Non-destructive characterization of wrinkle morphologies in composite materials by means of experimentally validated finite element analysis

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Abstract
Fiber waviness in composite materials, also referred to as wrinkles, can be considered as one of the most significant manufacturing effects. The severe knockdown of mechanical properties, such as stiffness, strength and fatigue leads to a dramatically reduced load carrying capacity of the material. Wavy plies can appear in arbitrary shapes and locations. It becomes increasingly important to detect these effects as early as possible in the product development and manufacturing stages. The decision whether these irregularities are considered as manufacturing features, respectively effects, or as defects, is dependent on the size, number and location of the effects in the component. The assessment of out-of-plane fiber waviness in composite materials is strongly dependent on the accuracy of detection and quantification of the wave parameters such as the amplitude, wavelength and the position in the laminate. In addition to ultrasonic testing, which is the standard method for the evaluation of composite materials in the aviation industry, infrared thermographic test methods (IRT) and digital shearography have been increasingly used in recent years. In this study, IRT and digital shearography are applied on test plates with artificially embedded waviness with varying amplitudes, wavelengths and positions in the laminate. Both methods have shown great potential for the detection and characterization of embedded out-of-plane fiber waviness in composite materials. However, the experimentally determined signals are not always conclusive. For this reason, these experimental methods are accompanied by finite element simulations to gain a deeper insight into the physical phenomena of the NDT methods applied to laminates containing wavy plies. Numerous simulations are carried out to investigate the influence of various test parameters and to find correlations on signal shapes and strengths as a basis for a further development of transfer functions. These transfer functions, i.e. correction factors, should link the obtained signals and known input parameters to the actual existing wave geometry in the laminate.

Keywords: Composite materials, out-of-plane fiber waviness, wrinkles, non-destructive testing, finite element analysis

1. Introduction

Along the value chain of carbon fiber reinforced polymer (CFRP) products many different physical testing methods are successfully applied for the detection of flaws in composite materials [1]. The early detection of manufacturing effects such as out-of-plane fiber waviness is of great importance for the production in order to reduce rejects and for the stress department which needs an exact representation of the manufacturing effect in order to conduct further mechanical analysis. The possibilities of online and in-situ process monitoring to detect manufacturing effects in the CFRP manufacturing process are manifold. Since hardly any scientific work has dealt with the quantitative evaluation of the wave depth using infrared thermography or digital shearography, the question is whether the depth of the fiber waviness can be determined or up to which depth the methods are applicable. This work provides a good basis for quantitative determinations of fiber waviness using IRT and qualitative statements using digital shearography.
2. Experimental methods

2.1 Test plate fabrication

The pre-impregnated polymer composite IM7-8552 (Hexcel Corporation, Stamford, USA) is used in this study. The nominal cured ply thickness of the unidirectional (UD) prepreg layer is 0.131 mm, according to the material data sheet. The test plates with a dimension of (400 x 150) mm² are fabricated in a two-step autoclave process following the recommended curing cycle for monolithic components. The lay-up procedure is schematically shown in Figure 1. Two wave configurations with varying depth positions in the laminate, i.e. center, top and bottom, were realized using a one-side male metal plate tooling in which the defined sinusoidal wave configurations where milled in with identical amplitudes A=2 mm but varying wavelengths L₁=15 mm (wave 1) and L₂=10 mm (wave 2). The thickness of the UD cross ply laminate (0/90) including the two types of sinusoidal waves was realized by 61 plies for ~8 mm laminate thickness for plate 1 and 76 plies for plate 2-4 respectively, leading to a laminate thickness of ~10 mm. The realized wave configurations and their positions in the laminate are schematically depicted in Figure 2. The laminate quality was verified by measuring the fiber volume fraction (67.2%, 0.9% STD) using wet chemical fiber extraction according to EN 2564 for 9 specimens.

![Figure 1](image_url)  
**Figure 1.** Two-step manufacturing method of cross-ply test plates with embedded out-of-plane fiber waviness using a male tooling.
2.2 Optical microscopy on polished samples

Samples were cut from each test plate and wave configuration (in total 8 images) and progressively polished using a Struers LabPol grinding and polishing machine (Struers GmbH, Willich, Germany), with a final polish using 1 µm grit paper. Microscopic images were obtained using an Olympus BX61 optical microscope (Olympus, Tokio, Japan). To obtain an adequate image resolution enabling the identification of individual fibers, several images with a magnification of 50x were taken from the cross-sectional area and automatically stitched together using the post-processing image analysis software Olympus Stream (Olympus, Tokio, Japan).

