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A novel textile composites design and analysis tool

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Abstract

With the ever increasing use of textile reinforced composite materials in structural applications an analysis tool is needed that would provide: Ease of use, computational efficiency, accurate results, variety of output formats and links to industry standard design tools. Such an integrated composites design and analysis tool is currently under development at the Katholieke Universiteit Leuven.

The core of the program consists of a geometry preprocessor, mechanical analysis modules and an output postprocessor. The geometric preprocessor can currently generate the geometry for 2D and 3D woven fabric reinforced composites. It should be pointed out that this preprocessor is not just another CAD-like geometrical tool but a truly predictive model based on the mechanics of flexible yarns.

Two mechanical analysis modules are available. The first one is a cell model which predicts the stress state within the unit cell of a material using energy principles, and is particularly suited for 2D and 3D weaves and braids. The other module is based on Eshelby's transformation principles in conjunction with a short fibre analogy, and is mainly aimed at microstructures with a high degree of disorder, including knits, short fibre composites and particles. The integrated approach allows the combination of both modules on different homogenisation levels. The output postprocessor links output from the different mechanical modules to a variety of design and analysis tools.

The mechanical models can predict with very good accuracy elastic properties (both in- and out-of-plane ones) as well as the onset of failure. Mechanical loading and some thermal effects can be considered during computations. The effect of moisture on stiffness and stress as well as stochastic

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effects will also be added in the near future.

The proposed tool represents a major step forward, towards the development of real composites design and analysis programs. It is hoped that it will prove to be a catalyst in the development of such tools.

1 Introduction

A variety of models is available in the literature for modelling the mechanical behaviour of textile composites. A graphical overview is shown in Fig. 2.1, where the models are classified according to their predictive accuracy (linked to the level of microstructural detail included) and computational efficiency (CPU time). Broadly speaking, current models can be grouped into four major classes. The majority of models is still based on laminate theory and orientation averaging techniques (the latter sometimes referred to as fabric geometry models) [1-6]. These models are primarily used to predict the thermoelastic behaviour of the textile composite but can only provide a very rough estimate of internal stresses, and hence cannot be used for damage and strength analysis.

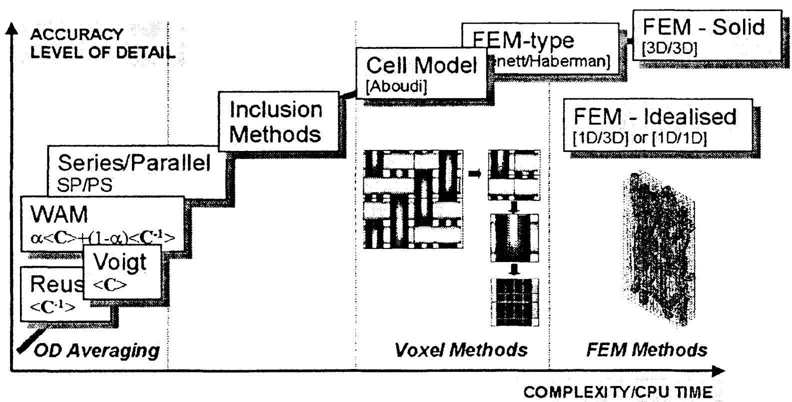

Figure 1: Schematic representation of the various mechanical models for composites.

Fibre dominated elastic properties (e.g. on-axis moduli) are predicted with acceptable accuracy but matrix dominated behaviour, like shear and out-of-plane properties, are predicted with significant errors. The other side of the spectrum is occupied by Finite Element models with different levels of detail

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and idealisations [7-10]. In addition to providing thermoelastic composite properties they also provide estimates of the internal stress/strain fields with moderate to good accuracy, which allows some of them to be used for progressive damage analysis. Unfortunately, Finite Element models are not computationally efficient and are, in most cases, cumbersome to use and not sufficiently generic. An important characteristic of the available models discussed so far is that they are all developed towards particular textile architectures, and that the meso-mechanics implementation is closely linked to assumptions made in the geometrical description of the textile microstructure.

