A NUMERICAL APPROACH MODELING THE BRAIDING PROCESS FOR ARBITRARY MANDREL SHAPES TO CALCULATE PREFORM PROPERTIES

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Keywords: Braiding, Preform, Process Simulation, Finite Elements

ABSTRACT

The braiding process is simulated numerically using a commercial finite element software. In order to ensure the high geometrical flexibility of the process, a procedure to determine mandrel’s velocity and movement for arbitrary mandrel shapes is presented. The extraction of necessary geometry information from mandrel’s CAD data is included. The friction coefficients needed as input parameters are quantified in experimental tests. A method to derive braiding angle and yarn distance from simulation results is introduced. For validation, a generic mandrel geometry is overbraided and the braiding angles of experiment and simulation are compared.

1 INTRODUCTION

The applications of composite materials in high volume production industries increase the demand for the development of automated manufacturing processes. The overbraiding process is a production method for near net shape, textile preforms. It is characterized by a high degree of automation, limited raw material waste and high flexibility in geometrical design. Yarns are spooled on bobbins, which are fixed on carriers. These carriers are moved by horn gears in contrary direction to create a textile structure, led over a guide ring and placed on a braiding mandrel, as shown in Fig. 1. The mandrel geometry is equal to the inner contour of the produced part. In combination with subsequent resin transfer molding (RTM) techniques, a high potential in cost reduction for mass produced products can be generated compared to autoclave cured prepreg materials.

![Industrial braiding machine](image1)

Figure 1: Industrial braiding machine (left) with horn gears moving carriers (right).

In the braiding process several process parameters must be determined:

- The horn gears rotate with a usual constant angular velocity $\omega_{HG}$.
- The mandrel is pulled/ pushed through the braiding ring by an industrial robot along a certain path and with a specific velocity $v_m$.
- A yarn tension is applied by a spring in each carrier. The tension can be adjusted by the choice of spring’s quantity.
Different friction properties between interacting parts occur, depending on yarn material type and sizing, guide ring and mandrel material and their surface properties.

These parameters and their combinations have a great influence on the yarn alignment. This influence will be studied in this work via the braiding angle \( \alpha \) and the spacing \( s \) between parallel yarns, as shown in Fig. 2. When the geometrical design flexibility is utilized, these preform properties strongly vary and cannot be predicted easily. The determination beforehand of the final braided architecture is important to predict the permeability of the preform, possible process induced defects (PID) and the mechanical properties of the produced part. Simulating the braiding process is a promising method to generate input for further virtual analysis like filling, structural and PID simulation. Furthermore, feasibility studies concerning the mandrel geometry can be run or necessary process parameters can be determined in advance to ensure placement of the preform on the mandrel or desired preform properties.

![Figure 2: Preform properties: Braiding angle \( \alpha \) and spacing \( s \).](image)

The braiding angle can be analytically deduced from the ratio of angular velocity of the horn gears and mandrel velocity:

\[
\tan(\alpha) = \frac{\omega_{HG} d}{v_m N_{HG}},
\]

where \( N_{HG} \) is the number of horn gears and \( d \) the diameter of the mandrel cross section. This equation can only be applied to cylindrical mandrels. In other cases, an equalized diameter \( d_{eq} \) must be derived to calculate a global braiding angle using eq. 1, while the local one can deviate both in the cross section and along a curved mandrel axis:

\[
d_{eq} = \frac{U}{\pi}
\]

The perimeter of the mandrel is \( U \). The spacing \( s \) of a cylindrical mandrel is determined by the following geometrical relationship:

\[
s = \frac{2 \pi d}{N_C \cos(\alpha)},
\]

where \( N_C \) is the number of carriers.

