DETEMINATION OF MANUFACTURE INDUCED VARIABILITY AND PREDICTION OF THE RESULTING MECHANICAL PROPERTIES OF A COMPOSITE

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Abstract

This study analyses the effect of yarn path variability on the resulting mechanical properties in a fibre reinforced composite. Automatic image analysis is employed to obtain statistical properties of a twill weave reinforcement after placement in the mould tool. This allows the determination of the variability within and in-between different reinforcement layers at the meso-scale before the manufacture of the part. The obtained data is used to create a model of the local lay-up geometry in zones where extracted test specimens failed. Correlation of these results with specific bundle arrangements will allow the identification of critical areas in a composite before the part is manufactured.

1. Introduction

In a composite, strong and stiff fibres carry the mechanical load and are embedded in a resin matrix. The orientation of these fibres greatly influences the resulting properties of a component. Aligning the fibres precisely in the loading direction yields optimal properties. Unintentional misalignments of these fibres will result in a reduction of the mechanical properties. For instance, a deviation of just 2.5° reduces the compressive strength by 10% [1]. The significant consequences of these small variations require manufacturers to overdesign, using costly, large safety factors.

For the numerical prediction of composite properties it was shown that the often employed periodic unit cell approach, which ignores intrinsic variabilities, leads to an overestimation of properties [2]. On the example of a plain weave it was demonstrated numerically and experimentally that just different configurations of stacked unit cells will influence the resulting mechanical properties differently [3]. Variabilities on a larger scale, such as in-plane bundle waviness, were found to also significantly influence the reinforcement properties [4, 5].

Exact determination of geometrical variabilities within and in-between the textile reinforcements will enable to estimation of the resulting composite properties. Available analysis techniques, such as micro-computed tomography, allow visualisation of the internal structure of textile reinforcements. These studies are, however, usually restricted to small areas [6] and are applicable only after completion of the part manufacture.

In this study, a method to measure the geometrical variability within every single textile layer during the lay-up process is proposed. Images of the fabric taken during the lay-up process provide information on the fabric distortion within and in-between single layers. Combining this data with experimental observations such as local strains or areas of specimen failure will enable prediction of precise composite properties. This will allow virtual testing of a component with its specific characteristics while it is still being manufactured. This study aims to demonstrate this process on the example of a 2/2 twill weave.

2. Materials and manufacturing

To study the influence of geometric variabilities within and in-between reinforcement layers on the resulting properties of a part, rectangular composite panels (250mm x 250mm x 2mm) were manufactured by RTM. Five layers of a carbon fibre 2/2 twill weave (Table 1) were used as the reinforcement fabric. The layers were oriented with the nominal fibre directions parallel to the mould tool edges. Warp and weft directions of the layers were kept constant between different layers. After mould closure, the lay-up was impregnated with Prime 20LV epoxy resin in combination with the slow hardener. The circumferential resin injection was driven by vacuum pressure only. After demoulding the composite plates were post-cured following the manufacturer's recommendations. The resulting fibre volume fraction of the composite plates was 53%.

Manufacturer:	Sigmatex
Product:	TC4111250
Weave:	2/2 twill
Warp, weft yarns:	T700SC 12K 50C
Ends, Picks:	24 ± 1.2 / 10cm
Areal density:	380 g/m^2

Table 1. Fabric data from datasheet

3. Determination of geometric fabric variability at the meso-scale

Information on local fabric distortions were gained by optical imaging of the surfaces of every single reinforcement layer immediately after placement in the mould tool. This allowed quantification of the degree of intrinsic misalignment. The images of the fabric were taken using a standard SLR camera (Sony DSLR-A200) equipped with a N50 lens. To achieve a sufficiently high image resolution, overlapping images at a high magnification were taken using a positioning frame. An image resolution of approximately 5.6MP / 10 cm^2 was used for the subsequent analysis. Lens distortions [7], camera rotations and translations were corrected before the images were tiled [8].

The fabric meso-structure was determined automatically by a morphological analysis technique implemented in a purpose developed Matlab program. This image analysis method is based on the determination of colour gradients [9, 10] of visible individual bundle sections [11]. By this method, tedious and time consuming manual determination of the bundle bath [12] can be avoided. Compared to other automated image processing techniques proposed in the literature [13, 14], the implemented approach does not depend on a known unit cell and additional variability of the fibre bundles, such as bundle width changes, can be measured in a time efficient manner.

