PROCESS-DEPENDENT MATERIAL PROPERTIES FOR STRUCTURAL SIMULATION OF COMPOSITES MADE BY TAILORED FIBRE PLACEMENT

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Abstract

The applied embroidery process of the Tailored Fibre Placement (TFP) technology uses a zigzag stitch pattern for fibre fixation causing a slight waviness of reinforcement fibre rovings. To evaluate the influence for mechanical properties of a carbon fibre reinforced plastic (CFRP) composite made by TFP experimental tests have been carried out varying the waviness referring to the process parameters wavelength and amplitude. Additionally a direct optical measurement of the waviness has been performed as basis for a frequency equivalent description, which has been verified by an optical full field measuring of tensile loaded specimens. The observed effects and results are the basis for future numerical studies and the simulation of composite structures made by TFP.

1. Introduction

For the manufacturing of extreme lightweight parts made of fibre reinforced plastics (FRP) a variable-axial composite design can increase the mass-specific stiffness and strength dramatically [1]. In contrast to multi-axial composites made of fabric, non-crimp fabrics or prepreg material, the reinforcement fibres are locally placed curvilinear with almost arbitrary orientation [2] even with small radii down to $R = 5\ mm$. With help of the Tailored Fibre Placement (TFP) technology, developed at the Leibniz-Institut für Polymerforschung Dresden e. V. (IPF) in 1990s, a variable-axial composite preform can be manufactured automatically by using embroidery machines [3]. The principle of the TFP process by fixing roving material with the help of zigzag stitches on a base material is shown in Figure 1.

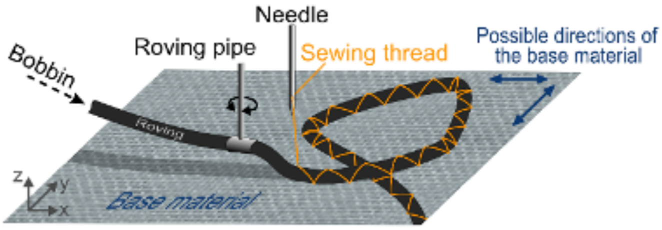

Figure 1. Principle of the Tailored Fibre Placement technology

In recent years the high potential of this preform technology was successfully proven on several structural parts, e.g. the AIRBUS A350 window frame [4]. However, this potential of variable-axial composite structures cannot be fully exploited so far. One of the main reasons is the complex and difficult structural description of appropriate models for finite element (FE) simulation. For example a locally varying fibre angle in combination with a locally varying distance of adjacent rovings results in a non-uniform thickness distribution. Using a recently developed method an automatic FE modelling process based on a simple 2D-CAD pattern for the TFP process can be carried out [5]. Based on a homogenised composite material model, this modelling approach is suited for conventional finite element analysis software suits supporting standard anisotropic volume elements. However, adequate information of the effective material properties are still required as input data.

TFP technology offers different process parameters for the fibre fixation procedure, like the stitch length and the stitch width (R-value), which can influence the resulting waviness. The principle of waviness of a reinforcement roving caused by the applied zigzag stitch type is shown in Figure 2. The waviness is defined as the amplitude divided by the wavelength [6]. Additionally the undulation can also be affected by the material type used for reinforcement fibres (e.g. raw material, number of filaments), the stitching thread, the base material and the number of stacked layers.

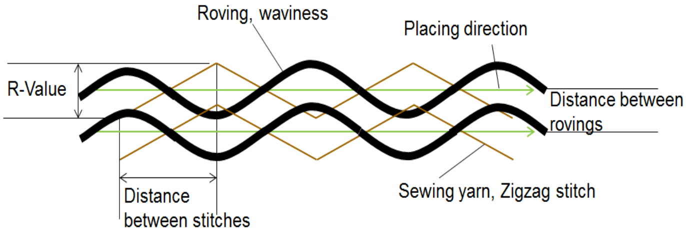

Figure 2. Schematic of the waviness of a reinforcement roving fixed with TFP technology

In the following work the waviness influence on the unidirectional material properties is studied by optical evaluation and mechanical testing for a better understanding of the effective material properties of TFP made structures and a possible numerical simulation of a parametrically built representative volume element.

