CREATING FINITE ELEMENT MODEL OF 3D WOVEN FABRICS AND COMPOSITES: SEMI-AUTHOMATED SOLUTION OF INTERPENETRATION PROBLEM

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Abstract
As one of the problems in the modeling of the 3D woven composites is given by geometric yarn interpenetrations, this paper presents a solutions for a E-Glass 3D woven case. The solution is validated by comparison of the corrected geometry obtained from specific adjustments and the geometric measured from literature. The 3D model is generated using the WiseTex software, which creates approximate fabric models with the constant cross-section shapes of the yarns. According to experimental measurements, the yarn cross sections are modified to approach the actual shapes and hence adequately represent the intra-yarn fiber volume fraction. The yarn interpenetrations are corrected by adjusting nodes of discretized yarn contours. The FE analysis results show good agreement with the experimental data for the elastic properties of the composites.

1 Introduction
The state-of-the-art of meso-level (UC) FE modelling of textiles and textile composites includes a number of numerical tools for creation of adequate FE models of textile unit cell, either dry or impregnated. However, it is quite often that the models reported in literature deviate from the reality of the modelled material in an important parameter such as the intra-yarn fibre volume fraction, which is often overestimated and may reach non-realistic values of over 80%, or even close to 100%.(e.g. [1,2]) This deviation is caused by the necessity of combining several modelling restrictions. On one hand, the overall fibre volume fraction and thickness of the composite must be preserved, as these are two main factors determining the mechanical response of the material. On another hand, the geometrical preprocessors, used as a basis for the FE model, introduces assumptions on the shape of the cross sections of the yarns (e.g., elliptical shape) which limits the possibility of defining the internal geometry with the given total volume occupied by the fibres without interpenetration of the yarn volumes. The less of yarn volume yields overestimated fibre volume fractions inside the yarns. Different approaches have been proposed to solve the interpenetration problem in FE

modelling of textile composites [3, 4]; however, a general solution has not been found yet.The problem is especially grave for 3D woven and braided architectures, where the constraints of yarn interaction are complex. This paper describes a solution for interpenetration problem for 3D orthogonal woven reinforcements and the validation of the solution by comparison of the elastic properties estimated with the FE model (Abaqus) against experimental data [7].
As reported in [7], the material studied is 3D woven composites with thickness of 2.60±0.06 mm and a total fiber volume fraction of 48.9. The fiber architecture of the material is formed by three warp layers of PPG Hybon 2022 roving and four fill (a.k.a.weft) layers of Hybon 2022 roving interlaced by through thickness (Z-directional) Hybon 2022 roving. The middle warp layer is made of 450 yield roving and the other two layers, placed symmetrically with respect to the mid-surface, are made of 218 yield roving. The warp end density of 2.75 ends/cm is used. All four fill layers are made of 330 yield roving. The fill insertion density is 2.64 picks/cm. The 1800 yield Z roving is inserted by two harnesses with 2.75 ends/cm density, one Z to one warp end.

2 Geometry and FE modelling

2.1 Correction of yarns interpenetration

The work presented in this paper is based on a UC geometry model generated using WiseTex software [3] which gives correct overall parameters, as: weave topology, fiber volume fraction, unit cell dimensions, including thickness, yarn spacing, dimensions (width and thickness) of the yarns and yarn paths. However, the shape of the yarn cross sections is subjected to the restrictions of the geometry modeller and does not correspond exactly to the reality. As a result, the geometry model has yarn interpenetrations and intra-yarn fiber volume fraction is overestimated. Hence, to solve these problems two steps are identified:

1. Before the transfer of the model to Abaqus/CAE the real internal geometry of the unit cell is measured to get realistic yarn cross sections; these parameters are then input to the Python script, which transfers the WiseTex geometry description into Abaqus model
2. After the transfer of the model to Abaqus/CAE, the interpenetrations are corrected by moving several control points on the yarn contours by means of *ad hoc* Python scripting, subsequently the matrix volume generation is done by Boolean subtraction of the yarns from the UC volume.

2.1.1 Yarn section identification

In order to modify the elliptic WiseTex native yarn cross section shape, optical microscopy cross-sectional views are taken from [7] and used to estimate yarn cross section shapes for warp and weft directions, Figure 1. The aim is to simplify the real cross section shape to a rectangular or trapezoidal geometry. To do this, the yarns are first grouped together based on similar shapes and dimensions.

