EFFECT OF MANUFACTURING PROCESS INDUCED FIBER WAVINESS ON MECHANICAL PROPERTIES OF COMPOSITE STRUCTURES BY EXAMPLE OF A PREPREG FORMING PROCESS

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Abstract

In this paper an approach to include the effects of a forming process on preimpregnated fibers into the design of composite structures by analysis of the resulting fiber waviness is presented. Therefore the influence of the forming process and a measurement method for fiber waviness is discussed. Fiber waviness in formed composite parts is characterized by the power spectral density and the resulting fiber angle distribution. This modeled using a discrete inverse fast Fourier transformation. Subsequently the mechanical properties are calculated based on these fiber angle distributions in a finite element analysis. An additional comparative experimental analysis of a specimen manufactured with and without the influence of the forming process is presented. The measured fiber angle distributions are analyzed and resulting first ply failure for both cases is predicted using the presented method.

1. Introduction

1.1. Motivation

In preimpregnated fibers (prepregs) which are commonly used in the aerospace industry, an initial degree of fiber waviness is present [1]. Manufacturing processes like forming of prepregs further influence fiber waviness [2]. The influence of misaligned fibers on mechanical properties of fiber reinforced plastics (FRP) has been investigated in numerous studies [1, 3]. When designing composite parts it is crucial to combine the knowledge about how fiber waviness is influenced by manufacturing processes and how in turn misaligned fibers reduce stiffness and strength. A better understanding of the correlation between manufacturing processes and the resulting mechanical properties thereby provides a means to include manufacturing processes and its properties into the design. This will lead to an integrated design process which is one research topic of the research project HP CFK.

1.2. High Performance Production of CFRP-Structures (HP CFK)

The interdisciplinary research project HP CFK combines the three research topics aircraft design, material science and manufacturing technologies in a single process chain oriented research project. For that purpose the Institute of Production Engineering and Machine Tools, the Institute of Aircraft Design and Lightweight Structures and the Institute of Polymer Materials and Plastic Engineering established a cooperative research group located in the research center CFK Nord (Stade, Germany). The methodology used in HP CFK allows an interaction of design, materials and manufacturing developments through the process chain [4]. The interdisciplinary research results are demonstrated on a panel commonly found in large aircrafts. The process chain for the panel combines prepreg and infusion technologies (Fig. 1). First the fuselage skin is laid up on flat tooling in automated fiber placement (AFP) and then formed into its designated geometry. Afterwards foam cores for the local stiffeners are placed on the skin and covered by continuing AFP prepreg layup. Foam cores for the global stiffeners are positioned, dry carbon fiber textiles are draped on it and an infusion on the still uncured fuselage skin is executed. Finally the whole panel is cured in one autoclave cycle.

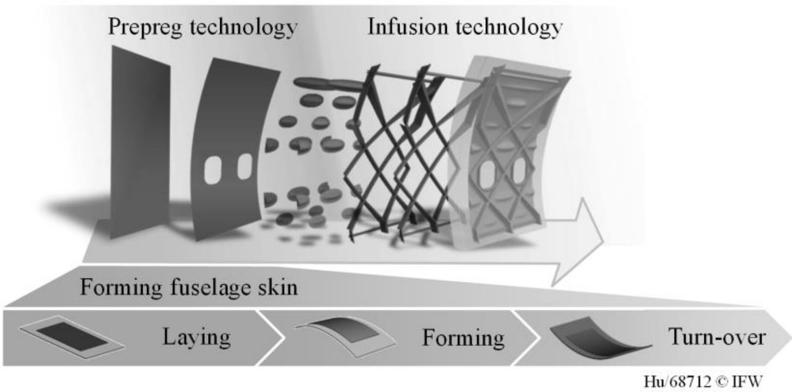

Figure 1: HP CFK process chain

2. Process induced fiber waviness

2.1. Forming of prepregs

Prepreg forming processes are used in several carbon fiber reinforced plastic (CFRP) manufacturing technologies to reach designated part geometries. One example is the hot diaphragm process [5]. The quality of parts consisting of thermosetting prepregs formed via diaphragm forming is influenced by forming temperature [5, 6], forming rate [6] and layup sequence as well as interlayer material properties [7, 2]. If designated geometries have double curved surfaces with rapidly changing curvature or process or part parameters do not meet requirements, defects could occur, such as in-and out-of-plane fiber waviness.

