BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Tomul LXI (LXV), Fasc. 1, 2015
Secția
CONSTRUCȚII. ARHITECTURĂ

APPROACHES IN MODELLING THE MECHANICAL CHARACTERISTICS OF POLYMERIC COMPOSITES REINFORCED WITH WOVEN FABRICS

BY

ANDREI AXINTE[1,*], NICOLAE ȚĂRANU[1], LILIANA BEJAN[2] and VICTORIA ROȘCA[1]

[1]“Gheorghe Asachi” Technical University of Iași
Faculty of Civil Engineering and Building Services
[2]Faculty of Machine Manufacturing and Industrial Management

Received: January 24, 2015
Accepted for publication: February 14, 2015

Abstract. The structure of the fabric, when it is used as a composite reinforcement, have a major influence on the mechanical properties of a fabric reinforced composite material. Composite design and analysis requires a computer tool, not only to link composite properties to fabric micro and macro geometry, but also to link fabric micro geometry to the weaving pattern. The complex structure of textile composite comprises of several hierarchical levels: macro (composite component or sub-component), meso (unit cell of the reinforcement structure) and micro (fibre placement inside yarns and fibrous plies). The most specific to textile composites is meso level, where the structure dependent behaviour of the material is most pronounced. This is the most important level at which the optimization of the structure and the constituents should be performed. Continuous and discrete approaches are possible for the forming simulations of composite textile reinforcements because of their multi-scale structure. In recent years, due to the advancement of structural and material modelling technology, a relatively accurate geometrical textile composites models have been developed through computer aided engineering and textile

---

[*]Corresponding author: *e-mail*: aaxinte0@yahoo.com

geometric modelling software. This paper emphasizes the modelling procedures of mechanical elastic proprieties specific to woven laminated composites.

Key words: textile composites; mechanics of woven composites; unit cell; composite reinforcements.

1. Introduction

Textile composites are fibre reinforced composite materials, the reinforcement being some kind of textile fabrics. Textiles are flexible, anisotropic, inhomogeneous, porous materials with distinct viscoelastic properties. These unique characteristics makes textile structures to behave essentially different when they are compared with other materials. The mechanical behaviour of woven fabrics is difficult to predict due to complex interactions of yarns in the fabric and the interaction of fibres in each yarn. Indeed, the associated problem of characterizing the multiple scales is the greatest obstacle to unrestricted implementation of woven fabrics. The intricate nature of the textiles makes them ideal candidates for a mechanical analysis using computer based methods.

Historically, the efforts in textile composite mechanical analysis have focused mainly on the prediction of effective elastic material properties of a unit cell. The approaches developed so far could be divided into three main categories: analytical model based on the classical laminate theory, stiffness averaging and homogenization method and, finally, finite element method.

The mechanics of textile structural composites can be best studied by taking into account their hierarchical organization (Barbero, 2011; Chen, 2010) . There are usually four important levels in the manufacturing process of textile composites: fibre, yarn, fabric and composite (Fig. 1).

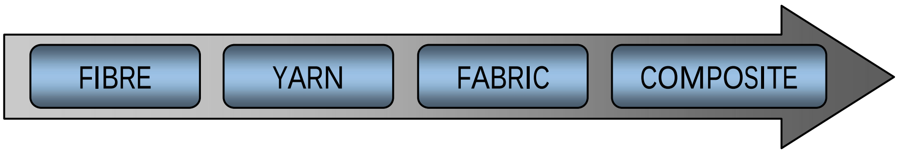
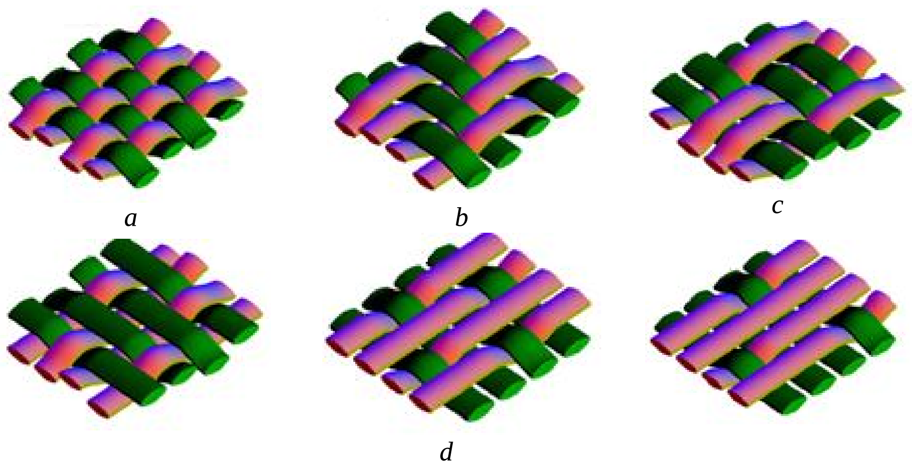


Fig. 1 – Levels of the manufacturing process of textile composites.

