Comparison between Traditional Non-Destructive Techniques and Phase Contrast X-Ray Imaging applied to Aeronautical Carbon Fibre Reinforced Polymer

Matthieu GRESIL 1, Vincent REVOL 2, Serafina CONSUELO GARCEA 3, Roland CHEMAMA 4, Georges KANDERAKIS 5, Konstantinos KITSIANOS 4, Ilias KOULALIS 4, Marc-Olivier SAUER 4, Hervé TRÉTOUT 6, Ana-Maria MADRIGAL 2

1 i-Composites lab, School of Materials, University of Manchester, Manchester, UK
2 Centre Suisse d’Électronique et Microtechnique - CSEM, Neuchatel, Switzerland
3 Manchester X-Ray Imaging Facility, University of Manchester, Manchester, UK
4 GMI Aero, Paris, France
5 National Technical University of Athens, Athens, Greece
6 DASSAULT Aviation, Argenteuil, France

Contact e-mail: matthieu.gresil@manchester.ac.uk

Abstract. The EU-project EVITA (Non-Destructive EValuation, Inspection and Testing of Primary Aeronautical Composite Structures Using Phase Contrast X-Ray Imaging) aims at bringing Grating-based Phase Contrast X-ray imaging technology to Non-Destructive Evaluation and Inspection of primary and/or complex aeronautical composite structures. Grating-based Phase Contrast X-Ray Imaging (XPCI) is based on the so-called Talbot-Lau interferometer, which is made of the combination of a standard X-ray apparatus with three transmission gratings as documented in the literature.

This study presents a comparison of three traditional non-destructive techniques (NDT): ultrasonic through transmission and ultrasonic phased-array, infra-red thermography (IRT), and X-Ray computed tomography (X-Ray CT) with the developed phase contrast X-Ray Imaging applied to aeronautical carbon fibre reinforced polymer (CFRP). This comparison process will concentrate on carbon fibre laminates. Typical defects produced during manufacture will be examined as part of the testing and validation procedure. The following defects have been identified as being those most likely to be detected more effectively by the XPCI process than other state of the art industrial NDT techniques: porosity, foreign objects, cracks, resin rich, cut fibres, and wavy fibres. The introduction of this innovative methodology is expected to provide the aeronautical industry with a reliable and detailed insight of the integrity of thin and thick composite structures as well as of complex geometry ones, such as integrated closed boxes and sandwiches.

This paper will first present the grating-based phase contrast X-Ray imaging developed in this project applied to Aeronautical carbon fibre reinforced polymer. It follows with a discussion of the comparison methods on porosity and cracks detection.
1. Introduction

Grating-based Phase Contrast X-Ray Imaging is based on the so-called Talbot-Lau interferometer, which is made of the combination of a standard X-ray apparatus with three transmission gratings as documented in the literature [1-4]. The method derives its potential from the fact that three different contrast mechanisms are combined in a single measurement. Indeed, not only the conventional absorption image can be extracted but also the refraction image (also called differential phase contrast image) and the scattering image (also called dark field image), which are related respectively to the refraction of the X-ray beam inside the sample and to the ultra-small angle scattering caused by its microstructure. Preliminary studies have shown that the scattering image provides a powerful tool to detect any change in the arrangement of the fibres due to the presence of defects such as porosity, fiber waviness, micro-cracks or resin rich/resin poor areas [5-8].

Within the project EVITA (www.evita-project.eu), the requirements and needs of the aeronautics industry in terms of the non-destructive inspection of thick and thin composite components were collected and analysed. From there, a customized demonstrator was designed and realized in order to benchmark this novel technology against the following non-destructive inspection (NDI) techniques: water jet ultrasonic, phased array ultrasonic, thermography and computed tomography.

2. Experimental

2.1 Grating-based Phase Contrast X-Ray imaging (XPCI)

A schematic view of the grating-based Phase Contrast X-Ray Imaging system is shown in Fig. 1. It consists of a standard high power X-ray source (Varian HPW-160-11) and pixelated detector array (Dexela DEX2315) coupled to three gratings forming an X-ray interferometer. The principle of the X-ray grating interferometer is explained in details in the literature [1-3, 9]. A collimator made out of lead is used to control the illuminated area while a shutter allows to block the X-ray beam during the idle time of the detector. In the present configuration, the sample can be moved independently using an XY gantry (IAI axis).