The large gap between the simple, but inaccurate orientation averaging techniques and the elaborate and less generic Finite Element models has more recently been bridged by two other classes, based on inclusion methods [11, 12] and energy approaches using the method of cells [13-15].

The method of cells predicts the microstress field within the unit cell of a composite material using energy principles, and originates from the work of Aboudi [16] and Chen and Cheng [17]. They were the first to propose a mechanistic solution (using the complementary variational principle) as opposed to the orientation averaging schemes which have been dominant in mechanical properties prediction for composite materials. Such models have been applied up to now to composites reinforced with 2D and 3D weaves and braids. The prediction of internal stress fields is a unique capability of the cell method, which sets it apart from everything else available up to now. Most of the orientation averaging schemes assume the existence of a constant stress or strain state throughout the material unit cell, which overemphasises the role of the matrix or the fibre reinforcement on the overall behaviour. Consequently, predictions carried out using iso-stress/strain models may have significant errors associated with them. In addition, they do not allow the prediction of failure. The ability of cell models to predict stresses inside the material gives them a unique advantage. These models can accurately predict the engineering constants and failure progression in a composite material.

Inclusion models on the other hand compute the elastic properties of a composite using a mean field approach based upon the equivalent inclusion theory. Derived from models for short fibre and particle reinforced composites, as well as models for polycrystalline materials in metals applications, they were for the first time extended towards textile composites by KULeuven. Inclusion models are very efficient, can be used for a variety of composite materials (UD, random fibre mats, knits, weaves and braids) and solve the major shortcomings found in orientation averaging models. Inclusion models also abandon the iso-stress/strain assumption and allow the prediction of stiffness and failure with good accuracy. An advantage they have over cell models is there computational efficiency and their ability, in principle, to be applied to virtually any textile architecture.

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Fundamental concepts are available to relate textile or textile composite properties to the basic characteristics of the textile structure and those of the used fibres and yarns. However, these concepts have to be translated into workable models for predicting:

- the full geometrical description (or yarn architecture) in relaxed and deformed textiles
- the mechanical properties of the textile (incl. formability, drapability, compressibility)
- the permeability of the textile. The mechanical properties of textile based composites.

For each of these areas (mechanics and geometric modelling), models are under development at the department MTM - K.U.Leuven. These models are being implemented into software packages, which can be used as a design and optimisation tool by textile and composites engineers. This means that:

- the calculation times should be limited, e.g. in order to allow parametric studies, or to connect the model output as input to structural finite element calculations
- the software should be robust, and act as a "black box", so that for instance a composites engineer can use it without having to study in depth textile technology - the different software packages should be integrated into one single "Integrated Design Tool"

2 The integrated design tool

The composites group of K.U.Leuven is currently putting a large effort on the development of theoretical models for the prediction of the microstructure and behaviour of textiles and their composites. A unique feature of this research is the integrated, hierarchical approach in which the different models are being developed and linked together. This strategy is schematically outlined in Fig. 2.

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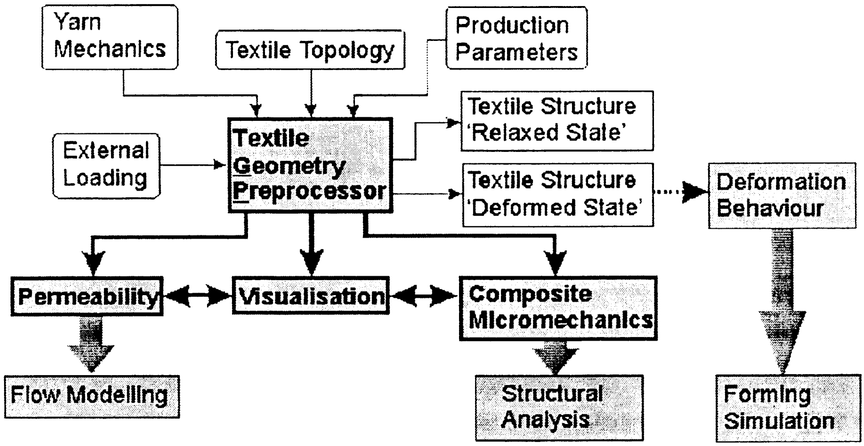

Figure 2: Schematic representation of the Integrated Design Tool concept.

