Laminographic Inspection of Large Carbon Fibre Composite Aircraft-Structures at Airbus

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Abstract. Airbus manufactures aircraft parts made of Carbon-Fiber-Reinforced Plastic (CFRP). The inner quality is secured by ultrasonic testing (UT) of each part. In case of unclear indications an adapted X-Ray Planar-Tomography technique (coplanar translational laminography) was developed together with BAM as an escalation method to analyze the indications in a three dimensional high resolution data set. Several hundred radiometric projections in small angle steps are acquired. The tomographic reconstruction yields a three-dimensional (3D) representation of the material structure and included defects. This is equivalent to a micrograph.

The laminography based inspection system was designed, constructed and tested to visualize porosity, flat gas inclusions between layers and open material separations (e.g. delaminations) of areas with an angled structure of about 90° between flat structure elements on up to 18m long aircraft components. Test samples were successfully compared to cross-sections. Special reconstruction software was developed to calculate 3D volume images in less than a minute. Ongoing validation tests are performed to evaluate the performance of the technique and to develop acceptance criteria.

Introduction

The demand of composites parts in aeronautics is increasing. This results in a higher effort for testing elementary parts. Standard testing method is still ultrasound either in full or local immersion but mainly phased array technology. Physics of ultrasound limits testability of certain geometrical features like radius or areas with double-T’s. This results in a demand of complementary non-destructive testing technologies based on other physical principles in order to support ultrasound.

Testing of flat or slightly curved structures with automated ultrasonic testing machines is currently state of the art (see Figure 1). At Stade plant large ultrasonic scanners equipped with phased array technology inspect big composite aircraft structures like vertical tail planes or wing cover shells of A400M and A350. It is getting interesting if parts are that complex that it will be a challenge to test them with ultrasound. Then it will be difficult to get valid results based on the signals coming from material and geometry.

As example we want to focus on radius inspection e.g. on C-shaped frames. Especially for small radii of 5-8mm combined with higher laminate thickness of approx. 20mm it will be difficult to get a stable backwall-echo. According to AIRBUS regulations if there is an...
intermediate echo and no backwall echo this indication must be decided as material separation. This could lead to the decision, depending on location of indication, to scrap the part. Aim of the presented research project between AIRBUS Operations and BAM is to demonstrate that defects in radius areas can be detected and visualized with an X-ray method based on a laminographic technique. The laminographic technique was first used to characterize metallic welds and was modified for large CFRP-aircraft components like A400M VTP-shells [3].

Aim of the research project between AIRBUS Operations and BAM is to demonstrate that defects in radius areas can be detected and visualized with an X-ray method based on a laminographic technique. The laminographic technique was first used to characterize metallic welds and was modified for large CFRP-aircraft components like A400M VTP-shells [3].

Digital detectors as phosphor imaging plates (IP) and digital detector arrays (DDA) enable radiographic inspection with higher efficiency and improved image quality in comparison to the classic film technique. The application of DDAs also permits more complex inspection arrangements as e.g. Computed Tomography, Computed Laminography and Tomosynthesis for in-field inspection. Many stationary industrial Computed Tomography (CT) systems have been introduced during the last years in different NDT areas, for serial testing of casting especially for automotive industry. These stationary devices require the transport and positioning of the objects to the CT testing facility. Nowadays CT is applied more and more for flaw detection and dimensional measurement.

**Digital Coplanar Laminography at Large Composite Plates**

The planar tomography allows the three-dimensional (3D) representation of the material structure and included flaws. This is equivalent to a non-destructive cross sectioning (micrograph). The hardware design is based on a coplanar manipulation system for control of an X-ray tube with a wide window [1-3] and a high resolution digital detector array [5]. The movement of the tube is strictly parallel to the detector plane and aligned with the pixel matrix direction.

For in situ inspection of large aircraft components under production a gantry based planar tomograph for laminographic investigations was constructed and tested for inspection of the integrity of large flat panel components (see Figure 2). The manipulation system was constructed and tested with a specially developed X-ray tube [6] and a large DDA with a pixel size of 200 µm [4]. CFRP panels (Carbon Fibre Reinforced Polymers) of aircrafts of up to 3 x 9 m size were tested with this tomography configuration.