Textile or fabric reinforcements are, by definition, made by fibres, which are assembled in yarns or tows. Textile composites have innovative characteristics because of their complex reinforcement geometries (Fig. 2).

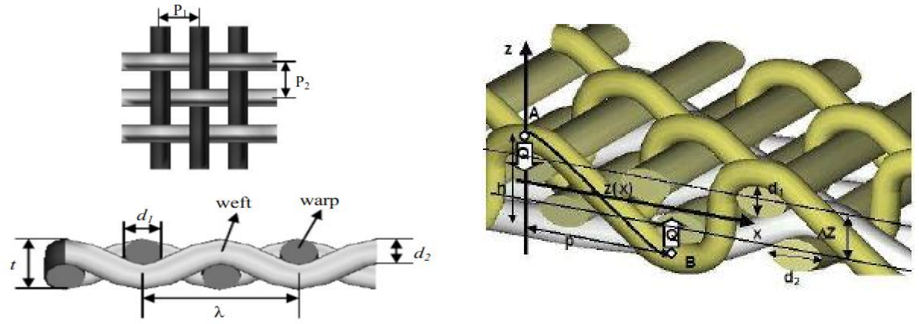
The particularities of these composites provide a variety of possible spatial functions to define different curved yarn shapes in structural or load bearing applications. Moreover, these materials are overwhelmingly superior to general composite materials from the points of view of the strengths and stiffness, hence the textile structural composites are considered an advanced material with a performance that is superior to other materials.


a *b* *c*

d

Fig. 2 – Schematics of woven composites: *a* – plain weave, *b* – twill weave 2 × 2, *c* – basket weave, *d* – satin weave: 4-Harness, 5-Harness & 8-Harness (adopted from Goyal, 2003).

2-D woven fabric consists of two orthogonal series of yarns, referred to as warp and fill yarns, interlaced to form a self-supporting textile structure (Fig. 3).

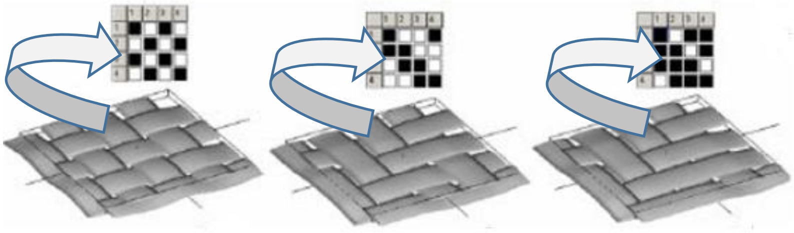


a *b*

Fig. 3 – Model of weave fabric: *a* – top view and cross section (adopted from Azrin Hani *et al*., 2013), *b* – structure of woven fabric (Verpoest & Lomov, 2005).

The textile pattern of interlacing/braiding yarns is defined by positions of the yarns at crossovers, where a yarn in one direction can either go on top of a yarn of another direction or dive under it. Such a pattern can be coded in so called paper-point diagrams, which maps crossovers (marked with black in Fig. 4) where warp yarns are on top of the fill yarns (Lomov & Verpoest, 2005).

One of the basic features of these patterns is *the step* (the distance along a yarn between two neighboring intersections, measured in terms of number of crossovers). The step defines the tightness of textile, or the freedom of yarns to move.



a *b* *c*

Fig. 4 – The woven textile pattern of interlacing yarns: *a* – plain weave, *b* and *c* – twill weaves (adopted from Ivanov, 2009).

2. Modelling the Mechanical Characteristics of Woven Fabrics

In the past decades, complex composite reinforcements such as textiles have become widely used in the industry, due to their inproved manufacturing techniques, easy handling and good mechanical properties. However, these materials have a complicated internal architecture which makes their analysis not so straightforward. Moreover, due to handling during the production process of the composite, the textile can be deformed quite significantly and hence their mechanical properties and damage behaviour will be altered accordingly.