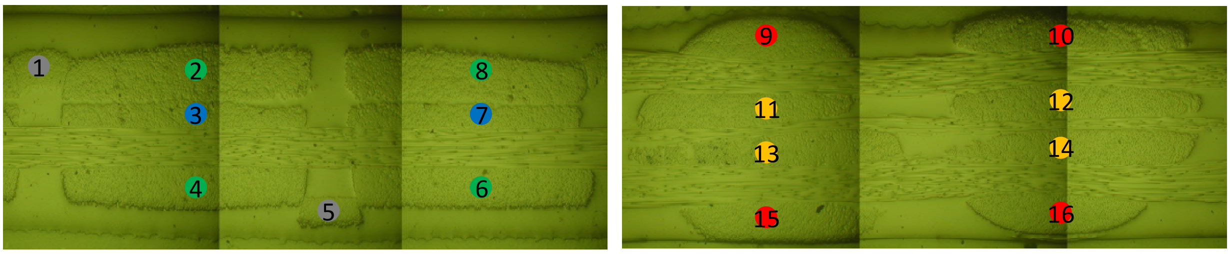

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Figure 1. Optical microscopy cross-sectional views, yarns numbering and main yarn shapes identification: (a) Warp yarn cross sections, (b) Weft yarn cross sections. Yarns with the same colours of the numbers form a group.

For each group the yarns are measured and an average cross section area is evaluated ([11]). From the measurements, most of the yarns are well approximated by a rectangular shape except the top and bottom weft yarns which are approximate by a trapezoidal shape.
The fundamental dimensions of the sections are obtained using:
i) the thickness of the yarn declared by the WiseTex model and ii) the width is calculated from average area and yarn thickness. In the trapezoidal shape case, the major base is calculated using the yarn thickness declared by the manufacturer, the calculated average cross section area and the average of the minor base measured on the images.
In **Figura 2**, data measurement and the respective calculated shapes are reported for each yarn group, while **Figure 3** shows the superposition of the calculated shapes on the real yarn cross sections.

