AVOIDING INTERPENETRATIONS AND FIBRE VOLUME FRACTION CORRECTIONS IN REPRESENTATIVE UNIT CELLS FOR TEXTILE COMPOSITES THROUGH ADVANCED GEOMETRY GENERATION

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Abstract
A novel method for the geometrical generation of Representative Unit Cells (RUC) of textile composites is proposed. The advanced technique retains the advantage of an analytical formulation from the current state-of-the-art but introduces variable asymmetric yarn cross sectional shapes and paths which can be tailored to the yarn shapes and cross sectional areas as measured from in-situ microscopy. In this way, interpenetrations and incorrect fibre volume fractions, which occur when using traditional RUC generation techniques [1, 2], are avoided. In addition, meshing becomes easier and no stiffness corrections are required. The new technique is validated through a comparison of the novel RUC to: 1) a RUC with constant cross section; and 2) a RUC constructed from direct in-situ micro computed X-ray tomographic measurements of a carbon-epoxy weave. The technique is also an excellent alternative for advanced unit cell generation techniques based on production process simulations, e.g.[3], in the case that the production process is unknown or an analytic periodic geometry is required.

1. Introduction

One of the cornerstones of multiscale modelling is a good geometrical representation of the sub-level structure [4–7]. In the case of textile composite materials the geometrical representation is focused on the meso-level, the length scale where yarns and matrix can be clearly distinguished. An example of this geometry is presented in Figure 1.

For fabric composites, geometrical modelling can be done using shape functions [8–10], by a mathematical representation, or through the assignment of material properties to a voxel mesh [11, 12]. Although generating complex shape functions or geometry from experimental observations is state-of-the-art [4, 8], most works still use the more common elementary idealized shapes because of their ease of use, Figure 2. Also, most research only considers a single ply of woven material and does not take into account nesting.

During geometry generation, it is important that the correct fibre volume fraction of the yarns is respected. Otherwise unrealistic stress distributions are predicted which affect stiffness and failure predictions. In realistic geometry, however, neither the path of the yarns is sinusoidal, nor is the yarn cross section symmetrical or constant throughout the cell. To capture this behaviour, more complex shape

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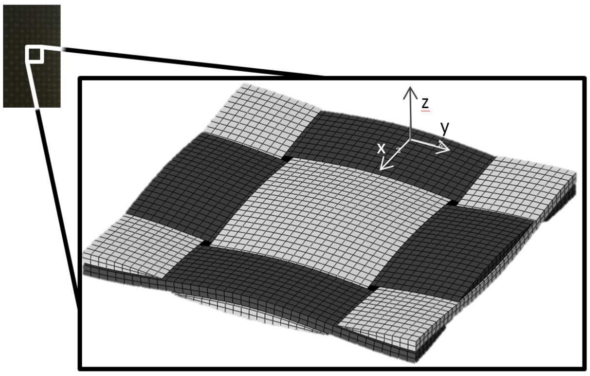

Figure 1. Meso-level geometric RUC of plain woven textile composite

generators should thus be used. The existing advanced methods [11, 12], however, focus on accurately representing measured shapes of the individual yarns in a complete stacking of layers. While very accurate, these models have the drawback of being computationally intensive and do not result in periodic RUCs which can be used for reliable stiffness and failure predictions with periodic boundary conditions (PBCs).

To reduce computational effort and provide periodic geometry, there is thus the need for some form of idealization of the structure. This idealization must, in contrast to the simple geometric shape functions, still be representative of the internal variability of the structure. Accounting for these requirements, the authors propose the Measurement Enhanced Shape Identification (MESI). In this procedure, the process of geometry generation is carefully undertaken by using advanced mathematical shape functions in combination with observations from μCT scans of the material. With this procedure, a RUC can be constructed where the shapes and paths of the yarns resemble the ones from observation. This RUC can take into account the effect of nesting, and reliably be used to predict stiffness and failure with PBCs.

2. Geometrical Models

Three geometrical models are constructed based on in-situ measurements of the material; an idealized RUC which uses the standard shape functions, a model where the yarn shape is mapped linearly from in-situ observations and the MESI-RUC . These in-situ measurements are taken using X-ray μ-tomography and reduced to a stack of 2D images which represent slices at different positions of the laminate. The path and contours of each individual yarn are identified from the slices and grouped according to whether the yarn runs in the warp or weft direction. All contours from a particular direction are queried and their variation in width, height, cross sectional area and shape compared.

From this comparison, it is observed that the heartlines of the individual yarns (the path through the cross

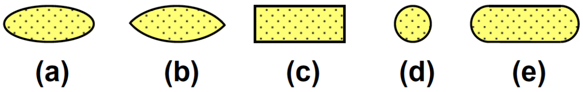

Figure 2. Geometrical yarn shapes; (a) Ellipsoidal, (b) Lenticular, (c) Rectangular, (d) Circular, (e) Racetrack, [8]

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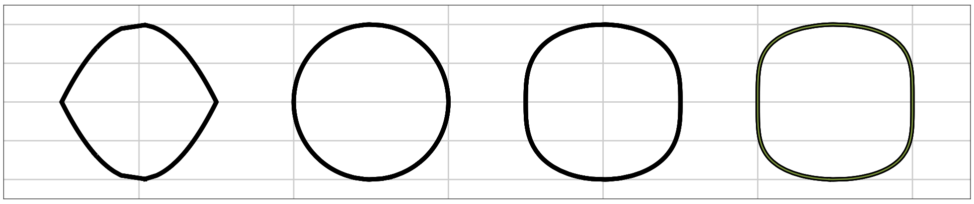


