solid model. The approach of Munro et al. (Munro et al., 1997b) was verified qualitatively by modelling realistic yarn situations. The yarn models were meshed by dividing them into layers where the layer interfaces were surfaces perpendicular to the yarn axis. Each layer was split into a number of finite elements ranging from 1 to 22. Initial configurations were arranged so that the fibres within the elements followed idealized helical-yarn geometry. A multi-layer yarn model consisting of 9 elements per layer was subjected to axial extension and axial compression. The model presented the expected, in terms of quality, deformation behaviour. Thus the necking of the yarn piece was caused by the helical winding of the fibres appeared during extension. Moreover the elements of the model were opened significantly during the

axial compressing test since the fibres were buckled to avoid compression of the fibre material.

The advance and easy manipulation of CAD tools, in the last few years, allowed the construction of 3D solid models of textile structures. By the use of the attributes of these tools, such as numerical interpolations, mirroring abilities etc. the representation of the structures became feasible. A yarn modelling approach based on the assumption of helicoid filaments of a constant helix radius and a circular filament cross-section for the loose and a dense structure are presented in the Figure 8 and Figure 9 respectively.

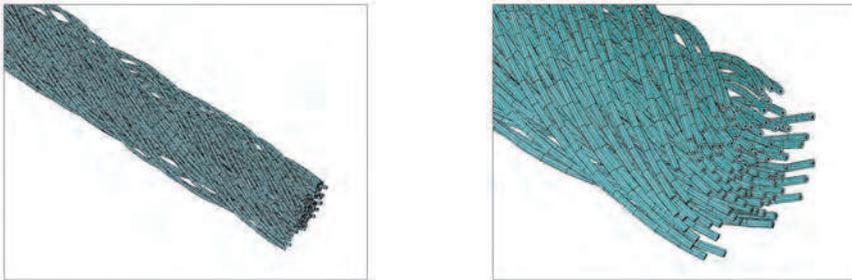


Fig. 8. Beam model of filaments in random locations for loose yarn structure.

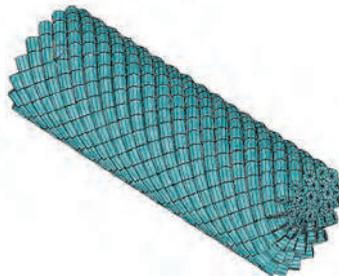


Fig. 9. Beam FE model of 50-filament twisted yarn (Vassiliadis et al., 2010).

Parametric solid modelling software packages are currently available allowing the construction of complex woven structures (Figure 11). The complete design flexibility provides the selection of weave pattern, yarn size or spacing. The yarn representation is still based on the assumption of the homogenous material for the simplification of modelling and the computational time saving (Toney, 2000). The advance moreover of the FEA codes allowed the mechanical simulation of the unit cells of the modelled textile structures. The mesomechanical modelling of textile structures was improved by the employment of advanced finite elements types and libraries of material properties including linear, nonlinear, elastic, plastic, viscoelastic, isotropic, orthotropic, anisotropic options etc. Additionally the introduction of contact algorithms and large strain effects was essential for the realistic results of the simulated tests. Lin et al. (Lin et al. 2008) studied the mechanical behavior of woven fabrics under compression implementing the finite element analysis using solid elements and nonlinear material properties. Furthermore, Durville (Durville, 2010) approached the textile simulation of woven structures' problem at the fibres scale by

means of 3D beam model, providing interesting data useful in the incorporation of fibres in composites structures.

Significant progress noticed in the modelling of complex structures of fabrics. Tarfaoui and Akesbi (Tarfaoui & Akesbi, 2001) presented the model of the twill woven fabric and the mechanical simulation using the FEM. The unit cell is composed by three warp yarns that intersect with three weft yarns, presenting a different type of crimp. Furthermore, B-spline curve methods have been successfully used to model woven yarns (Turan & Baser, 2010 Jiang & Chen, 2010).

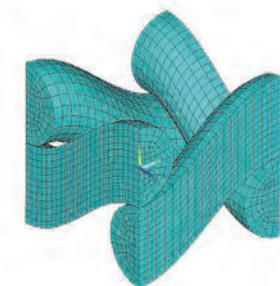


Fig. 10. Solid FE model of unit cell of plain woven structure.



Fig. 11. Solid FE model of unit cell of twill (left) and satin (right) woven structure (Vassiliadis et al., 2008).