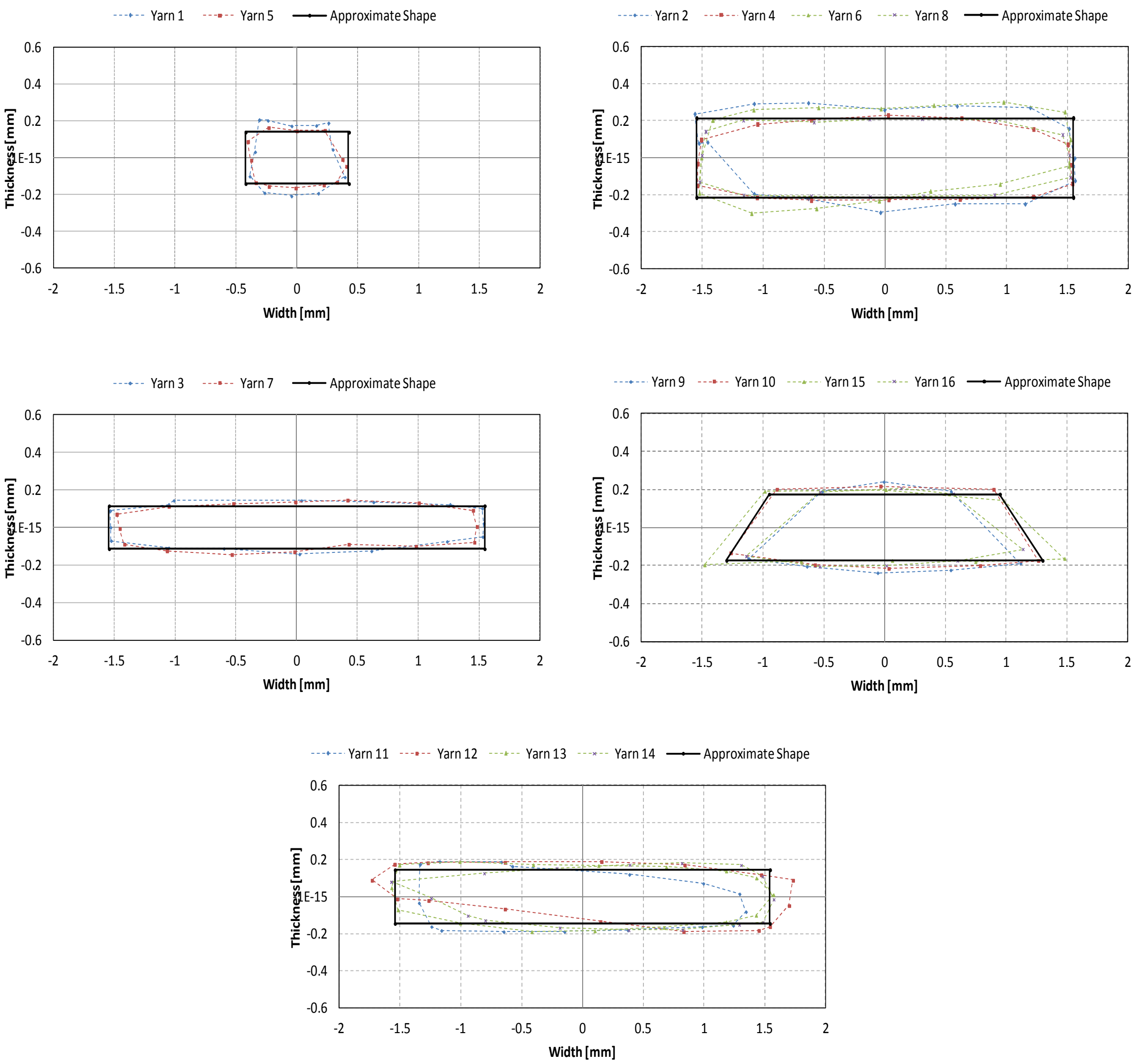

Figura 2. Cross-sectional shapes of the yarns: dotted lines – individual measurements, black solid line – the geometric approximation of the cross section shape.

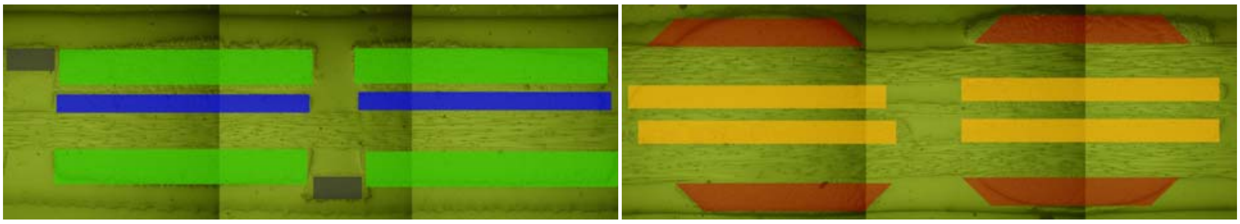

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Figure 3. Superposition of the approximated cross section shapes above the optical microscopy cross-sectional view: (a) Warp yarn cross sections, (b) Weft yarn cross sections.

Finally, the fiber volume fraction is evaluated, for each calculated shape, by means of Equation 1. The properties of each yarn used in the calculation are taken from [5].

$$V_f = \frac{T}{\rho A} \tag{1}$$

Yarn no.	Tex	Area	Approximate Area [mm^2]	V_f [%]
1, 5	276	Rectangular	0.1595	68.1
2, 4, 6, 8	2275	Rectangular	1.2659	70.8
3, 7	1100	Rectangular	0.6619	65.4
9, 10, 15, 16	1470	Trapezoidal	0.7897	73.3
10, 11, 12, 13	1470	Rectangular	0.8627	67.1

Table 1. Evaluation of the Yarns cross section volume fraction of the approximated cross section shapes.

The V_f values, reported in Table 1, approximate well the V_f=67.7% used for the calculation of elastic properties of the same composite with orientation averaging and inclusion methods in [5]. The calculated shapes are implemented into the Python script used to transfer the WiseTex geometry model with all the parameters into Abaqus/CAE.

2.1.2 Interpenetration correction and final geometry model

Once the geometry model is transferred inside Abaqus/CAE environment, several yarn interpenetrations are present which can be grouped in three repetitive macro types, as reported in Figure 4. As in the preceding subsection, the geometry correction does not have to change the thickness of the whole fabric so the criterion adopted is to adjust the interpenetrations starting from the external one, close to the outside UC boundary, towards the internal one (close to the UC core).

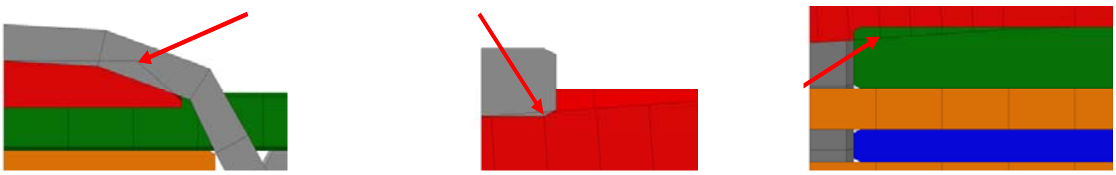

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Figure 4. Three different types of interpenetrations: (a) I warp z-yarn interpenetrates into weft top and bottom yarn, (b) II warp z-yarn interpenetrates into weft top and bottom yarn, (c) weft top and bottom yarn interpenetrates warp top and bottom yarn.

