



Probability of Detection Analysis of Air-coupled Ultrasound Inspection of Thermoplastic CFRP Tapes

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Abstract

Besides the aerospace industry, fiber reinforced plastics have also spread towards many further applications such as automotive or civil engineering. Their superior strength and stiffness to mass ratio made them the number one material for achieving high performance. Especially continuous fiber reinforced plastics allow for the construction of structures, which are custom tailored to their mechanical loads. The two main constituents of CFRP are carbon fibers and matrix. Two possibilities for matrix material exist: thermosetting and thermoplastic matrix. While thermosetting matrix may yield better properties, thermoplastic materials open a wide range of applications due to weldability and compatibility to e.g. thermoplastic injection molding materials. In this work we report on a Probability of Detection analysis (PoD analysis) of an air-coupled ultrasound inspection of thermoplastic CFRP tapes. Several preliminary works were performed in order to optimize the data set being involved within the PoD analysis. The influence of the tape temperature on the ultrasonic transducers and the behavior of the ultrasonic signal in thermoplastic tape at elevated temperature of up to 120 °C were examined in a specially developed testing rig. For maximizing the resolution of ultrasonic transmission measurements a cone design was developed. Special emphasis was given to both the achievable signal-to-noise ratio (SNR) and the spatial resolution. The POD analysis was determined for artificial cuts through the thickness of the tapes and different fitting models were applied. For further information of submission, please contact Wolfgang Essig (wolfgang.essig@ikt.uni-stuttgart.de).

1. Introduction

Whilst most prepregs are manufactured from carbon fiber and thermosetting matrix, latest developments tend to replace the thermosetting with a thermoplastic matrix. The most common method of production is the pultrusion process, impregnating the fibers with molten thermoplastic pellets. After the pultrusion process the carbon-fiber reinforced prepreg with thermoplastic matrix (CFRP tape) is wound on a spool and ready for further processing (1).

For the analysis of the tapes, air-coupled ultrasound testing was chosen because it is a well-known technique; it does not need any radiation shielding or coupling agent and offers a range of possible experimental set-ups (2). Besides that, non-destructive testing may be part of an inline-quality inspection, just as demanded within the upcoming concept of “industry 4.0” (3). Recent research was performed on the electromechanical response of polypropylene ferroelectret transducers (4), air-coupled cellular polypropylene transducers as mentioned in (5), as well as the resonance-free measuring and excitation of ultrasound (6).

2. Experimental setup and PoD

For all experiments a pair of transducers manufactured by the Ultrason Group was used, namely NCG200-P38 with a theoretical point focusing distance of 38 mm. Both transducers were driven by a Dassel Airscope TT, wired to a laptop, which was used for the ultrasound user interface.

2.1 Experimental setup

A continuous tape test rig was developed in order to simulate the inline testing in the production process. The test rig was equipped with a ceramic infrared heating element in order to simulate the pultrusion temperature (figure 1).

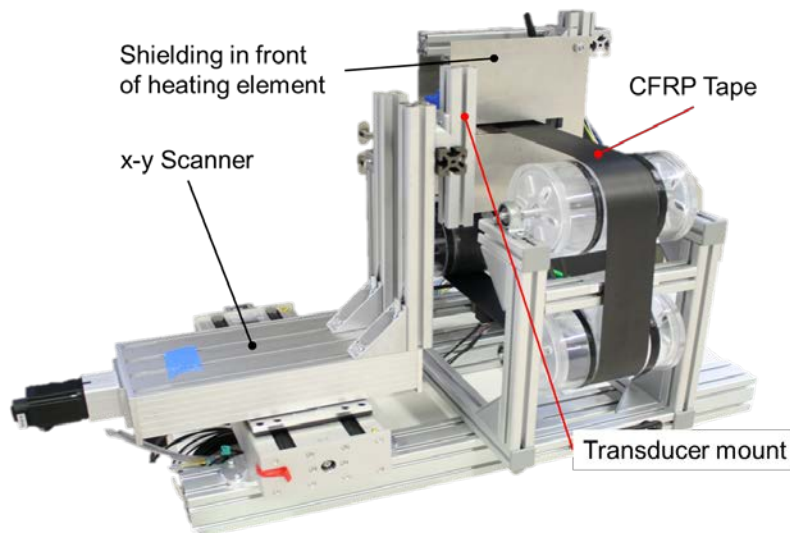


Figure 1: Experimental set-up for testing continuous tapes under elevated temperature

All measurements were conducted using the normal transmission mode (NTM), where transmitter and receiver are on the opposite side of the tape, respectively (figure 2). The whole tape width could be scanned using the test rig and an external linear axis. Depending on the desired resolution, A-Scans were recorded triggered by optical encoders.