Existing research regarding fabric reinforced composite behaviour can be divided into two groups: geometric model and mechanical model. The geometric model describes fabric using the pin-jointed fishnet like model and geometrically maps the fabric to an elastic/rigid body surface. This model is efficient, but ignores the mechanical behaviour. The mechanical model describes fabric using finite elements and mechanically simulates the fabric deformation process. The mechanical continuous model uses finite shell or membrane element to represent fabric. The mechanical bi-component model uses a combination of finite shell/membrane element and truss/beam element to model fabric.

An important aspect of modelling the mechanics of woven fabrics is finding realistic stress-strain behaviours, which are invariably anisotropic, nonlinear, and hysteretic in that they feature irrecoverable deformation when loadings are removed from the fabric. Several methods were adopted for the mechanical modelling and analysis of the textile structures. A basic classification, according to the modelling method used, splits them into analytical and numerical or computational approaches.

The Micro-Meso-Macro simulation approach (Fig. 5) has proven to be successful for predicting elastic mechanical properties, taking into account the above mentioned problems.

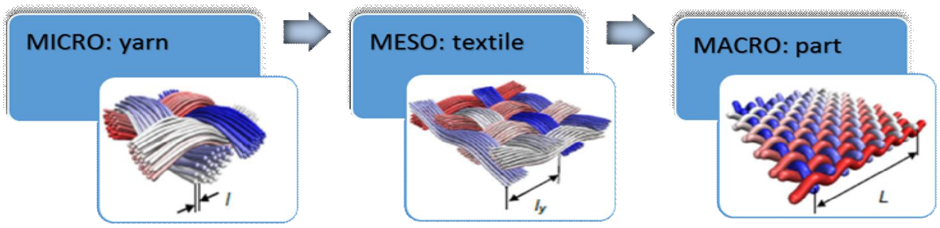


Fig. 5 – Multi-level simulation approach (adapted from Samadi, 2013).

In the first modelling stage, the fibre properties and the yarn structure (yarn type, number of fibres and their orientation) are introduced as input parameters for the mechanical analysis of the yarn in order to find the yarn properties. Then the yarn properties are transferred in the second modelling stage. The selection of the required yarn properties and their assignment to the modelled yarns corresponds to a homogenization procedure that connects the first two individual stages. Moreover, the woven fabric structure is introduced in the meso-mechanical modelling stage. In this stage, the yarns are represented as continuum structures and the analysis is limited to 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 assignment to the continuum fabric models. At the end of the chain comes the macro-mechanical modelling stage, based on the generation of simplified structure (usually continuum material), which predicts the mechanical performance of extended fabric pieces, in complex deformations. Each individual modelling procedure presents significant obstacles.

Although the mentioned modelling stages were developed as distinct analysis approaches, their integration in a compound modelling approach was necessary. Thus the textile society implemented a modelling hierarchy (Takano *et al*., 1999; Lomov *et al*. 2001; Bogdanovich, 2006) based on those three modelling scales: the micro-mechanical modelling of yarns, the meso-mechanical modelling of the fabric unit cell and the macro-mechanical modelling of the fabric sheet (Fig. 6).

The modelling process is based on the geometrical concept of a periodic textile: unit cells or repetitive unit cells (RUC). The repeating unit cells of 2-D plain woven textile composites are illustrated in Fig. 7. These unit cells usually suggest that the entire textile structures can be constructed from spatially translated copies of these cells, and effective elastic moduli can also be estimated from these basic cells. Using this geometrical classification, several textile composite types can be characterized.

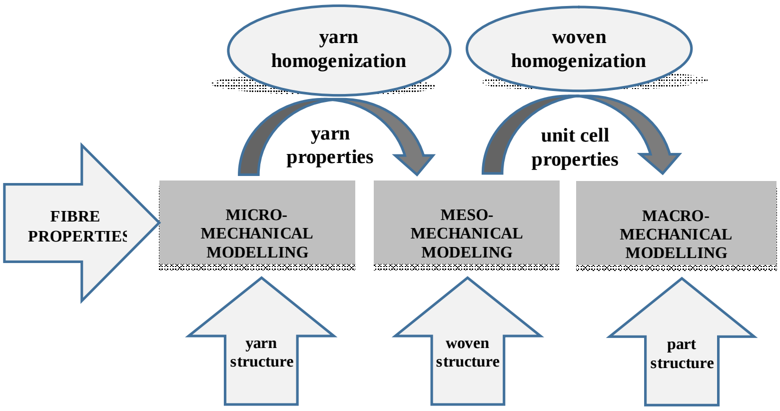


Fig. 6 – Integrated textile modelling
(adopted from Vassiliadis *et al.*, www.intechopen.com).

