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MODELLING PATTERNS FOR FABRIC REINFORCED COMPOSITES

BY

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Abstract. Textiles are considered to be among the most effective reinforcements for composite materials, most of them in the form of fabrics. However, fabric reinforced composite materials have a complex internal architecture and their analysis is not so straightforward. Therefore it is recommended to implement a standard modelling hierarchy based on integrated concept of textile modelling, organized in three scales: fibre’s micro-mechanical modelling, unit cell’s meso-mechanical modelling and fabric’s macro-mechanical modelling. The paper presents the principles of modelling fabric reinforced composites and various patterns for the unit cell, which is the basic step for mechanical performance evaluation and optimization of the mechanical properties for these materials.

Keywords: textile reinforced composite; fabric reinforced composite; textile modelling; unit cell (UC).

1. Introduction

The development of modern fibres was seen by engineers as a challenge, when they decided to use textiles in high performance applications, such as construction industry and aeronautics (Hu, 2008). Textiles are considered to be among the most effective reinforcements for composites and the successful use of fabrics, based on carbon, glass or aramidic fibres, enabled

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the increase of their use in many industrial applications (Ratna *et al.*, 2004). Globally, the largest amount of composite materials are utilised in automotive (over 30% of the total volume of composite materials) and aeronautical industry (over 20% of the total volume of composite materials), followed by civil engineering and wind energy sector.

Textile composite materials have innovative features, due to the complex geometry of the reinforcements. The specifics of these composites offer a variety of possible spatial models, through various forms of curved shapes and can be used to strengthen the building structures made of traditional construction materials. More than that, these materials are superior to general composite materials in terms of strength and rigidity.

Mechanical behaviour of a fibre reinforced composite material depends on the properties of each component, the proportion of the components, the shape and orientation of the yarns relative to the direction of stress, the mechanical strength of the interface matrix-yarn (Fig. 1).

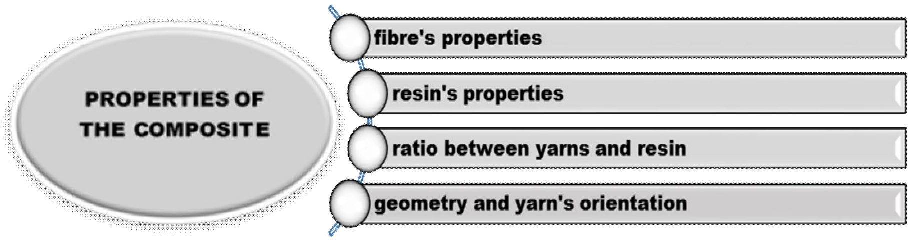


Fig. 1 – Components influencing the composite.

Given the process of making fibre reinforced composites by stacking laminae in layers, as well as their theoretical and experimental properties, they can be divided into single-layer and multilayer composites. Multilayer composites consist of distinct layers, having identical orientations and properties (for example, 0°/0°/0°/0°), thus granting the structure with one-way characteristics (Fig. 2 *a*), or may be of several layers with different orientations of the yarns and possibly different thicknesses from layer to layer, so as to meet specific design criteria (for example, 0°/+45°/–45°/90°), thus creating the properties of a quasi-isotropic material (Fig. 2 *b*).

Yarns direction have a decisive influence on anisotropy, entailing one of the major advantages of these materials, which is controlled anisotropy, by choosing an appropriate orientation of fibres in order to better withstand to specific operating loads.

The most popular textiles used as reinforcement are woven fabrics. Reinforcing with fabrics offers good mechanical characteristics especially for thin weaves, good flexibility, outstanding drapeability, all of that for a very good strength/weight ratio.

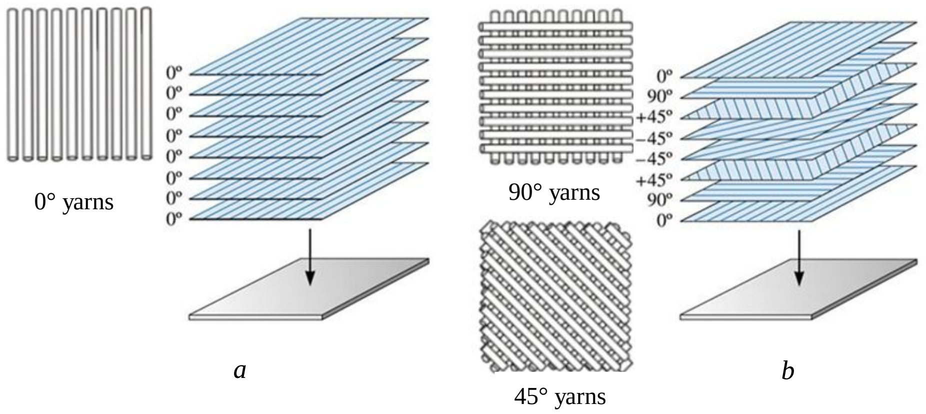


Fig. 2 – Composite types by yarn orientation: *a* – unidirectional orientation (one-way), *b* – multi-directional orientation (Askeland *et al*., 2010) .