2.3 Infrared thermography (IRT)

In this study, pulse thermography measurements were conducted using a high-resolution infrared camera FLIR X8400sc (FLIR Inc., Wilsonville, USA) equipped with an indium antimonide (InSb) detector. The cooled 1280 x 1024 pixel focal plane array camera has a noise equivalent temperature difference (NETD) of about 25 mK and is sensitive in a spectral range of 1.5 to 5.1 micron. The measurements were carried out with a frame rate of 12.5 Hz for transmission mode with an approximate spatial resolution of 160 µm. For the optical excitation in reflection mode, two synchronized flash lamps PB G 6000 Z (Bläsing/ELWA GmbH, Essen, Germany) with a 2 ms long flash and a nominal energy of 6 kJ each are used. They are positioned on the left and right side next to the camera with a distance and incidence angle suitable to create a strong but homogeneous illumination and to avoid direct reflexions. With transmission mode measurements to excitation is positioned on the opposite side of the IR camera. Due to a better accessibility only one flash lamp with a lower distance and a perpendicular incidence angle was used in transmission mode. Polymethylmethacrylate (PMMA) sheets have been mounted in front of each flash lamp to reduce disturbing IR radiation.
of the hot lamps after flash excitation. Pulse thermography measurements (in the time domain) were conducted in both reflection and transmission mode (Figure 3 (a) and (b)) and from both sides of the plate, i.e. top and bottom. Additionally, the temperature field was measured over the cross-sectional area of the test plate, to investigate the heat flux over the entire embedded fiber waviness.

![Test plate, Flash lamp, IR camera](image)

**Figure 3.** Test set-up of active infrared thermography testing of out-of-plane fiber waviness in transmission (a), reflection mode (b) and the heat flux evaluated at the cross-sectional area (c).

Pulse thermography allows the determination of the diffusion time $t_d$ with the following relationship between the thickness $L$ of the material and the effective thermal diffusivity $\alpha$.

$$t_d = \frac{L^2}{\alpha} \tag{1}$$

The diffusion of the heat absorbed from the optical energy is dependent on the sample geometry, the existence of defects inside the material and the thermal diffusivity $\alpha$. The thermal diffusivity depends on the thermal conductivity $k$, the density $\rho$ and the specific heat $c_p$ and is given by

$$\alpha = \frac{k}{\rho \ c_p}. \tag{2}$$

The method used for diffusion time $t_d$ imaging in transmission mode, is the Linear Diffusivity Fitting (LDF) method [2], which is based on two assumptions: i) a one-dimensional time dependent heat diffusion model and ii) the assumption of a delta-like (Dirac pulse) optical excitation. The diffusion time in reflection mode is determined by the Thermal Signal Reconstruction (TSR) method [3]. The TSR method is based on the analytical solutions of the one-dimensional heat conduction equation for the finite and semi-infinite body without convective losses. Both the LDF and TSR are independent of local changes in illumination, surface absorption or local thermal emission coefficients as long as they do not cause (too strong) lateral heat diffusion.

Fiber waviness diverge the heat flow due to major differences in thermal conductivities in fiber direction and transverse direction. Typical values of thermal conductivities for both fiber and transverse direction are shown in Table 1. Even though the thickness of the laminate may be constant in regions of embedded waves, the deviation of fibers in thickness direction and the accompanying local resin accumulations and increased porosities affect the heat flow in different ways. Typical thermal signatures resulting from reflection and transmission configurations are schematically shown in Figure 4. When a wavy region is thermally excited
from the bottom side, an increased temperature is measured at the center of the wave for both reflection and transmission configurations. In reflection, the elevated temperature results from the lower thermal conductivity of the CFRP in transverse direction at the center of the wave. In transmission, the thermal peak results from a bundling of the heat flux due to the higher thermal conductivity in fiber direction which is transformed in thickness direction due to the wave shape. The opposite is observed with excitation on the top side of the test plate. In reflection mode, a cold spot is located at the center of the wave because the fibers draw heat from the surface. When propagating in thickness direction, the heat flux spreads into two main directions due to the wave morphology. This spreading of heat flux leads to two local temperature maxima in the vicinity of the start and end point of the wave and a temperature minimum at the center of the wave for bottom side evaluations in transmission mode.