Referring to Figure 4, all the geometry adjustment are made by Python script:

- Fig. 4a. The top points of the weft yarn (red) are manually identified in the model and used as Reference Points (RP). The interpenetration is solved moving to RP the 2 nearest cross section sketch of the Z-yarn (grey) while they are kept parallel to their initial position during the translation.
- Fig. 4b. The same approach shown at the point Fig. 4a is used, with the difference that the RP are taken on the bottom of the Z-yarns (grey) and the sketch cross section moved belongs to the top weft yarn (red).
- Fig. 4c. The bottom points of the top weft yarn (red) are manually identified in the model and used to define a segmented line with which the top warp yarn section (green) is modified to avoid the interpenetration.

The last operation in order to obtain the final UC geometry, is to generate the matrix volume by Boolean subtraction of the yarns from the UC volume.

2.2 Elastic FE modelling

A Python script is used to generate the mesh, starting from weft yarns, then warp yarns, Z-yarn and finally the matrix. The 7.58x7.24x2.65 mm^3 UC is meshed with 1164172 4-noded tetrahedral elements with an approximate global size of 0.1 mm and a curvature control with maximum deviation factor of 0.1 (h/L) (Figure 5).

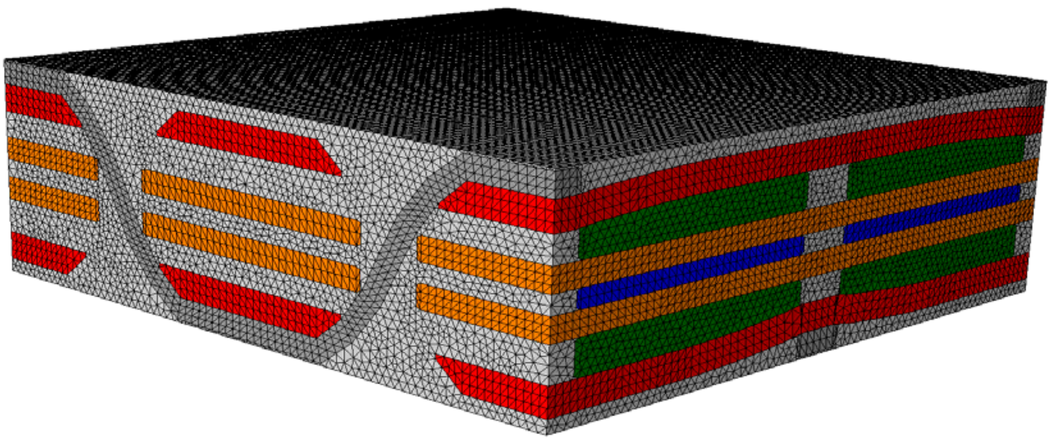

Figure 5. Meshed model.

Each yarn element has its own local coordinate system, aligned to the fiber direction, as generated by the geometry transfer Python script. The orthotropic elastic properties of the impregnated yarns, reported in Table 3, are calculated by Chamis formulae [6] using the constituent material mechanical properties shown in Table 2.

	E [GPa]	**V_f [%]**
E-Glass	72.5	0.23
Derakane 8084 Epoxy-Vinyl Ester	2.9	0.35

Table 2. Constituent material mechanical properties.

Yarn	V_f FEM [%]	E_1 [GPa]	E_2, E_3 [GPa]	ν_{12}, ν_{13}	ν_{23}	G [GPa]
1,5	69.4	51.1	14.5	0.267	0.330	5.4
2, 4, 6, 8	74.0	54.00	16.6	0.261	0.326	6.3
3, 7	65.4	48.1	12.9	0.271	0.332	4.9
9, 10, 15, 16	73.2	53.8	16.2	0.262	0.327	6.1
11, 12, 13, 14	67.0	49.6	13.5	0.27	0.332	5.1

Table 3. Homogenised properties of the yarns obtained by Chamis formulae [6].

The boundary conditions (BC) are defined in order to keep the periodicity of the stress and strain fields. Therefore, taking advantage of the material symmetry, simplified periodic boundary conditions can be applied, as reported also in [9] and [10].