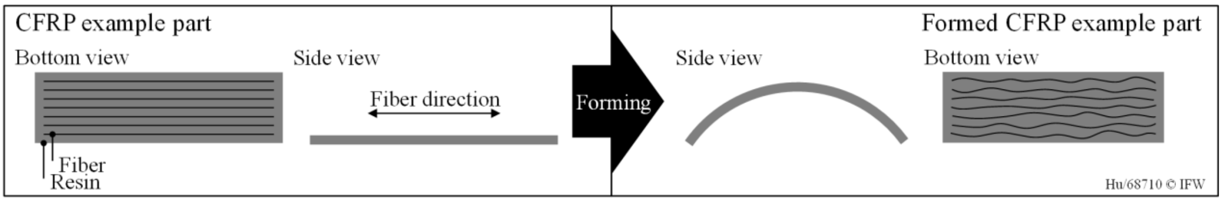

Figure 2: In plane fiber waviness after forming process

The thermosetting prepreg forming process of the HP CFK process chain is inspired by the idea of diaphragm forming technology [8]. Prepreg material is fixed and compacted under vacuum bagging in flat state on a flexible tooling surface. After heating up the prepreg to forming temperature, the tooling surface and the prepreg is formed actor based into the designated geometry and then cooled down to room temperature. While forming a laminate the prepreg layers are stretched or compressed depending on the resulting deformation degree of each single layer, since friction between the layers prevents sliding. In this process the fiber length remains equal as mechanical properties of the fiber eliminate elongations or compressions. Thus during forming of uncured prepreg parts, fiber waviness changes in curvature direction (Fig. 2).

2.2. Measuring fiber waviness

Measuring fiber angle distribution in cured composite parts is crucial to integrate the effects of fiber waviness in design approaches. A measurement method has been proposed by S. W. Yurgatis [9], analyzing section cuts of cured composite parts. Methods that further measure wavelength and amplitudes of fiber waviness in cured parts where proposed by Creighton et al. and Kratmann et al. [10, 11]. In this paper, fiber angle distributions are measured in cross sections using methods based on the work of Yurgatis with an angled grinded embedded cut out sample. Therefore a small cut out of the part along the fiber direction is embedded in resin and grinded at an angle of 5° to the fiber direction (Fig. 3). As a result the fibers show up as ellipses, where the length of an ellipse is correlated to the fiber angle in reference to the designated fiber direction. The ellipses in the microscope images of the cross sections were analyzed using a self-developed software algorithm for Matlab® environment.

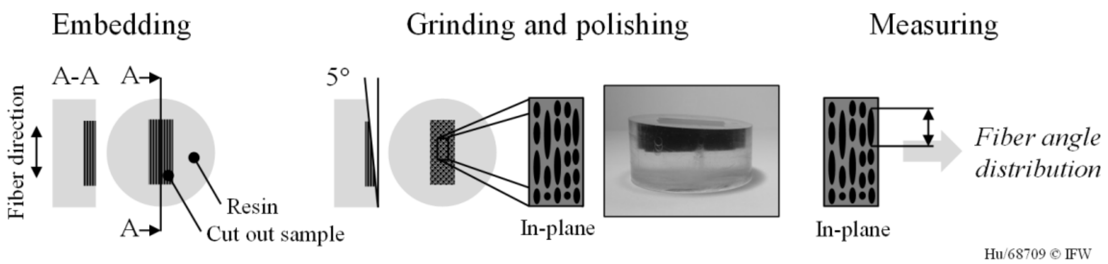

Figure 3: Specimen preparation and fiber waviness measuring procedure

3. Experimental Analysis

3.1. Concept and sample manufacturing

The idea of the experimental analysis is to have two comparable sample parts, a flat reference and a formed one, both cured under the same environmental conditions. The primary goal of this analysis is to quantify the distribution of fiber angles and qualify the effect of the forming process on the distribution. In order to get flat specimen for standard mechanical testing procedure, the formed test part is produced using a reverse forming procedure. The prepreg layers are placed onto a curved geometry and are formed into the flat state (Fig. 4). The forming process is done at a temperature of 70 °C, with a vacuum build up to keep the laminate flat during forming. From both parts multiple specimen are cut and prepared for measurement of fiber waviness as described in 2.2.

