X-ray computed tomography in bonded aircraft repairs for composites

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Abstract
As bonded composite repairs are gaining importance for modern civil aircraft, it is necessary to investigate such repairs in detail under relevant environmental conditions. In this work, X-ray computed tomography (XCT) was performed on bonded repairs for carbon fiber (CF) reinforced epoxy matrix composites before and after cyclic conditioning between dry/cold and hot/wet conditions. In detail, high resolution XCT scans in absorption contrast (AC) mode as well as Talbot-Lau grating interferometer (TLGI)-XCT scans to obtain additional differential phase contrast (DPC) and dark-field contrast (DFC) modalities were performed. The repair bonds’ constituents could be identified by the high resolution XCT scans. Additional information about fiber alignment, at least of the fiber bundles, could be extracted from the TLGI-XCT scans. In order to gain detailed information on certain specimen features, specimen dimensions were reduced for additional high resolution XCT scans.

Keywords: Bonded composite repair, environmental conditioning, X-ray computed tomography, Talbot-Lau grating interferometer

1 Introduction
Composite materials, especially produced from CF reinforced epoxy resins, have been gaining acceptance in modern passenger aircraft in the past [1]. In these aircraft, composite materials are nowadays used in nearly all types of structures, which leads to the demand for suitable repair methods, especially for structural parts [1–4]. Due to the fact that mechanically fastened repairs are no ideal choice for composite materials, a deeper understanding of bonded repairs has to be developed [2,3,5]. In terms of bonded repairs, scarfed repairs have their merits regarding e.g. repair size and load transfer capability [4].

As a consequence of the need to repair composites via bonding, selected XCT techniques have been used in this study to inspect repaired specimens and to investigate the influence of cyclic conditioning between -30 °C and 70 °C / 85 % r. h. In addition to previous work performed by Röper et al. [6], where high resolution XCT images were obtained from specimens in dried condition and after cyclic conditioning, a scan on a sample with reduced dimensions was performed in the present study to enhance the resolution of the obtained images. This additional work was performed because, despite the fact that it was possible to identify the tracer yarns as well as the adhesive and the knit carrier within the adhesive in specimens with a size of (14 x 14 x 2.5) mm³, it was not possible to distinguish the CF from the epoxy matrix in the parent as well as the repair laminate [6]. Furthermore, TLGI-XCT images using AC, DPC as well as DFC mode were additionally taken to extract information about the laminate layup as well as on resin rich areas.

2 Experimental part
All information on the experimental procedures were given in detail in the previous publication [6]. Consequently, the procedures will be described briefly in this section.

2.1 Materials, specimen preparation and conditioning
The repaired specimens were produced by following a soft patch repair approach. In contrast to the hard patch repair, which is performed by adhesively bonding a pre-cured repair patch to the tapered parent laminate, the repair plies as well as the adhesive used are co-boned in the soft patch repair process [1,7]. For the production of the parent laminate and the subsequent soft patch repair, the following steps were performed:

1. Stacking of prepreg plies (woven carbon fibers pre-impregnated with epoxy resin) to form a quasi-isotropic parent laminate with the stacking sequence [(± 45/0/90)/±45/0/90]s.
2. Autoclave curing of the laminate plates according to the prepreg manufacturer’s specifications (180 °C for 2 h at 6.6 bar)
3. Ultrasonic inspection of the cured plates to ensure the laminate quality in terms of e.g. voids or inclusions.
4. Tapering of the parent laminate according to the taper ratio of 1:9 (± taper angle of 6,3°) using a manual angular grinder with sanding paper grit 100.
5. Thorough cleaning of the resulting tapered surface with lint-free wipes.
6. Layup of one layer of epoxy based, knit carrier supported film adhesive and the repair patch matching the parent laminate material and layup sequence ([± 45/(0/90)/±45/(0/90)]s).
7. Co-bonding of the repair patch and the film adhesive following the same procedure as already used for curing of the parent laminate (autoclave curing at 180 °C for 2 h at 6.6 bar).
8. Cutting of individual specimens with dimensions (14 x 14 x 2.5) mm³ subsequent to an ultrasonic inspection as already described in step 3. Cutting of the specimens was performed on a circular saw (Diadisc 5200, Mutronic Präzisionsgeratebau, Rieden, DE) by a diamond coated blade (water cooled). The specimens were prepared by firstly extracting the taper area from the repaired plates at a length of ≈28 mm and secondly separating the resulting piece into two samples with the specified dimensions. This procedure ensured, that the investigation of the entire taper area was possible.

