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On the influence of fabric layer shifts on the strain distributions in a multi-layer woven composite

Aurélien Doitrand *, Christian Fagiano, François-Henri Leroy, Anne Mavel, Martin Hirsekorn

ONERA, The French Aerospace Lab, F-92322 Châtillon, France

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ABSTRACT

The influence of the relative shift between fabric layers on the local strain distributions at the mesoscopic scale of a four-layer plain weave glass fiber/epoxy matrix composite is studied through Finite Element (FE) modeling. The surface strain fields of several representative unit cells, consisting of compacted and nested plain weave layups with different layer shifts and the matrix complement, are compared to strain fields measured experimentally by digital image correlation. The layer shifts only have a small impact on the calculated homogenized macroscopic mechanical properties. However, the local strain fields are influenced significantly. Good quantitative agreement is obtained between the measured surface strain distributions and the numerical results if the layer shifts of the tested specimen are used in the FE model. The most frequently used models without layer shifts or with maximum nesting do not provide satisfactory surface strain distributions.

1. Introduction

Composite materials containing textile reinforcements are increasingly used for aeronautical and automotive lightweight applications. One of the advantages of woven composites is the high flexibility of the fiber reinforcement, which can be directly shaped to the final form of a part, resulting in a reduction of assembly operations and of the number of weak points in a structure.

The reinforcement architecture of a woven composite has a strong influence on damage onset and propagation [1,2]. For instance, different damage kinetics are observed for 2D [2,3] and 3D woven composites [4]. Therefore, an experimental characterization of the damage mechanisms and of their influence on the material behavior is needed each time a different architecture is considered. The number of tests may be reduced using predictive models that take into account the reinforcement architecture, which is defined at the so-called meso-scale [5]. At this scale, the composite reinforcement is represented by two sets of interlaced yarns (warp and weft yarns) that are modeled as homogeneous materials embedded in the matrix.

At the meso-scale, the fiber reinforcement of woven composites is approximatively periodic, even if small variations are induced by (i) the weaving process, (ii) the handling of the fabric and (iii) the resin injection during composite manufacturing. Olave et al. [6] showed that the mechanical properties of the composites are not significantly influenced by these variations. Moreover, repeating damage patterns were observed along the edge of a woven composite specimen [7]. Therefore, perfect periodicity is often assumed to model woven composites, using a pattern representative of the whole material (called a representative unit cell, RUC), in order to reduce computational costs.

The shifts between the layers in a multi-layer woven composite may be controlled during the manufacturing process [1,8]. However, this is a difficult operation and, in practice, random layer shifts are observed in most woven composites [6,7,9,10]. These layer shifts are often neglected in meso-scale models. In several published papers, only one layer is modeled, assuming 3D periodic boundary conditions [11–16]. Some authors [17–19] modeled all the fabric layers of multi-layer composites, but using in-phase layer stacks, thus not taking into account the layer shifts.

The influence of layer shifts on the mechanical behavior of woven composites was studied by several authors. Breiling et al. [20] showed that a variation of up to 32% on the ultimate strength of a carbon epoxy five-harness satin was obtained by varying the stacking configuration. Le Page et al. [21], solving a 2D problem, showed that the energy release rate of a cracked textile composite is strongly dependent on the stacking pattern. Ivanov et al. [22] found that the strain distributions were influenced by the layer shifts by comparing an in-phase and a shifted layup of an idealized geometry of a twill. The same authors showed in another paper [23] that damage onset was also strongly influenced. Daggumati

* Corresponding author. Tel.: +33 (0)146734658.
E-mail address: aurelien.doitrand@onera.fr (A. Doitrand).

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et al. [24] studied the sensitivity of the surface strain distributions to different simplified stacking sequences (in phase, out-of phase and step stacking) of a 5-harness satin. A step stacking gave a better qualitative agreement compared to experimental data than in phase and out-of-phase stacks. However, the real layer shifts of the tested specimen, the fabric compaction and the nesting between the layers were not taken into account in the model.

In most models, the layer shifts are simplified for numerical convenience, thus not representing experimentally observed lay-ups. Moreover, during the production process of a textile composite, the reinforcing fabric is usually compacted in order to increase the fiber volume fraction. As a consequence, the fabric layers nest into each other. The aim of this article is to evaluate numerically the influence of the layer shifts on the surface strain distributions in the case of a compacted and nested four-layer plain weave glass fiber/epoxy matrix composite. The results are compared to surface strain distributions measured experimentally by digital image correlation (DIC) on the specimen surfaces. The experimental tests are presented in Section 2. Then the generation and meshing of five different RUCs is described in Section 3. These RUCs contain compacted reinforcements with (i) no shifts between the layers, (ii) shifts resulting in maximum nesting and (iii) the layer shifts determined experimentally on three specimens. Section 3 also includes the comparison between a geometry resulting from the numerical simulation of the compaction and a geometry extracted from a micro-computed tomography (μ-CT) observation of a specimen. In Section 4, the homogenized properties and the surface strain distributions obtained numerically with the different RUCs are compared with the experimental observations.

