MAIzfp – A Joint Research Effort on NDT of Fiber Reinforced Composites within the Leading-Edge Cluster MAI Carbon

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Abstract. In January 2012, the cluster MAI Carbon was nominated as the Leading-Edge Cluster during the cluster competition of the Federal Ministry of Education and Research in Germany. MAI Carbon is made up of companies, training and research facilities active within the field of carbon-fibre reinforced plastics in the region of Munich-Augsburg-Ingolstadt (MAI). Cluster members include all sectors of high-performance fibre-composite materials use. The goals of MAI Carbon are the introduction and establishment of high-performance fibre-composite materials in automobile manufacturing, aerospace engineering, as well as mechanical engineering branches. As non-destructive testing is an integral part of a sophisticated process chain in fibre-composite materials, the joint research project MAIzfp "Combined NDT methods for quality assurance of fibre-composites" was funded with 2.6 M€ to assist in this respect. The focus of the project is on the combination of NDT methods to improve the reliability of NDT inspection, automatization of testing procedures, numerical modelling of NDT methods and standardization of NDT approaches. Bridging the worlds of automotive, aerospace and mechanical engineering MAIzfp benefits from different perspectives on a common challenge. The presentation will introduce the key goals of the joint research project MAIzfp and present the relevant technical findings accomplished within the project.

1. Introduction

Fuel consumption and thus also the associated CO_2 emissions can be reduced by decreasing the weight of a structure. Carbon fibre reinforced plastics (CFRP) therefore represent an intelligent solution for lightweight constructions. In the process of manufacturing these materials energy efficiency can be increased substantially if the products are manufactured

with a lower rejection rate. Non-destructive testing methods play a key role in reducing the rejection rate and to accurately assess the quality of the produced components.
The Leading-Edge Cluster MAI Carbon offers the unique opportunity to promote non-destructive testing (NDT) of fibre reinforced composites and to establish such testing in an industrial environment. While non-destructive testing has already been successfully used in the aerospace industry for years, NDT on fibre reinforced composites in automotive manufacturing and mechanical engineering is still in the early stages. At the same time, requirements vary widely within the industrial sectors and therefore require new approaches to testing: Quantities that the aerospace sector produces in a year may sometimes be produced on a daily basis in the automotive industry.

Based on the combined efforts of the involved partners Airbus Group Innovations GmbH, Airbus Helicopters Deutschland GmbH, Automation W+R GmbH, BMW AG, KSB AG, Siemens AG Corporate Technology, TU Munich and the University of Augsburg as well as the associated partners Fraunhofer EZRT and DLR-ZLP the MAIzfp project aims to review and extend the present state-of-the art in NDT of fibre reinforced composites. For this purpose, round-robin tests were performed using a total of twelve non-destructive testing methods, and the results were evaluated in terms of PoD studies. Further parts of the program deal with development of automated NDT solutions for optical inspection techniques. To improve the understanding of the NDT methods, numerical modelling is performed for several approaches. The level of detail reached in these calculations covers the entire length scale ranging from the microscopic scale of the defects to the macroscopic scale of the signal detection. Such model evaluations are intended to facilitate the selection of adequate NDT methods for future CRFP inspections and to increase the development speed of new methods. Last but not least, the heterogeneous and intersectoral consortium in MAIzfp is highly valuable to discuss and propose standardisation approaches for NDT approaches. This is realized by definition and development of a generic structure for NDT of fibre reinforced materials.

2. Research topics

In the following the key research topics within the project MAIzfp are described and the relevant findings in each part of the program are pointed out.

2.1 Intersectoral approaches for NDT

The consortium of MAIzfp is composed of companies representing the aerospace sector, the automotive sector and the industrial engineering sector plus leading research institutions in NDT of fibre reinforced composites. This combined expertise provides a sophisticated basis to discuss the present state-of-the art in NDT of fibre reinforced composites and to extend the established approaches. In the beginning of the project, quantitative porosity evaluation, classification of fibre undulations and quantification of damaged areas after impact were identified as common challenges to all sectors. It was also clearly identified, that no common nomenclature exists to define and describe these anomalies. Also, no common approach was identified among the different participants on how to approach the three target anomalies. Based on the availability of NDT equipment and the individual background of the representants, different approaches were named as first choice. Thus it was evident from the beginning on, that harmonization and unprejudiced comparison of the methodology and standardization of the terminology is one of the key challenges to overcome.