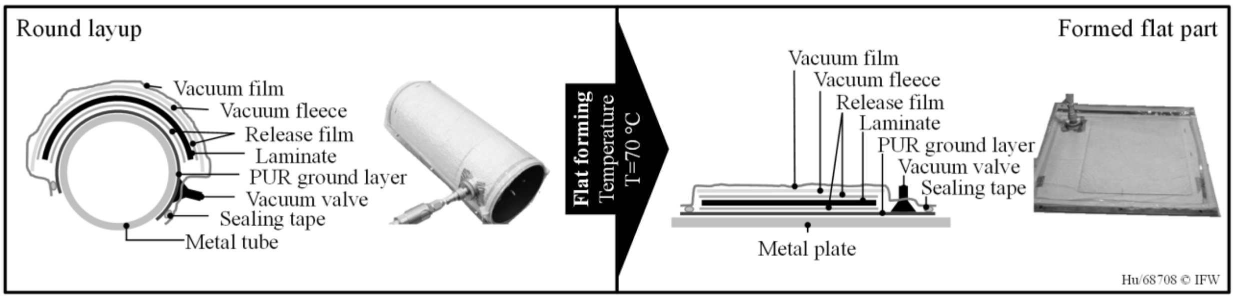

Figure 4: Manufacturing of flat example parts in an inverse forming process

3.2. Results

The resulting distributions of fiber angles are measured for each layer in the cured part. Figure 5 shows the derived fiber angle distribution. Starting from the upper layer (origin is the upper surface of the sample part) and ending with the bottom layer (the layer that touched the tooling surface during the forming process) of the sample part, results are shown left hand side. Right hand side a filtered black and white image of the cross section of the specimen emphasizes the ellipses.

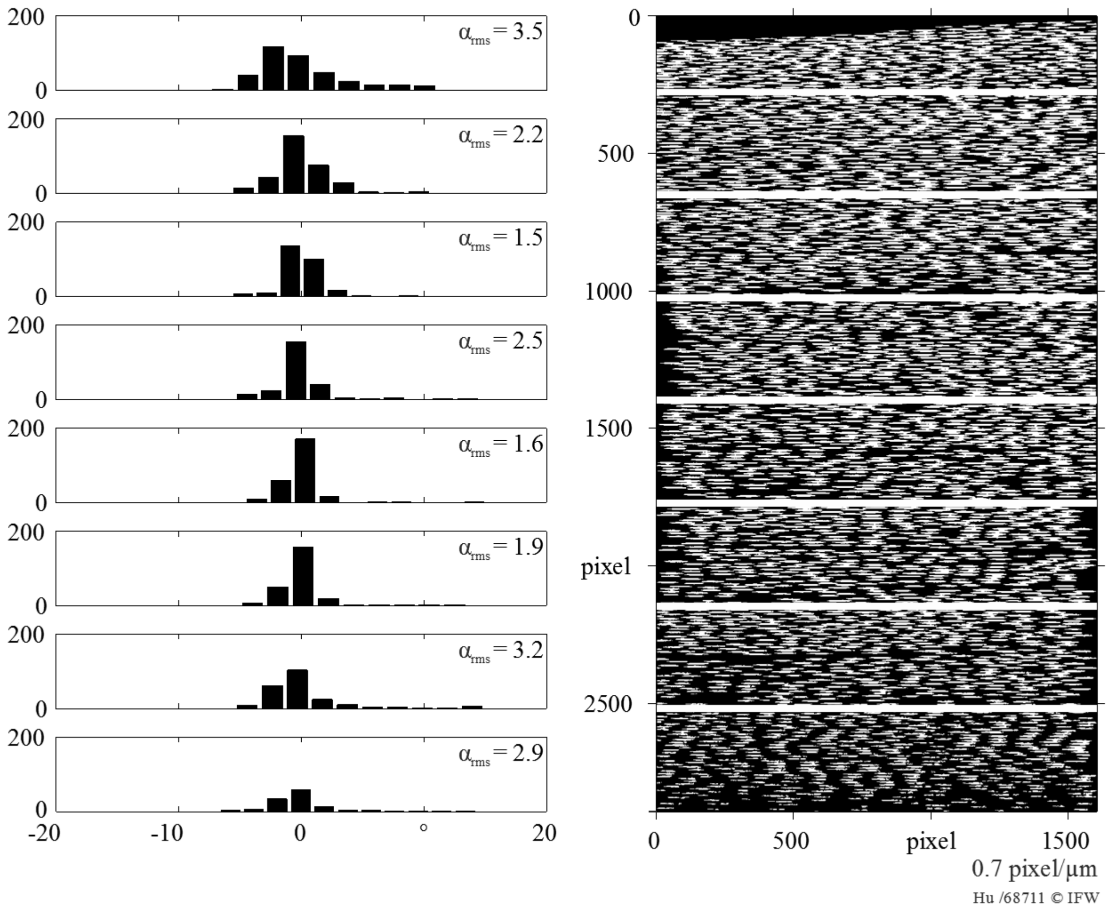

Figure 5: Analysis of fiber angle distribution of the reverse formed part *left:* derived fiber angles; *right:* filtered black and white microscope image of the formed part