2. Optical evaluation of the waviness of dry unidirectional TFP preforms

Fixing a single carbon roving straight on a base material made of paper the resulting waviness can be qualitatively analysed by visual information.

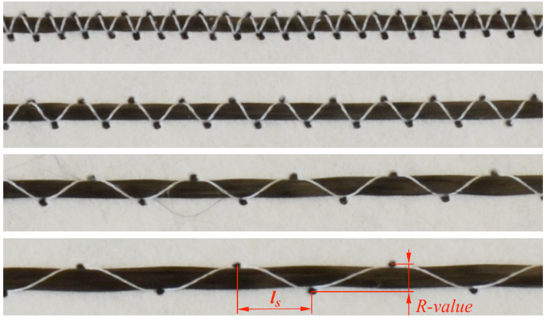

Figure 3. Waviness of the carbon roving (Toho Tenax HT-S, *800 tex*) caused by different stitch lengths of $l_S = 1$ *mm, 2 mm, 4 mm, 6 mm* (from top to bottom) and a constant R-value of *1,8 mm*, as stitching thread a polyester yarn of *10 tex* was applied

Depended on the stitch length of l_S = *1 mm*, *2 mm*, *4 mm*, *6 mm* a different waviness can be optically observed applying an *800 tex* (*12 k*) HT-S carbon roving from Toho Tenax and a polyester yarn stitching thread of *10 tex*, as shown in detail in Figure 3. To evaluate the waviness quantitatively a frequency analysis with Fast Fourier Transform (FFT) was applied on resin infiltrated unidirectional TFP made preforms. Resin infiltration was carried out using vacuum assisted process (VAP).

Using high resolution pictures of unidirectional TFP preforms with varying stitching parameters, after applying a numerical rectification of a possible optical misalignment of the camera, a manual generation of polylines along the edges of single rovings was carried out. As commercially applied TFP preforms show mostly a closed area of several side by side placed roving material the waviness analysis have been additionally carried out within the body and along the edge of unidirectional TFP-CFRP samples as shown in Figure 4. For the used roving type a parallel roving distance of at least *2.2 mm* was necessary to apply in order to avoid gaps. Next to the stitch length the R-value was also varied systematically.

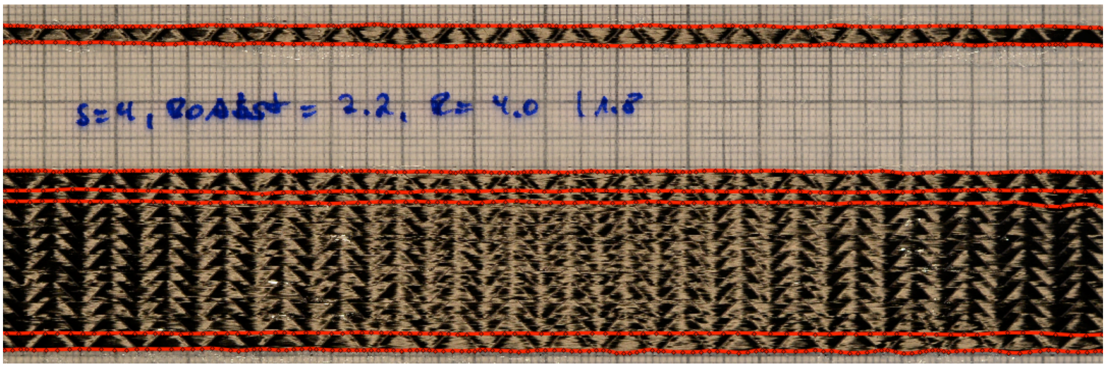

Figure 4. Digital rectified pictures of a UD TFP-CFRP sample with a manually added course along the roving edges (red lines) at a single roving as well as within and at the margin of an area of closely placed carbon rovings