Figure 4. Principle of active infrared thermography testing of out-of-plane fiber waviness. An excitation on the bottom side of the test plate leads to a bundling of the heat flux, whereas an excitation on the top side of the test plate leads to a spreading of the heat flow along the thickness direction of the laminate. Typical resulting thermal signatures are shown for both reflection and transmission mode at the top and bottom side of the test plate. This characteristic Mexican hat shaped signatures can be obtained in both reflection and transmission configuration. The local maxima and minima of the signal very good correspond with the wavelength of the embedded wave. However, dependent on the shape of the embedded wave and laminate thickness, the Mexican hat signal gets smeared due to lateral heat flow with increasing measurement time.

2.4 Digital shearography

Digital imaging laser speckle interferometry (short Shearography) [4,5] is a fast non-destructive test method that is used to detect, measure and analyse surface and subsurface anomalies or defects in materials and structures by imaging very small changes to a test part surface when an appropriate stress is applied, e.g. through mechanical loading or thermal, pressure, vacuum, acoustic, vibration excitation. The selection of a suitable excitation method is of crucial importance for a successful shearographic examination. Digital shearography is contactless, doesn’t need a coupling medium and allows the testing of a large area. When the test object is illuminated with coherent light, i.e. a laser expanded point source, the scattered wave fronts from optically rough surfaces are passing through a Michelson interferometer and are focused on a charge-coupled device (CCD) detector array. Due to the so-called shearing, which is achieved e.g. by tilting one mirror of the Michelson interferometer, each pixel of the CCD array
is hit by two beams emanating from two different object points. Due to the coherent illumination, these beams interfere and as a result a characteristic interference pattern is measured which changes due to a deformation induced shift in the phase relation of the two beams. The mathematical equation of the intensity on the specklegram detected on each pixel of the CCD matrix is:

\[ I = I_0(1 + \mu \cos(\varphi)) \]  

(3)

Where \( I \) is the intensity distribution of the speckle pattern at the CCD array, \( I_0 \) the intensity of the sheared images, \( \mu \) the amplitude of the speckle patterns modulation and \( \varphi \) represents the random phase difference between scattered wavelet from two points \( P(x,y) \) and \( P(x+\delta x,y) \) on the object surface. When the object is deformed slightly, the intensity distribution of the speckle pattern is changed to \( I' \), and \( \Delta \) phase difference denotes the surface deformation which is shown in the following equation:

\[ I' = I_0(1 + \mu \cos(\varphi + \Delta)) \]  

(4)

By adding the interference speckle patterns, Eqn. (3) and (4), obtained before and after the occurrence of the deformations and by applying algorithms of signal conditioning methods, it is possible to visualize images of sub-surface defects, described as:

\[ |I_d| = |I + I'| = 2I_0 \left[ \mu \sin \left( \frac{\Delta}{2} \right) \sin \left( \frac{\Delta}{2} \right) \right] \]  

(5)

Phase-shifting shearography allows the determination of the phase difference \( \Delta \) via the addition of a known phase using the controlled phase-shifting mirror in the Michelson interferometer. For each state of load four intensity images are captured, each with an additional phase of \( \frac{\pi}{2} \).

\[ I_1 = I_0(1 + \mu \cos(\varphi + 0)) \]  
\[ I_2 = I_0 \left( 1 + \mu \cos \left( \frac{\varphi + \frac{\pi}{2}}{2} \right) \right) \]  
\[ I_3 = I_0(1 + \mu \cos(\varphi + \pi)) \]  
\[ I_4 = I_0 \left( 1 + \mu \cos \left( \frac{\varphi + 3\pi}{2} \right) \right) \]  

(6)

The phase \( \varphi \) for the unloaded test object is then given by

\[ \varphi = \arctan \left( \frac{I_2 - I_4}{I_3 - I_1} \right) \]  