2.2 Round-Robin-Tests

In order to begin with an objective comparison of the individual approaches, reference specimens with artificially prepared porosity, undulation and impact damage were fabricated. Following established routines of previous research programs porosity specimens were prepared by means of spatially different consolidation pressure upon laminate consolidation, resulting in distinct porosity gradients across the test laminates. Undulation specimens with different aspect ratios of in-plane waviness and different aspect-ratios of out-of-plane waviness were prepared by curing of individually pre-stressed layers. Impact damage specimens were prepared following established standards (such as AITM 1.0010) using a drop-weight impactor. All specimens were tested at several participants' facilities using twelve different NDT methods. As NDT method, contact ultrasonics, immersion ultrasonics, air-coupled ultrasonics, acoustic microscopy, guided wave ultrasonics, scanning eddy current testing, lock-in and transmission thermography as well as X-ray computed tomography and X-ray imaging were used as standard methods. For selected specimens, destructive testing was carried out at the end of the round-robin test using digital image correlation techniques as well as acoustic emission analysis to monitor the damage progression during mechanical loading. The ultimate goal of these measurements was the comparison of the methods capabilities as well as the comparison of the individual approaches of the different partners.

As assessed in various previous studies (e.g. [1], [2]), the expected strengths and weaknesses of the various NDT methods in application to fibre reinforced composites were found. In extension of these previous studies a focus was given to not only detect, but to quantify the degree of porosity, to quantify the angle of waviness and to quantify the damaged impact area. While qualitative indications of the aforementioned defects were found by almost all of the methods named above, turning their information into a quantitative figure has proven to be a difficult exercise. Careful referencing was made using high-resolution X-ray computed tomography. Several approaches have been evaluated to derive meaningful absolute values from the different methods. Among the more useful approaches, X-ray computed tomography itself has proven very reliable when using skilled evaluation [3]–[5] to retrieve absolute values for the degree of porosity. Evaluation of ultrasonic signal attenuation has also proven its significance. Compared to that, approaches using thermography have clearly demonstrated their capability to detect the presence of porosity, but do come with less detection sensitivity. Regarding undulations, ultrasonic inspection, X-ray imaging, thermography and eddy-current testing were found to provide clear indications, but no established approach was found capable to quantitatively determine the angle of waviness. For impact damage, the already established method of ultrasonic C-Scans has been clearly identified as best choice for quantitative evaluation. Thermography imaging has also provided significant indications, but is limited in application to thicker laminates.

As an example for the different level of detail revealed by different methods, figure 1 presents a comparison of a laminate section with a steep gradient of the included porosity (lower left is approximately 0%, upper right is about 5%). The false-colour information of both ultrasonic methods originates from the intensity of the back-wall echo. Presence of voids smaller than the wave-length causes diffuse scatter of the incident wave thus resulting in reduced intensity of the back-wall echo. Similar, in thermography the local change in thermal properties causes a difference in heat flux affecting the detected phase depended on the porosity change. Even in the cross-section of the scanned CT-volume the porosity is seen. This is visible as appearance of small black dots (see magnified inset). In order to evaluate and compare the results PoD calculations were performed following the approach of Berens [6], [7]. Details of this study are presented in [8].

