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Predicting the effect of voids on mechanical properties of woven composites

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Abstract. An accurate yet easy to use methodology for determining the effective mechanical properties of woven fabric reinforced composites is presented. The approach involves generating a representative unit cell geometry based on randomly selected 2D orthogonal slices from a 3D X-ray micro-tomographic scan. Thereafter, the finite element mesh is generated from this geometry. Analytical and statistical micromechanics equations are then used to calculate effective input material properties for the yarn and resin regions within the FE mesh. These analytical expressions account for the effect of resin volume fraction within the yarn (due to infiltration during curing) as well as the presence of voids within the composite. The unit cell model is then used to evaluate the effective properties of the composite.

1. Introduction

Woven fabric reinforced composites at micro level are heterogeneous materials however, the modelling of structural response using FEA or analytical techniques is generally carried out at ply level and requires the user to assume an effectively homogenized material with a set of effective material properties for this homogenized material. The number of constants required depends on the assumed behaviour. The most common approximation used is orthotropic elastic and requires input of nine material constants. Besides the resin and fibre types and their relative volume fraction, these constants are also sensitive to other factors such as weave architecture, extent of compaction, void content and extent of resin infiltration within yarn. In case of existing materials, the constants can be evaluated using standard ASTM tests. Performing these tests however, is often, time consuming, expensive, requires specialized test fixtures, and in some case suffer from poor repeatability. In particular, the reliance on testing is not practical for development of new materials or optimization of manufacturing (e.g. curing) parameters (such as temperature and pressure etc.). In these cases, ideally one needs a capability to theoretically

predict the properties of resultant composite even before the material is made, with only few tests required at the end to validate the model.

Methods of determination of effective engineering constants of composites using micro-mechanical modelling are now sufficiently well developed for both unidirectional as well as fabric reinforced composites. Micro-mechanics based strength prediction of composites on other hand is more challenging. Failure initiation is often well estimated but final failure seldom is; this is because final failure in composites is progressive and heterogenous in nature and not necessarily periodic. Strength prediction is even more difficult for composites with a significant voids content or with those having matrix toughening inclusions.

Several analytical as well as FEA based modelling methodologies have been presented by various authors for micro-mechanics based estimation of composite properties e.g. [1–9]. The analytical methods vary widely in terms of accuracy and input data requirements. There always seems to be an inevitable trade-off between simplicity and correctness. Techniques such as Periodic Microstructure Modelling (PMM) [6] provide quite an accurate estimate for unidirectional fibre reinforced composites but are difficult to implement and need a lot of input parameters, which at times may be difficult to obtain. Analytical methods for woven composites are even more difficult to implement however some of them are now available in the form of free to use codes. Barbero for example has made his algorithm [10] available to wider audience in the form of online software CADEC. More recently, analytical methods have also been presented and validated for orthogonal 3D woven composites [11,12]. Analytical models are quicker for evaluating property trends and thus better suited to inform development of new materials. Their accuracy is often limited because of the assumptions made and all properties are not predicted equally well with a single model, thus requiring use of multiple models for various problems. Most of the analytical models are less generic and change in parameters such as weave architecture for example may require a significant development effort rather than just specification of some new parameters.

FEA methods although more time consuming to implement and solve can be used to reliably and accurately predict the effective properties of any proposed weave architecture. The accuracy of FEA model in principle depends on a) accuracy of the geometric model and mesh used to construct the RVE, b) correct representation and implementation of periodic boundary conditions for the unit cell. While the latter is a mathematical constraint and with due diligence one can insure sufficient correctness, the former depends highly on available resources. Firstly, the resources for capturing and representing the internal architecture correctly and secondly the computational resources for the solving a highly accurate mesh. Given the fact that resources are always finite, reasonable assumptions must be made to simplify the representation of internal architecture. The geometric model and subsequent FEA mesh for FE micro-mechanics is often produced employing major simplifications which include,

a) modelling the yarn as homogenous solid (as opposed to modelling individual fibres within a yarn),

b) ignoring the weave compaction that takes place during manufacturing and curing process, i.e. pre-cure weave architecture as opposed to post cure,

c) assuming no infiltration of resin within the yarn and assuming resin and fibre to be perfectly bonded and dispersed.

d) ignoring voids as well as any inclusions within matrix.