In this study, a numerical approach is presented using the commercial explicit finite element solver of Abaqus (Dassault Systèmes Simulia). To analyze arbitrary mandrel shapes, a method to extract geometrical information from the computer aided design (CAD) model of the mandrel is introduced. The mandrel’s path and velocity are determined by a Matlab routine (Mathworks). The friction coefficients used as input parameters are derived in separate tests. The simulation results are processed to an algorithm which calculates the preform properties \( \alpha \) and \( s \) (Fig. 2).
2 BRAIDING PROCESS SIMULATION APPROACH

A simulation model of the braiding process is shown in Fig. 3. The presented curved mandrel geometry with a trapezoidal cross section is used as an example of a generic mandrel in order to introduce the simulation approach and to validate it.

The represented parts are the yarns, the mandrel and the guide ring. One end of the yarns is fixed on the mandrel’s surface, the other end is connected to a control point using a non-linear connector spring which applies a defined constant load. The control points are placed where the carriers are located in the braiding machine. The boundary conditions assigned on the points are represented as sine and cosine functions with amplitudes numerically equal to half of their wavelength. Mandrel and guide ring are modeled as rigid bodies, since their deformation can usually be neglected. The yarns are described using truss elements. Their cross section shape is therefore simplified to a circle with a constant radius throughout the simulation. The cross section area is chosen to be equal to the tightly packed area of the filaments. Bending stiffness is neglected by using truss elements. This represents a justified simplification, since a yarn consists of a high number of filaments. Its bending stiffness is very low compared to a continuum with a cross section described before.

The simulation model can be adapted to biaxial and triaxial braids of any braid pattern. An overview of these is presented in [1]. In this study, a biaxial braid with a common 2x2 pattern is analyzed.

Three different friction coefficients are needed as simulation input parameters: the friction coefficient between the yarns and the mandrel $\mu_{YM}$, the yarns and the guide ring $\mu_{YR}$ and between the interacting yarns $\mu_{YY}$. Last one is taken from a literature study for yarns of parallel orientation: $\mu_{YY} = 0.507$ [2].

A single yarn was pulled over the guide ring using the industrial robot of the braiding machine and the force was measured on both sides to derive $\mu_{YR}$. A tensiometer DTBX 5000 produced by Hans Schmidt & Co. GmbH was attached between the carrier and the ring to measure $F_1$, and a load cell was fixed in the three-jaw chuck of the robot to measure $F_2$, both shown in Fig. 4.
Figure 4: Experimental setup to measure the friction coefficient between the yarns and the guide ring.

The friction coefficient is determined using modified capstan relation [3]:

\[ \mu_{\text{YR}} = \frac{2}{\pi} \ln \left( \frac{F_2}{F_1} \right) = 0.348. \]  

(4)

A braided preform is fixed on one side of a rectangular metal block, while the specimen is pulled over the mandrel. The friction coefficient \( \mu_{\text{YM}} \) is determined by dividing the measured pull-off force \( F_R \) by the total weight \( F_N \) of the specimen:

\[ \mu_{\text{YM}} = \frac{F_R}{F_N} = 0.367. \]  

(5)

The following method to derive the boundary conditions of the mandrel in the process simulation is applicable to any mandrel geometry. It is subdivided in two parts: providing necessary geometry information and calculating mandrel’s movement.

First, the surfaces of the mandrel are extracted from the CAD-model. Its position has to be equal to the starting position in the simulation: the global coordinate system is placed at the center of gravity of the starting cross section and the mandrel is designed in positive \( x \)-direction, as shown in Fig. 5. Following procedure is automated in a Catia Visual Basic for Applications (VBA) script: points are set along one mandrel edge at regular intervals. The distances between the points are equal and can be freely chosen. Planes through the points and normal to the edges are generated. The mandrel is cut along the planes. As illustrated in Fig. 5, the axis points \( P_i \) equal to the center of gravity of each created cross section and the corresponding normal vector \( n_i \) are generated and exported together with the local perimeter of the cross sections \( U_i \). These data are imported into a Matlab routine.

Figure 5: Sketch of the mandrel with exemplary axis points and vectors.