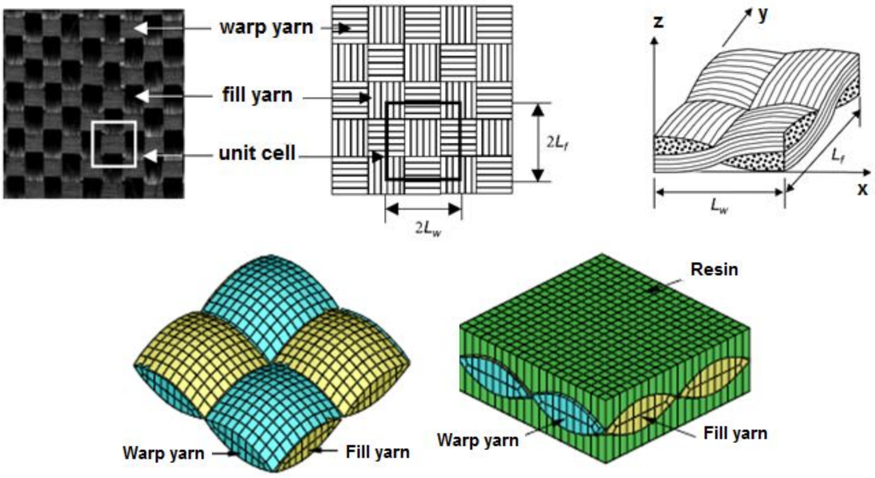


Fig. 7 – Schematics of repetitive unit cells of 2D plain woven fabric with and without resin (Lee *et al*., 2003; Hae-Kyu, 2006).

Modelling on the micro/meso level can be described as assembling the representative volume element of textile composites (or unit cell), using geometrical models on micro level (fibre distribution in yarns and fibrous plies) and on the meso level (yarn/plies architecture of the reinforcement).

This assembling results in a full description of the reinforcement as a structured fibrous assembly (Fig. 8). When ready, this description is used as input data for homogenization of the mechanical properties of the composite on the meso (unit cell) level; these properties can then be integrated into structural analysis on the macro level. It has been of recent interest to study the effects of these parameters and understand which the driving factors for both elastic and inelastic response are.

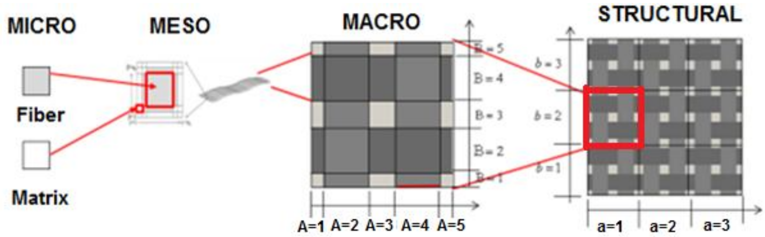


Fig. 8 – Multi-scale framework for parametric variation
(adopted from Liu, 2011).

The method requires that a representative geometry of the composite configuration be defined. As mentioned earlier, the unit cell is a basic building block for the material structure. Its constituents are the matrix and fibres, as well as the reinforcement geometry (Fig. 9).

The geometry can be considered one of the constituents, since it directly affects the behaviour of the unit cell, as well as that of the composite structure.

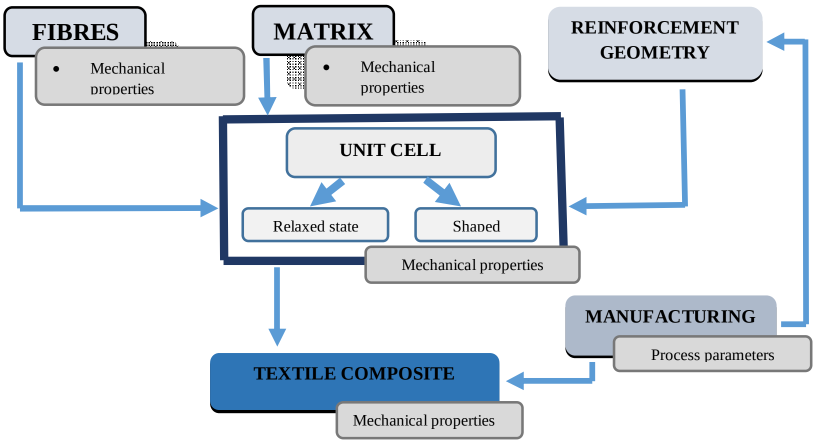


Fig. 9 – The unit cell and its relation to the textile composites
(adopted from Prodromou, 2004).

