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Geometric model for 3D through-thickness orthogonal interlock composites

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ABSTRACT

The elastic properties of 3D through-thickness orthogonal interlock composite materials are affected by the curvature of the yarns caused by compaction during the manufacturing process. However, most of the models in the literature do not take into account this fact resulting in not so accurate predictions. A novel geometric model accounting for the compaction and curvature effects on the cross-section and distribution of fill and warp yarns in 3D through-thickness orthogonal interlock composite materials is presented in this work. The model assumes sinusoidal functions to represent the curvature along the length of the fill and warp yarns due to binder. Then, with only a set of preform parameters combined with few geometric measurements in optical micrographs of specific sections the geometry of the material can be fully determined. The model is compared and validated with the real geometry and fibre area fraction of the warp and fill yarns of a 3D through-thickness orthogonal interlock carbon/epoxy composite and the predictions of an analytical model present in the literature. After the comparison, it can be concluded that the model is a useful tool to describe the real geometry and can be used with finite element analyses to obtain its elastic properties.

1. Introduction

During the last years different researchers have investigated the benefits of using through the thickness reinforced textiles in composite materials for aircraft structures [1]. The use of these materials has increased because of their superior properties with respect to 2D textile composites: they are more resistant to interlaminar fracture or delamination and they show better performance in front of low-velocity and ballistic impact events [2]. For this reason, three-dimensional (3D) woven composites are used more and more in structural components for aerospace applications where mechanical and thermal stresses in multiple directions are present.

As in the case of 2D textile composites, the determination of the mechanical properties of 3D woven composites can be done through more expensive experimentation, or through more affordable analytical or numerical predictive approaches. However, the availability of types of 3D reinforcement architectures (such as through-thickness angle interlock, through-thickness orthogonal interlock, layer-layer angle interlock and layer-layer orthogonal interlock) and the complexity of taking into account the real geometry of the reinforcement result in not so accurate predictions when using current analytical or numerical approaches.

Many models have been proposed in the literature to analyse and predict the mechanical properties of this type of materials. Most of the models focus on a single 3D architecture of the reinforcement and they are not suitable for predicting these properties for other types of 3D woven reinforcements. Moreover, all the models available in the literature are based on a series of geometric simplifications that can lead to inaccurate results.

Cox et al. [3–5] and Buchanan et al. [6,7] focused on through-thickness angle interlock 3D woven composites and formulated two different analytical models assuming that the yarns have, respectively, a circular or an ellipsoidal cross-section. Nehme et al. [8] and Hallal et al. [9] proposed analytical models for layer-layer angle interlock reinforcements considering that the transversal section of the yarns has an ellipsoidal or racetrack cross-section (being a racetrack cross-section a rectangle with semi-circles on its edges). The model presented by Naik et al. [10,11] is valid for two types of 3D wovens: layer-layer orthogonal interlock and through-thickness orthogonal interlock. In the model, Naik and co-workers adopted the simplification of circular

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yarns. Different analytical models have been formulated for the most commonly used type of 3D woven reinforcement: the through-thickness orthogonal interlock. In these models, different geometries have been assumed for the cross-section of the yarns, such as rectangular (Tan et al. [12]), lenticular (Quinn et al. [13]) and ellipsoidal (Brown and Wu[14], Wu [15] and Buchanan et al. [16]). Lomov et al. [17] reviewed the developments made in modelling and characterisation of 3D woven interlock composites, both angle and orthogonal, and implemented a procedure to model them in a software suite, WiseTex [18,19].

Desplentere et al. [20] used X-ray micro-Computed Tomography (micro-CT) to characterise the microstructural variation of different orthogonal interlock 3D composite materials. By comparison with optical micrographs, they found that micro-CT is an appropriate technique to obtain the structure and structural variation of the reinforcement. They reported variations in the structure up to 16% and analysed the effects of these variations on the mechanical properties of the material by virtual testing using WiseTex. The authors concluded that these effects on the mechanical properties are about only 5%.

Different detailed reviews about modelling of 3D woven composite materials, including some of the previous models, can be found in the works of Byun et al. [21] and Ansar et al. [22].

Unlike most of the previous models, Green et al. [23] used the finite element method to numerically model 3D woven fabrics taking into account the geometry of dry orthogonal 3D woven preforms. The method is based on meshing the real geometry of the preform and predict the effects of compaction on the geometry of the yarns. Although the authors mention the general applicability of the method to any 3D woven fabric type, it does not take into account the presence of the resin in the material. In addition, a recent study of the same authors [24] presents a finite element analysis to compute stress–strain curves for an orthogonal 3D woven composite under tensile loading using realistic geometry.

