Influence of process induced defects for biaxial carbon fiber braids

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Abstract. The influence of different machine settings for the manufacture of biaxial carbon fiber braids is investigated using numerical models and compared with experimental results. For these studies different process parameters like yarn pre-tension and rotational speed of the bobbins have been varied to generate cylindrical biaxial braids with an average braid angle of ±45°. From a test program the non-uniform distribution of the braid angle and cover factor is observed using image processing techniques of the produced samples. In parallel, ongoing work is using numerical simulations of the braiding process to identify defects, and investigations have been able to correlate numerical results with experimentally observed defects.

1. Introduction

Rotary braiding is an effective manufacturing technique to produce near net-shape preforms in a cost- and time-efficient manner, and is a widely used textile preforming process in the automobile, aerospace, sports and other industries. This process uses two sets of bobbins that move in sinusoidal paths in the radial braiding machine; one set rotates clockwise, whereas the other set rotates counter-clockwise. The final shape of the preform and fiber architecture is determined by the size of the machine, the mandrel geometry and machine settings such as mandrel take-up speed, yarn pre-tension and rotational speed of the bobbins. However, one drawback in this process is the interaction of these parameters, which can cause different kinds of defects like those depicted in Figure 1.

![Figure 1](image-url): a) Varying braid angle; b) Varying cover factor; c) Fiber damage in form of broken filaments.
1.1. Braid angle
The braid angle is defined as the angle between the longitudinal axis and the direction of the off-axis yarns. For a biaxial preform produced over a cylindrical mandrel this angle can be calculated from simple kinematic relation [1] as

\[ \tan \alpha = \frac{2 \pi \omega d}{v n} \]  

where \( \omega \) describes the rotational speed of the bobbins in revolutions per seconds, \( d \) the mandrel diameter in millimeter, \( v \) the mandrel take-up speed in millimeter per seconds and \( n \) the number of horn gears of the braiding machine. However, in practice this angle may not be constant as seen in Figure 1a and can vary due to irregular mandrel take-up speed, a varying geometry, different yarn pre-tension or stick-slip effects during the braiding process.

1.2. Cover factor
The cover factor describes the ratio of the yarn cover on a surface to the whole surface of the mandrel geometry for a single layer. It has a high influence on the in-plane mechanical properties, and therefore most applications require a fully closed braid for best mechanical properties [2]. The low cover factor shown in Figure 1b is caused by variations in the yarn width, which is mainly influenced by friction causing a compaction of the yarn during the rewinding or braiding process. Alternatively, a large mandrel diameter, insufficient bobbins or excessive mandrel/bobbin velocities will also produce preforms with a low cover factor.

1.3. Fiber damage
The fiber damage mentioned in the present work is shown in Figure 1c, which has resulted in significant breakage of single filaments. This is induced by excessive friction and will result in some loss of composite mechanical properties. Furthermore, fiber breakage during manufacture is undesirable in the workplace since this can cause health problems and is dangerous to other electrical equipment which are likely to short circuit.

Experimental testing is very costly and time-consuming and the influence of different process parameters like yarn pre-tension or machine speeds cannot be tested for every possible machine configuration. A purely analytical approach is unable to account for the afore-mentioned parameters, consequently the use of the finite-element method is investigated here as a means to undertake a holistic simulation of the process chain that includes the effects of imperfections. The main goal of this paper is therefore to transfer the results from a process simulation, with included defects, to a structural mechanical calculation which enables effective stiffness to be calculated.

For this study biaxial 2D carbon fiber braids with a twill weave pattern have been manufactured on a radial braiding machine. Different process parameters were used to generate biaxial ±45° braids, from which quantitative analyses of fiber angle, cover factor and yarn width are made. From simulations of the braiding process it is possible to correctly capture imperfect yarn architecture and to estimate fiber damage. These results can then be used to construct FE models of the imperfect architecture for stiffness analysis, and two different approaches are demonstrated here.

2. Experimental test program and defect characterization
This section gives a brief overview of the test program and characterization of the defects mentioned in section 1. After a short description of the different machine settings used, the methods of characterization are explained, followed by measurement results at the end of this section.