Table 1
Layer shifts in warp and weft directions with respect to the top layer (the layers are numbered from top to bottom).

Shifts [mm]	Layer 1 (top layer)	Layer 2	Layer 3	Layer 4
0°-specimen	Warp direction	−0.61	−0.59	0.43
	Weft direction	−0.30	3.43	2.93
90°-specimen	Warp direction	1.32	2.50	−3.56
	Weft direction	1.71	3.24	4.09
45°-specimen	Warp direction	−2.57	0.58	−2.31
	Weft direction	−0.63	0.29	0.59
No nesting	Warp direction	0	0	0
	Weft direction	0	0	0
Nesting max	Warp direction	2.27	0	2.27
	Weft direction	2.50	0	2.50

2. Experimental analysis

The composite under investigation consists of four layers of a plain weave reinforcement of E-glass fibers embedded in Araldite LY564 epoxy resin. The thread count of the unbalanced plain fabric is 2.2 warps $cm^{-1} \times 2$ wefts cm^{-1}. The fabric mass per unit area is 504 ± 40 g m^{-2}, the linear density of the yarns is 1200 TEX (g/km) and the mass density of the fibers is 2.54 $g.cm^{-3}$. The four layers composing the dry fabric were placed into a steel mold and compacted by tightening the screws that keep the mold closed. Due to the relative shift between adjacent layers, nesting occurs during compaction. After compaction and matrix injection, the mean fiber volume fraction in the material is 47%. Three rectangular specimens were tested under tensile loading in order to evaluate the in-plane elastic properties of the material and to measure the surface strain distributions using DIC. The orientation of the fiber reinforcement in the load direction of each specimen is respectively 0° (warp direction), 90° (weft direction) and 45°.

2.1. Reinforcement architecture

First, the specimen edges were observed using an optical microscope in order to determine the layer shifts of each specimen. These shifts are given in Table 1 for the three lower layers with respect to the top layer. The layer shifts that are modeled in most published works, i.e., in-phase stacking resulting in no nesting and the shifts resulting in maximum nesting, are also given. These five stacks are used in Section 3 for the generation of the Finite Element (FE) meshes of the composite RUCs.

Microscope observations on the edge of the specimens only provide a surface description of the reinforcement architecture. Therefore, the 0° specimen was scanned by means of an X-ray μ-CT, in order to obtain a full 3D description of the reinforcement architecture of one of the specimens. The scan covers 2 RUCs. The zone, where the layer shifts were observed and used to generate the FE model (Section 3), is shown in Fig. 1a. A 3D geometrical represen-

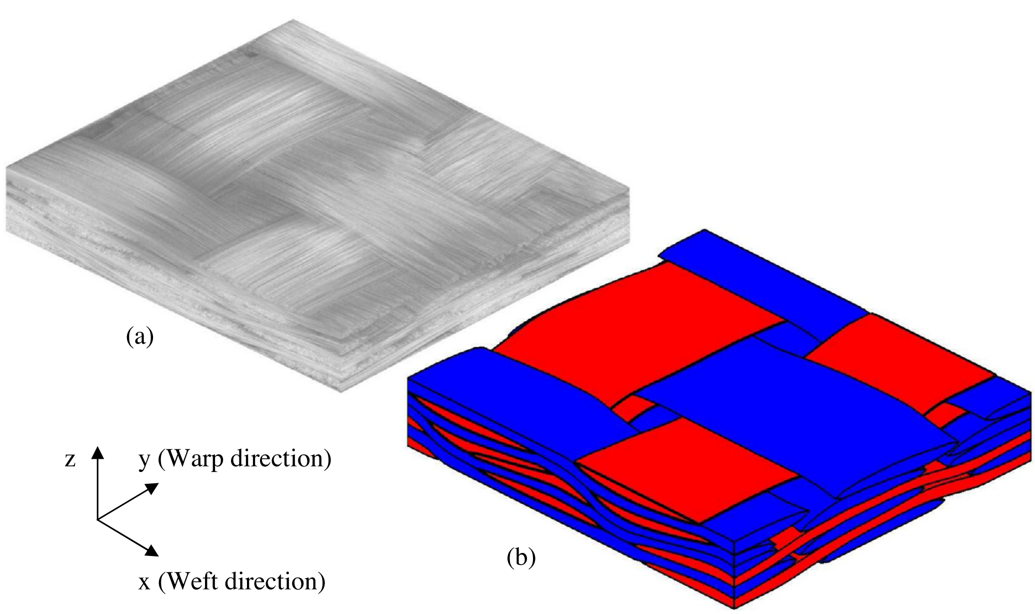

Fig. 1. Geometry of the reinforcement of the 0° specimen (one RUC) obtained (a) from the μ-CT scan and (b) from compaction modeling.