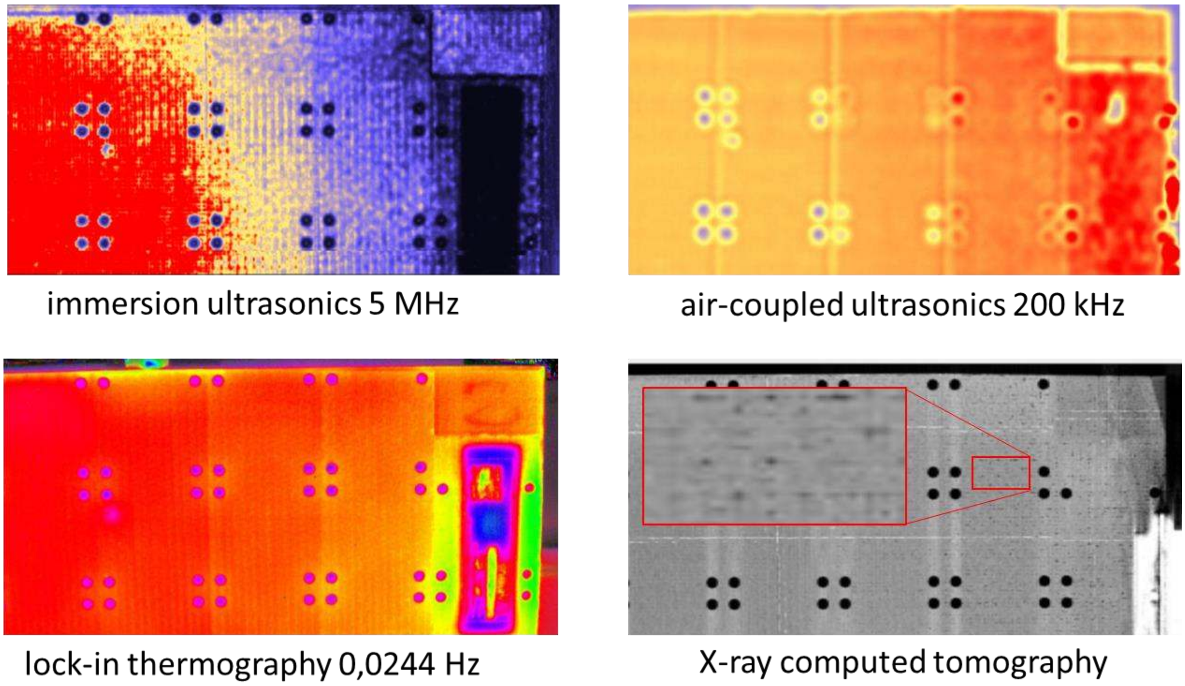

Fig. 1. Comparison of detail visibility of different NDT methods as applied to detect the presence of porosity (porosity is almost 0% at the lower left edge and about 5% at the upper right edge).

2.3 NDT method development

In addition to the round-robin test, some specific NDT methods were more closely examined in their capabilities. Phased array (full matrix capture) ultrasonics was investigated and compared to results of classical single-head transducers. Details of this study are presented in [9]. In previous studies eddy current testing has revealed interesting perspectives in application to CFRP. Recent technological advances now also allow scanning capabilities to yield C-Scans similar to conventional ultrasonics. Within the project one focus was given to measure fiber orientation directly based on the complex electrical impedance of the coil instead of image information. To this end, a coil configuration with directional sensitivity was used to measure in four different angles to the laminate to obtain a polar diagram of the laminate stacking. One of the techniques that is used in practice is the so-called coin-tapping test where the surface of a component is mechanically exited to local vibrations. To transform this more qualitative way of testing into automated quantitative evaluations the Local Acoustic Resonance Spectroscopy (LARS) was further developed and tested at CFRP components of the aeronautical and automotive industry [10]. Vibration and modal analysis techniques using a more global vibration of a component have been further developed also. In the field of acoustic emission analysis the accuracy of source localization procedures was significantly improved by using a neural network based approach [11]–[13] and comparison was made relative to other NDT methods such as thermography [14], digital image correlation or computed tomography [15].

2.4 Automated NDT approaches

Another aim of the project MAIzfp is to contribute to a continuous automated process chain for CFRP production and a significant scrap reduction via inline inspection methods. Within the project a robot based inspection system was implemented that is able to inspect manufacturing edges, drill holes, etc. and asses their quality. For this purpose, the project

partners examined different test bodies with defined characteristics. The main goal for the automated inspection was the application of combined optical process to minimize excess rates in production.
Automation W + R newly developed a method for a precise measuring of fiber directions and the special software algorithm for the task including a demonstration setup to determine the practicality of the method. The optical sensor principle belongs to the contrast methods, whereby multiple consecutively taken images are used to calculate the end result. In combination with the 3D-inspection, the demonstrator collected 3D-data of parts and determined the fiber orientation in every surface point.