The woven fabrics usually consist of two sets of yarns that are overlapping in orthogonal directions and are connected to each other in a regular pattern or style of weaving. The interlacing system (weaving) influences the flexibility and workability of the fabric, as well as the direction of the best mechanical properties. The main types of connections between the threads of a fabric systems are fundamental links, mixed links and derivative links or bonds. As far as the fundamental links are concerned, there are plain weave fabrics, twills and satins (Fig. 3).

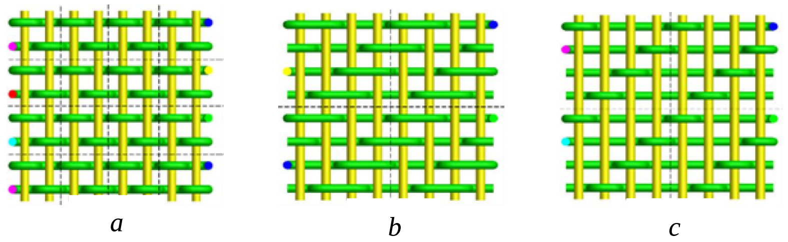


Fig. 3 – Types of woven fabrics a. - plain weave, b.- twill, c. - satin

The analysis of textile structure, used as reinforcement in composites, must account for two basic criteria: textile geometry and its processing style (Hu, 2008).

2. Modelling the Textile Reinforced Composites

To accurately describe the shape of the textile reinforced composites, some models adopted from micro-mechanics have been utilised. The textile reinforced composites modelling is more difficult when compared with unidirectional fibre reinforced composites, due to the complexity of the wires interlacing. Refined and precise models are required to analyse these complicated architectures. Therefore, using efficient analytical or numerical modelling techniques must be included in the analysis of these structures, in order to save time and cost. The vast majority of models developed so far, can be divided into three main categories: classical lamination theory (CLT) methods, stiffness averaging methods (SAM) and finite element methods (FEM). Of all methods, FEM is the most promising, because it enables analysis of nonlinear systems with general boundary conditions and can be adapted to complex geometries.

By studying the existing specialised literature regarding the modelling of fabric reinforced composites, associated with the process of deforming fabrics, one may find two types of approaches: the geometrical model and the mechanical model. The geometrical model depicts the woven fabric using a network similar to a fishnet (pin-jointed fishnet pattern) and sees the fabric as a surface consisting of smaller elements. This model is efficient, but ignores certain mechanical behaviour aspects. On the other hand, the mechanical model is using finite elements to define and simulate the mechanical deformation of the material. The continuous mechanical model make use of "shell" or "membrane" finite elements to represent the material. The bi-component mechanical model uses a combination of finite element of "shell"/"membrane" and "truss"/"beams" to model the fabric. An important aspect in shaping the fabric is to correctly capture realistic stress-strain behaviour, which is invariably anisotropic, nonlinear and retain permanent deformations after the loads are removed, (hysteresis behaviour).

The geometric characteristics of the preform can be studied at three different scales, (Fig. 4):

a. microscopic scale, about 10 µm to 100 µm, used for diameter of fibres;
b. mesoscopic scale, from 1 mm to 1 cm, used for yarns and unit cell (UC);
c. macroscopic scale of the composite material – over 1 cm.

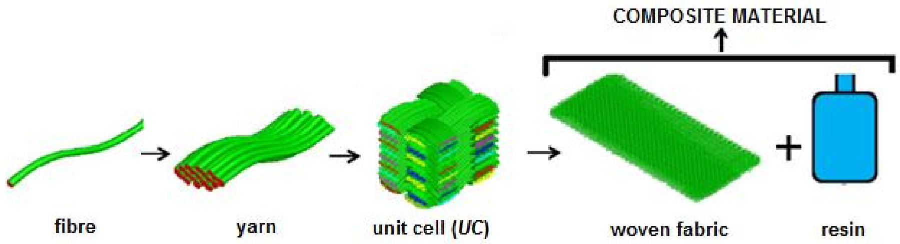


Fig. 4 – Steps involved in manufacturing and analysis of textile reinforced composites (Huang, 2013).