(7)

and for the deformed test object with intensities according to Eqn. (4)(3) by

\[ \varphi + \Delta = \arctan \left( \frac{I_2' - I_4'}{I_3' - I_1'} \right) \]  

(8)

This allows the determination of the phase difference \( \Delta \) by subtracting Eqn. (7) and (8). Subsequent denoising and possibly necessary phase unwrapping lead to a phase-difference image as shown in Figure 19 [5].
Surface deformations in z-axis direction (normal to the part surface) can be measured down to 2-20 nanometers with this method, depending on the environmental or background noise. Anomalies at the surface or subsurface cause changes to the thermal expansion and in the case of embedded out-of-plane fiber waviness additional effects of varying heat flows due to higher thermal conductivities in fiber direction occur. The principle of shearography testing of embedded out-of-plane fiber waviness is schematically shown in Figure 5.

**Figure 5.** Principle of shearography testing of out-of-plane fiber waviness. The higher coefficient of thermal expansion in fiber direction and also temperature differences due to thermal conductivities into the laminate may lead to the formation of an indentation at the top side and/or a bulge at the bottom side of the wave due to the negative coefficient of thermal expansion of carbon fibers in fiber direction.

In this study, shearographic measurements were performed using the SE3 sensor from isi-sys GmbH (Kassel, Germany) consisting of a Michelson interferometer (shear element) and a CCD chip with a maximum resolution of 1024x768 pixel and 15 images per second. The measurements were carried out with an approximate spatial resolution of 122 µm. Out-of-plane illumination is provided by an array of 4 laser diodes which are expanded by diffusion lenses. The wavelength is 650 nm. The software isi-Studio 2008 NDT Edition from isi-sys was used to evaluate the measurement results. The measurements were conducted in reflection mode (Figure 6) with (common) halogen lamps used for a homogeneous thermal excitation of the entire test plate.

**Figure 6.** Test set-up of shearography testing of out-of-plane fiber waviness in reflection mode for a) top side and b) bottom side of the test plate.

### 3. Finite element analysis

The experimental procedures described in Section 2 were simulated using the Finite Element Method (FEM) to gain a deeper understanding on the influence of fiber waviness on the measured results.
3.1 General modelling

For the comparison between the simulations and the experiments, the cross-sections (i.e. x-z plane) of the produced samples were reconstructed in CATIA V5R19 by using the microscopic images, as shown in Section 4. The 2D simplification is valid due to the fact that the characteristic of the embedded fiber waviness is constant in y-direction and no heat transfer occurs in this direction. Additionally, the y-direction is experimentally large enough to avoid additional signatures from potential edge reflections of the heat pulse. Due to anisotropic thermal and mechanical behavior of composite material, each layer is modelled separately to assign the anisotropic material properties. For the FEM simulations the software ABAQUS CAE 2019 was used.

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
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</thead>
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<tr>
<td>Density, $\rho$ [g/cm³]</td>
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<td>[6]</td>
</tr>
<tr>
<td>Conductivity longitudinal, $k_{\text{long}}$ [W/mK]</td>
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<td>[7]</td>
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<td>Conductivity transversal, $k_{\text{trans}}$ [W/mK]</td>
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<td>[10]</td>
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<td>[10]</td>
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<tr>
<td>Heat transfer coefficient (surface film coefficient), $U$ [W/m²K]</td>
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<td>[9]</td>
</tr>
</tbody>
</table>

For the numerical analysis of infrared thermography (heat transfer) and digital shearography (coupled temperature-displacement) measurements, standard triangular elements of linear geometric order are used. The material parameters used for the simulations are shown in Table 1.

3.1 Infrared thermography (heat transfer)

The optical excitation of the test plates was modeled as a delta-like Dirac pulse. A heat flux of $3.5 \times 10^6$ [W/m²] was assumed, which shows the same temperature difference between undisturbed and wave region and approximately the same averaged temperature of experimental and simulation results. Thermal convection, conduction and radiation were assumed to be negligible due to the very small temperature differences.