The gratings were manufactured at CSEM using MEMS fabrication processes on Silicon wafers of diameter 150mm, which allows to achieve a grating size of 100×100mm on a single wafer. The parameters of the demonstrator are summarized in Table 1.
Table 1. Key parameters of the EVITA demonstrator

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source acceleration voltage</td>
<td>40 – 70 kV</td>
</tr>
<tr>
<td>Maximal sample thickness (CFRP)</td>
<td>50 mm</td>
</tr>
<tr>
<td>System length (source to detector)</td>
<td>1.45 m</td>
</tr>
<tr>
<td>Measurement area (stitching mode)</td>
<td>1×0.5 m²</td>
</tr>
<tr>
<td>Image size (single field)</td>
<td>7 × 7 cm²</td>
</tr>
<tr>
<td>Effective pixel size</td>
<td>50 - 60 µm</td>
</tr>
</tbody>
</table>

Three images are obtained using the EVITA demonstrator, namely the absorption, refraction and scattering images. The absorption image corresponds to the conventional X-ray image, except that the blurring effect due to the Compton scattering is suppressed in the direction perpendicular to the grating lines. The absorption image is related to the attenuation coefficient of the material and its thickness.

The refraction image is proportional to the refraction angle measured pixel-wise by the interferometer. The refraction angle is linked to the derivative of the phase shift in the direction perpendicular to the grating lines (direction y in Fig. 1). In contrast to the absorption image, the refraction image is thus related to the refraction coefficient as well as to the thickness of the sample [4].

Finally, the scattering image is related to the ultra-small angle X-ray scattering of the beam inside the sample. It has been shown that the USAXS can be expressed in terms of variations of the electronic density of the material at the microscopic level [10]. The scattering image is thus a perfect tool to probe the microscopic texture of composite materials and detect porosity, cracks and variations of the fibre density or orientation [11].

The images were reconstructed using the phase stepping method [9], where the phase stepping was achieved by translation of the grating G2. The X-ray tube source was set to the small focal spot (0.4×0.4mm²) with the acceleration voltage at 60kVp and the anode current at 10mA. 19 phase steps were acquired over 4 periods with an individual exposure time of 750ms. The measurement was repeated 4 times and averaged. The measurement time for a single field inclusive reconstruction amounts to about 60s.

2.2 Materials

The samples were made out of Epoxy-carbon prepreg (HexPly 914C-T300H(6K)-5-34%). Two thickness composite materials were made, 4mm and 20mm. The results presented here were obtained with a 32 and 160 plies quasi-isotropic lay-up (+45°/90°/-45°/0°)4s and (+45°/90°/-45°/0°)40s, respectively. In order to test the capability of the PCI technique, manufacturing routes were developed which produced controlled defect in a repeatable manner. Table 2 shows the range of defect reference samples investigated in this publication. The results obtained with the EVITA demonstrator were benchmarked against four state-of-the-art NDI methods: Ultrasonic through transmission (UTT) (i.e. water jet and immersed), phased array ultrasonic (PA), and conventional X-Ray computed tomography (X-Ray CT). In our preliminary work [12], the EVITA demonstrator was benchmarked on two different types of artificial flaws: fiber cut and out-of-plane wrinkle. These two flaws were detected.
by the EVITA demonstrator with a comparably fast exposure time. No other NDI method used for the benchmarking was able to detect both flaws.

Table 2. Composite Sample list

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Defects</th>
<th>Materials</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>137186-14</td>
<td>porosity &lt;2%</td>
<td>Monolithic, Epoxy-carbon prepreg layup</td>
<td>thick (20mm)</td>
</tr>
<tr>
<td>137186-16</td>
<td>porosity 2 to 5%</td>
<td>Monolithic, Epoxy-carbon prepreg layup</td>
<td>thick (20mm)</td>
</tr>
<tr>
<td>137186-18</td>
<td>porosity &gt; 5%</td>
<td>Monolithic, Epoxy-carbon prepreg layup</td>
<td>thick (20mm)</td>
</tr>
<tr>
<td>137186-2</td>
<td>cracks</td>
<td>Monolithic, Epoxy-carbon prepreg layup</td>
<td>thin (4mm)</td>
</tr>
</tbody>
</table>

3. Results and Discussions

3.1 Porosity Detection

Fig. 2, Fig. 3, and Fig. 4 show the results of the comparison for the first samples, where different porosity contents were introduced during the manufacturing process. The porosity can be detected in the scattering image using the EVITA demonstrator as well as with the UTT and PA systems. All other benchmarking methods (i.e. IR-thermography and X-Ray CT) were not able to detect the defects. The same colour bar on the scattering image is used for all the samples with porosity. Moreover, Moiré artefacts are observed in the absorption and refraction image.