Specimens were dried at 70 °C for 4 days for the inspection in dried condition. This procedure was also used as initial drying procedure for the subsequent conditioning steps, which were performed in a Memmert CTC 256 climate chamber using the ASTM 5229 [8] standard as a guideline. Specimens designated for subsequent cyclic conditioning between -30 °C and 70 °C / 85 % r. h. were kept at 70 °C / 85 % r. h. for 7 weeks (wet condition). For cyclic conditioning, the climate chamber was set to maintain 70 °C / 85 % r. h. for 2.5 h, to cool to -30 °C within 3 h, to hold this temperature for 1.5h and to finally return to the initial setting of 70 °C / 85 % r. h. in 1 h. This cycle was repeated for 100 times. In order to prevent changes of the specimens’ moisture content during transport, they were sealed in airtight bags.

2.2 Computed tomography

To obtain optimal results regarding three dimensional materials characteristics of bonded aircraft repairs for composites, multiscale and multimodal X-ray based, non-destructive approaches were applied [9]. XCT inspections for conventional absorption contrast were conducted on a Nanotom 180NF (GE Sensing & Inspection Technologies, Wunstorf, DE), which is equipped with a 180 kV sub-µ-focus X-ray tube. A tungsten target on a CVD window or a Mo target on a beryllium window can be equipped to the X-ray tube. A 2304 x 2304 pixel flat panel detector (Hamamatsu, Hamamatsu, JP) was used as detector. To achieve additional modalities for materials characterization, such as differential phase contrast (DPC) and dark-field contrast (DFC), a Talbot-Lau grating interferometer XCT (TLGI-XCT) was used. For this purpose, scans were performed on a SkyScan 1294 device (Bruker microCT, Belgium), which can measure three different modalities (AC, DPC, DFC) in one scan using a phase stepping approach [10–12]. All experiments were performed at room temperature (RT). Detailed parameters and resulting voxel size for the individual test setups are listed in table 1.

Table 1. Applied scan parameters for the individual samples

<table>
<thead>
<tr>
<th>XCT system</th>
<th>Image modalities/ XCT modes, sample size</th>
<th>Scanning parameters (tube voltage; Tint; Nr. of images; Target-material, Pre-Filter)</th>
<th>Voxel size (µm³)</th>
<th>Scanning-time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanotom 180 NF</td>
<td>XCT (14 x 14 x 2.5) mm³</td>
<td>70 kV; 900 ms; 1900; W; 16xAl</td>
<td>7 µm³</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>ROI-XCT (14 x 14 x 2.5) mm³</td>
<td>80 kV; 1000 ms; 1800; Mo; -</td>
<td>2 µm³</td>
<td>184</td>
</tr>
<tr>
<td></td>
<td>XCT (2 x 2 x 2.5)mm³</td>
<td>60 kV; 1000 ms; 1900; Mo; -</td>
<td>0.9 µm³</td>
<td>288</td>
</tr>
<tr>
<td>SkyScan 1294</td>
<td>AC, DPC, DFC (14 x 14 x 2.5) mm³</td>
<td>40 kV, 600 ms; 1500; W; Al 0.5 mm</td>
<td>22.8 µm³</td>
<td>652</td>
</tr>
</tbody>
</table>

For reconstruction, the tools of the XCT-manufacturer, mainly based on filtered back projection algorithms, were applied. VGStudio MAX 3.3 (Volume Graphics GmbH., Heidelberg, Germany) was used as standard software tool for voxel dataset handling, manual registration of each individual scan, feature segmentation and visualization. Open_iA [13] was applied for new approaches regarding multimodal data-visualizations.

