ABSTRACT

Components made of Composite materials viz, Glass Fibre Reinforced Plastics (GFRP) & Carbon Fibre Reinforced Plastics (CFRP) are extensively & effectively used in Aerospace structural applications, for their better strength to weight ratio. Composite usage is increasing especially in the weight sensitive aerospace Industries. Blades made of composites forms part of Rotary wings, and maintenance of Helicopters are mainly influenced by dynamic components like Main Rotor Blade (MRB) & Tail Rotor Blade (TRB). CT during manufacturing and service, helps in Structural Health Monitoring (SHM) & damage tolerance related studies resulting in extension of the life of aerospace components. Inter laminar shear strength (ILSS) variations are considered while studying the sensitivity of compaction level on the performance of blades before & after service. Experiments were carried out to obtain correlation between Ultrasonic A-Scan, C-Scan, CT density mapping with different compaction levels.

Keywords: Inter Laminar Shear Strength, Structural Health Monitoring, Monolithic, Compaction level, Delaminations, Life extension, Density Mapping

1. INTRODUCTION

CT is an advanced form of X-ray radiography. Conventional radiography provides a two-dimensional presentation of a three-dimensional object as the image plane is approximately normal to the x-ray beam. CT creates a digital representation of a thin slice parallel to the x-ray beam. Typical slice thickness ranges from 0.025 mm to 3 mm, with pixel sizes (picture elements) ranging from 0.025 mm to 1 mm. The CT image represents the point-by-point linear attenuation coefficients in the slice, section by section or slice by slice information which depend on the physical density of the material, the effective atomic number of the material, and the x-ray beam energy. The CT image is unobscured by other regions of the test piece and is highly sensitive to small density differences (<1%) between structures.

Typical Medical CT-scan system for composite testing
1.1 Quantification of Fiber Composite Structures

By the representation of the material cross-sections through attenuation coefficients the material data will be generated. So the material qualities become quantifiable based on the density mapping throughout the section for various composites materials of different combination having different density values. These are derived through CT number (HU). The medical scanners do not use directly the attenuation coefficients but use CT-number. This number was established by Hounsfield. The Hounsfield (HU) scale standardises the reconstructed attenuation coefficients (µ) to the linear attenuation coefficient of water at a photon energy of 73 keV.

\[ C_{TR} = \frac{\mu - \mu_{\text{water}}}{\mu_{\text{water}}} \times 1000 \ [HU] \]

Therefore water has by definition the CT-number zero. Cured epoxy resin is <50 HU & Air has -1000 HU, GFRP 1200 to 1400 HU and CFRP 200 to 500 HU.

Hounsefield number (density) will be varying with respect to variation in compaction level and it can be optimized through improving process. The same compaction variation can be monitored through CT number and it will be monitored before and during service of the parts.

2. Defect detection

The normalisation of the attenuation coefficients by the CT-number has the advantage, that materials of fiber composites become comparable. The CT-numbers are represented at the screen as grey value distribution. One grey value has always the same CT-number, independent of the maximum attenuation differences of the component. Therefore visually and quantitatively comparable CT-images are obtained. This is quite essential prerequisite to analyse the CT-images automatically by image processing analysis. CT will distinguish between the spatial (geometrical) and the density (contrast) resolution.

2.1 Spatial resolution

Spatial resolution is generally quantified in terms of smallest separation at which two points can be distinguished as separate entities. The limiting value of the resolution is determined by the design and construction of the system and by the amount of data and sampling method. It must be distinguished between the spatial resolution within the scan plane (slice) and vertical to the scan plane dependent on the slice thickness. The spatial resolution affects the detectability of defects e.g. delaminations, fiber cracks, layer waviness or air pockets within fiber composites. The geometrical resolution within the scan plane is indicated by the MTF-curves. The grey values visible in the CT-images represent the attenuation differences (CT-numbers) caused by the local variable resin- and glass distributions.