2.1. Test program & setup
The investigated braids are produced on a fully mounted radial braiding machine Herzog RF 1/64-120 at the Institut für Textiltechnik (ITA), see Figure 2a. Braids were produced over a cylindrical mandrel of 85 mm diameter with Tenax®, E HTS40 F13 24K 1600tex yarns. Since yarns are delivered on spools
it is necessary to do a rewinding operation. This step is done with a Herzog SP 280 as shown in Figure 2b. A constant tensile force is required to ensure a proper rewinding, which is done with a pre-tensioner as shown in Figure 2c, where the yarn is guided through two eyelets and a normal force is applied with a spring. One potential problem of this operation is that high friction forces can create fiber damage, before the actual braiding process is started.

![Figure 2: a) Radial braiding machine Herzog RF 1/64-120; b) Rewinding machine Herzog SP 280; c) Pre-tensioner to apply a constant rewinding force.](image)

The investigated process parameters as well as the calculated mandrel take-up speed according to equation (1) are listed in Table 1.

| Reference | Yarn pre-tension [g] | Bobbin rotation speed [rpm] | Mandrel take-up speed [mm/s] | Calculated mandrel take-up speed [mm/s] |
|-----------|----------------------|-----------------------------|-----------------------------|----------------------------------------|
| A         | 100                  | 50                          | 14                          | 13.91                                  |
| B         | 100                  | 150                         | 40                          | 41.72                                  |
| C         | 350                  | 100                         | 30                          | 27.82                                  |
| D         | 700                  | 50                          | 14                          | 13.91                                  |
| E         | 700                  | 150                         | 32                          | 41.72                                  |

For every configuration a total number of three braids were manufactured and subsequently cut from the mandrel for further investigation of variabilities and defects. This characterization is performed with a CanoScan LiDE 200 flatbed scanner from Canon as shown in Figure 3.

![Figure 3: Experimental setup for the characterization of the braided preforms.](image)
The braid is surrounded by a template which contains the dimensions as well as a reference coordinate system that is also scanned during the characterization process. The main advantage of this approach is the possibility to identify the fiber architecture for the future coupons, as the braids are not moved anymore until they are infiltrated with resin and fully cured.

2.2. Test evaluation

The evaluation of the scanned braids is mainly done automatically. For the calculation of the braid angle a software tool from the Faserinstitut Bremen e.V. (FIBRE) is used, that was originally developed within the scope of the EU project IMac-Pro [3]. Each preform has a length of 1300 mm and is divided into 10 single scans. A part of the scanned raw data can be seen in Figure 4a. In the next step, the scanned image is segmented into 6 x 10 subcells for which the fiber angle is calculated as shown in Figure 4b. The braid angle for every layer contains about 600 measuring points. The mean as well as the standard deviation for all three layers are listed in Table 2.

For determination of the cover factor a MATLAB-script is used. The scanned raw data is taken and converted into a grey-scale image which only contains black and white pixels as depicted in Figure 4c. For a correct allocation of the pixels a threshold is set manually and black and white pixels are counted, whereby black indicates cover of the mandrel surface and white specifies gaps in the braid.

![Figure 4](image)

**Figure 4:** a) Scanned raw data; b) Analysed braid angle; c) Grey scale image for automated cover factor determination.

The measuring of yarn width is done manually, supported by the open source software GIMP. Hereby, a scale is scanned which is taken as a reference to convert the pixels into a length unit. As every braid consists of 10 single scans, a total of 10 x 40 measuring points are recorded for a single layer. An overview of the results of the characterization can be seen in Table 2. Considering the process parameters of Table 1, a comparison of RefB (150 rpm, 100 g) and RefE (150 rpm, 700 g) shows that a higher process speed leads to a wider distribution of the braid angle. The cover factor is not influenced by the process speed, however, the yarn width shows the lowest value for those two configurations. The yarn pre-tension does not have a significant influence on the yarn width, as demonstrated by the comparison from RefA (50 rpm, 100 g) and RefD (50 rpm, 700 g) which show nearly equivalent results.

![Table 2](image)

**Table 2:** Results of the characterization of the dry braids.
3. Numerical investigations

This section describes the numerical investigations made to virtually produce the braids using the same process parameters as listed in Table 1. In a second step, the results are transferred to a structural analysis containing the imperfect yarn architecture.