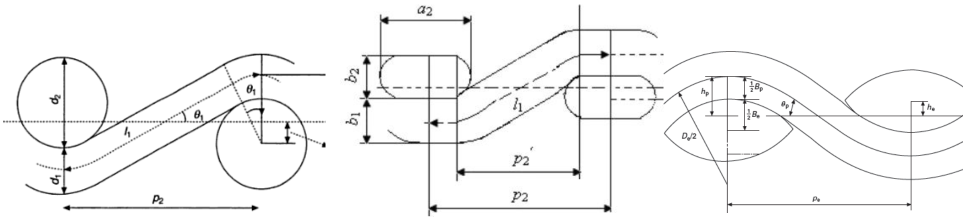
According to the integrated concept of textile modelling, the only inputs in the design procedure are properties of fibres, yarns and fabric structure. In the first stage of modelling the properties of fibres (fibre type, number of fibres, yarn orientation) are introduced as input parameters for analysing mechanical properties of the yarns. Then, the yarn properties are transferred to the second stage of modelling. The selection of yarn properties and transferring then to the wire or strand, corresponds to the homogenization procedure, which connects the first two individual steps. Subsequently, the structure of the fabric advance to meso-mechanical modelling phase. At this stage, the yarns are represented as continuous structure and the analysis is limited to studying the *UC*. Then, another homogenization step is required for connecting the second and third phases of modelling, finding the desired properties of the *UC* and assigning them in continuous fabric patterns. Finally, at the macro-mechanical level, the model is based on a simplified structure (usually a continuous material), which predicts the mechanical performance of textile parts, considering their stretch and strain. An important feature of available models is that they are all specific to a certain textile architecture. A more generalized model of fabric, where fabric pattern can be itself a parameter, is necessary (Lomov *et al.*, 2001). Also, the relations between geometric parameters have not yet been fully investigated in published studies, in order to determine accurately how a parameter can be changed and how its effects are interrelated with other design parameters (Lee *et al.*, 2003).

3. Geometric Patterns for the Unit Cell

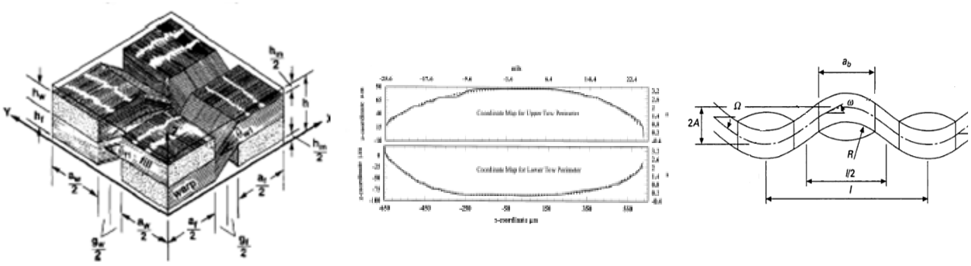
Analytical/numerical textile modelling techniques are using a small representative piece of material, called unit cell (UC), which repeats over and over, completely describing the whole fabric. Therefore, the properties of the textile are predicted on this UC.

One of the first geometric patterns, extremely idealized, for the UC of a plain weave fabric was presented in 1937 by Peirce. Peirce's model (Fig. 5 *a*) considers yarns cross-sections to be circular and incompressible. In 1958, Kemp altered Peirce's model by using elliptic shape for the yarns cross-sections (Fig. 5 *b*), thereby achieving a more realistic representation for the geometry of the fabric. Later on, in 1978, Shanahan and Hearle (1978) came with a new geometric pattern for the yarns, with cross-section of lenticular shape (Fig. 5 *c*) and introduced energy based calculation methods. Then, Ning and Chou (Ning *et al.*, 1998) have developed a more idealized UC model, in 1998 (Fig. 5 *d*), in order to find the effective thermal conductivity for a plain wave fabric. Another representation of the yarns section was proposed by Searles in 2001 (Searles *et al.*, 2001), who has used used functions to describe the upper and lower half of the cross section of the yarns, relative to the position of centre of gravity line

(Fig. 5 *e*). Concurrently, Hofstee and van Keulen (2001) developed a geometric model for the fabric's UC, using variable section yarns (Fig. 5 *f*).