The ultimate goal is to develop unified, integrated design methods for textiles and textile composites. The core of this design framework is formed by a Textile Geometry Preprocessor (TGP). Additionally, mechanical loads that are relevant for composite manufacturing - including fabric compression, shear and biaxial tension - will be taken into account to compute the fabric geometry in the deformed state. Apart from the mechanistic approach involved within the textile geometry model, the TGP under development will be unique in the sense that different textile classes including 2D/3D weaves, braids and knits will be treated using an identical, hierarchical top-down analysis.

The output of the TGP will be converted into several formats to allow further processing in the textile processing and composite meso-mechanics modules.

2.1 The textile geometry preprocessor (TGP)

The main research direction in this area is the development of a Textile Geometry preprocessor. A mathematical model of the internal geometry of textile structures - woven, knitted and braided - is used as a unit cell geometry preprocessor for meso-mechanical and permeability models of composite materials. The model computes the spatial placement of all the yarns in a fabric repeat, based on the topology and the geometrical and mechanical parameters of the yarns. The topology input is obtained from the manufacturer, and the mechanical behaviour of the yarns, in bending and compression, can be measured on standard textile laboratory equipment. The principle of minimum energy of a fibrous assembly leads to the prediction of the yarn crimp, the forces in the yarn contacts and the yarn compression within the fabric. The output can be formatted as per the input requirements of the mechanical models. Additionally tools for the 3D representation of the structure, to create unit cell sections and to compute

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the unit cell porosity are provided(Fig. 3).

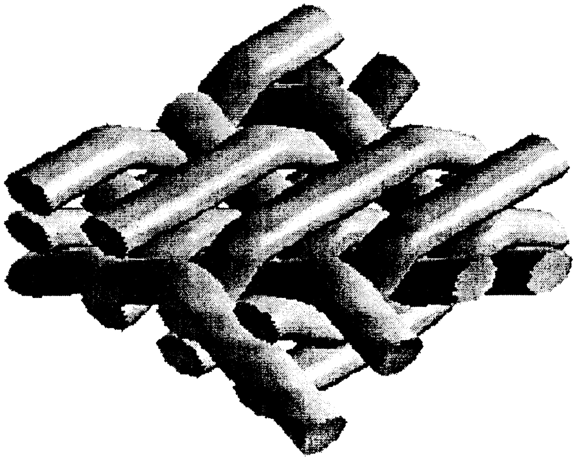

Figure 3: Sample geometry for a 3D woven textile generate by the Textile Geometry Preprocessor.

A software package — CETKA-KUL — which is restricted to woven fabrics, has been developed and linked to the existing meso-mechanical software (TexComp and FlexComp) to prove this concept (an early version of this model was reported at the previous CADCOMP conference). The advantage of this software is that it allows an *a priori* prediction of the woven fabric geometry, which can be imported into the meso-mechanical models. Hence, it becomes possible to estimate the mechanical properties of the composite prior-to-manufacture. For woven glass reinforcements, computations performed with the CETKA-KUL software were compared with experimental measurements, showing good agreement. A more general package, called WiseTex, covering braided as well as knitted architectures is currently under development.

2.2 The complementary energy model (CEM)

This modelling scheme consists of a multilevel automated geometric decomposition of a representative volume element (unit cell) into smaller elements (micro cells) containing yarn and matrix parts. This way, the problem of stress analysis for the whole unit cell is split into a number of subproblems at each level of the decomposition scheme. This top to bottom decomposition is followed by a bottom to top homogenisation scheme in which internal stresses (sub-unit cell level) are linked to external ones (unit cell level). The complementary variational principle[16] has been utilised to implement this [14, 15]. This procedure results in the prediction of stiffness, internal stress

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fields and failure of the composite. Additionally the model is capable of predicting the onset of failure. This model has been implemented in the TEXCOMP package. Two and three dimensional woven and 2D braided fabric composites can be modelled at present.