There are different modelling approaches: *kinematic*, *discrete*, *continuous* and *semi-discrete*.

The *kinematic approach* also called “geometrical draping approach” is commonly used to predict the resulting fibre re-orientation for double curved fabric reinforced products. In the kinematic models, developed to simulate fabric forming, the yarns are assumed to be pinned together at the crossover points of the weave and the yarns are inextensible, incompressible and free to rotate around the pin-joints.

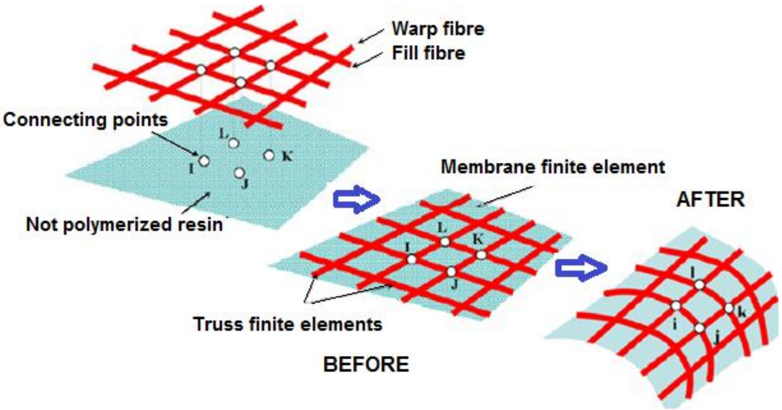


Fig. 10 – Discrete modelling: truss elements used for fibres and membrane elements represent the resin (Cherouat *et al*., 2010).

The *discrete modelling* uses finite element (FE) models of the components of fibrous reinforcement at low scale (Fig. 10). These components can be yarns, woven cells or stitching, and also sometimes fibres. Because these elements are usually at the meso-scale, the approach is also known as meso-mechanical modelling.

The *continuous approaches* consider the fibrous reinforcement as a continuum. FE analysis of composite forming requires modelling of all the different aspects involved in the process and especially a constitutive mechanical model of the fibrous reinforcement. The advantage of the continuous approach is that it can be used in commercial FE code. The main difficulty in using the continuous approach is capturing the effects of the fibre architecture and its evolution during forming processes.

The *semi-discrete approach* is a compromise between the above continuous and discrete approaches. A finite element method is associated to a mesoscopic analysis of the woven unit cell. Specific finite elements are defined that are made of a discrete number of woven unit cell.

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 to be 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. The mechanical discrete model incorporates the textile weaving pattern and describes each yarn or fibre individually. In the discrete model, yarn-to-yarn interactions and even fibre-to-fibre interactions can be gracefully reflected. Modelling fabric deformability at the fibre-level produces the most accurate results.

3. Conclusions

The modelling complexity of woven reinforced composites arose from the structural hierarchy of textiles and is handled adopting a relative modelling hierarchy. Three basic modelling scales were developed: the micro-mechanical modelling of yarns, the meso-mechanical modelling of the fabric unit cell and the macro-mechanical 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. With the unit cell approach, the material designer can create custom material configurations with complex features or behaviours at micro or meso scales. Unit cell modelling has been used in the multi-scale computational technique and for non-linear analysis with a plasticity model.

There are different modelling approaches: *kinematic*, *discrete*, *continuous* and *semi-discrete*. In the kinematic models, developed to simulate fabric forming, the yarns are assumed to be pinned together at the crossover points of the weave and the yarns are inextensible, incompressible and free to rotate around the pin-joints. The *discrete modelling* uses finite element (FE) models of the components of fibrous reinforcement at low scale. The *semi-discrete approach* is a compromise between the above continuous and discrete approaches.

REFERENCES

Azrin Hani A.R., Shaari M.F., Mohd Radzuan N.S., Hashim M.S, Ahmad R., Mariatti M., *Analysis Of Woven Natural Fiber Fabrics Prepared Using Self-Designed Handloom.* Internat. Conf. on Mechan. Engng. Res. (ICMER2013), July1-3, 2013 Bukit Gambang Resort City, Kuantan, Pahang, Malaysia Paper ID: P042 (2013).

Barbero E.J., *Introduction to Composite Material Design, SE*. CRC Press, 289-337, 2011.

Chen X., *Modelling and Predicting Textile Behavior*. CRC Press, 144-179, 2010.

