MATERIAL MODELING OF 2X2 BRAIDED COMPOSITES USING A BEAM APPROACH

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Abstract

Braiding is an automated preforming process for liquid molded composite materials. As braided composites offer a big variation in the textile yarn architecture, a material modeling approach has to predict the influence of yarn architecture on material stiffness and strength. The approach presented in this paper uses a finite element unit cell model to calculate the homogenized macroscopic material properties of a 2x2 biaxially braided carbon/epoxy composite. To reduce the effort for mesh generation, beam elements represent the longitudinal properties of the yarns and continuum elements represent transversal properties of yarns and matrix pockets. The predicted elastic properties show good correlation with micromechanical results. Further studies about the influence of out-of-plane boundary conditions and coupling of beam and continuum elements are outlined.

1 Introduction

1.1 Braiding technology

In the last years the demand for carbon fiber reinforced polymers (CFRP) in high volume production has increased strongly. This accelerated the trend from manual and expensive hand layup towards automated and robust manufacturing processes. Most automated processes are in the field of liquid composite molding (LCM): first the fibers are manufactured to a dry fiber preform and subsequently impregnated with a polymer resin using a LCM process. A robust preforming is required to achieve stable LCM processes as well as high and constant part quality.

The braiding process offers the possibility to produce near-net-shaped preforms. Braiding machines (Figure 1) are used to overbraid shaped mandrels: the yarns, stored on bobbins, counter-rotate around the braiding center and create an interlaced yarn pattern that deposits directly on the mandrel. The yarn architecture of a biaxial braid can be compared to a woven fabric, with the difference that the braid offers more variability, e.g. the two yarn directions can be non-orthogonal. The orientation of the yarn directions is defined by the braiding angle θ, which is the angle between the take-up direction and the yarns. A global configuration of the yarn architecture (e.g. braiding angle, preform thickness, etc.) can be adjusted for mandrels with constant cross-section using the braiding machine process parameters. If either shape or dimension of the mandrel cross-section changes, the yarn architecture varies, which leads to locally changing material properties on the structure.

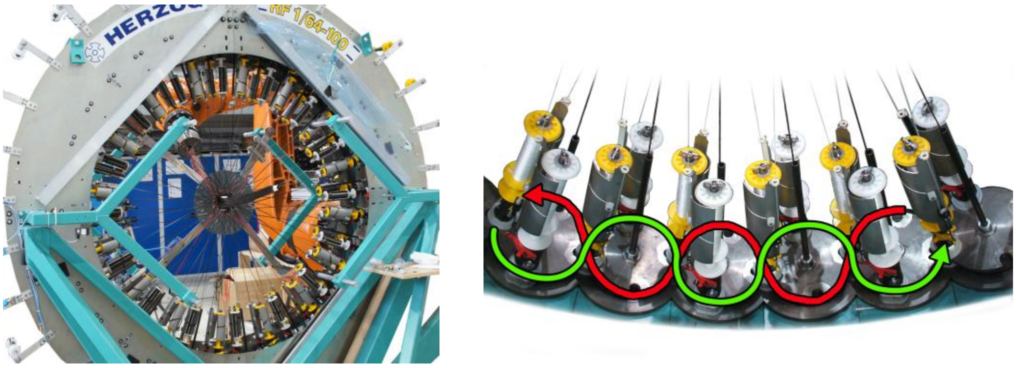

Figure 1. Braiding machine (left) and principle of bobbin movement (right)

For the goal of a structural simulation of braided composite components, these local variations of material properties are the main challenge. A material modeling approach has to be able to characterize or predict the yarn architecture and cover its influence on stiffness and strength of the material. This paper uses a multi-scale modeling approach for this purpose: the yarn architecture of the braided composite as well as the mechanical properties of fiber and matrix are used to build up a mesoscopic unit cell of a 2x2 (±30°) carbon/epoxy biaxial braid. The unit cell is transferred to the commercial finite element (FE) code Abaqus, where the nonlinear material behavior can be predicted and the mechanical response for various yarn architectures can be calculated. The unit cell results can further be used to feed a macroscopic structural analysis using conventional shell elements with varying mechanical properties from element to element depending on the local yarn architecture.