Intensive researches were conducted in the field of woven fabrics composites due to their progressive spread in industrial applications. Actually the exceptional characteristics of woven fabrics composites, as high stiffness and strength, light-weight and efficient manufacturability are determinant for their expansion in automotive, marine and aerospace industry. Zhang and Harding presented one of the first numerical studies for the evaluation of the elastic properties of the plain woven composite structures (Zhang & Harding, 1990). Their approach was based on a strain energy method applied to a one-direction undulation model using the FEM. The drawback of this approach, reported also by the authors, was the consideration of the tow undulation in one-direction that is a non-realistic assumption for woven fabrics. Naik expanded the above approach taking into account the strand cross-section geometry, possible gap between two adjacent strands and the two-direction undulation geometry (Naik & Ganesh, 1992). Actually his detailed model demands a large

number of geometrical parameters to describe the undulation and varying thickness of the tow structure. The evolution of numerical methods in the next years produced the first 3D finite element models of the plain woven composites. Whitcomb studied the effect of quadrature order, mesh density and material degradation on the predicted failure resulting from the in-plane loading (Whitcomb & Srirengan, 1996).

The 3D solid modelling of the composite structure consists in the generation of the volumes representing the woven unit cell and an external volume (with the apparent dimensions of the composite unit cell). Then subtracting volumes of the woven structure from the external volume, the volume of the matrix material is resulted (see figure 12).



Fig. 12. Geometrical model of composite woven structure (woven reinforcement, matrix, composite)

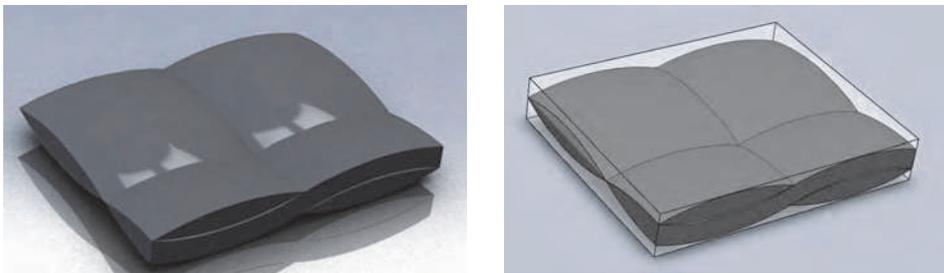


Fig. 13. Geometrical model of a woven structure of tows and a composite structure.

Several approaches were based on the prediction of the homogenized elastic properties of fabric composites using the unit cell of the composite structure. The geometrical representation of the tows was based on certain assumptions such as circular, elliptic, compressed hexagonal and lenticular cross-section areas were considered (Figure 13). The used tows (usually made of glass or carbon fibres) were assumed as transverse isotropic material and the matrix (usually resin) as isotropic material. The homogenized elastic properties of the unit cell results from the mesomechanical analysis using FEM. A relative approach proposed by Ng et al. (Ng et al., 1998) has been applied for the prediction of the in-plane elastic properties of a single layer 2/2 twill weave fabric composite. The compressed hexagonal shape was considered for the tow cross-section. The modelling and mechanical analysis was programmed using the ANSYS Parametric Design Language (APDL). The 8-node solid elements with 3 degrees of freedom (translational) per node were used.

Indicatively a model of approximately 52000 finite elements and 12000 nodes was generated. The contact areas generated during the subtracting operation (for the generation of matrix material) were assigned to be shared entities for both the yarn and the matrix volumes, to ensure the transmission of loading. Choi and Tamma (Choi & Tamma, 2001) dealt with the prediction of the in-plane elastic properties of a composite structure reinforced with plain woven fabric. The predicted elastic properties were used in continue for the damage analysis of the laminated composite structures. The superposition principle was applied for the evaluation of homogenised properties of the woven fabric composite. The generated model of composite unit cells consists of 520 wedge elements for the yarns and 256 brick elements for the matrix. The progressive damage was evaluated simulating the in-plane tensile and shear deformation introducing a respective incrementing load. The degradation of elastic moduli and Poisson ratios was considered for the mechanical damage analysis.