The detected bundle shapes were fitted with four sided polygons which were considered to be a sufficiently good representation of individual bundle sections. As a result, data such as dimensions and relative positions of the edges of fibre bundle sections were obtained. This enabled the reconstruction of entire fibre bundles by connecting adjacent bundle sections. Assuming continuity, invisible bundle sections were approximated by a linear fit between visible bundle sections. Ignoring the three dimensional nature of the material and hence the out-of plane crimp at this point, a schematic of the single layers and their relative positions in the mould tool can be reconstructed (Figure 1). This allows an estimate of the influence of in-plane bundle waviness and relative positions between individual layers.

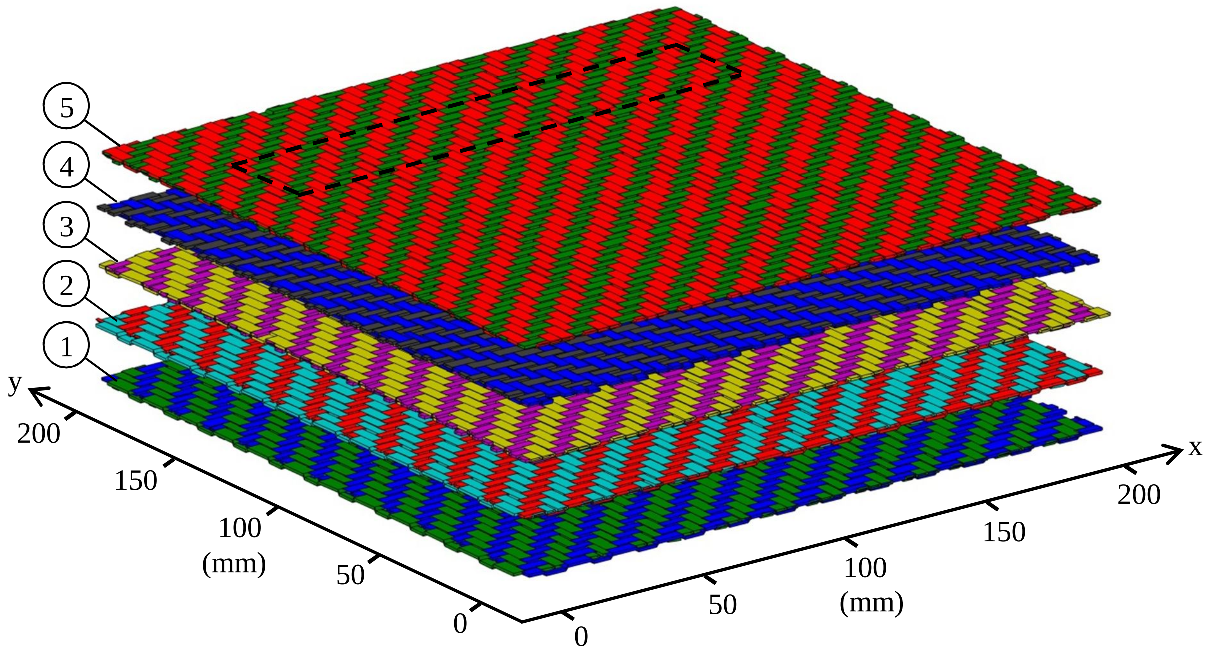

Figure 1. Schematic of the five reconstructed reinforcement layers based on the data gained during the lay-up process. The tensile test area of Figure 3 is outlined.

4. Fabric layer analysis

From the automated image analysis of the individual reinforcement layers (Section 3) several parameters such as the degree of in-plane waviness and handling-induced shear within the textile layers, both of which affect the fibre angle, can be determined. In addition, it is also possible to identify effects of long-range interactions between fibre bundles as a result of fabric distortions within the textile layers. Hence, the quality of every single layer can be evaluated.

The data supplied by the manufacturer suggests that the twill weave is symmetric (Table 1). The measured average bundle width (Figure 2) shows, however, significant differences in warp and weft direction (y and x-direction in Figure 1, respectively). This observation coincides with the findings of Skordos and Sutcliffe [13] who reported a larger variability in bundle path variations in the weft direction. These variations are probably related to the weaving process. The measured smaller average value in bundle width in the analysed material will more than likely affect the properties of the resulting composite panel. Larger gaps between the bundles can, for example, lead to an increase in matrix rich regions in the panel or promote bundle nesting, both of which will affect the local properties of the lay-up.