3 Results and discussion

In figure 1, the location of a pre-existing delamination in the vicinity of the interface between the adhesive and the laminate is indicated in the 3D representation of the specimen as well as in cross-section. Additionally, the adhesive layer as well as tracer yarns can be identified in the 3D image. It has to be noted, that in this context, pre-existing means that the delamination was also found in images of the specimen in dried state. A detailed depiction of the delamination found in the specimen in dried and wet condition as well as after cyclic conditioning can be found in figure 2. It was not possible to detect significant growth of pre-existing delamination after the cyclic conditioning with the current specimen dimensions using the high-resolution XCT in AC mode [6]. Only the contrast and sharpness of the delamination after cyclic conditioning seems to be slightly higher, which can
be an indication of a slightly increased crack width or of marginally better XCT-measurement conditions during the scan time of 175 min (e.g. fewer thermal drifts or focal spot drift).
Apart from the previously described delamination, a pre-existing crack-like structure was found embedded in the higher attenuating adhesive is depicted in figure 3 for the specimen after cyclic conditioning. Details of this structure could be obtained by physically extracting a smaller volume with $(2 \times 2 \times 2.5) \, \text{mm}^3$ from the original specimen, which led to a resulting voxel size of $0.9 \, \mu\text{m}^3$ (see figure 4). From the additional details gained, the structure does not seem to be a crack, but however contains some voids. In order to identify the exact nature of the structure, it has to be further investigated, e.g. via energy dispersive X-ray spectroscopy. Due to the higher resolution resulting from the decreased dimensions of the specimen, the individual CF as well as voids can be distinguished from the surrounding matrix. It has to be noted, that the scans of the samples with the reduced geometry have been performed several months after the initial scans. Consequently, the specimens were not in the conditioned state. However, in this case, the scope of this additional work was to demonstrate the capability to further investigate certain features of the specimens, e.g. the single CF.

![Figure 3: Specimen after cyclic conditioning with focus on pre-existing crack-like structure in the bulk of the laminate. VS: 7 $\mu\text{m}^3$](image)

![Figure 4: Different “Field of View” of different voxel size scans (top row) and comparison of pre-existing crack-like structure already depicted in figure 3, with a VS of 7 $\mu\text{m}^3$, 2 $\mu\text{m}^3$ and 0.9 $\mu\text{m}^3$, respectively (bottom row).](image)
The high sensitivity of DPC imaging for differences in atomic number [14] makes TLGI-XCT especially useful for low density materials with similar attenuation properties. In the case of CF reinforced polymers, regions with low CF content (resin rich areas) can be visualized due to their difference in refraction properties. Furthermore, the directional sensitivity of the DFC modality can be exploited to gain information about the CF orientation. In other words, fibers oriented perpendicular to the gratings of the Talbot-Lau interferometer yield a strong scattering signal, while others cause a relatively low amount of scattering [15]. Thus, with repeated scans combined with rotation of the specimen, differently oriented prepreg-layers can be identified. Results of these scans of the specimens after cycling with a size of (14 x 14 x 2.5) mm³ are depicted in figure 5. With this additional information gathered by DPC and DFC as well as with the information from AC combined, it was possible to create a 3D rendered model of the specimen including orientation of the CF. This makes it possible to investigate the stacking sequence of the parent and the repair laminate. Despite the theoretical possibility to identify existing micro cracks in DFC images [16], none resulting from cyclic-conditioning could be found in the specimens.

4 Conclusion and Outlook
In this paper it could be shown that with XCT methods, information regarding pre-existing delaminations before and after cyclic conditioning could be obtained from repaired composite specimens. Additionally, it was possible to make individual features of the specimens visible, e.g. the parent and the repair laminate or the tracer yarns. Identification of individual CF or CF bundles was possible either via high-resolution XCT scans in AC mode by reducing the sample geometry or by the use of TLGI-XCT in DFC mode, respectively. The combination of images obtained from TLGI-XCT in AC, DPC and DFC mode enabled the 3-dimensional reconstruction of the repaired specimen including segmentation of the fiber bundles, resin rich areas and the adhesive. Hence, the stacking sequence of the parent and repair laminate can be investigated. In addition, it could be shown, that a multiscale approach, starting at low resolution to get an overview of the entire test specimen finishing at highest resolution below 1 µm³ voxel size is recommendable to e.g. verify or discard crack-like structures. However, additional research regarding unclear features by further destructive target-preparation using conventional grinding process followed by scanning electronic microscopy are advisable.

Figure 5: TLGI-XCT slice images of all three modalities AC, DPC and DFC showing different visible material features (left). The adhesive layer, resin-rich areas as well as fiber bundles are indicated by blue, green and orange arrows, respectively. The 3D rendering (right) shows fiber bundles color coded in blue, green, red and yellow for the four different directions as well as the adhesive layer in grey.

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References