The control point of the mandrel is placed at the center of gravity of the first cross section. The boundary conditions in global coordinates are applied on this point. The mandrel movement is subdivided in \( n \) time increments \( \Delta t_k \) equal to the number of axis points. These increments are calculated dividing the distance between corresponding axis points by the velocity of the mandrel determined using eq. 1 and 2. The global braiding angle and the used angular velocity of the horn gears have to be chosen here.
This algorithm ensures that the axis points go through the center of the braiding machine equal to the origin of the global coordinate system, while the corresponding axis vectors are parallel to its $x$-axis. Thus, the rotation axis $R_k$ at time $t_k$ is calculated using the vector cross product of the corresponding normal vector and the $x$-axis,

$$R_k = \mathbf{n}_k \times \mathbf{x},$$

while the rotation angle $\phi_k$ is equal to their vector dot product:

$$\cos(\phi_k) = \frac{\mathbf{n}_k \cdot \mathbf{x}}{|\mathbf{n}_k| |\mathbf{x}|}$$

The whole mandrel axis is rotated for each time $t_k$:

$$P'_k = \begin{bmatrix} R_{k,x}R_k x(1-c) + c & R_{k,x}R_k y(1-c) - R_{k,x}s & R_{k,x}R_k z(1-c) - R_{k,y}s \\
R_{k,y}R_k x(1-c) - R_{k,z}s & R_{k,y}R_k y(1-c) + c & R_{k,y}R_k z(1-c) - R_{k,x}s \\
R_{k,z}R_k x(1-c) - R_{k,y}s & R_{k,z}R_k y(1-c) - R_{k,x}s & R_{k,z}R_k z(1-c) + c \end{bmatrix} \cdot P_k,$$

with $c = \cos(\phi_k)$ and $s = \sin(\phi_k)$. The coordinates of the corresponding axis point after rotation, which has to end at the center of the braiding machine, are set as boundary condition. The rotation boundary condition is calculated by the product of $R_k$ and $\phi_k$.

In the following step, the numerical model is build up. All process parameters can be freely chosen as the model is parametrically implemented in an Abaqus python routine. The simulation outcome gives the virtual braided preform, described by the node coordinates of the yarns and closest to this node. The braiding angle is derived using the vector dot product of the yarn number and $a,m$, is found. A normal vector $\mathbf{n}_k$ is derived:

$$\cos(\alpha) = \frac{\mathbf{n}'_k \cdot (K'_{a,m+1} - K'_{a,m})}{|\mathbf{n}'_k| |K'_{a,m+1} - K'_{a,m}|}$$

The derivation of the spacing is illustrated in Fig. 6. First, the node $K'_{a+1,n}$ of the nearby yarn $a+1$ and closest to $K'_{a,m}$ is found. A normal vector $\mathbf{n}_{a,m}$ is derived:

$$\mathbf{n}_{a,m} = (K'_{a+1,n} - K'_{a,m}) \times (K'_{a,m+1} - K'_{a,m})$$

This vector is crossed with the vector between the two nodes along yarn $a$ to determine $\mathbf{n}_{a,m,dis}$:

$$\mathbf{n}_{a,m,dis} = (K'_{a,m+1} - K'_{a,m}) \times \mathbf{n}_{a,m}.$$
Thus, the braiding angle and the spacing are calculated for each finite element of the yarns, which are discretized using an element length of 2 mm. Thereby, the results provide a highly detailed information of the braided preform, which can be used for further virtual analysis. The results are visualized on the CAD-model of the mandrel. A Catia VBA macro is implemented to realize this. For the braiding angle, the yarn elements are represented by cylinders generated based on the projected node coordinates. The spacing is visualized by spheres, each diameter is equal to the represented spacing. Both cylinders and spheres are colored depending on the resulting values of braiding angle and spacing to visualize them in a contour plot, represented in Fig. 7.