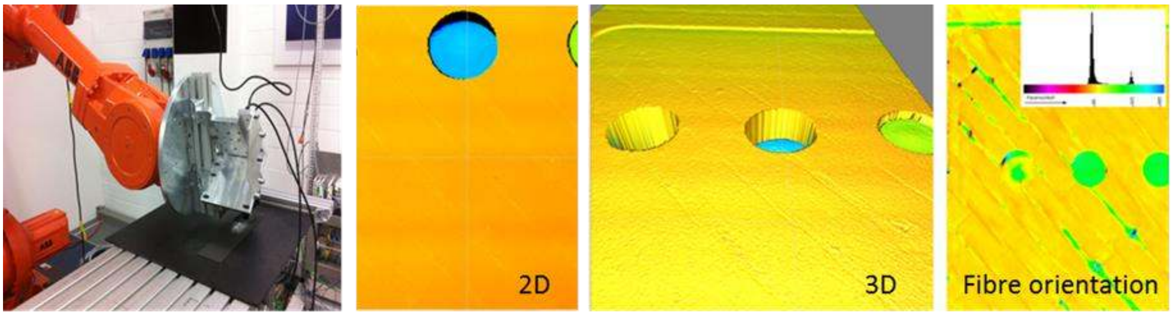

Fig. 2. Automated drill hole inspection with measurement of drill hole dimensions and simultaneous colour coded superposition of the measured fibre orientation at Automation W+R.

For this project, the following images in figure 2 of drilling holes were examined. The dimensions of each drill hole were characterized and combined with a simultaneous measuring of the carbon fiber direction.
In the aeronautical industry it is necessary that an automated ultrasonic inspection operates reliable and efficient on CFRP components. To reach this a NDT qualification process is mandatory to demonstrate the reliability of the automated UT inspection. In this context the developed UT numeric models (see section 2.5) are used to support the qualification process. To validate the simulation methods samples with natural defects such as porosity were manufactured and were subject to automated ultrasonic inspection (see figure 3).

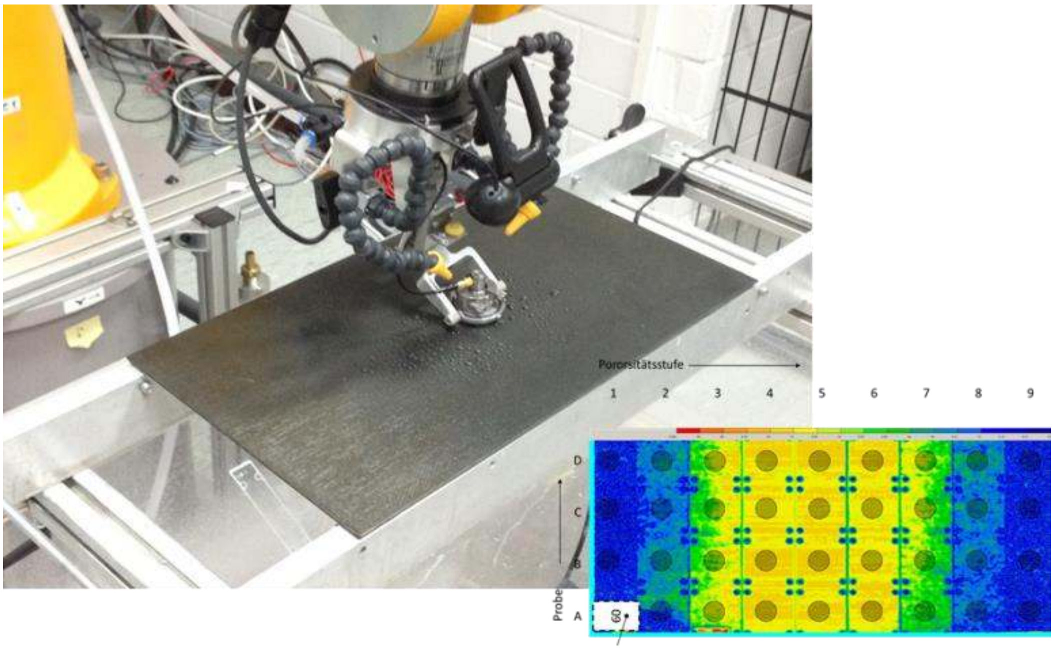

Fig. 3. Automated Ultrasonic inspection of porosity test samples at Airbus Helicopters.