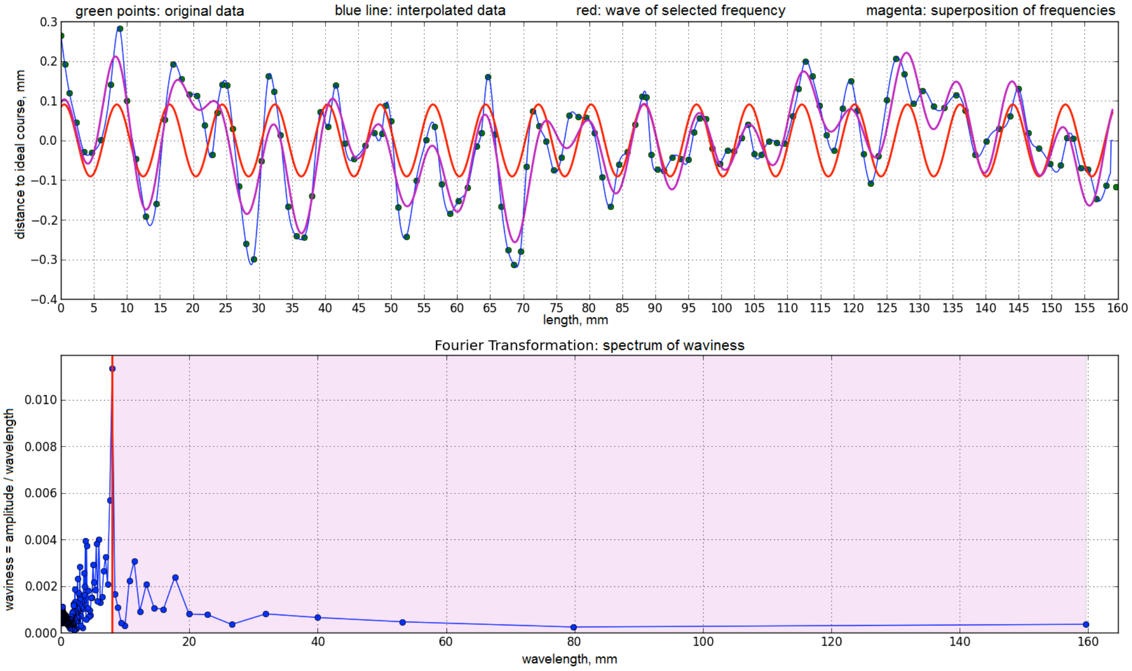

Figure 5. Top: waveforms of interpolated measured data (blue), as superposition (magenta) and homogeneous waveform (red); bottom: intensity of waviness according to considered wavelengths spectrum

In the upper diagram in Figure 5 an interpolated blue line represents the distance of manually chosen measuring points relative to an average ideally straight fibre course with a very high magnification on the vertical scale. On the lower diagram the blue line indicates the waviness versus the wavelength spectrum.

Based on the FFT algorithm a superposition of the different frequencies is drawn as a magenta line in the upper diagram and in the lower diagram as a filled area the considered range of frequencies. Finally, the red line represents a single homogeneous waveform on the upper diagram and the according position within the wavelength spectrum.

As visible on the given example for a specimen with a stitch length of $l_S = 4$ *mm* the waviness shows a maximum at a wavelength of *8 mm*, which is twice the stitch length. This effect was found for all considered stitch lengths of $l_S = 3$ *mm*, *4 mm* and *5 mm* with a respective maximum at *6 mm, 8 mm* and *10 mm*. At the same time a small increase of waviness with a rising of the stitch length for rovings within the closed preform area and a much higher waviness as well as a higher increase of waviness for rovings at the edges of the preforms was observed as shown on Figure 6. However, in case of a varying *R-value* from *1.9 mm* up to *3.9 mm* no significant tendency for the three considered stitch lengths could be found.