3.2 Digital shearography (deformation)

As the thermal load from the experimental setup was not exactly known, it was defined in the simulation with 500 W/m² as well as with 50,000 W/m². According to literature, the applied heat fluxes vary from 100 - 400,000 W/m² [11–13] for standard heating lamps. It could be determined that the qualitative deformation as function of time remains identical for both magnitudes, i.e. 500 and 50,000 W/m². Therefore, a heat flux of 500 W/m² was used for further studies. A heat transfer coefficient of 10 W/m²K was defined on the top and bottom of the plate to account for the convection to the environment. Since a layer of polystyrene was placed between the outer edges of the test plates and the aluminum frame, where they were attached.
in the experimental test setup, conduction was neglected in the simulation. Thermal radiation was also neglected due to the low temperature differences. The initial plate temperature was set to 23°C.

4. Results and discussion

In the diagrams that are plotted for the evaluation of the experimentally determined result in this section, average values in y-direction of predefined areas with a size of 40 x 80 mm (red rectangle in Figure 7) are evaluated in order to avoid edge effects and reduce signal noise.

![Figure 7](image)

**Figure 7.** Region of interest (ROI) used for the evaluation of experimentally measured results in order to avoid edge effects. For plotting the resulting signals, average values are calculated along the y-direction to reduce noise.

4.1 Optical microscopy on polished samples

Figure 8 shows microscopic images of the manufactured test plates containing the two wave configurations ($A = 2$ mm, $L_1 = 15$ mm, $L_2 = 10$ mm) with varying positions in the laminate.

![Figure 8](image)

**Figure 8.** Optical microscopy images of polished samples.

4.2 Infrared thermography (heat transfer)

Representative images from infrared thermography, i.e. diffusion time $t_d$, obtained from the top side of the test plates are shown in Figure 9. A comparison of simulation and experimental values obtained by infrared thermography from the undisturbed region of the test plates are shown in Figure 10. On the left side, the comparison of a reflection mode measurement from the top side of the plate is shown. Whereas, on the right side, data of transmission mode measurements can be seen. The temperature profiles of the simulations perfectly correspond with those of the measurements.
Figure 9. Overview of infrared thermography results, i.e. diffusion time $t_d$, obtained in transmission mode measurements from the top side of the test plates.

To investigate the temperature distribution over the entire embedded fiber waviness, the IR camera recorded the intensity of the temperature orthogonally to the cross-section of the test plates, with an excitation from the bottom and top side, respectively. This allowed an exact observation of the heat flux passing through the entire wave over time. A representative visualization of the temperature difference obtained from experimental measurements is shown in Figure 11 (a). The results of the same plate evaluated by FE analysis is shown in Figure 11 (b). This Figure shows the temperature field at $t=15s$ after excitation on the top side of the test plate 3 containing wave 1. The data of the temperature differences of the experiment were visualized using MATLAB.

Figure 10. Comparison of the temperature profile of the experiment (blue) and simulation (red) of the undisturbed region of plate 1 in reflection mode analyzed at the top side (left) and in transmission mode analyzed on the bottom side (right) of the test plate.
Figure 11. Temperature differences at 15 seconds of plate 3 with wave 1 obtained from (a) experimental setup and (b) FEM simulation.

In both images the shape of the wave can be clearly recognized. A temperature difference of 0.5 K can be determined over the entire area in both plots, although more noise is observed in the experimental data. The temperature distribution of the simulation and the measurement are in excellent agreement. Based on the signal shape, it is simple to determine the orientation of the fiber waviness. The heat flux shown in Figure 12 is either spread (a) or bundled (b), depending on the side of excitation or orientation of the fiber waviness, respectively. Thus, the orientation of the fiber waviness can be determined from the signal shape.

Figure 12. Representative FEM result of the spreading (a) and bundling (b) heat flux due to excitation on the top and bottom side, respectively, for plate 2 containing wave 1.