1.2. Unit cell modeling of braided composites

The basic idea of unit cell modeling is to calculate the mechanical properties of a material by applying a homogenization scheme to a small and representative volume of the material. The size of the unit cell generally depends on the internal structure of the material, but can be chosen quite obvious for braided composites, as the yarn pattern itself is periodic. For braided composites with high fiber volume fractions (50-60%), as required in aerospace or automotive industry, the main issue lies in the geometry and mesh generation of the unit cell. The high fiber volume fraction results in a complex yarn architecture: the cross-sectional dimension, orientation and shape of the yarns varie in the composite and overlapping of adjacent yarns can be observed (Figure 2). As these changes in yarn architecture show a strong variation within a braided composite, idealizations on the geometry are needed for unit cell modeling. Commonly, the cross-section of the yarns is assumed to have a simple geometrical shape (e.g. elliptical or lenticular) and the dimensions are kept constant along the yarns [1]. These simplifications are needed to achieve a simple and robust geometry creation of the unit cell, but suffer the drawback that the yarn volumes may penetrate each other, which inhibits a proper meshing of the unit cell. To account for this problem, several approaches have been made to e.g. automatically correct these penetrations [2] or simplify the mesh generation by using a Domain Superposition Technique [3]. The approach in this paper bases on the idea of the "binary model" first published by Cox [4], who used truss elements to model the yarns in a 3D woven composite. Core of the concept presented here is to simplify the unit cell geometry by using beam elements for the yarns and thus reduce effort for meshing and handling interpenetrations.

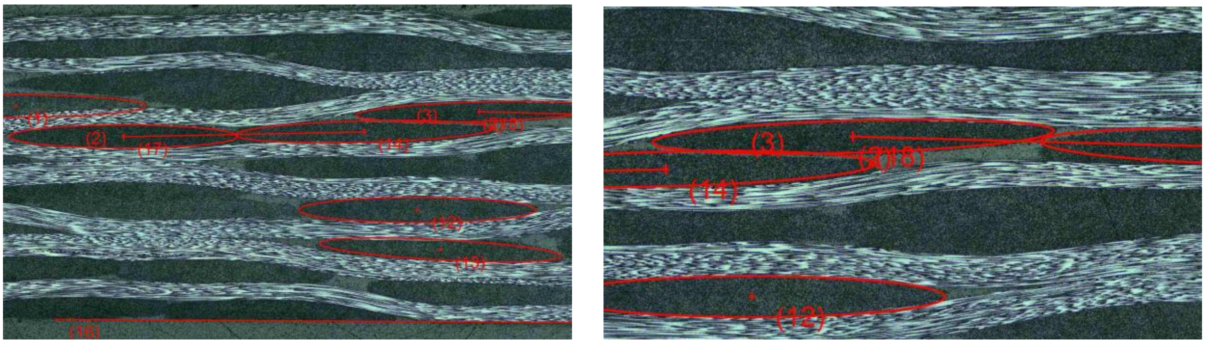

Figure 2. Photomicrographs of a (±45°) biaxial braid (left) area with overlapping yarns (right)

2. Beam unit cell

In this paper, a 2x2 (±30°) biaxial braid with 12k HTS carbon fibers and RTM6 epoxy matrix is modeled using a FE unit cell consisting of beam and continuum elements (Figure 3). The beam elements represent the axial and bending properties of the yarns and so called *effective medium* continuum elements represent the transversal yarn and matrix pockets properties.

2.1 Geometry of the unit cell

The geometric model of the unit cell is built using the WiseTex-software developed at the KU Leuven [5]. The yarn architecture of the braided composite is characterized using photomicrographs. An overview of the measured mean values is provided in Table 1. The spacing between two adjacent yarns is assumed to be identical to the yarn width. Using the geometric input, WiseTex calculates the paths of yarns within the unit cell.

Yarn width [mm]	Yarn height [mm]	Spacing [mm]	Braiding angle [°]
3.05	0.304	3.05	30

Table 1. Mean values of the yarn architecture parameters

WiseTex allows an export of the yarn paths and cross sections to an ASCII file, which is used to import the geometry into Abaqus using python scripting. The matrix elements are created using Abaqus by means of a simple rhomboid, which describes the boundary of the unit cell, and plane periodic boundary conditions are applied to the unit cell: the nodes on the vertical faces of the unit cell are coupled using constraint equations described in [6] and non-structural nodes are used to introduce loads into the unit cell. As laminates of braided composites normally are built up from a limited number of plies, periodicity cannot be assumed in the thickness direction. For that reason, different boundary conditions in the thickness direction were investigated and compared as described in section 3.2.

The modeling approach reduces the effort for model generation and allows an easy implementation of changes in yarn architecture (e.g. yarn cross-section). Furthermore, as a rather coarse mesh can be used, the approach reduces the computational effort and avoids highly distorted elements, which are unfavorable for nonlinear analysis.