3 Results and Discussion

3.1 Geometry model validation

The final geometry model presents no interpenetrations and realistic approximate cross section fiber of the yarns. Although, as shown in Table 4, there is a slight variation of the intra-yarn volume fraction, the values relative to the corrected model are realistic for E-Glass yarns.

	V_f [%] Average Shape	Average V_f [%] WInter	Average V_f [%] WOInter
Yarn 1 5	68.1	69.4	69.4
Yarn 2 4 6 8	70.8	70.7	73.9
Yarn 3 7	65.4	65.3	65.3
Yarn 9 10 15 16	73.3	73.2	73.1
Yarn 11 12 13 14	67.1	67.1	67.1

Table 4. Comparison among intra-yarn fiber volume fraction of Approximate Shape cross section, Model with interpenetration (WInter) and without interpenetration (WOInter).

The final thickness of the model is slightly increased from 2.60 to 2.65 mm, although keeping the deviation within the experimental scatter [7], in order to avoid yarn outcropping on the top surface. For this reason, the overall fiber volume fraction of the model results 47.7% against the 49.3% measured in [7].

3.2 Elastic behavior prediction

The FE predicted elastic properties are calculated in the uniaxial loading case in warp (1), weft (2) and Z (3) directions, respectively. In Figure 6a the orientation of the yarn material is shown, while in Figure 6b the stress distribution on a section through the UC in the warp direction loading case is reported.

The three Young's moduli and the Poisson ratios of the 3D woven composite are reported in Table 5. In the table, the FE homogenized properties are scaled to the experimental volume fraction V_f=49.3% and compared with i) the experimental data (exp) [6] and ii) with prediction obtained by analytical models (iso-strain, OA), inclusions (Mori-Tanaka, M-T), both implemented in TexCom [5] and iii) FE model with not realistic intra-yarn volume fraction [2].

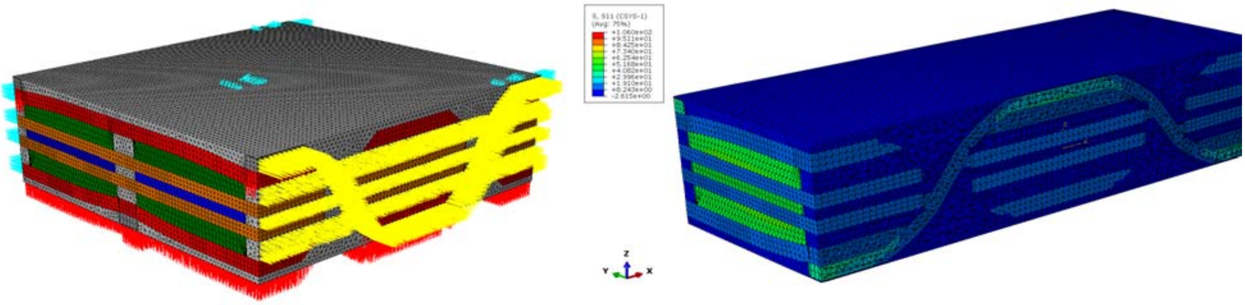

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Figure 6. FE model of the 3D woven composite: (a) Yarn material orientation, (b) Stress distribution on a section through the FE model, warp direction load case.

	exp	OA	M-T	FE [2]	FE @49.3
E_1, GPa	24.3±1.2	22.7	24.2	24^{n}	23.6
E_2, GPa	25.1±2.34	22.8	24.2	24.1^{n}	23.7
E_3, GPa	n/a	10.1	9.1	9.1	9.5
ν_{12}	0.141±0.071	0.109	0.161	0.136	0.128
ν_{13}	n/a	0.377	0.370	0.371	0.365
ν_{23}	n/a	0.380	0.368	0.370	0.359

Table 5. Measured and predicted elastic properties of 3D woven composites, ^{n} = normalized to V_f=49%.

Our model with correct yarn shapes and intra-yarn fibre volume fraction brings no improvement over this "bad" FE model in overall elastic properties. However, creation of an FE model with correct intra-yarn fibre volume fraction is important for the damage analysis, which will be reported in subsequent publications.

4 Conclusions

In this paper is described a methodology to solve two serious problems in the 3D textile composite modelling as the unrealistic intra-yarn volume fraction and yarns interpenetration.
The resulting geometry model presents a realistic over all and intra-yarn volume fraction and realistic yarn cross sections.
A FE model, based on this geometry, is used to predict the homogenized elastic properties which are compared with experimental data, analytical models and other FE model.
The final results show that elastic modules and Poisson coefficients can be well predicted with meso-FE analysis.

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