The measurement and simulation results were investigated and compared with respect to the intensity of the averaged signals from the undisturbed and wave region. Figure 13 to Figure 16 show a few representative variants of the measured and simulated waves. The x-axis shows the position of the wave and the corresponding signal is plotted on the y-axis. The dashed lines indicate the wavelength, i.e. $L_1=15$ mm, $L_2=10$ mm. The beginning and the end of the fiber waviness can be recognized clearly, as they appear in the signal exactly left and right of the characteristic Mexican hat-shaped function in the local minima and maxima, respectively.
In order to evaluate the change of the signal shape over time, representative results of plate 1 containing wave 1 in reflection and transmission mode are shown in Figure 17 and Figure 18, respectively. With longer measurement times, the typical Mexican hat function disappears due to lateral heat flows. In general, the wavelength of the embedded out-of-plane fiber waviness can be determined with sufficient accuracy for both wave configurations from the top as well as bottom side of the test plates. The wave amplitude may be approximated by the signal strength. The signal strength is assumed to be mainly dependent on the amplitude of the embedded fiber waviness and its position, i.e. depth, in the laminate. Furthermore, the heat loss and the smearing of the thermal data due to the lateral heat flow are expected to increase especially in thicker laminates, since longer measurement times are required.
4.3 Digital shearography (deformation)

Representative images from digital shearography, i.e. grey scale values of first derivative of deformation, obtained from the top side of the test plates are shown in Figure 19. To validate the accuracy of the conducted FEM simulations, the results were compared with experimental measurements. However, there are no absolute displacement or temperature values available for the experimental measurements. Therefore, the comparison was only made on a qualitative basis. For this purpose, the resulting deformations in y-direction on the top and bottom side of the simulation were exported and converted into the gradient of the deformation. These were compared with the results of the measurements. A representative result of measured (Figure 20) and simulated (Figure 21) deformation gradients of plate 1 containing wave 1 obtained in reflection mode from the top side shows qualitatively good agreement. The
measurements also show the first derivative, but directly derived from the grey values of the interfering laser beams. Furthermore, the respective wavelengths were plotted with dashed lines in the diagrams.

Due to the negative coefficient of thermal expansion in the fiber direction [9], an indentation occurs at the top side and a bulge on the bottom side. Figure 22 shows this warpage of the test plate, where the displacement in the y-direction of plate 1 containing wave 1 after 60 seconds with an excitation at the top side is shown.

**Figure 20.** Result of the digital shearography measurement. First derivative of the deformation on the basis of grey values. Plate 1, wave 1, excited and evaluated on the top side.

**Figure 21.** Result of the digital shearography simulation. First derivative of the deformation on the basis of the computed deformation. Plate 1, wave 1, excited and evaluated on the top side.

**Figure 22.** Representative deformation, i.e. displacement in y-direction, of a coupled temperature-displacement simulation of plate 1 containing wave 1 with an excitation from the top side at t=60s.

5. Conclusions and outlook

This study has focused on the non-destructive detection and evaluation of composite materials containing artificially induced out-of-plane fiber waviness from both an experimental and numerical point of view. The performed non-destructive tests, i.e. infrared thermography and digital shearography, have shown great potential for the detection of embedded out-of-plane fiber waviness. However, due to the various types and characteristics of fiber waviness that can occur in composite manufacturing processes, which are comprehensively described in [14], a general statement on the detectability can hardly be made. The presented results and statements are valid for the type of test samples used in this study. By using active thermography, it was possible to determine the defect as well as the orientation of the fiber waviness from the appearance of the resulting signal, regardless whether the measurement was performed in transmission or reflection mode. The wavelength can also be determined accurately based on the results of the experimental measurements as well as numerical simulations. Nevertheless, for a subsequent evaluation of the structural integrity, the amplitude was found by [10,15] to be
a more important parameter than the wavelength. Additionally, the depth up to which the wave is detectable could also be determined. With increasing depth of the fiber waviness, a decreasing course of the signal duration above a specific threshold value could be noticed. In further research activities, several additional variations of wave configurations and positions, i.e. wavelengths, amplitudes and depths in the laminate, have to be investigated analytically, numerically and experimentally to describe the relationship between the depth position of the wave and the intensity and duration of the signal. In this study, a qualitative investigation of shearography was considered. Therefore, no quantitative statements about the depth of the wave can be provided. However, the wavelength was clearly visible based on the signal of the deformation gradients obtained from FEM simulations as well as from experimental measurements. In a next step, the experimental digital shearography test setup will be carried out in combination with temperature measurements and digital image correlation to obtain valid data for the simulations, i.e. temperatures and deformations. This study provides a good basis for the determination of the characteristics of embedded fiber waviness, i.e. amplitude, wavelength and depth in the laminate. Moreover, the promising results point out the huge potential of these NDT methods for further research and applications in industry.

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