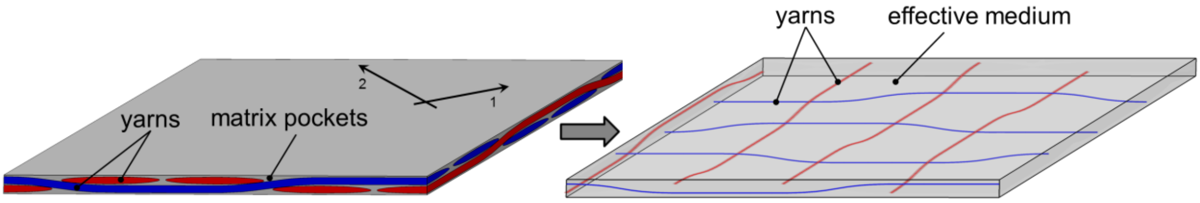

Figure 3. Idea of the beam unit cell: yarns are represented by 1D beam elements

2.2 Material model

In general, the finite element unit cell model of a textile composite is composed of volumes of yarns and matrix, which means that mechanical properties of the yarn and matrix material are needed. Common continuum element unit cells of textile composites model the yarns as transversely isotropic and the matrix pockets as isotropic material. The nature of the beam approach requires a separation of the material properties into properties of the beam elements and properties of the *effective medium* continuum elements. Thereby, the beam elements represent the longitudinal and bending properties of the impregnated yarns, whereas the continuum elements represent the transversal and shear properties, as well as the Poisson effects of both yarn and matrix pockets. Consequently the material properties of matrix pockets and transversal yarn properties have to be smeared into the effective medium continuum elements. As for all textile composites, care has to be taken of the different fiber volume fractions (FVF) in the yarn (packing density κ) and in the whole unit cell. With a unit cell FVF of φ=60% WiseTex predicts a packing density of κ=74% in the yarn. As the directionality of the yarn properties is covered by the beam element formulation, an isotropic material behavior is defined for both, beam and continuum elements. The fiber and matrix properties given in Table 2 are taken from [7] and Hashin's micromechanical model is used to calculate the unidirectional (UD) properties.

HTS Fiber		**RTM6 Matrix**	
E_{1f}	238 GPa	E_m	2.89 GPa
E_{2f}=E_{3f}	30 GPa	υ_m	0.3
G_{12f}=G_{13f}	13 GPa		
G_{23f}	5 GPa		
υ_{12f}	0.28		

Table 2. Fiber and matrix properties for UD material parameter calculation [7]

To avoid a doubling of material, the transversal UD Young's modulus has to be subtracted from the longitudinal Young's modulus for the beam elements. Furthermore, it should be noted, that the FVF for the calculation of continuum element properties has to be equal to the unit cell FVF (φ=60%) since the *effective medium* represent the smeared properties of yarns and matrix pockets. The material properties implemented into the beam unit cell model are given in Table 3.

Beam properties (φ=74%)	**Continuum element properties (φ=60%)**	
$E^{BE} = E_1^{UD} - E^{EM}$	$E^{EM} = E_2^{UD}$	$G^{EM} = G_{12}^{UD}$
E^{BE} = 176.6 GPa	E^{EM} = 9 GPa	G^{EM} = 4.3 GPa

Table 3. Material properties for beam elements (BE) and effective medium (EM) continuum elements

2.3 Coupling of yarns and matrix

The approach presented in this paper separates the meshing procedures of yarns and matrix: beam elements (representing the axial stiffness of the yarns) are meshed independently from the effective medium continuum elements representing the matrix properties. As there is no inherent connection between the two, the elements have to be coupled in order to represent the constitutive behavior. Two coupling methods, namely *node sharing* (NS) and *embedded elements* (EE) are investigated in this paper.

The NS approach requires the mesh of the effective medium to place a node at the same position as a beam node. During the meshing procedure, the coincident nodes are merged by the FE preprocessor and the displacements of yarn and matrix are coupled. This procedure offers challenges regarding the meshing procedure that may result in poor element quality inside the continuum mesh. Contrarily, the EE approach introduces constraint equations between beam and continuum elements. A beam node positioned in a continuum element is coupled to the element nodes with multi point constraints (MPC) that are weighted by means of the beam node position. In Abaqus, this MPC coupling can be introduced by applying the "embedded region" function: all beam nodes are coupled to the associated "host" continuum element. This approach offers several advantages like the simplicity of mesh creation, which enables an automated model generation and an improved element quality for the continuum mesh.