All these simplifications can severely reduce the accuracy of the model unless these are accounted for in some way. Thus, in this paper we will present a methodology to account for these simplifications in a consistent manner using the example of a satin weave composite. The aim is to give recommendations so that the material designers and modelling community can make informed choices about the assumptions that they take while developing and using an FE based micro-mechanics model of textile composites.

2. Methodology

The modelling methodology proposed in this study can be outlined as a five-step process. These steps are demonstrated by applying on satin weave reinforced phenolic pre-preg (ACG SL246/40) composite. Full material specifications and details of manufacturing and layup are available in our earlier publication [13]. The test panels used for the study were vacuum bagged and cured using QuickStep ™. The volume fraction of fibers (V_{fe}) achieved was 39.9%, volume fraction of matrix (V_m) was 54.8% and the average void content was 5.3%.

2.1. Defining the Representative Volume Element (RVE)

Woven composites are characterized by a weave pattern that repeats in-plane periodically for each lamina. In this study the notation used by Barbero [10] is employed to define the RUC in terms of Harness/Shift/Interlace numbers. The representative volume element (RVE) used for FE micromechanics for a plain weave is $1/16^{th}$ of the RUC using symmetry and anti-symmetry considerations. In case of other weave patterns however, the RUC may not be reduced any further and in such cases the RUC and RVE are the same. Since in this study a satin weave is chosen as an example thus the term RVE and RUC are used interchangeably.

The RUC of the fabric used was 8/5/1 (Harness/Shift/Interlace). In real composites this RUC weave pattern repeats exactly, however other parameters such as the yarn thickness along fill and warp or the thickness of matrix region between layers, the cured shape of the yarn, the gaps between tows and any voids or air pockets will not repeat exactly. Small variations are always expected for these parameters. Therefore as suggested in [13], an approximate representation of the RVE, which is correct in an average sense is better than using an RVE directly generated from a scan of one very small region of the specimen. This is also important from new materials development point of view where the emphasis is not on getting an exact property value, rather, it is on generating realistic property bounds or ranges. In practice the RVE may be generated using the post-cure architecture of the desired woven composite by averaging the RVE parameters taken from a series of internal cross-sectional views generated from a technique such as X-ray microtomography or cross-sectional microscopy. In case of new material development study, the post-cure geometry used should be approximated from post cure geometry of a similar type of fabric resin combination. Alternately a procedure such as a one outlined in [8] can be used to model the compaction and consolidation of the proposed weave during curing. In this study the RVE was identified using average RVE parameter values from X-ray micro tomographic scans of the example composite. The main RVE parameters are summarized in table 1.

2.2. Creating a geometric model of the RVE

The RVE parameters such as the ones defined in table 2, can be used to generate the solid model of an RVE using any commercial solid modelling package and then this can be imported in FEA software such as ABAQUS ™. In this study however, a dedicated textile composite solid modeller and pre-processor called TexGen was used for ease of model and mesh generation. TexGen not only makes it simple to generate the geometric model, it also makes it easy to assign materials properties, apply orientations and create boundary conditions. Thus, the entire pre-processing is done in this environment. As is customary, while generating the RVE the cured yarn as opposed to individual fibres within the yarn are modelled and the yarn is approximated as an effectively homogenous albeit orthotropic solid with a lenticular shape as defined by average parameters defined in table 1. Modelling the individual fibres in yarn with a tow count of 3K or more in each yarn is firstly highly complicated with respect to the process required for geometric model generation and secondly even if one were to generate such a model the resulting mesh will be computationally very expensive. Thus, in this study a secondary micro-mechanical model is proposed to generate the desired input mechanical properties of the yarn. This is explained in following section. It should also be noted that individual voids are not modelled discretely using the geometric model in this study. Instead as will be explained later an approach to account for these voids in an average sense is introduced and discussed later.