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3 VALIDATION

The mandrel geometry in Fig. 8 was overbraided using the braiding machine shown in Fig. 1 (32 horn gears). One single layer of Sigrafil C30 carbon fibers produced by SGL Group is overbraided. The take up speed of the mandrel is chosen in order to achieve a global braiding angle of 45° using eq. 1.
The braided preform is analyzed using an optical sensor produced by Profactor GmbH. Its functionality is based on Photometric Stereo and is documented in [4]. The sensor determines a fiber angle for each pixel of the analyzed preform extract, the resolution is 28.25 pixels per millimeter. An extract of approximately two fiber patches is analyzed for both fiber directions $\alpha^+$ and $\alpha^-$, as shown in Fig. 9.

![Sensor data in positive $\alpha^+$ (left) and negative fiber direction $\alpha^-$ (right).](image)

The data are averaged to a single value depending on the coordinate $u$ along mandrel’s perimeter (see Fig. 8). The results of the comparison between simulation and experiment are shown in Fig. 10. Both are compared at two points along the mandrel axis, in the center of the constant curvature $M_c$ and at a straight axis point $M_{st}$ (see Fig. 8), and for both fiber directions $\alpha^+$ and $\alpha^-$. Between two experimental data values one additional simulation data value is shown as these are also able to be determined in areas, where yarns in counter direction cover the examined one.

It is noted that the local braiding angle is not constant for presented non-circular cross sections. The detailed braiding angle distribution, shown in Fig. 10, is introduced following. The denomination of the edges used are shown in Fig. 8:

Looking at the experimental results at $M_{st}$, the braiding angle is higher on top and bottom edge compared to side 1 and 2 for both fiber directions. At the top edge, it is approximately constant while it is smaller in the middle of the bottom edge than at the beginning and the end. The so called s-form distribution is shown. This distribution is well known for braided parts with relatively long straight edges [5]. For $\alpha^+$, the braiding angle is constant on side 1 and increases on side 2 up to the same level as on the top edge. For $\alpha^-$, the angle decreases on side 1 starting from a value equal to the ones on top of the trapezoid and is approximately constant on side 2. At $M_c$, no significant difference can be noticed in the experimental data compared to $M_{st}$. 
Figure 10: Comparison of simulation and experimental results: Fiber angle along mandrel cross section at straight (top) and curved (bottom) position for both fiber directions (left, right).

The simulation results show the same trends as the experimental ones. An overall good correlation is confirmed. The discrepancies between experiment and simulation is smaller than 5° at all points. Certain effects in particular yarn interacting cannot be reproduced using truss elements. This happens because in the model yarns of same direction do not touch each other as they do in reality. This yarn contact limits specific trends in fiber alignment induced by mandrel geometry. Therefore, they are overestimated in the simulation results, e.g. described s-form distribution at bottom edges and increasing and decreasing braiding angles at side edges.

4 CONCLUSION

A numerical approach to describe the braiding process using finite element methods was presented. The method can be applied to any mandrel geometry as the procedure to determine the boundary conditions of any mandrel shape was given. The friction coefficients between yarns and mandrel and yarns and guide ring were determined in the context of this work in separate tests. A post-processing method to derive braiding angle and spacing from simulation results was presented. The simulation approach was successfully validated with a difference between simulation and experiment smaller than 5° at all measuring points.

Further research should concentrate on a method to characterize the friction coefficient between the yarns. These data were taken from literature study. A different material was used here. Furthermore, a parameter study using the FE-model has to be done to quantify the influence of the different friction coefficients, the yarn tension and different mandrel geometries.

The derived output quantities are calculated for each finite element of the yarn, thereby providing a highly detailed representation of the results and, therefore, a suitable input for further analysis such as
filling or structural simulations. The presented preform process simulation has to be connected to existing approaches of these kind of simulations.

ACKNOWLEDGEMENTS

The author would like to thank Mr. Gásper Kokelj, Mr. Patrick Hermann and Mr. Felix Anhalt for their investigations in the scope of their Master’s Thesis and Term Projects.

REFERENCES


