Investigation on complex shaped aerospace structure: Reliability and Cost balance

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Abstract

The objective of this work is to identify different types of defects in carbon fiber reinforced polymer (CFRP) specimen provided along ‘Student Challenge’ by using different nondestructive techniques, mostly focused on ultrasonic inspection. Due to complex geometry of the sample the aim of the team is to compare the performance of suitable non-destructive techniques in order to detect, locate, and size the defects. Factors affecting the performance of NDT techniques are sample structure, geometry, dimension, layer thicknesses, material characteristics and their capabilities due to physical phenomena. For each technique, most suitable measurement parameters have been selected: 10 MHz, 32 element transducers for phased array ultrasonic inspection, 15 MHz focused single element transducers for immersion tank inspection, 50 MHz focused transducers with acoustic microscope, and 200 kV voltage along with 600 mA current for X-ray tomography investigations. The results has been compared according to detectability of defects, cost, and time for the inspections. The five different inclusions are identified using different NDT techniques and the size of the defects has been measured. The team reported the quantified performance comparison for the different type of ultrasonic inspections along with the visual inspection and X-ray tomography NDT techniques.

1. Introduction

The rapid use of carbon fiber reinforced polymer (CFRP) material have become popular in transportation industry, especially aerospace, due to tremendous material properties such as high strength-to-weight ratio, corrosion resistance and low coefficient of thermal expansion [1]. Non-destructive inspection for the evaluation of composite structures is a must to control the quality of end product and prevent the abnormalities that can cause strength reduction or catastrophic failure [2].

This paper gives an insight on the detection and surveillance of carbon fiber reinforced polymer (CFRP) material, the foreign objects inclusions and contamination which were added artificially during the manufacturing.

The purpose of this study is to identify the artificial defects inside the CFRP sample and to show the capability of non-destructive methods and their possibilities to detect the flaws.

The main reason of using several non-destructive techniques is to carry out and understand which technique is more safe, reliable and cost effective for the challenging sample. The reliability and detectability of different type of defects differs for each NDT technique that has applied for the inspection of the sample with artificial defects. This is because various factors influence particular inspection [3]. In this work, the main factors affecting the probability of defect detection were identified for different NDT techniques and compared. In addition, analysis and comparison of experimental results has been reported in order to identify the most suitable technique considering NDT system reliability for different type and size of defects.

The following methods have been performed to inspect the CFRP sample: visual inspection with optical microscope, acoustic microscopy, ultrasonic immersion phased arrays, ultrasonic immersion method with through-transmission and pulse-echo, and X-ray computed tomography.

Among all techniques, visual inspection is the most common NDT technique which is used to detect surface defects [2]. In order to detect inclusions ultrasonic and electromagnetic NDT techniques such as radiography are suitable. For instance, phased array ultrasonic testing allows for detailed inspection of large components as well as complex geometries with electronic focusing and electronic scanning [4]. In order to maintain the contact on the complex geometry surfaces, the immersion ultrasonics are more feasible than contact methods. While the water prevents the complication that occurs due to contact loose on the complex surface, the focusing of the transducers is still a challenging task [5], [6]. Especially when using focused transducers, the focus distance should be set accurately in order to get results from the object under investigation. For high precision inspection of the components, acoustic microscopy can be used since high frequency focused transducers are used [7]. However, the uncertainties related to the focusing distance is multiplied by using acoustic microscopy system. On the other hand, X-ray inspection gives the high-resolution volumetric information inside the sample structure but the inspection
speed is slow and there are difficulties to identify the defects at the corners of the sample due to possible errors in reconstruction [8], [9]. The ultimate goal of this research is to identify inclusions in CFRP sample and compare their performances according to cost and reliability analysis. In this study, optical microscope has been used to identify the external defects on the object since these defects can lead to failure or contribute to failure. In order to detect inclusions, ultrasonic immersion techniques has been exploited. Complex shape CFRP sample have been investigated by using ultrasonic immersion tank system with pulse-echo and through-transmission modes. Also, immersion phased array system has been exploited. Additionally, the sample has been investigated with acoustic microscopy system. Last but not least, X-ray tomography has been performed. The performance of each technique has been compared.

2. Description of the sample
The object under investigation is made of CFRP and has a complex surface geometry. The thickness of the component varies from approximately 0.7-2 mm. The lay-up structure is woven and number of laminas differs on different spatial parts of the object. It is known that there are artificial defects (5 inclusions including contamination at T-joint zone according to information received) inside the sample.

The object was separated into 9 regions for orderliness and clarity of detected defects and shown in Fig. 1.

![Figure 1: Carbon fiber reinforced polymer (CFRP) sample divided into regions.](image)

3. Experimental investigations
The complex shaped CFRP sample has been investigated with different NDT techniques namely, visual inspection, ultrasonic inspections with phased arrays and with immersion tank, acoustic microscopy, and x-ray tomography. All experiments have been conducted at Ultrasound Research Institute, Kaunas, Lithuania.