The following type of defects are found in monolithic and sandwich fiber composite structures. Layer waviness, Fiber breaks, Delaminations and debondings, Curing cracks, Air pockets and porosity, Non-uniformity of resin and fiber distributions, Foam fractures and deformations, shifting of structural parts and Core crush.

2.2 Layer waviness

Layer waviness in the fiber laminate structures is harmful if they are located within high loaded zones. The fibers are only carrying loads if they are placed in the direction of load.
2.3 Delamination

Delaminations are detectable quite clear with the Computed Tomography. The good spatial resolution in the scan plane (axial tomograms) here, defines the limits of the detectability and shows the material integrity of the component.

3. Material Characterisation

Material Characterization is studied through Computed Tomography to evaluate the internal structure and properties of a material. Characterization can take in the form of evaluating and correlating CT Number with process key compaction parameters and mechanical strength like ILSS, porosity.

Due to improper and varying compaction level, process problems encountered are, Low mechanical strength, void content, less fibre volume content and layer waviness. CT Measurements with GFRP and CFRP-fiber samples with various ILSS, Void content and varying attenuations, fiber volume contents have shown that there is a linear correlation between fiber volume content & Inter-laminar shear strength inversely proportional to void content with the CT Number Fig. (3.1), (3.2), (3.3), (3.4).

<table>
<thead>
<tr>
<th>% of porosity</th>
<th>CT Number (HU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>53</td>
</tr>
<tr>
<td>1</td>
<td>41</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

FIG.3.1: Relationship between % of porosity & CT Number

The process of implementing a damage detection and characterization strategy for engineering structures is referred to as Structural Health Monitoring (SHM). Here damage was observed through CT during manufacturing and service, as changes to the material and properties of a structural system, changes to the boundary conditions of different compaction levels which adversely affect the product performance.

CT carried out under various service schedule to formulate the data before and after service conditions, the ability to normalize the data becomes very important to the damage identification process. As it applies to SHM, data normalization is the process of separating changes in CT Number reading caused by damage from those caused by varying operational and environmental conditions.
4.1 Methods of Analysis

The present study is intended to find out:

- Whether the material characteristics influence effectiveness of blades performance
- To check whether there are significant difference of density & attenuation limit noticed before & after service of the product
- To test the CT number variations influencing the effectiveness of internal structures.

CT was used to test the effectiveness of part internal structures with respect to material integrity by testing before and after service. There were many attributes/factors which were categorized viz density variation, dB difference, resin compaction monitoring and layer disturbance.

<table>
<thead>
<tr>
<th>Service schedule (TBO*) (Hrs)</th>
<th>No. of blades checked</th>
<th>Density variation (CT value variation) observed</th>
<th>dB difference observed</th>
<th>Resin rich (compaction level monitoring) observed</th>
<th>Layer disturbance observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-250</td>
<td>125</td>
<td>17</td>
<td>17</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>250-500</td>
<td>96</td>
<td>31</td>
<td>31</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>500-750</td>
<td>54</td>
<td>33</td>
<td>33</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>750-1000</td>
<td>38</td>
<td>18</td>
<td>18</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>42</td>
<td>9</td>
<td>9</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>

*Time Between Overhaul

**Analysis of Data:**

Reliability Analysis: An analysis was conducted for checking the reliability of the CT examination and the results were obtained from the various customers. The CT Number is measured/mapped for each and every cross-sections described by the design at critical zone separately for TRB & MRB. According to CT Number for GFRP material, from +1200 to +1400HU indicate reliability as they meet the minimum acceptable level of +1200HU.

