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Avoiding interpenetrations and the importance of nesting in analytic geometry construction for Representative Unit Cells of woven composite laminates

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ABSTRACT

A novel method for geometry generation of Representative Unit Cells (RUC) of textile composites is presented. The technique retains the advantage of an analytical formulation from industrial practice however introduces variable asymmetric yarn cross-sectional shapes and paths which can be fitted to the yarn shapes and cross-sectional areas as observed from in-situ measurements. In this way interpenetrations and incorrect fibre volume fractions, which occur when using idealized constant yarn cross sections for RUC generation, are avoided. Meshing becomes easier and no fibre volume corrections are required. The new technique is validated through a comparison of 1) the novel RUC to 2) an Idealized RUC with constant yarn cross section; and 3) a model constructed from direct in-situ micro computed X-ray tomographic measurements of a carbon-epoxy weave (In-situ Model). With all three models a reasonable agreement with experimentally obtained elastic properties is found. The stress predicted by the Idealized RUC is significantly different than predicted by the RUC generated with the new method and the In-situ Model. The latter two are in good agreement which indicates that the MESI RUC can be used for material strength prediction. The MESI RUC is also substantially less computationally intensive. Next to the construction of improved RUCs, the technique is an excellent alternative for advanced unit cell generation techniques based on production process simulations in the case that the production process is unknown or an analytic periodic geometry is required.

1. Introduction

Since the introduction of woven, braided and 3D fabric composite plies and laminates, researchers have attempted to predict the macro-mechanical properties of the laminates based on considerations of the internal meso-level structure (e.g. fibre bundles and matrix) [1]. Indeed, the premise of a significant reduction of the experimental test program, when constituent level properties are sufficient to accurately predict the assembled behaviour, is quite attractive. At the time of writing, this premise is a driver for research projects [2] and is connected to research fields such as multiscale modelling and composite mechanical behaviour prediction.

One of the cornerstones for research aiming to fulfill this premise is a good geometrical representation of the sub-level structure [3–6]. In the case of textile composite materials the geometrical representation is focused on the meso-level. An example of this geometry is presented in Fig. 1.

A good representation of the actual geometry of a meso-level structure can be estimated based on production process and compaction simulations [7–10]. For various reasons it might not be possible, or desired, to perform such a simulation. In this case, the

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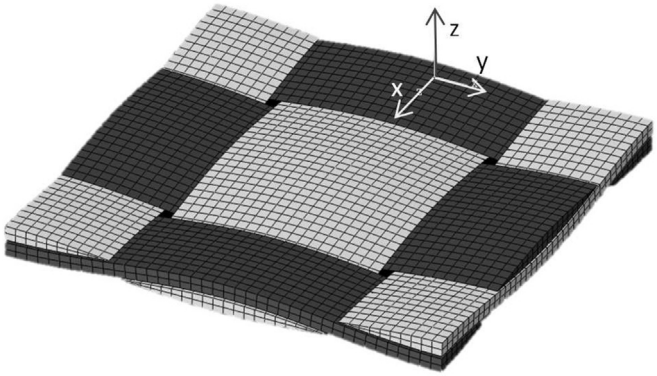

Fig. 1. Meso-level geometry of a plain woven textile composite.

starting point for meso-geometry construction is the consolidated material.

Starting from the consolidated material, a geometrical model for a meso-level structure can be obtained using shape functions [1,11,12], which results in a mathematical representation, or through the assignment of material properties to a voxel mesh [13,14]. The first geometrical models appeared in the eighties in the work of Ishikawa and Chou [1] and have evolved into two fields. In one field, the yarns at meso-level are generalized in a periodic Representative Unit Cell (RUC) (e.g. Refs. [12,15–19]). In the other field the in-situ measured geometry of the yarns is mapped to a 3D model (e.g. Refs. [20–23]).

The periodic RUCs use basic yarn cross-section shapes as shown in Fig. 2 and do not require significant computational resources. Due to the idealized structure, however, these shapes cannot represent the real in-situ cross section of the yarns accurately, [19]. This inaccuracy is often countered by decreasing the local yarn cross-sectional area and simultaneously increasing the fibre volume fraction, [18]. While these RUCs can be used to predict homogenized stiffness, the necessary modifications invalidate their use for intra-ply stress and strain prediction. The models where the measured geometry is mapped directly to a 3D model attempt to resolve this. Here it is necessary to model the entirety of all yarns in a laminate [23] which requires significant computational resources and results in a non-periodic geometric structure to which no Periodic Boundary Conditions (PBCs) can be applied.