Fig. 2. Sample with porosity < 2%. The images obtained by UTT and PA are shown in (a), (b) and (c). The absorption, refraction and scattering images obtained with the EVITA demonstrator are shown in (d).
Fig. 3. Sample with porosity 2 to 5%. The images obtained by UTT and PA are shown in (a), (b) and (c). The absorption, refraction and scattering images obtained with the EVITA demonstrator are shown in (d).

Fig. 4. Sample with porosity > 5%. The images obtained by UTT and PA are shown in (a), (b) and (c). The absorption, refraction and scattering images obtained with the EVITA demonstrator are shown in (d).

It was observed that the scattering signal is increasing with the porosity level. Moreover, in the zoom-in of the refraction image, elongated voids can be observed. In order to evaluate
quantitatively the relationship, the average and standard deviation of the absorption and scattering images were calculated over a region of 100x100 pixels (about 6x6mm). The averages of the absorption and scattering images are plotted in Fig. 5 as a function of the porosity level, where the standard deviation is represented as the error bar. For this graph, it was assumed that the porosity levels were equal to 1%, 3.5% and 7% (the levels were not precisely characterized).

The analysis shows that the scattering signal scales with the porosity level (as expected from the theory). Note that the relatively high standard deviation is due to local variations of the porosity over the region of interest (100x100 pixels) and does not correspond to noise in the measurements.

A linear dependence can be observed. These measurements demonstrate the ability of the EVITA system to determine the porosity level in composite components.

3.2 Cracks Detection

Micro-cracks are usually following the orientation of the fibre layup. For this reason, they display usually a clear orientation (typically 0° / 90° / +45° / -45°). A special geometrical filter was developed to enhance the crack signal. The following procedure is implemented: (i) remove low frequency from the image; (ii) filter the image using ellipsoidal Gauss kernels with angle scanning between 0 and 180° (1° step); (iii) combine the filtered images by normalising according to the filter response at each angle. An edge along the filter direction will have a greater response than all other edges in the image. And the edges which are not in the direction of the filter will be smoothed out providing a low response close to the average. Fig. 6 shows the results of the geometrical filter applied to the scattering images of samples with micro-cracks. This is clear that this geometrical filter strongly enhances the detectability and visibility of the elongated micro-cracks. These measurements demonstrate the ability of the EVITA system to detect micro-cracks in composite components.

3.3 Image fusion

The image fusion algorithm aims at visualising both the filtered structure and the background scattering image (unfiltered) at the same time. In the present case, we decided to display the scattering image as grey levels and to overlap the filtered refraction image with yellow colour. Fig. 7 displays an example of the image fusion for composite samples with different levels of porosity while Fig. 8 shows the example for a composite sample with micro-cracks.
Fig. 6. (left) Scattering image of a sample with micro-cracks and (right) corresponding image after application of the geometrical filter.

Fig. 7. Example of image fusion of the scattering image with the filtered refraction image for composite samples with different porosity.

Fig. 8. Example of image fusion of the scattering image with the filtered scattering image for a composite sample with micro-cracks.

4 Conclusion

The EVITA demonstrator was presented and its performance was illustrated using two coupon samples with two types of artificial flaws: porosity and cracks. The flaws could be detected and quantified by the EVITA demonstrator with a comparably fast exposure time. The EVITA demonstrator was benchmarked against other state-of-the-art NDI methods.
While phased array ultrasonic and through transmission ultrasonic were also able to detect the different porosity level, the ability of the EVITA demonstrator to quantify the level of porosity seems to be promising and will be further investigated in future research. Furthermore, while the detection of cracks can be readily achieved using the EVITA demonstrator and a geometrical filter, no other NDI method used for the benchmarking was able to detect the cracks induced in the structure. In combination with a relative fast exposure time (comparable to phased array ultrasonic), the EVITA demonstrator demonstrated unique features, which can benefit to the non-destructive inspection of lightweight materials such as composites.

The introduction of this innovative methodology is expected to provide the aeronautical industry with a reliable and detailed insight of the integrity of thin and thick composite structures as well as of complex geometry ones, such as integrated closed boxes and sandwiches. By increasing the level of detectability of defects in composite structures, as well as by detecting defects invisible to standard industrial non-destructive testing methodologies, the novel method will play a major role during the whole life cycle of composite components, reducing their inspection cost and increasing their reliability.

5 Acknowledgments

The authors acknowledge financial support from the European Union’s Seventh Framework Programme for research technological development and demonstration under grant agreement n°314735.

6 References

[12] Revol, V. et al. 2015. Non-destructive evaluation, inspection and testing of primary aeronautical composite structures using phase contrast X-ray imaging. 5th EASN International Workshop on Aerostructures, Manchester, UK.