Two cut out samples are exemplarily compared (Fig. 6). It is noticeable, that the root mean square of the fiber angles in both parts is not constant over the thickness of the part, but tends to be larger at the two outer layers. Considering the influence of the forming process, the formed part, showed larger deviations from the nominal fiber direction in the upper layer (layer 1 in Fig. 6). The deviation is characterized by the root mean square of the derived fiber angle distribution (α_{rms}).

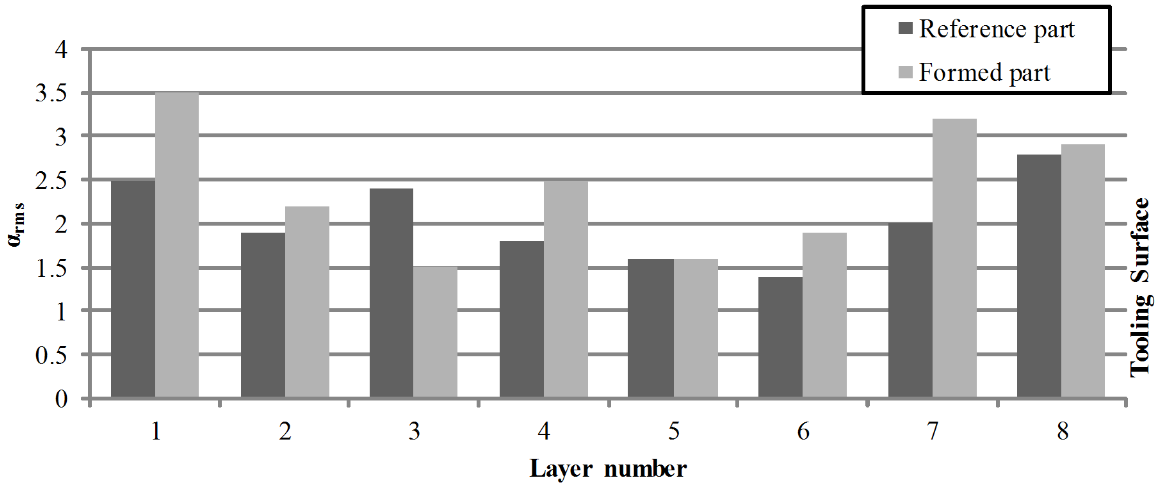

Figure 6: Comparison of the root mean square values of fiber angles (α_{rms}) between reference and formed part

4. Numerical analysis of fiber waviness

4.1. Concept

Fiber waviness in composite parts is random, i.e. the actual paths of fibers vary, unless great efforts are made. Mechanical properties of a region containing misaligned fibers differ from the material properties due to the inhomogeneous stiffness distribution resulting from inhomogeneous fiber angles. Fiber waviness is described as a fiber angle distribution which is characterized by its power spectral density (PSD). The PSD defines how each frequency contributes to the total mean square amplitude. The approach to generate fiber angle distributions adopted in this study was initially used by Slaughter and Fleck and Liu et al. [1, 3]. From each unique PSD multiple fiber angle distributions can be generated by randomly alternating the phase shift of each contributing frequency. Therefore the resulting mechanical properties for a unique PSD are subject to uncertainties. Fig. 7 shows the basic concept of the analysis module written in Python using Abaqus® as a means to calculate the properties of the model including fiber waviness.

