NUMERICAL MODELLING APPROACH FOR 3D BRAIDED COMPOSITES UNDER LATERAL LOADING

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Abstract

In this work a numerical analysis of a two-step braid using a 1D FE modelling approach is presented and its modelling strategy evaluated. Predicted properties are used to characterise its structural behaviour with respect to shear damage and compared to the mechanical response of a pultruded laminate under lateral loading.

1 Introduction

This paper presents preliminary results of on-going research on a numerical analysis to predict the mechanical behaviour of 3D braided textile reinforcements. In general, analytical and numerical methods are used to predict macroscopic linear-elastic properties. Numerical modelling of 3D textiles is mainly based on the Finite Element analysis in conjunction with the homogenisation approach. The three dimensional continuum element discretisation of a representative volume of textile reinforcements is the common approach found in recent literature. Apart from a large number of degrees of freedom that easily reach computational capabilities, the accurate representation of individual yarns and their interaction with resin is complicated or even impossible for modelling 3D braids.
In the past, numerical models for 3D braided composites have been mainly developed for 4-step braids to analyse their effective elastic moduli and stress as well as strain fields, using for example an idealized unit cell structure in which fibre bundles are oriented in the four diagonal directions of a rectangular parallelepiped [1]. Most of the approaches are based on simplified repeating unit cells similar to analytical models, such as the inclination model of Yang et al. [2].
In this paper, an effective and simple modelling strategy, the Binary Model [3] is used to simulate the mechanical response of the textile architecture and to evaluate the predictive capabilities of this model for 3D braided composites. Considering the complex geometry of a 3D braid and the resulting intricate representation of resin pockets in the composite, the Binary Model is facilitating modelling and needs less computational effort compared to a solid element model. A further objective of these numerical analyses is to study the structural behaviour of the braid with respect to shear damage, according to the ASTM standard D 2344 [4], and to compare it with the mechanical response of a pultruded laminate.

2 Analyses

2.1 Materials

The basis of comparison for this study is a pultruded laminate, made of polyester resin reinforced with three alternating layers of unidirectional E-glass rovings (UD) and continuous strand mats (CSM). The pultruded system has a thickness of 5 mm and a volume fraction V_f of 49.5%, as reported in a previous study [5]. Pultruded composites are mainly designed to carry axial loads, hence predominantly reinforced in the axial direction. The considered material in this study is a two-step braided composite with *[4,2]* yarn arrangement, made of glass-multifilament yarns in a thermoset matrix. Two-step braids are made of a large number of parallel, axially aligned, stationary yarns and a smaller number of braider yarns that intertwine the axial yarn array.

The periodic structure of the braid makes it sufficient to investigate the elastic properties of the macro-cell. In contrast to a unit cell approach, the macro-cell in Byun's model [6] is designed for the entire cross-section of the preform. Axial yarns in the centre of a two-step braid take a rhombic shape and outer surfaces along the preform edges are flat, resulting in a pentagonal shape, after resin consolidation, as depicted in Figure 1. The shape of braiders between axial yarns is assumed to be rectangular due to geometrical constraints of the axial yarns [7].

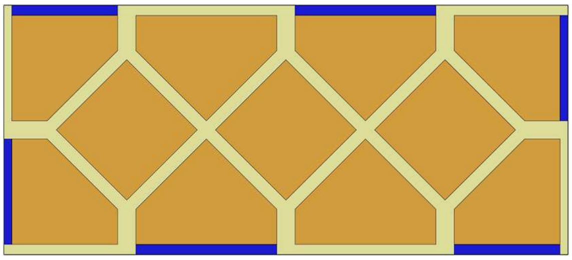

Figure 1. Schematic cross section of a rectangular [4,2] 2-step braided composite

Preform dimensions and parameters are calculated according to Byun et al. [6, 7] and listed in Table 1. The resulting preform dimensions are analogous to the dimensions of a short beam specified in the ASTM standard to study an entire preform, without curtailing its edges. The geometry as well as properties of axial and braider yarns are based on following roving properties: a glass fibre density ρ of 2.55 kg/m³, a linear density of 4800 tex for axial yarns as well as 1200 tex for braiders, and a packing fraction κ of 0.78, as measured by Du and Chou [8], were used. The braider yarn aspect ratio is 0.05 and the axial yarn aspect ratio 1.