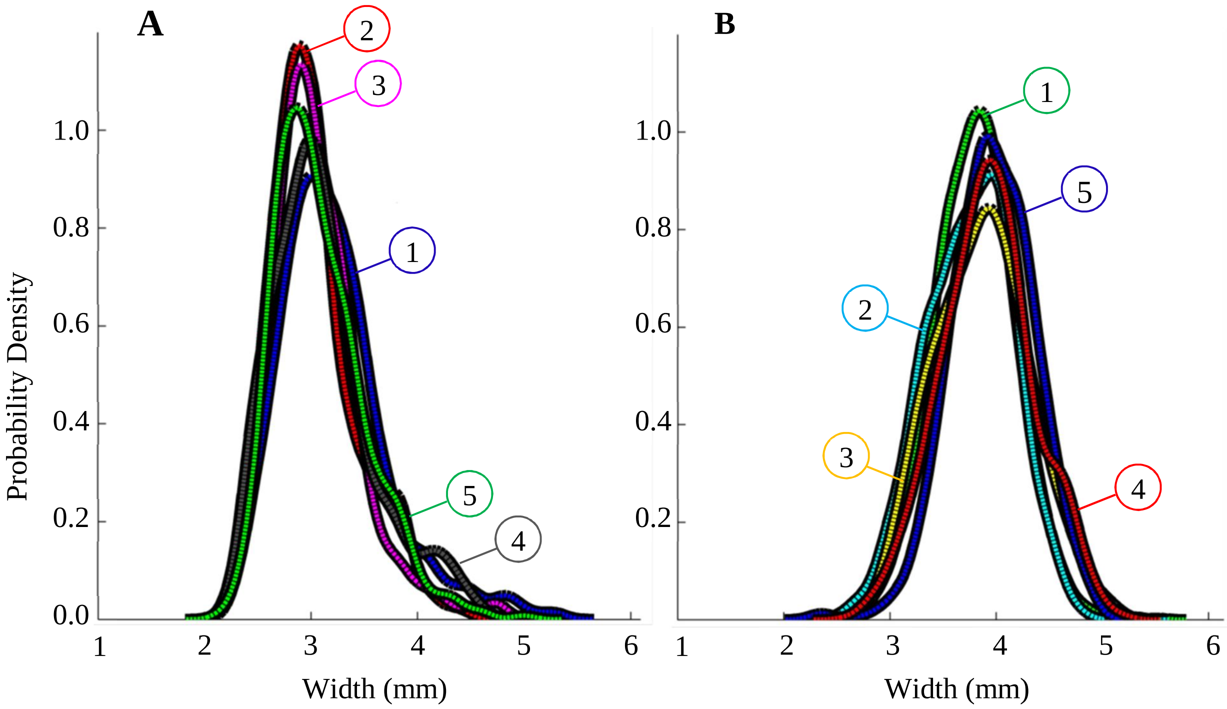

Figure 2. Measured bundle width distributions in A) weft and B) warp direction. The line colours correspond to the colours in Figure 1.

For the analysed reinforcement layers in the example of Figure 1, the average fibre bundle directions were determined (Table 2). The deviations of the filament path within a single layer with respect to the mould tool are rather small. The relative difference of fibre bundle paths between two adjacent layers can, however, be significantly larger locally and therefore have a significant influence on the mechanical properties (Section 1).

Layer	Warp	Weft
5	1.31° ± 0.84°	91.18° ± 1.56°
4	0.98° ± 0.71°	91.17° ± 1.74°
3	0.90° ± 0.75°	91.02° ± 0.91°
2	0.88° ± 0.83°	91.00° ± 1.46°
1	0.83° ± 0.73°	90.88° ± 0.74°

Table 2. Average fibre bundle alignment with respect to the quadratic mould tool.

With an image processing time of about 0.1 seconds / bundle section (Section 4), implementation of this analysis technique in the production process will allow the detection of these variabilities in real time and correction of the lay-up if desired.