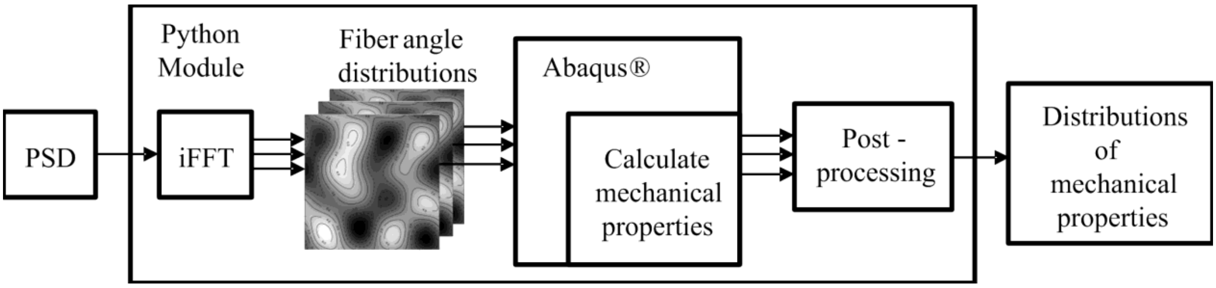

Figure 7: Analysis of mechanical properties of composite materials with random fiber waviness

4.2. Implementation

A Python module was implemented, which uses Abaqus® to calculate the mechanical properties of the specimen. The input into an analysis run are the characteristic parameters of the PSD, the cut off frequency ω_c and the spectral parameter S_0. A fiber angle distribution of a PSD is calculated using an inverse two dimensional Fourier transformation, implemented in Pythons Fast Fourier Transformation (FFT) package. Randomly alternating each contributing frequencies phase shift leads to differing fiber angle distributions. All distributions resulting from a unique PSD share the same value of α_{rms}, defined by the spectral parameter S_0.
In order to calculate the mechanical properties of a region subjected to fiber waviness, models with random fiber angle distributions were built in Abaqus® using shell elements (S4R). The fiber angles for each element are fed into the model using a discrete field, holding a fiber angle for each element. The Fourier transformation and the mesh in Abaqus® need to have the same discretization to be compatible. Kinematic periodic boundary conditions are imposed, enforcing identical deformations of opposite edges, following an implementation described by Kouznetsova et al. [12]. The deformation of the model is set by applying displacements to three corner nodes, with the displacement of the forth corner node being dependent on the other three. Load cases with deformation of the model parallel and perpendicular to the nominal fiber direction were analyzed, from which the stiffnesses $E_{\parallel}$ and $E_{\perp}$ as well as well as the strengths $R_{\parallel,+}$, $R_{\parallel,-}$, $R_{\perp,+}$ and $R_{\perp,-}$were calculated.
In order to calculate the mechanical properties from a load step, the equivalent stress is read by summing up the nodal forces on the corresponding edge which is then divided by the area it was subjected to dividing the equivalent stress on the model by the strain then results in the equivalent stiffness. The strength values of each load case are calculated using the Puck criterion [13], which distinguishes between two basic failure classes, fiber fraction and inter fiber fraction. In each load case the equivalent stresses at which fiber fracture and inter fiber fracture occur are calculated. The equivalent strength is defined by the minimum of both values.

4.3. Results

Stiffness and strength values were calculated for α_{rms} between 0,1° and 3,0° and ω_c between 0,8mm^{-1} and 3,0mm^{-1}. For each unique combination of α_{rms} and ω_c, 10 realizations where generated, calculating the equivalent stiffness as the mean value of the 10 realizations. Finally an analytical function is fitted to the calculated mean values (Fig. 8). The cut off frequency ω_c had no significant influence on the mechanical properties; hence only results for α_{rms} are presented. For strength evaluation the failure stresses predicted by the Puck criterion [13] are calculated. In all cases except fiber parallel loading, the first failure occurs due to inter fiber fraction. Considering fiber parallel loading a switch from fiber fraction to inter fiber fraction occurs at α_{rms} about 0,6° (see Fig. 8). Using classical lamination theory and the Puck criteria with the obtained reduced strength values a prediction for a first ply failure in specimen for material testing was made. The predictions were made for specimen gained from the same parts as were analyzed in 3.3, with a width of 10 mm.