Parameter	
Nº Axial yarns	11
Nº Braiders	6
Braider yarn angle [º]	10
Width [mm]	8.77
Thickness [mm]	3.98
Pitch length [mm]	32.05
Volume fraction [%]	59.4

Table 1. Parameters and dimensions of a [4,2] 2-step braided composite

2.2 FE model

The interlacing of yarns must be represented in correspondence to the real textile structure. However, an imperfect definition on yarn boundaries can be allowed [9]. Yarns generally vary in cross-sectional shape along their lengths, due to topological constraints and applied pressure during the fabrication of the preform. As an approximation, the cross-sectional shape of a yarn is often assumed to be uniform along an idealised centreline of the yarn path. A simple model with physically justified approximations was sought. The Binary Model is subdivided into two FE meshes made of 1D and 3D elements. The 1D element represents the axial properties of a yarn, while the 3D effective medium elements represent matrix-dominated properties of the composite, such as the transverse as well as shear stiffness and the Poisson's effect [3, 10].
The Binary Model calculations were executed with ABAQUS. Due to the use of truss elements is the resulting FE model computationally efficient. The two meshes were generated independently and joined by means of multi-point constraints, using the embedded element function. An example of the mesh model is shown in Figure 2. The effective medium mesh defines the specimen surfaces and is made of 8-noded solid elements that are separately generated inside ABAQUS. The yarns in the FE-model are represented by two-node line elements that are, together with the associated node coordinates for the braided preform, generated outside ABAQUS. The resulting data is integrated into the ABAQUS input file that defines the effective medium.

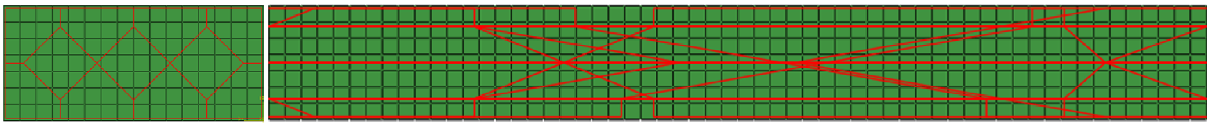

Figure 2. Mesh model made of 3D effective medium elements and 1D yarn elements (lines represent geometric centre of yarns)

Yarn segments in the elastic regime can be regarded as approximately unidirectional composites. The effective medium can be assumed as transversely isotropic. Elastic parameters of the yarns and effective medium are estimated by analytical models, according to McGlockton et al. [11]. The effective elastic properties of the macro cell are determined by subjecting the cell to longitudinal, transverse as well as shear loads. The homogenised stiffness tensor $\overline{C_B}$ of the braided composite can be obtained by applying an orientation averaging technique [12]

$$\overline{C_B} = \sum_y \left(V_y \sum_i \frac{L_i}{L_y} C_i \right) + V_m C_m \qquad (1)$$

where *V* denotes the respective volume fraction, *y* is the yarn type, *i* a yarn element, *L* the length of a yarn and *m* the effective medium.

Subsequently, the FE model of the two-step braid was used for a linear analysis of the structural behaviour of the braid under three-point loading, as depicted in Figure 3. The short beam shear test [4] was conducted to qualitatively compare the 3D braid with the pultruded laminate. The specimens were loaded at a test speed of 1 mm/min. Reaction forces and displacements were determined to calculate the short beam strength of the specimens.

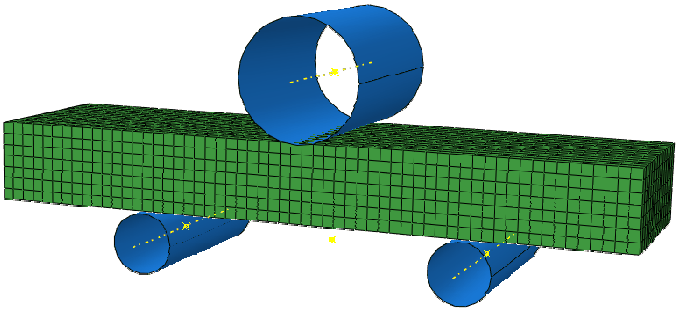

Figure 3. FE model of short beam shear test

3 Results

The Binary Model is a highly efficient modelling technique for simulating also 3D braided composites. The interlaminar shear strength was measured by the short beam shear test method [4]. The specimens were tested under three-point loading at a rate of 1 mm/min. The vertical displacement of the two-step braided composite and its textile preform is presented in Figure 4.