The present study reports the development of an analytical method to obtain the geometry and the volume fraction of 3D through-thickness orthogonal interlock woven composites. In contrast to most of the models present in the literature, the proposed model takes into account a more realistic definition of the geometry of the reinforcement, such as the curvature of the yarns along the longitudinal (also known as warp or stuffer) and transversal (also known as fill or weft) directions induced by the binder (also known as stitch) yarn. The model is based on the definition of a Representative Volume Element (RVE) for the composite defined through different geometrical parameters corresponding to the geometry of the reinforcement. The parameters are obtained from the architecture characteristics of the preform and optical micrographs of specific sections. According to the results of Desplentere et al. [20] this can be considered as a good approach for modelling 3D woven composites.

As a first step, the model has been validated by comparing its predictions of the fibre area fraction for each yarn with the results obtained from direct measuring with optical micrographs and the results of the analytical model proposed by Buchanan et al. [6]. Further development will allow for the prediction of the mechanical properties of the material with better accuracy.

2. Methodology

The current geometry of the different sets of fibre yarns conforming a 3D woven composite is determinant for the correct modelling and estimation of mechanical properties. Therefore, the analytical model proposed in this work takes into account the cross-section and curvatures of the yarns of the reinforcement.

As the architecture of the through-thickness orthogonal interlock preforms is periodical in the plane of the warp and fill yarns, the Representative Volume Element technique can be used to model this sort of materials in a more efficient way. The generation of the RVE of the material considered in this study is summarised in the following section.

2.1. Representative Volume Element (RVE)

A RVE is a plane periodically-repeating element that represents the whole composite woven structure and can be obtained by the replication of the basic geometry of the woven material, as shown in Fig. 1. In this figure, the basic geometry defining the RVE is marked with a dashed line. The fill yarns are oriented along the ZY-plane and the warp yarns are oriented along the ZX-plane and are between layers of fill yarns. The binder yarns interlock with the layers of fill yarns through the thickness.

The geometric parameters required to generate this RVE can be categorised into two different groups: preform parameters (also known as manufacturer specified parameters), and detail parameters. The preform parameters are: thickness of the preform, H, the interlock length (or the pitch between fill yarns), p_f, the interlock depth (or the pitch between warp yarns), p_w, and the lengths of the RVE, L_x and L_y. The number of layers of this material is defined by the sum of the warp, n_w, and fill, n_f, layers. These preform parameters allow for the definition of the main dimensions of the RVE. However, due to the distortion in geometry suffered by the preform during the manufacturing process, it is necessary to obtain certain geometrical parameters to define the final geometry of the RVE, detail parameters. An appropriate way to obtain these detail parameters is by taking optical micrographs of certain sections of the material and determine them.

As shown in Fig. 2, the basic geometry of the RVE can be fully-described by only considering a few sections in the ZX and ZY planes. Actually, due to the periodicity and the structure of the woven material three basic sections are taken into account in each plane, from which the rest of the sections can be interpolated. The basic sections in the ZX-plane are named as ZX0, ZX1 and ZX2 and the basic sections in the ZY-plane as ZY0, ZY1 and ZY2. As section ZX0 can be taken as a 180° rotation of section ZX2 with respect to centre of the section, only the geometry of sections ZX1 and ZX2 will be taken into account to define the ZX-plane. Similarly, only sections ZY1 and ZY2 will be considered to define the ZY-plane.

2.2. Geometric model

In order to define the whole geometry of the yarns, it is necessary to model their cross-section and their longitudinal profile along the length of the fibres. During the manufacturing process of the composite, the 3D woven preform undergoes geometrical distortions that affect the cross-section and undulation of the yarns. In certain areas this distortion is bigger because of the compaction of the binder yarn over the fill and warp yarns. Different authors, summarised in the review of Ansar et al. [22], have assumed simple and constant cross-sections along the length of the fibre for the fill and warp yarns, such as ellipsoidal, lenticular, rectangular, circular or racetrack. However, observing micrographs of different 3D woven composites it can be concluded that this is a simplistic approach and the real cross-section of the yarns cannot be considered as simple and constant geometries.

Fig. 3 represents the four schematic sections of a general 3D through-thickness orthogonal interlock composite without simplifications in the geometry of the yarns. As it can be seen in the figure, for the fill and warp yarns, the longitudinal profile can be defined by two longitudinal contours. The definition of the cross-sections in sections ZX1 and ZY1 requires of two transverse