The straightforward NS approach was used for the first simulations. A comparison between both approaches is given in section 3.3.

3. Simulation results

All simulations presented here have been carried out as linear elastic analyses using the Abaqus/Standard implicit FE solver version 6.11. Linear Timoshenko beams (B31) and linear hexagonal continuum elements (C3D8) were used for the analysis. Each yarn was meshed using ten elements per crimp interval and a similar mesh size was chosen for the continuum elements, as the node sharing approach was used. The whole model included less than 20 000 elements. Unfortunately, no coupon test data for stiffness and strength were available for the braided composite modeled in this paper. To assess the quality of results, comparisons to micromechanical results obtained from TexComp [8] analyses using the same WiseTex input file are used. As elastic constants predicted from TexComp were reported to have a good agreement to experiments [7], they provide a good basis for a first comparison.

3.1 Elastic constants:

A first comparison of results is provided in terms of elastic constants in the material coordinate system, where the 1-direction refers to the take-up direction of the braid (Figure 3). TexComp calculates the engineering constants by using the information about the yarn architecture provided by WiseTex and applying a homogenization scheme described in [8]. For the beam unit cell, two uniaxial loading cases in 1- and 2- direction as well as an in-plane pure shear loading are needed to calculate the elastic constants. The unit cell is loaded in the (1,2) material coordinate system and homogenization is used to calculate the macroscopic stress and strain state of the unit cell. A comparison of the elastic constants is given in Table 4: the beam unit cell results for Young's moduli and Poison's ratio agree well with the TexComp results, the deviations are smaller than 1% for all values. The shear modulus predicted by the beam unit cell is about 29% smaller than the TexComp result. This can be explained by the out-of-plane warping of the beam unit cell, which is induced as upper and lower face of the unit cell are free to deform. This effect will be further discussed in the following section.

Value	TexComp	Beam unit cell
E_1 [GPa]	41.4	41.1
E_2 [GPa]	9.0	9.0
G_{12} [GPa]	27.6	19.6
υ_{12} [-]	1.506	1.517

Table 4. Comparison of elastic constants predicted by TexComp and the beam unit cell

3.2 Off-Axis behavior

As shown above, the Young's moduli calculated using a single beam unit cell agree well with TexComp results, when the unit cell is loaded in one of the material principle axes. For an off-axis loading the results obtained using the beam unit cell strongly depend on the imposed out-of-plane boundary conditions. For a single ply unit cell (SUC) with upper and lower faces left free to deform, the stiffness in the ψ=30° off-axis direction (fiber direction) is around 15% smaller than the corresponding TexComp result (Figure 4). The discrepancy is due the local out-of-plane warping of the unit cell induced by unsymmetries at the yarn crossovers (Figure 5). This warping leads to a reduction of both the Young's modulus in the fiber direction and the G_{12} shear modulus.

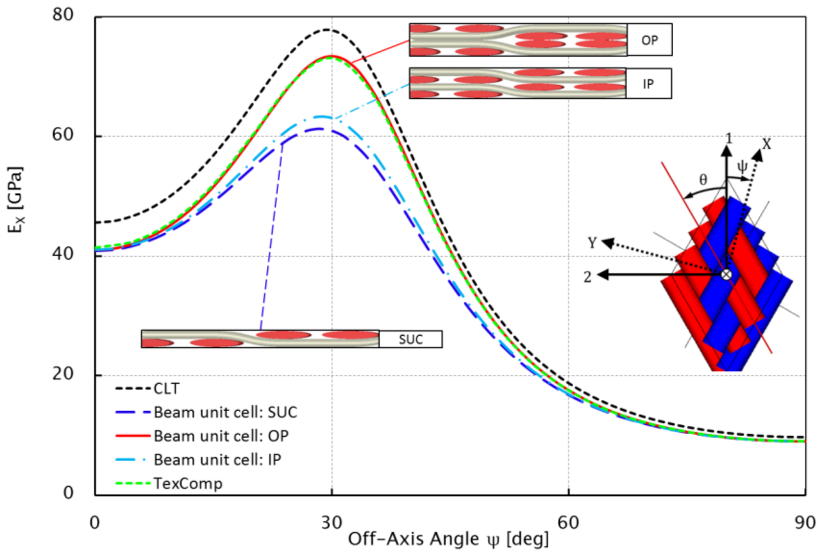

Figure 4. Off-axis behavior of the unit cell using different out-of-plane configurations

As a braid laminate normally consists of several plies, which are stacked on top of each other, the support of the adjacent plies should be included in the analysis. To account for different laminate stackings, two stacking configurations are investigated using a two-ply unit cell: in-phase stacking (IP) with the unit cells placed identically on top of each other and out-of-phase stacking (OP) with the two plies shifted by a half wavelength of the undulation.