2.5 Modelling of NDT methods

In close connection to the experimental approaches numerical modelling of active ultrasonics, guided waves, thermography and computed tomography was carried out. For each method, the aim was to extend the level of detail of existing numerical approaches for NDT methods and to enable their use for the field of composite materials. For the latter, the detailed geometrical description of the included anomalies is of key importance to accurately describe the interaction between the incident wave, heat or ray and the anomaly. In all models the aim was to perform quantitative modelling instead of qualitative modelling. Ultimately, validated numerical models are then an ideal tool to quickly perform parameter studies which are inexpensive and less time-consuming than the experiment. To this end, for contact ultrasonics and immersion ultrasonics a combined multi-scale and multi-physics model was developed within the software environment Comsol Multiphysics. This model comprises a detailed geometrical description of the anomaly as well as fully coupled transducer representation using piezoelectric conversion and simultaneous P-SPICE circuit simulation. The modelling approach was validated step-by-step using experimental data. At the end we were able to successfully model an ultrasonic signal voltage identical to the experimental signal (cf. figure 4) and to perform parameter studies regarding the influence of the composite material choice, the stacking, the type of anomaly and laminate thickness [16]. For the geometrical representation of the anomaly, synthetic geometries (e.g. spheres, cubes) as well as more realistic geometrical representations were evaluated. For the latter a specific approach was developed to extract the real 3D-geometry of characteristic defects from volumetric images [17], [18].