5. Mechanical test results

Tensile test specimens with dimensions of 35mm x 250mm x 2mm were extracted from the manufactured plate and tested under quasi static load using end tabs following EN ISO 527-4:1997. The tests were conducted on an Instron universal testing machine (Type 5985) equipped with a 250kN load cell. The tensile strains were determined by use of Digital Image Correlation (Dantec Q400). This enabled visualisation of local areas of high surface strain.

The measured tensile strength of the plates is 1112.2MPa ± 16.9MPa and the measured tensile modulus $E_{meas.}$ = 51.6GPa ± 1.7GPa. The latter is significantly lower than estimates based on a unit cell modelling approach E_{UC} = 59.1GPa using a TexGen [15] model and Abaqus CAE. The lower stiffness of the actual lay-up compared to the idealised unit cell estimate can be explained by the random lay-up. Areas of lower local stiffness in one layer, e.g. due to bundle misalignment, can form. These areas may, however, be supported by areas with higher stiffness in adjacent layers. The elastic deformation therefore averages over the entire specimen which results in a lower measured modulus. However, differences in stiffness (high or low strain respectively) can remain locally which may be critical for the finalised part (Figure 3). Unfortunately, the maps of surface strain gained from DIC show surface strains only which may not be able to explain the part failure in a certain area.

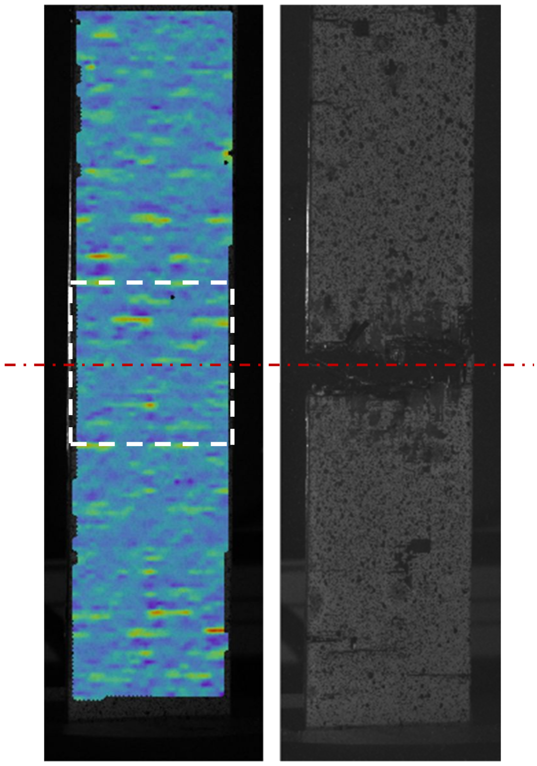

Figure 3. Example DIC results of the tensile test. The surface strains of the final loading step and the fractured sample are shown. The area used for modelling is indicated with dashed lines.

It is suggested that matrix cracking within composite materials precedes the fibre failure [16, 17]. This leads to additional stress concentrations locally and may lead to crack growth and failure. It is likely that the variability in local reinforcement geometries will promote the formation of such cracks. The measurement of bundle alignment and variability within and in-between reinforcement layers during lay-up will enable determination and numerical analysis of such critical areas.

6. Model generation

The measured textile geometries (Section 4) can be used to create numerical models of the actual fabric. This will allow a better understanding of the influence of geometric features within the reinforcement textile in zones which show an anomalous behaviour during testing. For example, textile geometries in zones where the specimen failed can be analysed in detail.

In addition, the cause of local high or low strains (Section 5) can be investigated. Combining this data in the future with measurements of the reinforcement taken during lay-up will enable prediction of sensitive zones of the finished composite part prior to manufacture.

From the image analysis, only data about the visible sections of the fibre bundles can be gained. The bundle heights are therefore estimated based on a determined relation of measured thickness to width ratios of fibre bundles extracted from the fabric. This data was gained from uncompacted bundles extracted from the textile reinforcement. If the estimated bundle thickness leads to bundle interference, the bundle thickness is set to half the layer thickness. The bundle shape was initially assumed to be lenticular. Based on the analysis of similar reinforcements this assumption is thought to be close to the actual shape but does need to be confirmed in the future.

For the example tensile test specimen in Figure 3, the TexGen [15] model of the area around the fracture zone is shown in Figure 4. This model can be used as input for a numerical prediction of the local specimen properties.