Table 1. Key RVE properties

Parameter	Mean value
Width of warp yarn 'Wp'	0.41 (mm)
Width of weft yarn 'Wt'	0.45 (mm)
Resin interface between consecutive yarns 'hint'	0.01 (mm)
Height of yarns 'hy'	0.12 (mm)
Thickness of resin layer between two consecutive lamina 'hr'	0.05 (mm)
Volume of fibers in the UC (V_f)	1.472 mm3
Volume of yarns in the UC (V_y)	1.895 mm3
Fibre volume fraction of the yarn (V_{fy})	0.7768
Resin Modulus of Elasticity (E_m), GPa	3.60
Resin Poisson Ratio (υ_m)	0.35
Fibre Modulus of Elasticity (E_f), GPa	73
Fibre Poisson ratio (υ_f)	0.23

2.3. Calculating Material property inputs for the RVE

Once the geometric model of the RVE is created correct material properties need to be assigned to each zone. As mentioned above the yarn as well as matrix have been idealized as homogenous materials. In reality, yarn is a composite of individual fibres, infiltrated resin within yarn as well as voids. Matrix on the other hand is a composite of resin, voids as well as resin inclusions such as toughening micro or nano particles in some cases. This results in the yarn and matrix properties to be different from those of dry fibre and pure cured resin. In this study we suggest using secondary micro-mechanics model to generate these properties.

2.3.1. Generating effective properties for yarn

The yarn can be approximated as a unidirectional fibre reinforced composite, as long as the material properties of yarn are assigned in a local coordinate system that rotates with the yarn along each material integration point within the FE mesh. Thus, existing analytical micro-mechanics based relations for effective properties of UD composites may be used for estimating these properties. Alternatively, an FE based micro mechanics model of UD composites may be used.

In this study a transverse isotropic behaviour was assumed for the yarn and analytical relations that were used are summarized in [13, Table 6]. In these equations the elastic modulus and Poisson ratio of neat cured resin (E_m, v_m) and dry fibre (E_f, v_f) are used as input. These equations also require the input of fibre volume fraction within yarn (V_{fy}). It must be noted that V_{fy} is different from the overall fibre volume fraction of composite. This is due to the fact that yarn is approximated as lenticular in shape (see e.g. figure 1) and due to this the total volume of fibres in the Unit Cell is different from the total volume of yarn in the unit cell. For, details of the calculation procedure the reader is referred to [13].
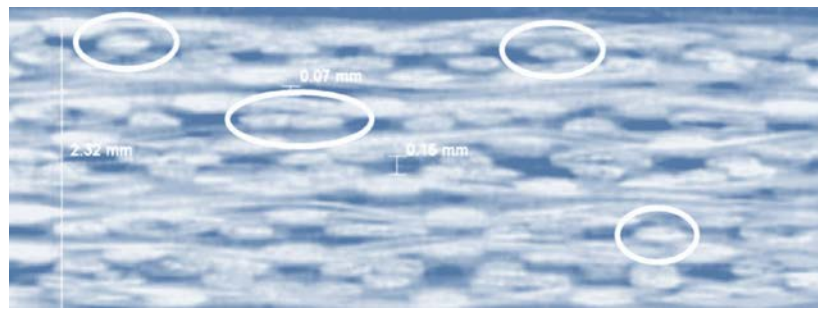
Figure 1. X-ray tomography image (right) [14,15] showing the lenticular shape of yarn in a cured composites (example woven composites satin weave ACG SL246/40)

2.3.2. Void compensation

The presence of voids (as well as any possible particulate inclusions) are expected to have a direct influence on resin properties (E_m, v_m), no effect on fibre properties (E_f, v_f) and an indirect effect on yarn properties (due to the change in input matrix properties in the relations outlined earlier). The dispersion of these voids or possible particulate inclusions are generally random and therefore, the response of matrix is expected to remain isotropic. In this study the resin used does not have any inclusions and thus the properties should only be modified to reflect the effect of voids.

A simple semi-empirical strategy was used to compensate for voids. The properties of resin in the presence of void may be calculated by assuming that the matrix properties can simply be reduced in proportion to the fraction of the void content present in the matrix. Thus, the void compensation factor may be calculated as an empirical factor, $V_{cf} = \frac{V_m}{(V_m + V_o)}$. The matrix input properties are then simply calculated by multiplying this factor with the properties of neat resin. The same reduced properties are also used in the analytical relations for calculating the yarn properties.