**Figure 1:** Ultrasonic Testing Machine at AIRBUS (left) and situation for manual ultrasonic inspection of radius areas (right).
CFRP aircraft shells need for stabilisation and stiffness the reinforcement by T-shaped stringer elements. The T-stringer is partly embedded in a CFRP shell of an aircraft [3]. Since the stringers are manufactured separately, a second polymerisation process is required, after the stringer is embedded in the shell. If unsuitable polymerisation conditions are selected and the surface of the stringers is treated incorrectly, they may crack after embedding (see Figure 3). The technology was tested and qualified. The total length of all measured areas amounted to about 14 m.

The qualification of the gantry based laminographic technique was successfully performed by comparison of the laminographic tomograms to cross sections after destructive micrograph of test samples. The probability of visibility of cracks was determined being > 90% at a confidence level of 95% [4].

**Inspection of long U-Shaped Structures**

In the next stage, an 18 m long U-shaped CFRP aeroplane structure was tested with laminography (Figure 4, left). The standard NDT-inspection is based on an UT scan in order to detect 6x6 mm defects. The ultrasonic (UT) inspection is not accurate enough to distinguish between large area material separations and clustered porosity. The UT inspection fails mostly at sharp material radii due to missing back wall echoes. X-ray based planar tomography was explored to obtain cross section images with higher resolution for
better evaluation of flaw types and measurement of flaw dimensions. A specially designed gantry was used to acquire projections in tangential direction to the radius. In order to inspect the complete test object over the length, a gantry gate based planar tomograph was developed and tested (Figure 4). The linear manipulator for the X-ray tube was positioned about 45° over the long area of the U shaped test object and parallel to the detector.

![Figure 4: Left: Schematic sketch of inspection setup. Only X-Ray Source is moving during image acquisition. Right: Inspection setup in production environment.](image)

The adjustable universal linear axes were mounted in a way, which allows any geometric setup of the X-ray tube and digital detector array. For the measurements a mobile 160 kV X-ray system [6] with 0.8 mm beryllium window was used. The penetrated material thickness was between 5 mm and 20 mm, resulting in an adjustment of the tube voltage between 25 kV and 55 kV. Copper of 0.2 mm thickness was used as a prefilter at tube port. A fan beam configuration of 90°x30° was used for exposure. The used high resolution DDA [7] had a sensitive area of approximately 15 x 12 cm. The physical pixel size amounted to 75 microns resulting in an image matrix of 1944 x 1536 pixels. The data acquisition was performed via a GigE- Ethernet link using the software “ISee-Pro” [8].

**Results of Measurements**

The test areas were determined by Airbus with ultrasound technique in advance. The alignment of the X-ray tube and detector array was carried out in the central position so that the central X-ray beam was perpendicularly directed to the detector area and was oriented tangentially along the curved area of the test object. The geometrical magnification was less than 1.1.

The exposure time of a single projection (frame time) amounted to 0.2 sec in the accumulation mode (frame number=10). The number of acquired projections was N=1000 in an angle of incidence range between +18° and -40°. The total measurement time depends on the exposure and read out time of the detector and amounted to approx. 35 minutes for one 3D-position.

**Fast Filtered Shift Average Reconstruction of 3D Data**

A “shift average” reconstruction algorithm was developed. It works with a shift of complete projection matrices. After a final correction of the complete reconstructed data set, the results are identical with those of a slower pixel-wise reconstruction [10, 11]. The filtered shift average reconstruction was optimized for high reconstruction speed utilizing the computing power of graphic processors. Therefore, the reconstruction time
could be reduced up to few seconds for one volume of 1000x1000 pixels by 304 slices and a voxel size of 75 x 75 x 75 µm³

Visualization and Measurement of Dimensions

![Figure 5: 3D visualization, classification by size of defect and definition of the filter value.](image1)

![Figure 6: Projection of the 3D dataset; for colour table see Figure 5.](image2)
Figure 7: Colour table for the depth of a defect ($F_{t_a}$) and classification by slices; for $L=0$ all detected defects are visible and for $L=6$ only one defect with size $A \geq 6\times6$ mm$^2$ remains visible.

The 3D visualization of the reconstructed volume was done with Volume Graphics StudioMax 2.2 [9]. The imported dataset was analyzed with a VG Studio defect algorithm that yielded the requested defect parameters length ($C$), width ($D$) and depth ($F_{t_a}$: Defect depth from outer side of radius). Those are determined by the length and the width of a “Bounding Box” that surrounds a defect whereas the depth is defined as the minimal distance from the defect to the outer surface of the reconstructed volume. The size of defect ($A \leq C^*D$) is derived from length and width and is used for a first defect classification as shown in Figure 5. The filter value ($L$) is introduced as the class identification number. The higher this value the more defects are filtered out in the visualization. For visual comparison of different filter values projections of the defect volume were used as shown in Figure 6.
In Figure 7 the filter value $L$ was increased in 1 mm steps. For this reason the number of considered defects with a size greater than $L \times L$ decreases. The depth of defect was used for a second defect classification (slice number) which was applied to the projections in form of coloured bounding boxes (Figure 7).