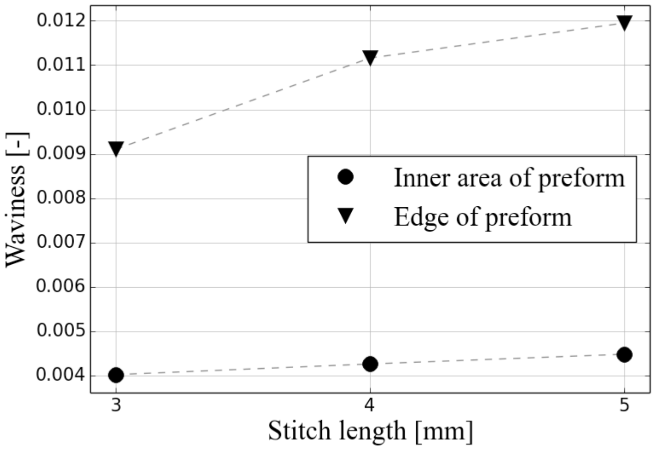

Figure 6. Waviness within and at the edge of a fibre places area of a UD preform plotted against the applied stitch length

3. Tensile tests of unidirectional TFP-CFRP composites specimens

In order to evaluate the effective material properties under tensile loading of UD CFRP specimens made by TFP different specimens according to DIN EN ISO 527-5 have been manufactured and tested. Using the fibre and base material, as described in Section 2, a vacuum infusion process was applied for consolidation using epoxy resin L20 in combination with the hardener EPH161. To achieve a nominal laminate thickness of $t = 1$ *mm* for a chosen roving distance of *1.8 mm* and a constant R-value of *3.6 mm* two layers had to be stitched upon each other. Additionally, all experimental data have been normalised to a fibre volume fraction of $\phi = 50$ *%*. For four different stitch lengths of $l_S = 1$ *mm*, *2 mm*, *4 mm*, *6 mm* the stiffness (Young's modulus) and tensile strength were found as shown in Figure 6. For comparison the ideal UD material properties have been added to the diagrams, which have been calculated by the rule of mixture, based on consideration of given material properties for fibre and matrix material. It can be seen, that in case of $l_S = 1$ *mm* the elastic modulus equals the ideal UD material properties. With an increase of the stitching length from $l_S = 2$ *mm* up to *6 mm* the Young's modulus shows a decreasing tendency, but differs only within a small range.

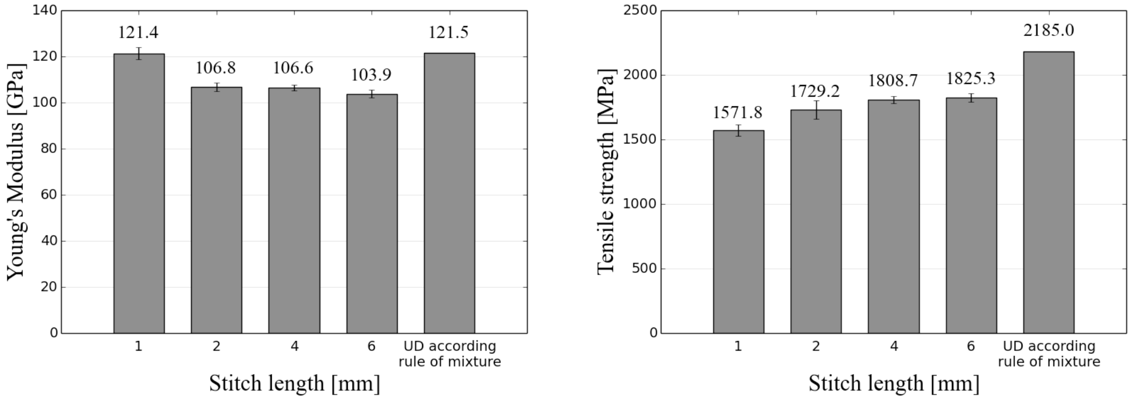

Figure 7. Young's modulus (left) and tensile strength (right) of tensile loaded unidirectional TFP-CFRP composite specimens plotted against applied stitch length together with the respective ideal material behaviour