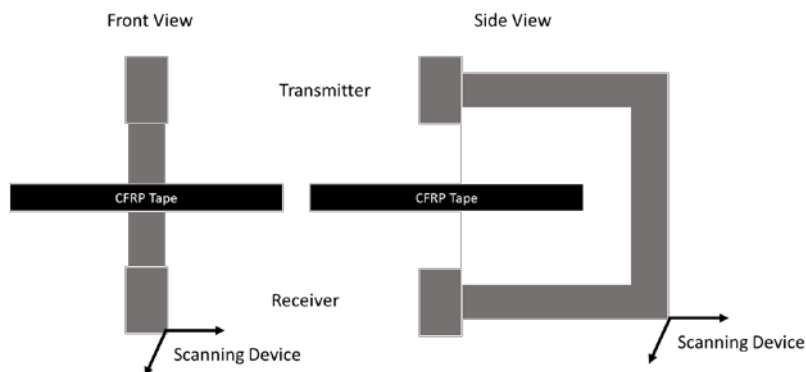


Figure 2: Experimental set-up for testing continuous tapes under elevated temperature

2.2 PoD measurements

The PoD measurement gives the probability of finding a defect with a specific property (e. g. defect size). Regarding figure 3, the SNR is shown over the normalized defect size. The quantity of every SNR occurred at a specific defect size is indicated via a distribution function.

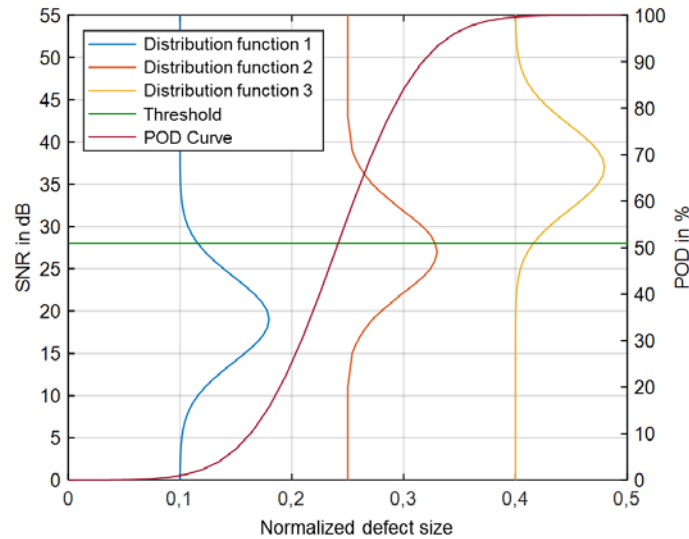


Figure 3: Distribution function and PoD curve calculated with a SNR threshold of 27 dB

In order to calculate the PoD curve, a certain threshold for the SNR has to be specified, in this case 27 dB. Every single PoD value can then be calculated using equation 1.

$$POD = \frac{\textit{right positive}}{\textit{right positive} + \textit{false negative}} \quad (1)$$

“Right positive” is determined by the area under the distribution function above the SNR threshold whereas “false negative” is determined by the whole area under the distribution function. A simple fitting procedure of the PoD values leads to a PoD curve, also shown in figure 3.

3. Ultrasonic signal and elevated temperature

Regarding the pultrusion process, thermoplastic tapes were produced by impregnating carbon fibers with molten plastic in a special impregnating tool, (1) where temperatures are particularly high (up to 230 °C). Since the tapes should be tested right after leaving the calibration die at the end of the pultrusion process, they still have temperatures about 80 °C up to 120 °C. The following section investigates the maximum transducer temperature due to convection and shows how the tape temperature affects the ultrasonic signal.

3.1 Determination of the maximum transducer temperature

The knowledge of the maximum transducer temperature is mandatory since too high temperatures lead to permanent damage. Two thermocouples type K were used to determine the maximum transducer temperature while testing the tape. One thermocouple was placed on the tape whereas the other was adhesively bonded on the surface of a sacrificial transducer 38 mm above the tape surface. The tape was heated from below with a ceramic infrared heating element and both, the temperature of the tape and the temperature of the transducer were recorded. Results are shown in figure 4, where the tape temperature and the transducer temperature are shown as a function of the infrared temperature. The transducer temperature limit of 65 °C was not reached even if the tape temperature reached melting temperature of the thermoplastic polyamide matrix. This result showed that the transducers could be used for this kind of testing setup, especially in the tape temperature region of 120 °C, the designated maximum.