Cherouat A., Borouchaki H., Giraud-Moreau L., *Present State of the Art of Composite Fabric Forming: Geometrical and Mechanical Approaches*. Materials, **2**, *4*, 1835-1857 (2010).

Goyal D., *Analysis of 2 × 2 Braided Composites*. M.Sc. Diss., Texas A&M Univ., 2003.

Hae-Kyu H., *Computational Modeling and Impact Analysis of Textile Composite Structures*. Ph. D. Diss., Virginia, 2006.

Ivanov, D.S., *Damage Analysis of Textile Composites*. Ph. D. Diss., Katholieke Univ. Leuven Parsons, 2009.

Lee S-K, Byun J-H, Soon Hyung Hong S-H, *Effect of Fiber Geometry on the Elastic Constants of the Plain Woven Fabric Reinforced Aluminum Matrix Composites*. Mater. Sci. a. Engng., **A347**, 346-358 (2003).

Liu K., *Micromechanics Based Multiscale Modeling of the Inelastic Response and Failure of Complex Architecture Composites*. Ph. D. Diss., Arizona State Univ., 2011.

Mettam G.R., Adams L.B., *How to Prepare an Electronic Version of Your Article*. In: Jones B.S., Smith R.Z. (Eds.). Introduction to the electronic age, New York: E-Publishing Inc, 281-304, 1999.

Prodromou A., *Mechanical Modelling of Textile Composites Utilising a Cell Method*. Ph. D. Diss., Katholieke Univ. Leuven, 2004.

Samadi R., *Particle-Based Geometric and Mechanical Modelling of Woven Technical Textiles and Reinforcements for Composites*. Ph. D. Diss., Univ. of Ottawa, Canada, 2013.

Soykasap O., *Analysis of Plain-Weave Composites, Mechanics of Composite Materials*. **47**, *2*, 161-176 (2011).

Stig F., *An Introduction to the Mechanics of 3D-Woven Fibre Reinforced Composites*. Lic. Thesis, KTH School of Engng. Sci., Stockholm, Sweden, 2009.

Strunk Jr.W., White E.B., *The Elements of Style*. 3rd ed., New York, Macmillan, 1979.

Vassiliadis S., Kallivretaki A., Domvoglou D., Christofer Provatidis C., *Mechanical Analysis of Woven Fabrics:the State of the Art*. Advances in Modern Woven Fabrics Technol., 2011, www.intechopen.com.

Verpoest I., Lomov S.V., *Virtual Textile Composites Software WiseTex: Integration with Micro-Mechanical, Permeability and Structural Analysis*. Composites Sci. a. Technol., **65**, 2563-2574 (2005).

MODALITĂȚI DE MODELARE A CARACTERISTICILOR MECANICE ALE COMPOZITELOR POLIMERICE ARMATE CU ȚESĂTURI

(Rezumat)

Proprietățile mecanice ale materialelor compozite armate cu țesături sunt determinate preponderent de structura țesăturii şi sunt influențate de modul de

întrețesere a firelor materialului textil utilizat. Proiectarea şi analiza compozitelor armate cu țesături necesită programe complexe de calcul, nu numai pentru a face legătura dintre proprietățile compozitului şi geometria țesăturii la nivel micro şi macro, dar, de asemenea, pentru a se putea evidenția dependența dintre modul de întrețesere a firelor şi micro-geometria armăturii. Structura complexă a unui compozit cu armatură textilă este alcătuită din mai multe nivele ierarhice: nivelul macro (componentul sau sub-componentul compozit), nivelul mezo (celula unitate a elementului de armare) şi nivelul micro (aranjarea fibrelor din interiorul firelor şi a straturilor fibroase). Caracteristic compozitelor textile este nivelul mezo, nivel la care comportarea materialului în funcție de caracteristica structurală acestuia este predominantă. Acesta este şi nivelul la care trebuie efectuată optimizarea structurii şi a materialelor constituente. În acest scop, pot fi utilizate metode ce utilizează variabile continue sau discrete pentru simularea materialelor compozite, din cauza structurii lor multi-scară. În ultimii ani, ca urmare a progresului tehnologiei IT din domeniul modelării structurilor şi a materialelor, au fost dezvoltate modele geometrice relativ exacte ale compozitelor armate cu textile prin utilizarea unor programe informatice specifice, punându-se tot mai mult accentul pe proiectarea asistată de calculator. În această lucrare se descriu unele principii de modelare a proprietăților elastice mecanice, specifice compozitelor laminate țesute.