In case of stitch length from l_S = *4 mm*, which is typical for TFP preform production, the unidirectional stiffness is reduced down to about *88 %* relative to ideal material properties. According the waviness analysis as described in Section 2 the waviness and thus probably the UD composite stiffness doesn't change much at a stitch length of l_S = *3 mm* respectively l_S = *5 mm*. The experimental stiffness analysis of a stitch lengths of l_S = *2 mm* and l_S = *6 mm* supports this assumption.

In contrast to the stiffness behaviour the UD tensile strength is increasing with a higher stitch length. It can be assumed, that a higher number of stitches, causing local breakage of fibres and additionally the locally induced waviness due to the stitching thread on a microscopic scale has a strong influence on the material failure properties. Furthermore, with none of the considered specimens the ideal fibre strength has been reached. For strain evaluation during the tensile test an optical full field measuring device was used. Using a high resolution digital camera with up to 16 megapixel even small differences of the surface strain can be identified. In Figure 8 the result of an optical full field analysis is shown for major strain for a specimen with a stitch length of l_S = *5 mm*.

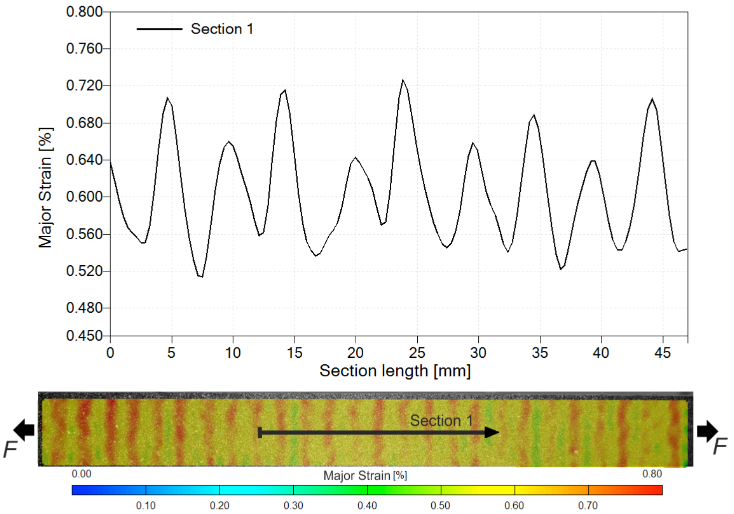

Figure 8. Full field measurement of the major strain on a tensile loaded UD-TFP-CFRP specimen with a stitch length of l_S = *5 mm* with section analysis

It can be seen with help of Figure 2 in Section 1 that along a distance of nearly half of the stitch length the strain oscillates between a minimum and a maximum. This behaviour reflects the local undulation angle between the tensile direction and the local fibre orientation with a minimum at the stitch positions corresponding to minimal strain and a maximum of angle deviation in between stitches corresponding to maximal strain.

4. Conclusion and outlook

The presented research deals with process induced undulation of fibre roving material of the TFP technology. It has been shown, that depending on the applied stitch length the stiffness and strength of a unidirectional TFP-CFRP laminate is reduced. Especially for the simulation of CFRP parts made by TFP the knowledge of the mechanical behaviour responsible for the stiffness reduction is important. The optical analysis of dry TFP preforms with respect to the waviness can be used as a basis for further numerical studies of the mechanical properties. With the help of a parametric finite element model representing a characteristic volume element the effective material properties can be analysed in future and applied as homogenised material properties for FE simulation of real TFP parts. Especially in case of a TFP manufacturing with varying stitch length in order to improve production speed and placement accuracy this plays an important role. A first attempt of this approach has been made recently [7].

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