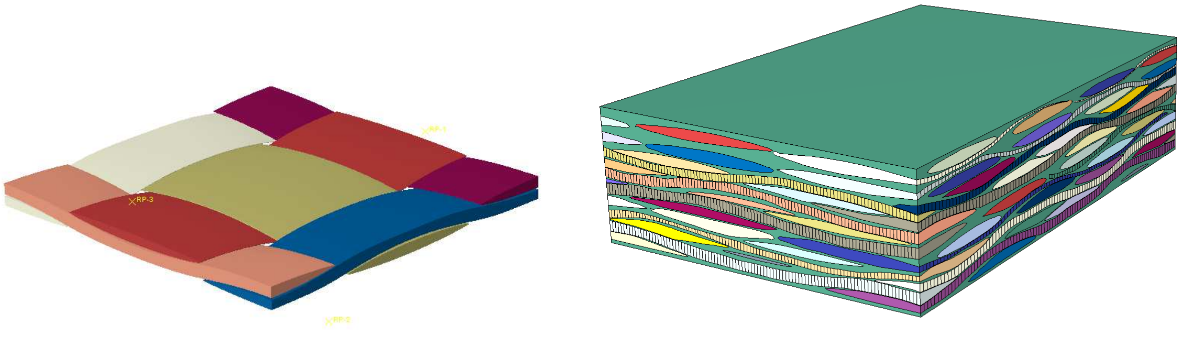
Figure 3. Examples of shapes that can be constructed with a superellipse as base

sections centroids) follow a periodic pattern which is continued in the variation of the height and cross sectional area of the yarns. In contrast to the basic geometry constructors, MESI targets and implements this periodicity in a RUC using advanced analytical shape functions which also ensure the geometric periodicity of the model.

Although the shape functions used for MESI are more advanced than the standard shapes in Figure 2, they still have to be convenient to use and interpret. In an effort to approach a realistic cross section, it is possible to use a more versatile superelliptic shape, Figure 3. In combination with 3D lofting, and locally adapting the fitting parameters of this shape, the cross section of the yarn can be varied, when it travels through the structure, in a comprehensible way. The parameters for the cross sectional shape are determined through a best fit of to the in-situ measurements.

The geometry of a single ply MESI RUC is shown in Figure 4(a). The geometry for the in-situ model is a direct mapping of the in-situ measurements to a 3D structure as shown in Figure 4(b). The geometry for the standard RUC is based on the lenticular shape and shown in Figure 5.

An initial validation of all the models is done by comparing the yarn-matrix volume fraction to the in-situ measurement. The yarn-matrix volume fraction is the ratio of the volume of the yarn bundles to total volume of the cell. As can be seen in Table 1, the volume fraction of the MESI RUC equals the experimentally observed. The volume fraction of the In-situ model should be equal as well. The value, however, is 3 % lower. This is caused by round-off errors and necessary small intersection corrections of the measured geometry while mapping to the 3D space. The low volume fraction of the idealized RUC is remarkable, however. The significant reduction in load carrying volume invalidates reliable stiffness and failure predictions from the idealized RUC and illustrates the need for more advanced geometrical modelling for multiscale analysis.



(a) Single ply MESI RUC

(b) In-situ Model

Figure 4. Enhanced geometric models

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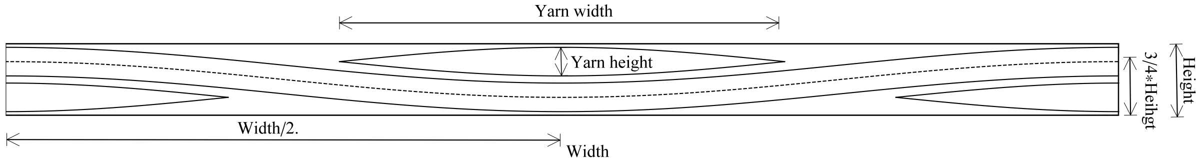

Figure 5. idealized unit cell geometry

3. Conclusion

This paper presents a novel advanced geometric generation method that the authors call Measurement Enhanced Shape Identification (MESI). The construction of a RUC based on versatile but comprehensible shape functions in combination with in-situ measurements is central to this approach. The method is primarily developed for meso-level RUCs of textile composites. The philosophy can easily be applied to unit cells for other types of materials with periodic structure.

MESI has a number of advantages over the current existing methods. The experimental yarn-matrix volume fraction can be respected, in contrast to the standardized method. Although the approach is slightly more complicated than the standard method, the shape functions are kept comprehensible through the use of well known but versatile mathematical functions. The analytic periodic geometry can be paired with periodic boundary conditions for multiscale predictions of a textile ply's stiffness and a detailed identification of the inter- and intra-yarn stresses. Once validated, the RUC can even be used for the prediction of microcracking at the mesoscale.

In this paper, only a comparison of the three different models to the yarn-matrix volume fraction is presented. Future work will focus on further validation of the RUC constructed from MESI by comparing the homogenized stiffness to experimental ones and the internal stresses and strains between the models. The authors believe that the MESI approach can significanlty increase the understanding of the behaviour of composite textile materials.

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Table 1. Comparison of yarn-matrix volume fractions

Model	v_y (%)
Experiment	80
MESI-RUC	80
In-situ model	77
Idealized RUC	50

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