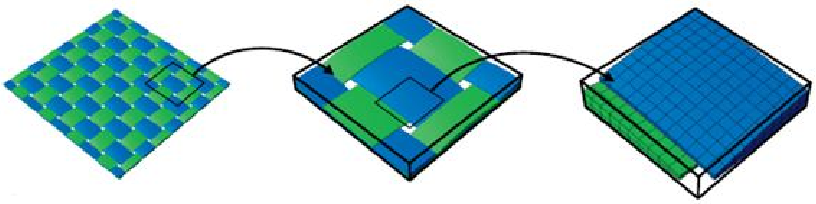
a. Pierce model (1937) *b*. Kemp model (1958) *c*. Shanahan and Hearle model (1978)



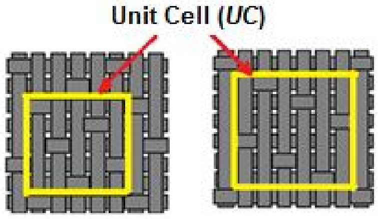
d. Ning and Chou model (1998) *e*. Searles, Odegard and Kumosa model (2001) *f*. Hofstee and van Keulen model (2001)

Fig. 5 – UC modelling evolution.

Various analytical approaches were developed to establish constitutive equations of the textile composite material by Hashin and Rosen in 1964, Chamis in 1989, Suquet in 1993, Yeong *et* al. in 1998. They were primarily used as code analysis to predict the general properties and mechanical response. The simplest of these methods are based on the rule of mixtures and classical lamination theory. In this method, laminated composites are considered to be homogeneous materials. Volume partition approaches were developed for the description of the fabric's geometry and of the system of heterogeneous materials. Tabiei and Jiang proposed a method to mesh the UC by dividing it in sub-cells (Tabiei & Jiang, 1999). As shown in Fig. 6, for plain wave textile type, the repetitive unit cell is divided into four sub-cells (Tanov & Tabiei, 2001). Later, in 2002, Tabiei and Yi (2002) have extended this method using finite element analysis, which can provide a more accurate prediction on the effective stiffness of woven composites. A new technique, based on finite volume elements (voxel) was tried by Bogdanovich in 2006, to represent architecture textile composite woven into three dimensional space (3-D), where the volume of representative composite fabric was defined as homogeneous and anisotropic. The elastic properties of representative volume was determined by volumetric averaging the stresses and strains in the sub-volumes (sub-voxel).



a. fabric architecture *b.* unit cell (UC) *c.* sub-cell



d. UC of 5 and 8 harness satin

Fig. 6 – Modelling the plain wave fabric at mesoscopic scale.

3. Conclusions

Competitive mechanical properties of fabrics, combined with a better knowledge of manufacturing technologies, their easy handling, have led to an impressive widespread use of composite materials in industrial applications. However these materials have a complex internal architecture which complicates their analysis.

The modern design is a complex process that involves, among other things, optimizing structures, the use of modelling and analysis methods, which rely on the use of computers and computer programs. The methods commonly used in the structural analysis and optimization may lead to considerable cost calculation, depending on the complexity of the problem.

Mechanical performance of fabric reinforced composite materials can be determined either experimentally or by numerical simulations, latter variant being more convenient when searching for the mechanical properties of fabrics. Hierarchical steps of the analysis of textile reinforced composites include micro-mechanical modelling of yarn, unit cell meso-mechanical modelling and macro-mechanical modelling at the scale of the fabric. Based on afore mentioned modelling steps, distinct analysis methods were developed, in order to be later integrated in a complex modelling approach. An important feature of available models is that they are all developed for a particular textile architecture, lacking a generalized model, where fabric pattern can be seen itself as a parameter, which is major challenge for design engineers.

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SOLUȚII DE MODELARE A COMPOZITELOR ARMATE CU ȚESĂTURI

(Rezumat)

Textilele sunt considerate printre cele mai eficiente armături pentru materialele compozite, cele mai utilizate fiind țesăturile. Materiale compozite armate cu țesături au însă o arhitectură internă complexă, ceea ce face ca analiza lor să fie complicată. De aceea s-a convenit implementarea unei ierarhii standard de modelare, bazată pe conceptul integrat de modelare a textilelor, considerând trei scări de modelare şi anume: modelarea micromecanică a firelor, modelarea mesomecanică a celulei unitate de material şi modelarea macromecanică a țesăturii. În lucrare se prezintă principii de modelare a compozitelor armate cu țesături, precum şi modelele pentru celula unitate, care stau la baza evaluării performanțelor mecanice şi optimizării proprietăților mecanice ale acestor materiale.