3.1. Process simulation

The software code used for the braiding simulation is the Virtual Performance Solution 13.0 from the ESI group [4]. The numerical model is built-up following methods discussed in [5], using the same configuration as the real machine. The 64 braiding yarns are therefore moving on a sinusoidal path, whereas the mandrel translates with constant speed. In order to consider the effect of different yarn pretensions the bobbins are modelled as spring elements that apply a constant tensile force on every yarn. The mandrel and the braiding ring are modelled as rigid bodies while the discretization is done with shell elements. The yarns are also discretized with shell elements, as it has been shown that this approach is best suited for process simulation [6] since yarn width can correspond to the width of the shell elements. The physical distance between the yarns is controlled by the contact properties and should be defined as the subsequent yarn thickness. A constant friction coefficient of $\mu = 0.2$ is applied to all contact interfaces. The virtual braiding process is shown in Figure 5.

![Figure 5: Braiding process simulation.](image)

To compare the numerical results with the tests from Table 2 the braid angle is measured and the mean values, as well as the standard deviation are plotted in Figure 6.

![Figure 6: Comparison of the braid angle from the numerical process simulation and the test results.](image)
It can be seen from Figure 6 that the simulation fits the experimentally determined braid angle quite well. For all cases, except RefA, a process-dependent tendency can be observed and the influence of the investigated process parameters is reflected in the numerical results. The remaining deviation of numerical and experimental results can be caused by several factors such as the yarn material model or simplification of the constant friction coefficient. These influences will be further investigated in ongoing work.

As mentioned in section 1.3, fiber damage is mainly caused by excessive friction. In order to estimate the influence of the different process parameters on this particular defect, the dissipated frictional energy from simulation models is depicted in Figure 7.

![Figure 7: Frictional energy of different process parameters in consideration of fiber damage.](image)

A comparison of RefA and RefB shows a minor influence of the bobbin rotational speed respectively the process speed. On the other hand, comparing RefA with RefD reveals that the yarn pre-tension has a strong influence on contact friction energy and therefore the fiber damage. This can also be seen in the graphs of Figure 7. The braid angle is approximately constant for RefA and RefE, but increasing fiber damage can be observed. In summary, it can be said that the process simulation is capable of capturing the fiber architecture as a function of the process parameters and can also be used as an indicator for fiber damage.

3.2. Structural simulation

This section describes two methods to transfer the results from the process simulation to a numerical analysis for prediction of elastic stiffness including the effect of irregular braid angle.

3.2.1. Voxel method

The first method uses volumetric pixels or short voxels, where the meso-scale composite is represented by a regular 3D mesh. In contrast to other works [7], [8] and [9], the presented method aims to generate a three-dimensional yarn based on the two-dimensional mesh with an irregular yarn architecture. This procedure is depicted schematically in Figure 8 and detailed in Figure 9.

![Figure 8: Schematic procedure of the voxel method. a) Shells overlaid with solids. b) Final yarn segmentation based on the selected search volume.](image)
The algorithm to set-up the voxel analysis is implemented in a python script and is undertaken as following. In a first step, the region of interest is extracted from the process simulation results according to Figure 9a. The shell mesh is then superimposed with solid elements as shown in Figure 9b. These two steps are performed manually in the used CAE environment. Thereafter a search area is defined that characterizes the yarn cross-sectional area and is expanded in the third dimension by using the shell-element length. This generates a three-dimensional search volume. As this is done, the script automatically calculates a centroidal node for every solid element. This serves to speed up the algorithm as it checks whether the centroidal node is inside the search volume or not. If so, a new part identification number as well as the material principal axes are assigned to the corresponding element. By iterating through all elements the fiber architecture is segmented. The final voxel mesh is shown in Figure 9c, as well as a section cut of the yarn architecture. As can be seen the specified ellipsoidal cross-section is well developed. In a last step the user defines the material properties, boundary conditions and applied loading manually. By computing the resistance to deformation the elastic properties of the composites volume are determined.

![Figure 9: Voxel method: a) Cut-out of the sample; b) Overlay with solid elements; c) Final yarn architecture discretized with volume elements.](image)

Due to the step-wise discretization of the yarn surface (see Figure 8b), stress concentrations do occur at the connection of fiber and matrix parts due to the high mismatch of modulus and the meshing. This is unimportant for determination of the homogenized elastic stiffnesses, since these properties are not influenced by local stress concentrations. However, for a prediction of damage onset and failure this method can be expected to lead to premature failure due to the unrealistic stress concentrations [7] and is therefore not suitable. In order to overcome this limitation an alternative approach is described in the following section.