![Figure 7: Histogram based on data from Figure 6.](image)

The histogram (Figure 8) combines both classifications for an enhanced clarity of the defect size distribution and their depth localization within the sample.

**Technical qualification**

A Technical Qualification was performed at Airbus to demonstrate compliance of an applied process to the related standard process specification. In this case it was demonstrated that translational laminography can detect pores and delaminations reliably and the detectability limitation (minimum detectable thickness) was determined. Furthermore it was demonstrated that defect position and size (length, depth) are measured correctly.

Translational laminography was already qualified at Airbus in 2008 for inspection of cracks in A400M Vertical Tail Plane shells [3, 4]. That qualification contains especially a POD analysis (POD = Probability Of Detection). The result was that flaws can be detected (visualized) with a probability of 90% within a confidence interval of 95%. The POD analysis mentioned is still valid and is not repeated for this application.
A typical result for porosity detection with X-ray planar CT is shown exemplarily in Figure 9. Several voids are visible with Planar CT (small picture below), confirmed by micrograph (top).

The sizes of several pores (voids) measured with planar CT are compared to micrograph analysis. Both results are comparable. The defect length, thickness and depth from outer radius measured by CT are correlated with the reference values from micrograph. The measured correlations are sufficient for the defect analysis, see example in Figure 10.

In order to check the capability of Planar CT to detect delaminations, natural delaminations have to be used. Flat bottom holes cannot be used to simulate delaminations (this is the standard approach for ultrasonic testing), because X-ray is sensitive to all volume changes, and thus the hole would be detected in any case. A scrapped part with a
natural delamination was selected for this investigation, see Figure 11. The delamination was detected by UT and then confirmed by micrograph. Only one half of the part was used for the micrographic analysis, the other half of that sample (were the delamination continues) was used for X-ray laminography.

![Figure 11: Comparison of Planar CT (top) and micrograph (bottom) for a natural delamination.](image)

The measured length by micrography is 7.4 mm while the length of the same delamination measured by laminography is 5.8 mm. Both values are comparable. The thickness of that delamination is displayed larger by laminography compared to micrograph image: The measured thickness by micrograph is about 30 to 50 µm, the laminography value is 163 µm. The reason is that due to the pixel size (pitch) of the digital detector array of 75 µm all small structures are displayed with ≥150 µm (twice of the pixel size, sampling theorem). However, the detectability is that of the thickness measured by micrograph, i.e. about 50µm.

The micrograph analysis confirm that it is possible to detect porosity and delaminations reliably by coplanar laminography and to measure size and shape in 3 dimensions quantitatively. The minimum detectable thickness of a delamination is about 50µm with the tested gantry based laminographic inspection assembly.

**Conclusion**

The currently used ultrasonic testing method is unable to distinguish between porosities and delaminations within CFRP radius structures. Therefore, a non-destructive escalation method was found with the X-Ray coplanar laminography. On specimen level different types of failures (porosities, natural delaminations) were investigated to find characteristics differentiating between the failure types. A test method
threshold could be determined for the coplanar laminography set up at 50 µm gap opening to distinguish between delaminations and pores. Conservatism is given by the UT results. Finally, the applicability of the coplanar laminography could be demonstrated on an 18m long aircraft composite structure in industrial environment, wherefore a mobile low cost gantry scanner was developed. The intelligent reconstruction software yields the required high spatial resolution and contrast sensitivity, even with the used light manipulation system.

Extensive effort was spent for the visualization, measurement and classification of the acquired data. Thus the location, length, circumferential width and height of the indications were measured. Furthermore, 3D distributions were reconstructed permitting the data analysis by substantial post processing.

The results of the coplanar laminography were validated in comparison to UT results and micro sections, to reach the level of industrial qualification and acceptance. A high degree of correlation and reproducibility of the defects in terms of position, size and defect type was demonstrated.

An industrial standard on visualization and defect characterisation shall be established/refined within the ongoing future tests. These tests will provide the baseline data for structural investigations developing acceptance criteria.

References