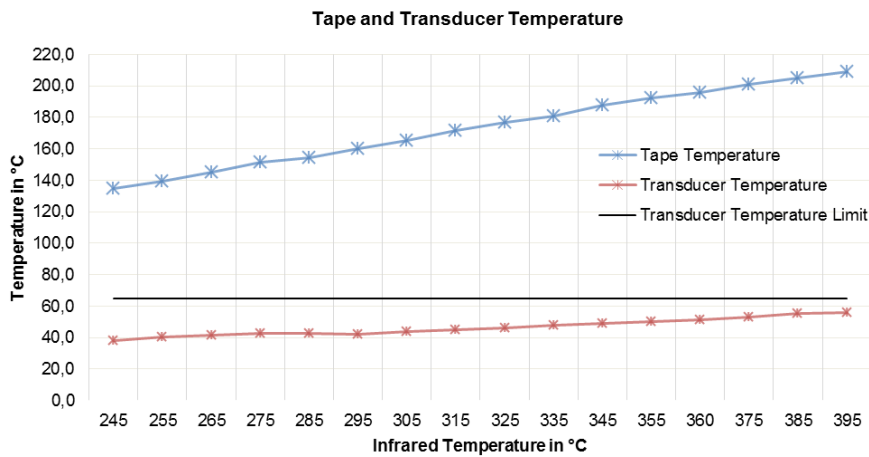


Figure 4: Temperature profile of the tape and a sacrificial transducer to determine the maximum transducer temperature

3.2 Tape temperature influence on the ultrasound signal

After investigating the influence on the transducer itself, the influence of the tape temperature on the ultrasound signal can now be investigated. Test setup shown in figure 1 and 2 was used while heating up the tape from both sides. The tape was moved between the two ceramic heating elements to obtain an even distributed temperature profile along the tape. Transducers were moved perpendicular to the tape propagation direction and the amplitude was recorded. Temperatures between 20 °C and 120 °C were examined in three sets and the average of the maximum amplitudes was calculated, respectively. Results are shown in figure 4 where the average maximum value of the amplitude is shown as a function of the tape temperature (measured with infrared sensor).

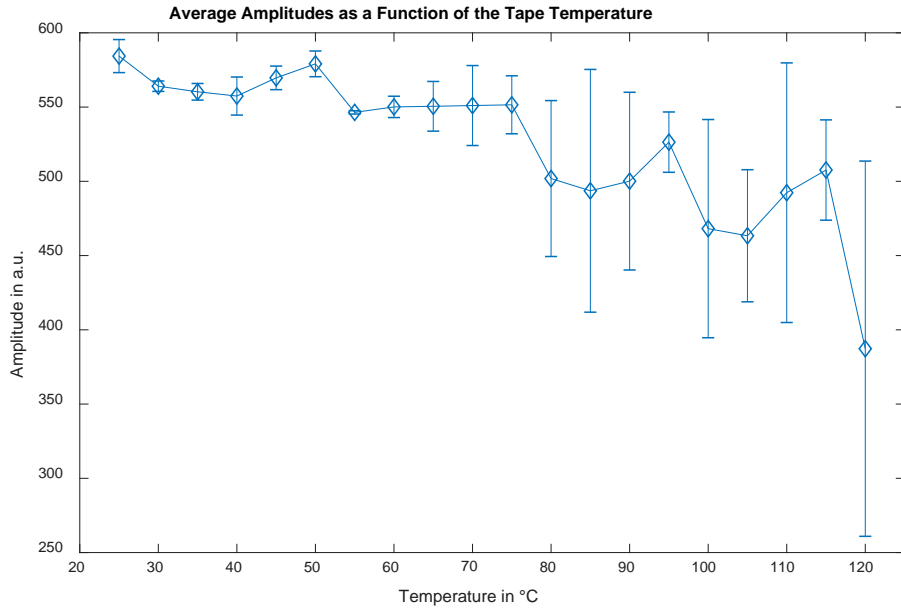


Figure 5: Maximum average amplitude as a function of the tape temperature

Decreasing amplitude and increased standard deviation with higher tape temperature can be obtained from this measurement. The general amplitude drop from about 580 at 25 °C to 380 at 120 °C can be explained by decreased Young's modulus and thus increased attenuation of the tape. In addition to that thermoplastic matrix of the tape is a polyamide with viscoelastic properties. Increasing temperature T in this case leads to stronger movement of the molecules ($\propto \eta$) and thus to an increasing damping coefficient α , according to Equations 2 and 3 (7), intensity I decreases with increasing temperature T , decreasing Young's modulus and absorption length x .