3.2.2. Embedded elements technique

This second method uses a mesh superposition technique, in which an embedded region constraint is imposed via an option available in Abaqus [10]. The underlying concept is to overlay two meshes where a group of elements is embedded in a set of host elements. The response of the host elements is then used to constrain the translational degrees of freedom (DOF) of the embedded elements. The main benefit of this approach is the independent meshing for the yarns and the resin, while a full model often leads to a poor element quality due to very thin gaps between the single yarns. However, one of the main challenges of this technique is the volume redundancy, which causes an added stiffness that must be taken into account. An interpenetration of the yarns must also be avoided, as this is not covered automatically by the embedded region constraint in Abaqus. In [11] a methodology is presented to overcome these problems and different cases are compared with full models, where a good correlation
has been shown. The basic idea of this technique is schematically depicted in Figure 10a, where the embedded nodes must not necessarily lie on the host edges, but can be located inside or even outside the host element. If an embedded node lies outside the host element, a geometric tolerance is used to define how far it can lie outside the host region [10].

\[ C_R' = C_R(x) - C_M, \]  

where \( C_R(x) \) designates the position-dependent stiffness matrix of the reinforcement and \( C_M \) the stiffness matrix of the resin. In order to avoid an interpenetration of the yarns while loaded under tension, a general contact is used with normal behaviour of \textit{hard contact} and tangential behaviour of \textit{rough} in accordance to [10]. So once the yarns are in contact, no slip will occur; this can be seen as a perfect adhesion condition. Reference [11] also presents an approach to calculate the correct stress- and strain fields for the reinforcement region which can then be used to predict damage onset and failure. A limitation of the embedded elements technique is the inability to represent fiber-matrix debonding, or delamination between layers. Since there is no suitable interaction criteria this effect has to be further investigated, as well as the influence of the non-constraint rotational DOF’s for the case that shell elements are embedded in solid elements.

3.2.3. Comparison of the presented methods with WiseTex

In order to evaluate the forecast quality of the presented numerical methods, the results are compared with WiseTex which is an established meso-scale analysis tool to determine elastic stiffness of textile composites [12]. As the embedded shell elements are not able to represent the assumed elliptical yarn cross-section, their geometrical thickness is chosen to have the same cross-sectional area as the elliptical yarns. The models are loaded in the longitudinal direction and the corresponding stiffness is described by \( E_{45^\circ} \). The WiseTex result is calculated with the Mori-Tanaka scheme and a comparison with the presented numerical methods can be seen in Table 3.
Table 3: Results of the stiffness comparison from WiseTex and the presented numerical methods.

|          | WiseTex   | Voxel method | Embedded elements |
|----------|-----------|--------------|-------------------|
| $E_{45^\circ}$ | 13689 MPa | 11206 MPa    | 13969 MPa         |

These results show that the embedded element technique corresponds well to the WiseTex results with only a small overestimate of stiffness of about 2%. The voxel method underestimates stiffness by about 18% which can be caused by a too low fiber volume fraction. Considering section A-A from Figure 9 it can be seen that the yarns are not in contact with each other which does not reflect reality and does lead to resin rich zones between the yarns. Further investigations are necessary to overcome this problem.

4. Results and outlook

In this work biaxial carbon fiber braids with an average braid angle of ±45° have been manufactured with different process parameters. A characterization of the preforms is done using image processing techniques. These results show that the braid angle and the yarn width are dependent on process parameters. For example, higher process speed leads to a wider standard deviation of the braid angle and a smaller mean of the yarn width. Also different yarn pre-tension does not significantly effects the braid angle, but can cause significant fiber damage.

For a virtual characterization the braiding process has been simulated and braid angles have been compared with experimental results. The influence of the process parameters is demonstrated in the simulation as well as the experimentally captured standard deviation of the braid angle. A comparison of the dissipated frictional energies shows a strong influence of the yarn pre-tension, which leads to higher fiber damage as observed in the experiments. A voxel method, as well as an embedded element technique, was presented to transfer the results from the process simulation into a structural analysis, which were shown capable to predict composite stiffness compared to the analytical results from WiseTex.

For future work the preparation of test coupons and their mechanical testing is planned with characterization of the strain-field to be undertaken using digital image correlation (DIC). Further investigations are also planned to quantify fiber damage using laser sensors.

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