The results for both cases are shown in Figure 4: the IP configuration leads to a slight stiffening compared to the SUC that can be explained by the similar deformation behavior of both unit cells, which offers only little resistance against the warping. Contrarily, the OP configuration drastically increases the stiffness in the fiber direction, showing a good correlation to the TexComp results. The stiffening is due to the opposing deformations of the upper and lower unit cell that neutralize the out-of-plane warping. In a real braided laminate, both stacking cases and mixtures will be present (Figure 2), so the laminate stiffness can be assumed to be in between the IP and OP values, which is also reported for strength of woven fabrics in [9]. The consideration of mixed stacking and comparison to test results is part of ongoing research.

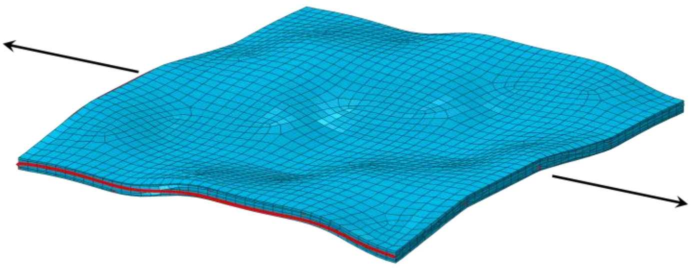

Figure 5: Out-of-plane warping of the unit cell under $\psi=30°$ off-axis loading (beam elements marked red)

3.3 Embedded elements coupling of yarns and matrix

The node sharing coupling approach requires the continuum mesh to have nodes positioned identical to the beam nodes. Since this restriction can lead to degenerated continuum elements, the embedded elements coupling approach, which allows a regular continuum mesh, has been further investigated.

Both approaches are compared in Figure 6: the predicted elastic constants are almost identical for both approaches, showing only minor deviations of about 2%. Furthermore, it can be seen, that both, the OP stacking case and the out-of-plane warping in the SUC case are covered well by the embedded elements approach. As the meshing effort is drastically reduced, the embedded elements approach offers a good basis for further research.

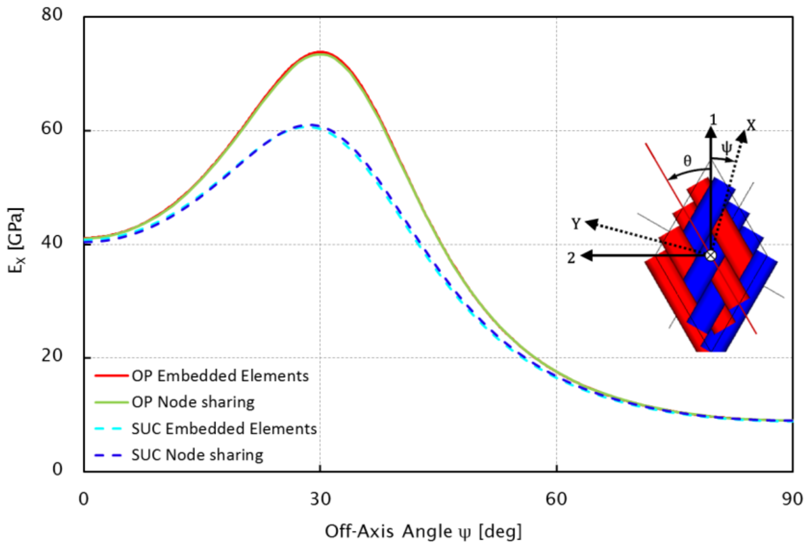

Figure 6. Comparison of elastic constants for NS and EE coupling approaches

4. Conclusion

An approach for material modeling of biaxially braided composites was presented in this paper. A FE unit cell with beam elements representing the longitudinal properties of the yarns and *effective medium* continuum elements to account for transversal properties of yarns and matrix pockets has been built up using WiseTex and Abaqus FE software. The approach reduces meshing effort and simplifies the model generation for complex yarn architectures. The elastic constants obtained by the beam unit cell correlate well with TexComp results, but are considerably influenced by the out-of-plane boundary conditions. An improved coupling method for beam and continuum elements shows good agreement to the results obtained by classical node sharing. Further studies will be conducted on the comparison of predicted values to experiments as well as on the prediction of nonlinearities and the failure behavior using the beam unit cell.

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