$$I(x) = I_0 e^{-\alpha x}, \quad (2)$$

$$\alpha \propto \frac{\eta}{E}, \quad (3)$$

Reasons for increasing standard deviation may be explained by the not evenly distributed temperature. Knowing these dependencies, further investigations were conducted at room temperature to obtain higher SNR and stable results. Regarding a cooling rate of approximately $10 \frac{K}{sec}$, a tape production speed of $5 \frac{m}{min}$ and a maximum temperature after the die of 120 °C, the tape propagates 0.83 m since it reaches room temperature. Compared to a theoretical production length of 7.2 km a day, the reaction time of less than 1 m seems sufficient enough.

4. Enhancing air-coupled ultrasonic resolution

In this chapter, the resolution of the air-coupled transducers will be improved using a forced focusing method. In order to reach this aim, a special cone was designed and 3D printed. The development process of these cones can be found in (8).

Sound fields of the transducers with and without cone were examined using vibrometry (9). figure 5 (left) shows the result of a transducer without forced focusing whereas figure 5 (right) shows the sound field with attached cone.

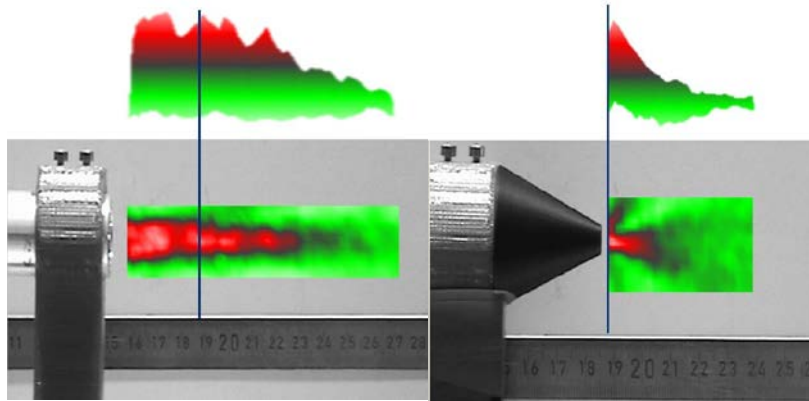


Figure 6: Sound field measurement of a NCG200 P38 transducer before (left) and after (right) forced focusing

Without forced focusing, the sound field at a distance of 38 mm shows a diameter of 14 mm and with forced focusing this diameter amounts 4 mm. The signal loss was determined to -6 dB with the cone attached. Taking into account that the tape thickness will be approximately 1 mm, the signal loss is acceptable. For comparing the resolution an aluminum plate with different holes was attached to a tape and c-scans were conducted, as illustrated in figure 7.

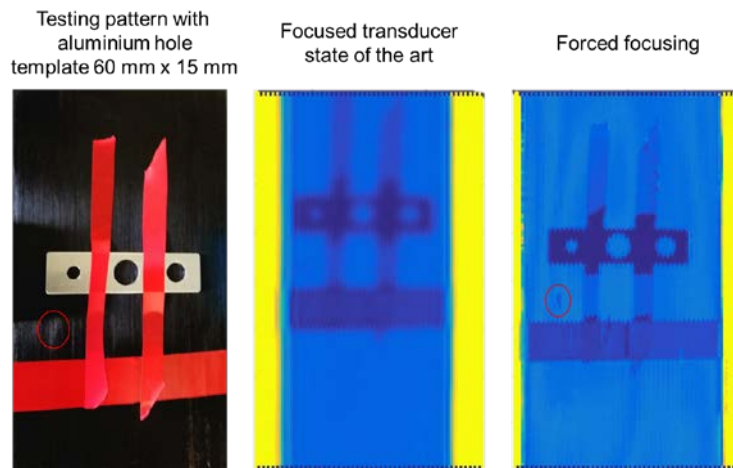


Figure 7: From left to right, picture of tape section with aluminum testing plate, c-scan with standard transducers, c-scan with forced focusing

The better resolution with attached cone is obvious in this case, so all further measurements were performed using the forced focusing method.

5. PoD analysis, results and discussion

Using information and improvements from chapter 3 and 4 PoD measurements were conducted at room temperature and with attached cone for forced focusing. PoD measurements were performed at a tape section where artificial defects (cuts parallel to

the fiber) were inserted via CNC-cutting. Crack lengths from 2 mm up to 15 mm with a gap of 3 mm were inserted. In summation 256 cracks (32 of each single length) were produced in one tape section. Several c-scan measurements were performed and evaluated using the transmission setup shown in Figure 2. One example of the PoD curve obtained is shown in figure 8 where the PoD threshold was determined by the summation of the amplitude in the defect area (threshold = 100 amplitude values).