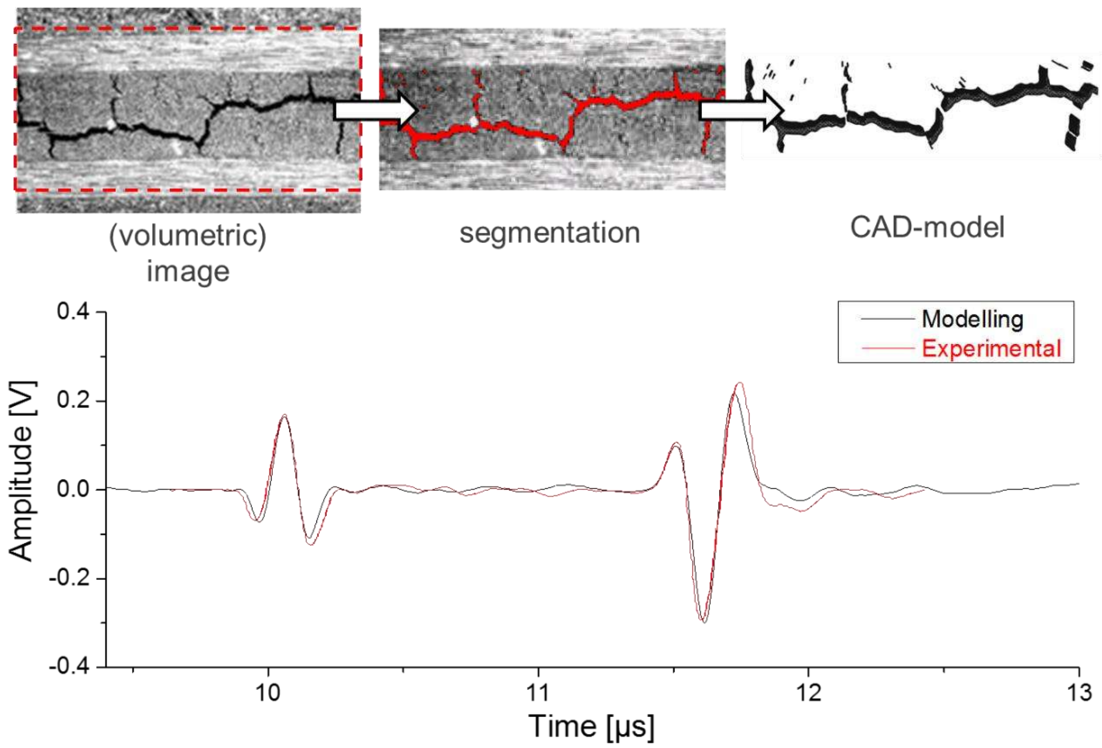

Fig. 4. Comparison between experimental and modelled A-Scan Voltage including effects of the probehead and the attached circuit.

For modelling of guided waves, a similar approach was taken in Comsol Multiphysics following a previously validated routine [19], [20]. For thermography, a multi-scale approach was chosen to embed the anomalies and to quantitatively model the resultant amplitude and phase images as typically obtained in lock-in thermography (cf. figure 5). The approach was validated using experimental methods and the influences of the heat source as well as the excitation frequency were studied. For numerical modelling of the computed tomography acquisition process the software platform CIVA was used. The goal was to achieve a detailed representation of the image acquisition process and to optimize the acquisition parameters by means of parameter studies [4], [5]. To this end, we evaluated real and artificial anomalies and validated the results against real measurements as presented in more detail in [21].

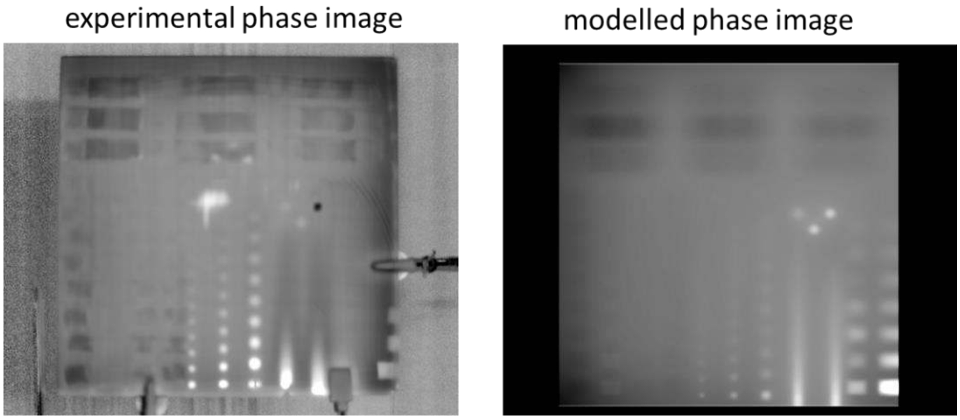

Fig. 5. Comparison between experimental and modelled phase image in lock-in thermography.

2.6 Standardization of NDT approaches

Based on the first discussions in the consortium it was evident, that no common terminology for anomalies in fibre reinforced materials exists. Thus first attempts were made to harmonize the catalogues of anomalies available by the different participants. Goals were set to also establish a generic structure to describe the NDT process in fibre reinforced composites. This generic structure should be capable to assess the capability of a NDT method regarding its suitability of an anomaly located at a specific position within a test object. Thus, a parameterization of the test geometry, a systematic categorization of defects and a generic description of the NDT method was developed within the project. This hierarchical interaction diagram constitutes a first step towards a database structure which could finally be turned into a software program. Ultimately such a tool could then be used in the design step of a composite structure to automatically assess the possibility for NDT inspection.

3. Benefits of the joint research program

Beyond the advances in NDT methods and NDT modelling, one of the largest benefits of the MAIzfp program rests in the experts' exchange across different companies and across different industrial sectors. The mutual benefit of this collaboration originates from the unprejudiced approach to compare different approaches established at the involved partners and the continuous discussion of technical developments inside and outside the project. Furthermore, the access to the NDT experts throughout the network of each partner and within the leading edge cluster MAI Carbon has resulted in multiple new contacts and allows to continue the started research efforts within new mutual and joint research programs.

Acknowledgments

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