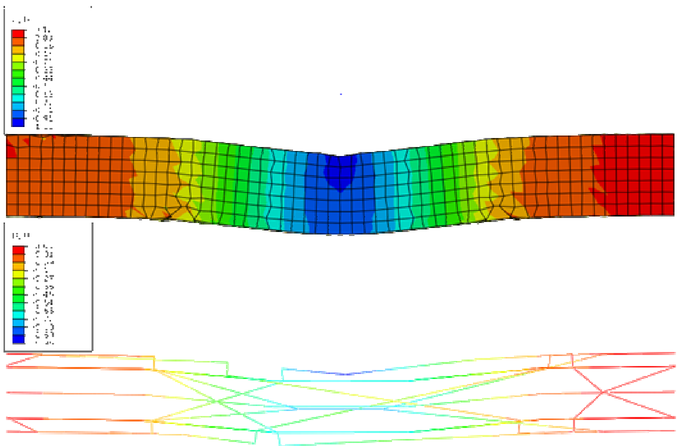

Figure 4. Vertical displacement of 2-step braided composite and its textile preform

Figure 5 presents the interlaminar shear stress distributions in the tested materials. Contact stresses induced at the loading and supporting points interfere a bit with the stress distributions in the specimens. Shear differences that indicate sliding of outer CSM layers and inner UD layer in the pultruded laminate are visible, see Figure 5(b).

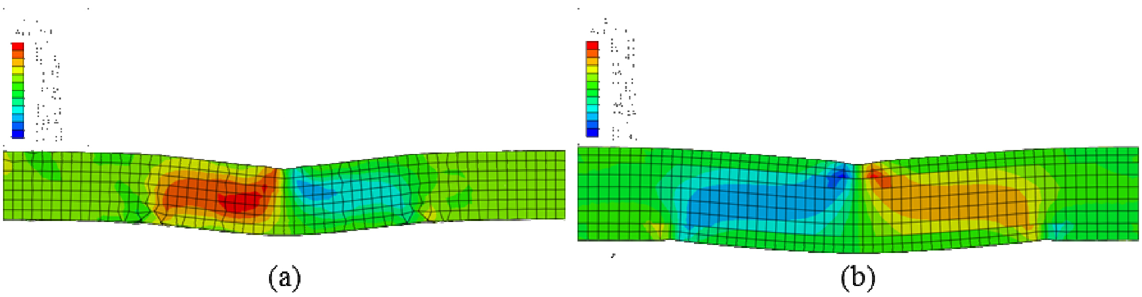

Figure 5. Interlaminar shear stress distributions in the 2-step braid (a) and in the pultruded laminate (b)

The short beam strength of both materials is shown in Figure 6. Fibre reinforcements in the out-of-plane direction are in general unfavourable for in-plane properties since fibre interlocking leads to additional resin pockets resulting in decreased in-plane properties [12]. However, the numerical results in this study indicate that the two-step braided composite presents a higher out-of-plane shear strength, due to superior transverse properties, compared to the pultruded laminate.

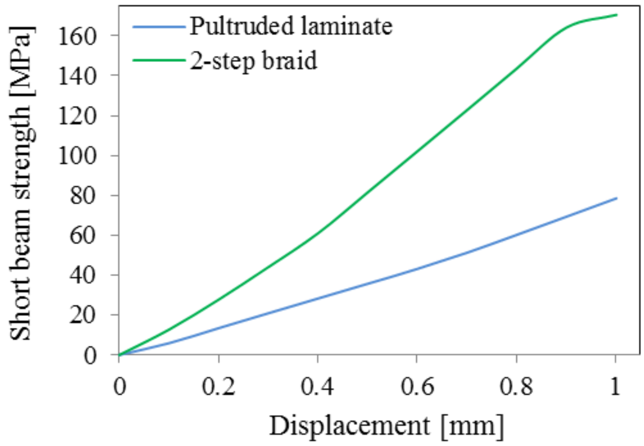

Figure 6. Comparison of the short beam shear strengths of the 2-step braid and the pultruded laminate

Cross-sections of yarns in 3D braids take various shapes. In the Binary Model the cross-sectional yarn shape is assumed to be uniform along the centreline of the yarn. The quality of the FE analysis depends, among others such as the material property input, on the representation of the centreline of the yarn path in the real textile architecture. Moreover, the size of the yarn segment defines the structural response of the textile.

4 Conclusions

A one-dimensional FE model, using the Binary model approach, was employed to examine the mechanical behaviour of a 3D braided composite, particularly a two-step braid. The interlaminar shear behaviour of the braid has successfully been characterised and compared with the mechanical response of a pultruded laminate. The two-step braided composite presents a higher out-of-plane shear strength due to superior transverse properties.
The Binary Model is a highly efficient modelling technique for simulating 3D textiles. The quality of the FE analysis depends, among others such as the material property input, on the representation of the centreline of the yarn path in the real textile architecture and the yarn segment size.

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