2.3 The inclusion models

Two inclusion models [11, 12] have been under development at KULeuven. As for the Complementary Energy Model they also work at the unit cell level. In principle this model can be applied to all kinds of reinforcement architectures. The hearline of the yarns in the unit cell is mathematically represented by cubic splines. The yarns are subdivided into small segments which are characterised by their orientation, local curvature and volume fraction. From these segments an equivalent model composite is derived by replacing them with straight ellipsoids (inclusions).

The elastic properties of the original composite can be computed by solving the equivalent composite using a mean field approach based on the equivalent inclusion theory. Two mean field schemes are under study: The Mori-Tanaka and the self-consistent methods. Since these models allow the prediction of internal stress distribution they can also be used for damage modelling. The FLEXCOMP software programme has been developed based on these schemes.

2.4 Permeability

From a literature survey, it becomes clear that there is not yet a generic tool available to predict fabric permeability. permeability is a complex property governed by the local details of the fabric structure. It remains an important parameter to be evaluated for the impregnation behaviour in currently common production techniques like resin transfer moulding (RTM) and resin infusion moulding (RIM). Work is under way to develop a permeability model that takes into account the very detailed aspects of fluid flow in complex fabric structures - including fabric deformation and layer nesting - and that will be applicable to a variety of textile classes. The software in development in based on the Lattice-Boltzmann method. Both regular and irregular lattice approaches are being considered for reduced computation time and modelling flexibility.

3 Discussion

The primary technological aim of the presented work is the rationalisation of the use of textiles in composite materials. The availability of design tools, which is already common practice in other material disciplines, will eliminate much of the trial and error methods in materials and textile structure selection as well as during composite production.

For this purpose the integrated software in development can be used as a stand-alone calculation tool for materials selection and optimisation.

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However, the ultimate aim is to link it to commercially available software packages for process simulation and structural analysis.

Permeability tensors are essential input for macroscopic flow programs, used to calculate mould design and mould filling times. They are currently measured experimentally, which is a time consuming and costly procedure, requiring specialised equipment. Numerical tools can easily assess the effect of influencing parameters like fabric structure, layer nesting and fabric compression.

Composite meso-mechanical properties can be used as objective functions to optimise material performance for a given application, but can also be used as input for structural analysis codes based on finite element analysis.

	E_x	E_y	E_z	ν_{xy}	ν_{xz}	ν_{yz}	G_{xy}	G_{xz}	G_{yz}
Z3 meas.	50.4	57.0							
FGM	46.8	57.1	18.8	0.075	0.397	0.388	7.35	7.69	8.90
SC	48.7	56.0	15.8	0.082	0.346	0.322	4.94	5.16	7.84
CEM	47.9	56.4	16.2	0.083	0.366	0.342	5.14	5.38	8.10
Z12 meas.	36.0	44.9							
FGM	37.2	35.3	18.8	0.106	0.319	0.345	6.44	7.31	5.90
SC	35.7	33.9	17.3	0.103	0.297	0.276	3.78	4.97	4.33
CEM	36.1	34.2	17.9	0.151	0.310	0.303	3.86	5.01	4.41

Table 1: Comparison of experimental data and model predictions for a 3D woven fabric composite: Iso- strain model (FGM), inclusion model (self-consistent - SC) and cell model (CEM). Z3 and Z12 are are samples of the 3D material having different warp weavers (3 and 12k yarns respectively)

Lastly, the fabric behaviour calculated by the TGP for the different deformation modes provides the constitutive behaviour of the unimpregnated textile, which is used to assess the feasibility of a shaping operation on a given component geometry by fabric formation software. The fabric geometry can also be output to commercial packages including CAD programs and finite element code via a neutral graphics format, for purposes of external design, validation and detailed analysis.

Comparison of experimental and model predictions for the various modules that make up the Integrated Design tool have shown very good agreement. An example of typical results for mechanical properties is given in table 1. Geometric output was compared to tomographic images with results proving the ability of the TGP to estimate the geometric structure of the reinforcement material.

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