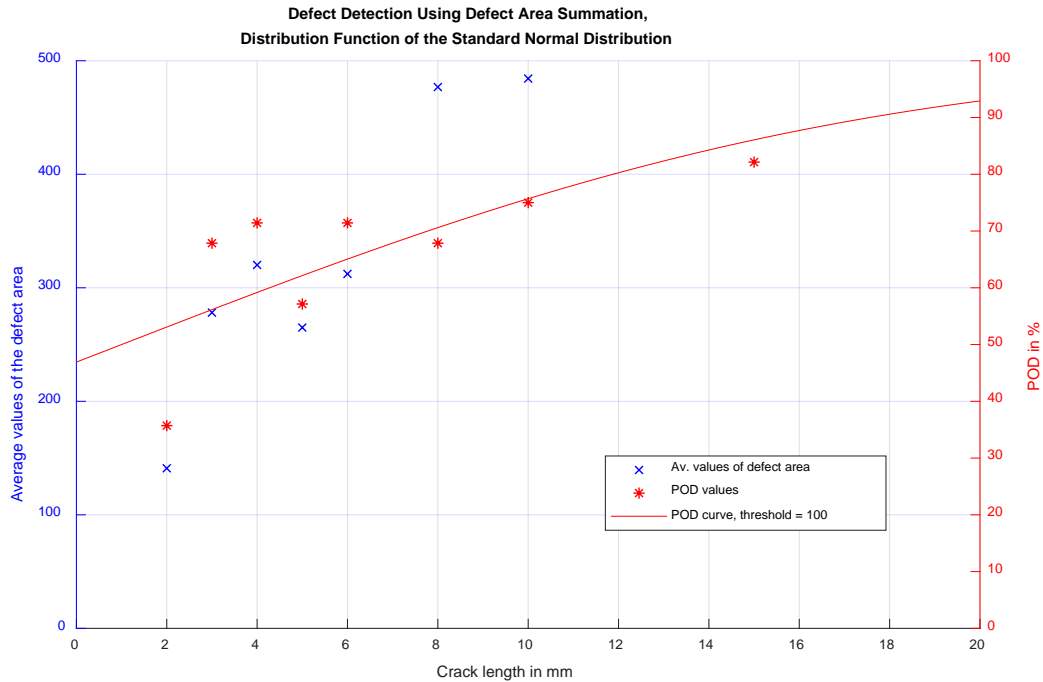


Figure 8: PoD curve determined by the defect area summation (top) and specific c-scan with automatically detected cracks (bottom)

Figure 8 shows the average values of the defect area summation, calculated PoD values and a fitted PoD curve as a function of the crack length. For calculation of the POD curve an automated algorithm shows the c-scan of the prepared tape section with crack positions projected, then determines if a defect was detected and calculates the desired amplitude summation 1 mm around the given crack position, figure 8. PoD values were calculated using equation 1 and a curve was fitted with the limited growth condition. Results show a kind of an “s” shaping of the PoD curve, as shown in Figure 3. Deviations from this idealized curve can be found in the defect itself. Since a crack in a tape can easily be found with air-coupled ultrasound, a simple evaluation using the SNR leads to a PoD curve that immediately reaches 100 % when a crack, independent from the size, occurs. For this reason, the evaluation using the summation of the amplitude around the defect was chosen. This leads to the decision on how high or low the threshold should be set and thus, how the PoD curve looks like. By varying the threshold the result of a PoD analysis can be embellished in a wide range although it is not expedient. For this reason the Receiver Operating Characteristic (ROC) should be calculated as well. The ROC compares the “right-positive” with the “false-positive” rate i.e. if a defect signal is shown although no defect exists. In this work, a ROC curve does not make any sense since at every defect signal corresponds to a specific crack. Further information can be found in (8).

6. Conclusion

Air-coupled ultrasound is capable of being applied as a quality assurance element for thermoplastic CFRP tapes. The signal itself shows strong temperature dependence so that measurements should be conducted at room temperature. It was shown that a cone in front of a transducer can enhance the resolution although signal loss of 6 dB occurs. Although PoD measurements showed good detectability of cracks in tapes, the PoD curve itself has not the desired shape. Therefore future investigations will be focus on tapes with different crack widths so a POD curve will be obtained depending on the air gap between the crack sides.

Acknowledgements

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