Table 2. Constituents input properties for RVE using corrected fiber volume fraction in yarn and with void compensation for matrix properties

	Material Parameter	Value
Matrix	Modulus of Elasticity (E_m, GPa)	3.285
	Poisson Ratio (v_m)	0.319
	Shear Modulus (G_m, GPa)	1.245
Yarn	Longitudinal Modulus of Elasticity ($E_{x(y)}$, GPa)	57.438
	In-plane Transverse Modulus of Elasticity ($E_{y(y)}$, GPa)	24.284
	Out-of-plane Transverse Modulus of Elasticity ($E_{z(y)}$, GPa)	24.284
	In-plane Poisson Ratio ($v_{xy(y)}$)	0.250
	Out-of-plane Poisson Ratio ($v_{xz(y)}$)	0.250
	Out-of-plane Poisson Ratio ($v_{yz(y)}$)	0.876
	In-plane Shear Modulus ($G_{xy(y)}$, GPa)	7.468
	Out-of-plane Shear Modulus ($G_{xz(y)}$, GPa)	7.468
	Out-of-plane Shear Modulus ($G_{yz(y)}$, GPa)	6.472

2.4. Finite Element Analysis (FEA)

The geometric model after assignment of material properties and orientations is meshed using solid elements (see figure 2). Periodic boundary conditions are also applied to the RVE at this stage and an input deck is generated for solution in commercial FEA software like ABAQUS. The details of FEA are covered in [13] and thus not repeated here.
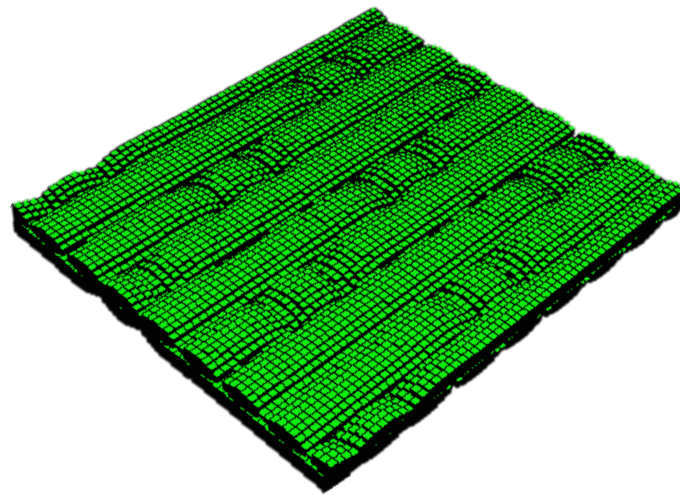

Figure 2. Finite element mesh of the RVE using 8 node cubic 3D solid elements with reduced integration (C3D8R) in ABAQUS

3. Results and Conclusions

In table 3, A comparison of FEA properties predicted using the above approach after void compensation and correction for fibre volume fraction in yarn is made with the analytical predictions obtained from the CADEC software as well as with experimental values for two data points.

Table 3. Effective orthotropic properties predicted in Case 3

Woven composite effective property	FEA micromechanics	Analytical Micro-mechanics (CADEC)	Experimental
Modulus of Elasticity in Warp Direction, E_x^0	20.33 GPa	20.62 GPa	20.512 GPa
Modulus of Elasticity in Weft Direction, E_y^0	20.03 GPa	20.98 GPa	-
Out-of-plane Elastic Modulus, E_z^0	8.312 GPa	$*$	-
In-plane Shear Modulus, G_{xy}^0	3.843 GPa	4.828 GPa	3.855 GPa
Out-of-plane Shear Modulus, G_{zx}^0	2.504 GPa	$*$	-
Out-of-plane Shear Modulus, G_{yz}^0	2.510 GPa	9.073 GPa	-
In-plane Poisson Ratio, v_{xy}^0	0.16	0.156	-
In-plane Poisson Ratio, v_{yx}^0	0.15	$*$	-
Out-of-plane Poisson Ratio, v_{xz}^0	0.47	$*$	-
Out-of-plane Poisson Ratio, v_{zx}^0	0.19	$*$	-
Out-of-plane Poisson Ratio, v_{yz}^0	0.48	0.156	-
Out-of-plane Poisson Ratio, v_{zy}^0	0.20	$*$	-

This comparison shows that the proposed methodology is able to produce highly accurate results. The advantage of using this methodology over the analytical methodologies are multiple. Firstly, the out of plane properties and shear properties can be predicted with same degree of accuracy using this approach. Secondly, the approach can easily be extended to account for hybrid weaves. This is a big advantage and can prove very useful in evaluating new and novel material combinations.

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