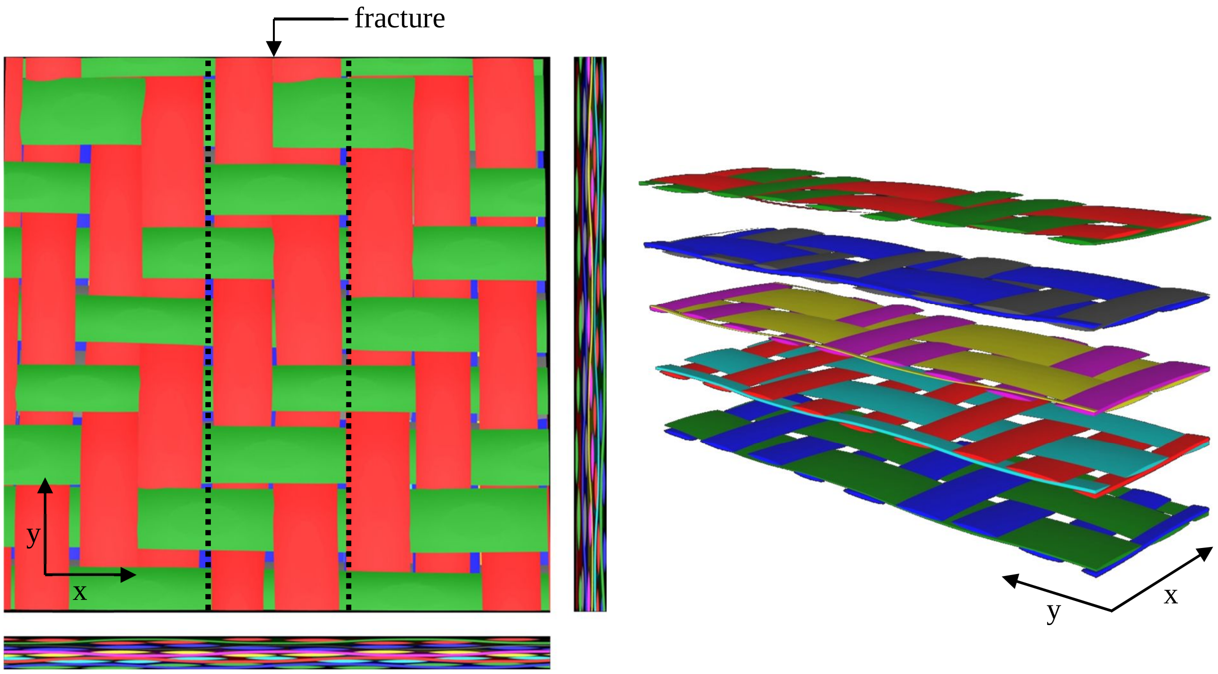

Figure 4. A) TexGen [15] model of the reconstructed area in which fracture occurred. The width and length are equal to the tensile test specimen width. The front and side views are shown in addition. B) Reduced schematic of the layers. The colour scheme corresponds to Figure 1.

Currently, the entire model is based on the information gained on the uncompacted layers before mould closure only. For future work, the geometric model needs to account for bundle deformation, e.g. bundle widening and nesting, as result of compressing the stack of reinforcements during mould closure. This can be achieved by, for example, creating an uncompacted model geometry and then employing a multi-chain element model approach [18] to estimate the final geometry.

7. Concluding remarks and future work

This study proposed a method of analysing the variability of a fibre bundle network within and in-between textile reinforcements. This data can help to determine the resulting mechanical properties of a composite before it is actually manufactured. It will also allow a virtual test of a component or sections of a component using data of the actual geometry rather than using a unit cell modelling approach or assumed geometrical variability.

Relating mechanical test data to actual local fibre bundle arrangements will allow a better understanding of which geometrical features have the most significant effect on overall mechanical properties. The current model is based on the geometry of uncompacted fabrics. Compaction during mould closure will lead to additional local yarn deformations, e.g. bundle widening and bundle nesting. The resulting three-dimensional geometric arrangement can be predicted employing a compaction model.

It is desired to extend the current analysis method to curved parts and other fabric styles in the future. In addition, it is intended to extend the image analysis method to prepreg materials. The presence of matrix material will, however, lead to additional challenges. The approach presented in this paper, to gain data about the composite structure before manufacture of the part, does offer a promising first stage towards a novel quality control methodology.

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