A main framework for the multi-scale modelling of woven composite structures for the damage prediction was proposed by Kwon (Kwon, 1993, 2001; Kwon & Hamilton, 1995; Kwon & Roach, 2004) and implemented in several following investigations. It is worth to mention that the damage of a laminated textile composite is presented as a matrix damage, fibre breakage, fibre - matrix debonding or laminated debonding (delamination). The proposed multi-scale approach is based on the integration of three individual modules: the fibre-strand module, the strand-fabric module and the lamination module. The fibre-strand module aims at the evaluation of the effective elastic properties of a unidirectional composite strand exploiting the material properties and structure of the constituent fibres and matrix. Moreover the current stage relates the stresses and strains of the strand with the stresses and strains of the fibre and matrix materials thus the damage criteria can be applied. The strand-fabric module focuses on the evaluation of the effective properties of the woven fabric composite (unit cell) exploiting the material properties of the unidirectional composite strand. In addition the current stage relates the stresses and strains of the composite structure with the stresses and strains of the strand. Finally the lamination module evaluates the effective properties of the laminated composite structure (multiple layer) using the material properties of the composite lamina. A classical lamination theory or a higher order theory is implemented in this stage. Thus the stresses and strains developed on the laminated composite structure are correlated with the stresses and strains of the lamina.

An innovative research in the field of fabric composites is conducted in the K.U. Leuven, initially focusing on the generalized description of the internal structure of the textile reinforcement. Lomov and his colleagues developed a model for the internal geometry of 2D- and 3D-weaves based on a minimum number of topological data and yarn mechanical properties. The mechanical model applies a yarn deformation energy minimization algorithm to predict the internal geometry of any 2D- and 3D-weave. This approach was systematically extended to 2D- and 3D-woven, two- and three-axial braided, weft knitted and non-crimp warp-knit stitched fabrics and laminates and incorporated in the Wise-Tex software package (Verpoest & Lomov, 2005; Lomov et al., 2000; Lomov et al., 2001). Regarding the damage analysis of the composite structures a three-level hierarchy was proposed: the micro-, meso- and macro-level. The micro-level defines the arrangement of fibres in the representative volume of the impregnated yarn. The meso-level describes the internal structure of the reinforcement and variations of the fibre direction and volume fraction within the yarn. Finally the macro-level defines the 3D geometry of the composite part and the distribution of the reinforcement properties.

5.2 Macromechanical modelling of complex deformations

The macromechanical modelling of fabrics or cloth modelling, as usually referred, attracted the interest of the textile community in the last decades. Many investigators attempted to approach computationally the macromechanical performance of fabrics for several purposes from the prediction of the drape behaviour of the fabric up to the virtual mode show (Gray, 1998). Depending on the purpose served and the application field different techniques were developed. The basic classification of the developed techniques is divided into computer animation models (graphic models) and the engineering design models. Many numerical techniques including the particle-based model, the deformable node-bar model and the FEM were developed for the engineering design of fabrics. Most of the efforts were focused on the prediction of the drapability of fabrics.

The used FEM for the drape simulation were based on a variety of element types from simple rods to complex shell elements. Collier (Collier et al., 1991) studied the drape behaviour of fabrics using a nonlinear FEM based on the classical nonlinear plate theory. The fabric was assumed to be two dimensional. It was considered as a linear elastic material with orthotropic anisotropy, where the symmetry lines are aligned in the warp and weft directions. Many corrective actions were assigned the following years by the researchers in the classical finite element techniques in order the realistic performance of fabrics to be approached.

The FEM and flexible thin shell theory was employed by Chen and Govindaraj (Chen & Govindaraj, 1995) to simulate the fabric drape. Their approach provides nonlinear solution since large displacements appear during drape test. Thus the loads are applied incrementally to the system, and at each step, the equilibrium equation system is solved by a Newton-Raphson method. The nonlinearity was handled by calculating the stiffness matrix in each step as a function of the displacement vector. The fabric was considered continuous orthotropic material. A 9-node, doubly curved shell element with 5 DOF per node was used for the simulation.

The simulation of the 3D drape test based on the FEM was also approached by Kang and Yu (Kang & Yu, 1995). The woven fabric was assumed to be an elastic material with orthotropic anisotropy. The fabric was considered as a thin flexible plate under the plane stress condition, and the transverse shear strain was included in the formulation. Since large displacements and large rotations are developed during draping, the drape phenomenon was considered as geometrically nonlinear and respectively the nonlinear analysis was adopted for the simulation. The Green-Lagrangian strains and the second Piolar-Kirchhoff stresses were used for the analysis. The formulation of the FEM was based on a total Lagrangian approach. 4-node quadrilateral elements were used with 5 DOF in each node. In order to avoid the shear locking phenomenon which is commonly observed in the thin plane analysis, a transverse shear strain interpolation method was applied. Almost the same approach was proposed by Gan et al. (Gan et al., 1995). In their analysis 8-node shell elements were used with 5 DOF per node. The adopted technique in this approach for the elimination of locking was a reduced integration with zero energy mode control.