Voxel methods have the advantage that they are easy to use, homogenize and apply boundary conditions to because of the simple repetitive structure of the Finite Element-mesh (FE). The discretization, however, results in a stepped surface of yarns which is structurally less efficient than a smoothed surface. This causes an increasing homogenized stiffness with voxel refinement and gives variations in the local stress state that fluctuate with mesh refinement rather than converging to a single value [3,24].

The discussion on meso-modelling is reaching maturity for the prediction of the pristine, undamaged mechanical properties of a material with meso-level structure. In the following years, focus is likely to shift towards prediction of damage. Before this can be done, a geometrical modelling technique is required which is both computationally feasible and can provide reliable predictions of the intra-yarn stress and strain.

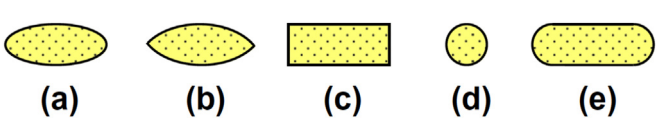

Fig. 2. Geometrical yarn shapes; (a) Ellipsoidal, (b) Lenticular, (c) Rectangular, (d) Circular, (e) Racetrack [11].

In terms of stress and strain prediction, the In-situ Models are the most accurate due to the absence of geometrical simplifications. The required computational effort for these models must be reduced. Therefore, some form of structural generalization is necessary. In contrast to the basic geometric shape functions, the generalization must still be representative of the internal periodicity of the structure or no reliable stress prediction will be obtained. 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 slightly more complex mathematical shape functions in combination with observations from micro-computed Tomographic (μCT) scans of the material. With this procedure, a RUC can be constructed using shapes and paths of the yarns based on observation, where the effect of nesting can be included and which provides more reliable stiffness and failure predictions.

The differences between MESI and the current state of the art are shown by comparing the model predictions to 1) an Idealized RUC constructed with basic shape functions for the yarn cross sections and paths and 2) a three-dimensional model from mapping in-situ measurements to a 3D volume. The in-situ measurements are obtained through μCT scanning of the material at hand, detailed in Section 2. In Section 3 the construction of the geometrical models is explained. This is followed by a comparison of the three models to experimental evidence and one another, Section 5. Discussion of the results and conclusions are presented in Section 6 and Section 7, respectively.

2. In-situ observations, μCT measurements

Except for the Idealized RUC, the MESI-RUC and In-situ Model are constructed based on detailed measurements of the internal structure of the material. The identification of the shape and path of the yarns is possible through the use of a μCT scan. The scanning process produces a 3D greyscale voxel set from which, based on the greylevel values of the voxels, individual yarns and matrix can be distinguished.

The material at hand, a plain woven carbon-epoxy fabric (TR3110 360GMP [25,26]) laminate with layup $[\#(0/90)]_8$, was scanned at the custom-designed μCT system HECTOR of the Ghent University Centre for X-ray Tomography (UGCT) [27]. The cross-sectional contours and paths of the yarns are identified from a region (size $\approx 5\times 10mm$) containing two consecutive unit cells. Automatic cross section identification is unfortunately not possible due to the low contrast between yarns and matrix. The identification is therefore performed by hand picking points of the contours of the yarn cross sections from the image slices every 50μm.

The width and height of the cross sections are identified using the bounding box method. The cross sectional area is obtained by calculating the area of the polygon from the cross section data points. Since these methods can be sensitive to outliers, the data was inspected for these beforehand. The mean width, height, and area of the cross sections for both yarn directions are provided in Table 1. From the Table, it can be seen that the warp yarns have, on average, a higher width and lower height when compared to the weft yarns. There is thus a clear difference between both directions. The difference, +12.5% for the width and −5.4% for the height, however only results in a negligible difference of the average cross sectional area.

The two main fibre directions, warp and weft, are analyzed separately and the variation in width, height, area and cross-sectional shape along the yarn path are investigated. The investigation reveals, as was also observed by Desplentere et al. [28], a