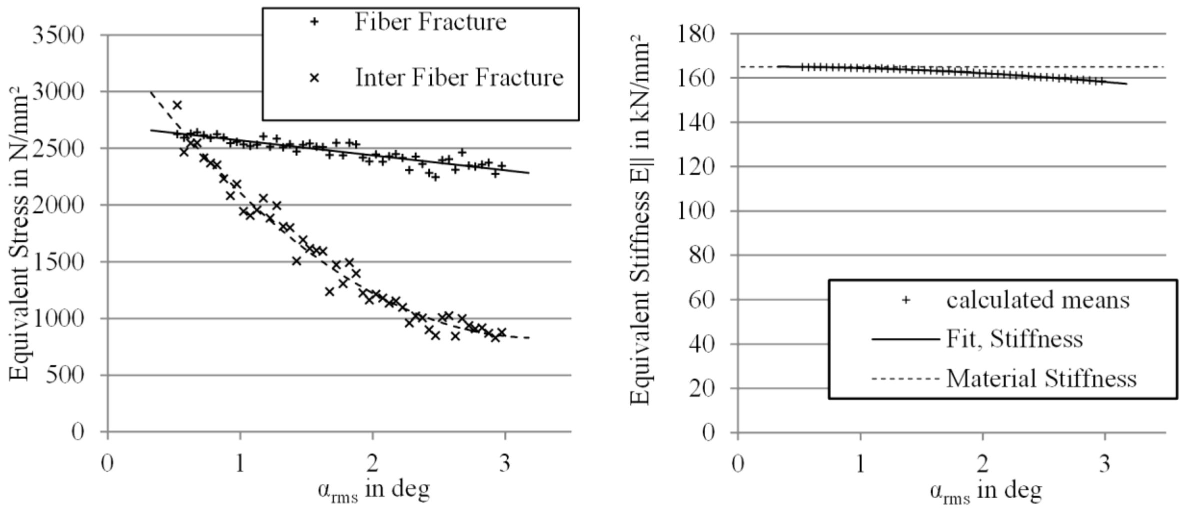

Figure 8: left: Fiber and inter fiber fraction stresses at fiber parallel loading right**:** Equivalent Stiffness parallel to nominal fiber direction as a function of the mean absolute fiber angle

Under fiber parallel loading first ply failure in the specimen from the reference part occurs in layer 1 (forming tool side) at about 18 kN and a strain of 0.55 %. For the formed part the predicted first ply failure occurs in layer 8 (outer face) at about 16 kN and a strain of 0.50 %, reducing stress at which first ply failure occurs by 10 %. Since there is no significant reduction either in strength or in stiffness perpendicular to the nominal fiber direction, prediction for both specimens showed no significant influence of fiber waviness in that direction (Tab. 1).

Mechanical property	Best fit for mean value	Reduction of property at α_{rms} = 3.0°
$E_{\|}$	$E_{\|,equivlent}(\alpha) = -800\cdot\alpha^2 + 79\cdot\alpha + 165139$	-4%
$E_{\perp}$	$E_{\perp,equivlent}(\alpha) = 9326$	-0.8%
$R_{\|,+}$	$R_{\|,+,equivlent}(\alpha) = \{ \begin{matrix} -130\cdot\alpha + 2700;\ 0^\circ < \alpha < 0.6^\circ \\ 253\cdot\alpha^2 - 1644\cdot\alpha + 3500;\ 0.6^\circ \le \alpha \le 3.0^\circ \end{matrix}$	-66%
$R_{\|,-}$	$R_{\|,+,equivlent}(\alpha) = \{ \begin{matrix} -77\cdot\alpha + 1586;\ 0^\circ < \alpha < 0.6^\circ \\ -336\cdot\alpha + 1869;\ 0.6^\circ \le \alpha \le 3.0^\circ \end{matrix}$	-45%
$R_{\perp,+}$	$R_{\perp,+,equivlent}(\alpha) = -0.17\cdot\alpha + 69{,}5$	-1.4%
$R_{\perp,-}$	$R_{\perp,-,equivlent}(\alpha) = -0{,}53\cdot\alpha + 208{,}6$	-1.4%

Table 1: Resulting mechanical properties for α_{rms} between 0° and 3.0°

5. Conclusion

A method to measure fiber angle distribution resulting from a forming process was proposed and an exemplary analysis was carried out. In the analyzed specimen, the forming process mostly influenced the distribution of fiber angles in the outer layer, furthest from the forming surface. The proposed approach to include the fiber waviness into the analysis of parts showed a high sensitivity of fiber parallel strength parameters, leading to significantly lower stresses for first ply failure. The influence of the forming process on fiber waviness was not equally distributed over the part thickness and mostly resulted in larger mean absolute fiber angles in the layer furthest from the forming tools surface. Further investigation is aiming at a better understanding of the correlation of forming process parameters and resulting fiber angle distribution. Furthermore experimental studies to validate the predicted influence of α_{rms} will be done next.

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