For the minimization of the computational power required for the simulation of fabric drape, a FEM using simple beam elements with 6 DOF per node was proposed by Ascough et al. (Ascough et al., 1996). The used beam elements include mass and stiffness properties and can represent iso- or orthotropic cloth properties. The large displacement effects were achieved with the addition of a geometric or initial stress matrix to the elastic stiffness

matrix to form the element characteristic matrix. Newmark's method was used to allow a time-stepping approach to the solution, with the advantage that the mesh geometry can be updated at each step. The proposed analysis includes also interaction of the cloth with the body form. Checks for a collision detection of material elements with the body model are made following each time step of the drape simulation. An iterative calculation process is executed until contact rather than penetration of cloth element with the body model occurs. An approach for the drape simulation of woven fabrics quite different from the traditional macromechanical methods was proposed by Breen et al. (Breen et al., 1994). The cloth was modelled as a collection of particles that conceptually represent the crossing points of warp and wefts threads in a plain weave. Important mechanical interactions that determine the behaviour of woven fabric are discretized and lumped at these crossing points. The various yarn-level structural constraints are represented with energy functions that capture simple geometric relationships between the particles. These energy functions account for the four basic mechanical interactions of yarn collision, yarn stretching, out of plane bending, and trellising. The simulation was implemented as a three-phase process operating over a series of discrete time steps. The first phase for a single time step calculates the dynamics of each particle and accounts the collisions between particles and surrounding geometry. The second phase performs an energy minimization to enforce inter-particle constraints. The third phase corrects the velocity of each particle to account for particle motion during the second phase.

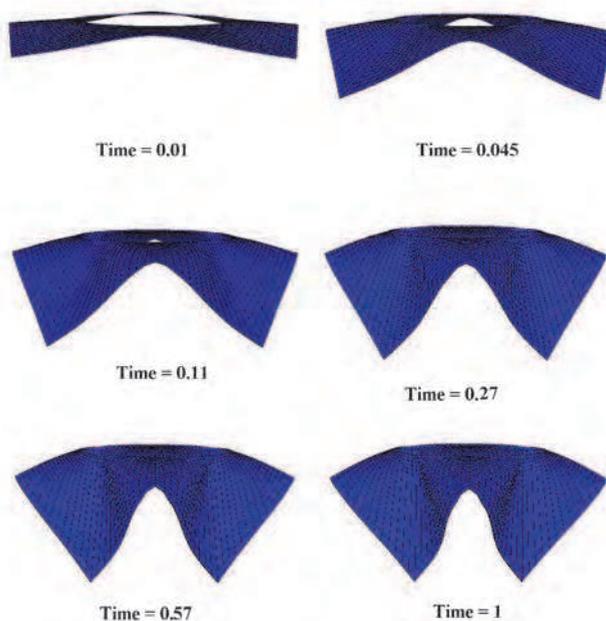


Fig. 14. Deformed FE model of square fabric in drape test (Provatidis et al., 2009).

Stylios et al. (Stylios et al., 1995; Stylios et al., 1996) proposed a node-bar model for the drape modelling of fabrics. The deformable elements were defined as consisting of one deformable

node with a number of rigid bars. Thus the patch of cloth is divided into a grid (the patch is divided as a series of elements, which can be of equal or unequal sizes). The material properties of the continuum in all elements are lumped together at these deformable nodes by integrating all the energies within those elements. The total energy density was considered as the sum of strain, kinetic energy density, and the energy density introduced by external and boundary forces. Viscoelastic terms were added in the energy equation. The cloth motion in continue was determined using the Euler-Lagrange equations.

The finite volume method employed by Hu et al. (Hu et al., 2000) for the drape modelling of fabrics. The mesh lines were aligned along the warp and weft direction producing rectangular internal volumes and triangular or quadrilateral boundary volumes in a circular fabric sheet. The equilibrium equations of the fabric sheet derived using the principle of stationary total potential energy. Geometric nonlinearity and linear elastic orthotropic material properties of the fabric were considered in the formulation. The full Newton-Raphson iteration method with line searches was adopted for the solution of the resulting nonlinear algebraic equation.