4.1.1 CT-SCAN OBSERVATIONS BEFORE SERVICE:

(During raw stage)

- A-Scan signal is passing and Attenuation is within limit
- Before service density is within limit and CT value Measures +1200HU
CT-SCAN OBSERVATIONS AFTER SERVICE:

Before service - CT value measures +342HU

After service - CT value measures +203HU

4.1.2 Ultrasonic observations (C-Scan)

Before service – Attenuation within limit (70dB)

After service - Attenuation variation observed (80dB)

After service A-scan signal is not passing & it shows attenuation variation (>6db)
During correlation study conducted between CT-Scan observation and UT with various test panels made of GFRP & CFRP material, it was found composite defects of similar type cleared for further service and monitored through UT in situ. Based on UT results the CT number variations will be analysed and it decides to increase the life of the product. This resulted in saving of time and cost to the organization leading to customer satisfaction.

After life extension of the composite blade, it was monitored through CT values & UT continuously and life of blades further extended from 500 service hours to 1000 service hours. Authors feel this is a noticeable achievement in rotor blade development.

4.2 CT during operation and maintenance

During service, the rotor blades are checked by visual inspection for external damages. The CT will be used for internal damages, when unusual events have been occurred and rotor strains were evoked which were above the limit loads, like loading of non-rotating rotor by over-flight and gust loads, at slope landings or manoeuvres on the ground with power or by foreign object damages or accidents. At such events the CT is used for inspection of the inner structure of the dynamic rotor blade attachment on possible damages. A further application of CT is to support during the fatigue test of helicopter rotor blades.

Rotor blades with higher flight hours are brought back from the customer and the residual strength is determined by fatigue test in comparison with the new rotor blade. The rotor blade attachment is checked by CT at the beginning, during and after the fatigue test. By that it can be found whether damages has been occurred within the structure by operational loadings and their effect on the fatigue of the structure.

Based on fatigue test results of service blades, life will be extended and it will be monitored at different cycles of fatigue test.

5. Results

The attenuation coefficient (dB/mm) vs CT Number(HU) is plotted ( fig.3.3 ) shows that CT Number gives a better correlation. The ultrasonic attenuation values (dB/mm) for Glass UD ( Uni Directional ) and BD ( Bi Directional ) / epoxy 135°C cured material systems were plotted against the corresponding CT values and studies were carried out.

It is found that with increase in CT Number, the energy attenuation decreases. This implies that when number of defects are more, they tend to absorb or scatter more ultrasonic energy and thus the back wall echo suffers a decrease in amplitude.

In the study, it is found that the critical void content is 6 %. for UD and BD, It confirms the present acceptable deviation in attenuation values, used in acceptance criteria.

It is observed that UD & BD laminates, have higher attenuation coefficient for a given porosity level. This is because, the weave pattern in a fabric as well as variation in compaction level adds to the attenuation in addition to the inherent material attenuation. Increase in porosity will increase ultrasonic attenuation level and decrease in CT Number.

The ILSS values are found to gradually increase with CT Number. There is a maximum reduction of CT Number with respect to void ILSS values. At higher temperature, the property is greatly lost because of expansion of voids and thus affecting the matrix properties and leads to low ILSS value and less CT number.

The graph at fig . 3.2, compares variation in ILSS value with CT Number.
Conclusion

Conclusion is based on the different level of service hours of rotor blades and summarized as following:

- Density mapping by CT was carried out during manufacturing and service of Helicopter composites blades. It is observed that there is no change in the in CT number during Manufacturing (compaction) and no change in CT number after service which validates the product for Life Extension for further service. Consequently if there is appreciable change in CT Number, life extension of the product is not possible & further study is required.
- The study also attempted to identify some of the density variation that help in examining further monitoring of blades in various service schedule/interval to evaluate the product. In situ CT & UT results are correlated in examining the achieved compaction level of effectiveness for life extension.

CT as advanced NDT technology is successfully used to monitor integral composite structures of Helicopters, and the results are extensively used for evaluating rotor blades made of composite materials, during development, production and service to enhance the component life.

Future direction in CT of composites is consolidation of defect catalogues, further improvement in image processing and ADR (Automatic Defect Recognition).

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