5.3 Evaluation of the numerical methods

The adoption of computational techniques in textile mechanics is essential to face and overcome the objective difficulties, as the geometrical representation, the complex deformations, the particular material properties, the contact phenomena and the large deflection effects. Moreover, the advanced computer based tools are suitable for the virtual representation of a product performance under loading. That is a significant facility for the textile designers since a realistic sense from the mechanical up to the aesthetic attributes can be provided.

Most of the mesomechanical modeling approaches implemented the finite element method using solid FE. The yarns were assumed as homogenous material with transverse isotropic elastic properties. The attribution of the yarn properties constitutes basic factor for the accuracy of the mesomechanical modelling stage. Thus the equivalent performance of the homogenous yarn, considering the discrete structure, in the tensile and bending deformation is required at least for the reliable attribution of yarn models. It is remarkable that most of the proposed models omitted the calculation of the real value of the yarn bending rigidity and its attribution at the modelled yarn.

The macromechanical modelling approaches are grouped in two basic categories. The first corresponds to the investigations based on the experimental measurement of the mechanical properties of fabrics and the generation of equivalent models describing their bending performance and drapeability (Collier et al., 1991; Ascough et al., 1996; Stylios et al., 1995; Hu et al., 2000; Araujo et al., 2004). The second category focused on the computational analysis of fabrics in the mesoscopic level and the generation of models presenting equivalent in-plane elastic properties (Ng et al., 1998; Choi & Tamma, 2001; Lomov et al., 2007).

The basic drawback encountered in the existing modelling approaches concerns the collaboration of the different modelling stages (micro, meso, macro) for the development of an integrated design procedure of the textile structures. Thus the modelling of the structure in the mesoscopic level should incorporate the micromechanical performance of the yarns. Whereas the modelling of the structure in the macroscopic level should incorporate the mesoscopic performance of the unit cells and therefore the microscopic performance of the

yarns. Consequently the collaboration of the discrete modelling stages is attainable generating realistic models and attributing the equivalent properties.

6. Conclusions

An extended review was conducted over the textile mechanical modelling area. It is obvious that despite the about 70 years of actual research it's not possible to conclude in an Integrated Computer Aided Engineering Environment. The absence of a global tool was remarked, that aggravates the textile design procedure in terms of time and cost.

The structural hierarchy of the textile structures (fibre – yarn – fabric) is correlated with the high level of complexity presented in the modelling procedure and the mechanical analysis of them. The difficulties are increased due to the high divergence of the dimensions corresponding to the fabric sheet (10^{-1} to 10^0 m) and the structural elements (fibre diameter, 10^{-5} m). The modelling complexity resulted from the structural hierarchy of textiles is faced adopting a relative modelling hierarchy. Thus three basic modelling scales were developed: the micromechanical modelling of yarns, the mesomechanical modelling of the fabric unit cell and the macromechanical modelling of the fabric sheet. The modular modelling of the textile woven fabrics is a systematic method to overcome the complexity of the mechanical structure and the nature of the materials involved. The global evolution of the modelling approaches seem to converge in this stepwise method and thus indicate a likely way towards the desired Textile Computer Aided Engineering environment.

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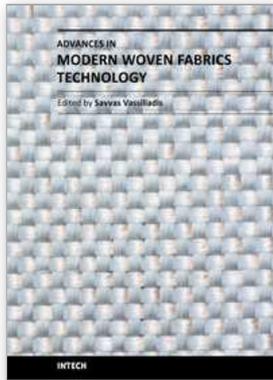
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The importance of woven fabrics increases constantly. Starting from traditional uses mainly in clothing applications, woven fabrics today are key materials for structural, electronic, telecommunications, medical, aerospace and other technical application fields. The new application fields of the woven fabrics is directly reflected in the contents of the book. A selected collection of papers in the technological state-of-the-art builds the book "Advances in Modern Woven Fabrics Technology". It is written by internationally recognized specialists and pioneers of the particular fields. The chapters embrace technological areas with major importance, while maintaining a high scientific level. This interdisciplinary book will be useful for the textile family member as well as for the experts of the related engineering fields. The open access character of the book will allow a worldwide and direct access to its contents, supporting the members of the academic and industrial community.

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