3.1. Visual inspection with optical microscope
Optical microscope investigations are playing a key role in identifying surface defects. The investigations are carried out with CFRP sample to detect surface flaws and characterize the material integrity. Optical microscope helps to understand a number of features of a composite structure such as resin rich areas, fiber misalignment, ply-lay-up, ply thickness. Characterizing the material with microscope can be especially valuable for the prior qualification test in the aerospace industry, where there is a need to fully understand the quality of the composite laminate before production and during usage.

Olympus SZX16 optical microscope has been used for visual inspection of the sample surface. The specification of the microscope is shown in Table 1. Five type of defects are noticed during the visual inspection: tiny holes, impact damage, rough edge, cracks and inclusion which are shown in Fig. 2. It is possible that, the tiny holes are formed due to lack of resin. The impact damage observed during the inspection and the size of the defect is about 6.5 mm in diameter. The rough edges and dent with cracks are noticed during the inspection as shown in Fig. 2, these defects might occurred during the fabrication due to mold imperfection or lack of finishing. The parallelogram shape defect was detected as well; the dimension is 20x20mm.

![Figure 2: Detected defects using visual inspection method.](image)
Influencing factors on the defect detection in the case of visual inspection are the inspector’s acuity, interpretation, lightening and technique capabilities.

Table 1: Specifications of the microscope.

<table>
<thead>
<tr>
<th>Microscope</th>
<th>1</th>
<th>Zoom</th>
<th>Mono-zoom variable magnification system</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Zoom Ratio</td>
<td>10:1 (0.63 X - 6.3 X)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Aperture Iris Diaphragm</td>
<td>Built-in</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Illumination Mode</td>
<td>Coaxial reflected light</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Light Path Selection</td>
<td>2 step binocular 100%/photo 100%</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Tilting Angle</td>
<td>0° - 23° continuously variable system</td>
<td></td>
</tr>
</tbody>
</table>

3.2. Ultrasonic investigations with phased arrays (PAUT)

The ultrasonic phased array inspection of the CFRP object was performed in an immersion mode. The immersion technique was selected in order to provide a proper contact between transducer and the complex shape surface of the object; to decrease acoustic impedance difference and attenuation. 10 MHz phased array transducer with 32 elements has been used with focusing in the sample (15 mm). The experimental set-up has been shown in Fig.3.

Affecting factors on defect detection in the case of phased array immersion inspection are as follows: capabilities of technique, sampling frequency, object positioning in the tank, alignment of inspected region to all length of 32 elements beams of phased array, object surface curvature, material thickness, defect size and depth, focus distance, attenuation, resolution of measurement instruments and system and human factor. It is important to mention that the results could be improved by using advanced electronic scanning algorithms such as surface adaptive ultrasonics (SAUL).
3.3 Ultrasonic inspection using immersion tank system

The complex shaped CFRP sample has been investigated with 11 degree of freedom TecScan industrial immersion tank system. Two focused, 15 MHz ultrasonic transducers have been used for through transmission inspections. The sample parts 1(a,b,c), 2(a,b,c), 3(a,b,c) have been investigated with through transmission techniques. Due to complex shape, side parts of the sample has been investigated with one 15 MHz focused transducer in pulse-echo settings. The set-up of the system is shown in Fig.6. While two transducers are shown as receiver and transmitter in Fig.6 that is used for through transmission inspection, only one transducer has been utilized as transmitter/receiver during pulse-echo measurements.

3.3.1 Pulse-echo ultrasonic inspection with immersion tank

The sample has been inspected from sides with pulse-echo ultrasonic inspection with immersion tank with one 15 MHz focused transducer. One defect has been detected on the top section of region 2(a) side view (Fig. 7).

A-scan and F-scan results shows that there is a high complexity and ultrasonic wave scattering due to curved side of the sample (Fig. 7). The results also show that there is no reflection from the possible defect position (X=105 mm, Y=3.6 mm), the inclusion is not a reflector for ultrasonic waves. Also, it is considered that the defect material properties might be similar to big rectangular inclusion in the previous image. The size of the defect has been measured by decibel (6 dB) drop method as 3.1 mm (Fig. 8).

3.3.2 Through-transmission ultrasonic inspection with immersion tank

The sample from front view has been investigated with through transmission ultrasonic inspection with immersion tank by using two identical focused 15 MHz transducers. During these investigations four delamination like defects where the ultrasonic wave either reflects almost completely or absorbed by the defect were detected. The size of the defects has been measured decibel drop method. First defect is observed on part 1(b) with a shape as parallelogram, with the measured inside acute angle of 63.7 degree (Fig.9). The length of the defect has been measured as 23 mm. Second and third observed defects are in part
2(c) and they are almost squares, with the length of 12.7 mm for big defect and 8.8 mm for small defect (Fig.10). The last delamination like defect has been observed on the edge of part 2(a) (Fig.11). The length of the defect has been measured as 4.1 mm.

Figure 9: C-scan image of part 1(b), along with A-scan and F-scan samples from defected (red) and non-defected regions (magenta and black). Top image: photo of sample and defect position (not to scale) along with C-scan correspondence.

In addition to time gate based C-scan images, the A-scan representations from several selected points, both where defect is present and absent, with corresponding F-scan has been presented for each detected defect. In Fig.9, it is clearly seen that the defect response is almost completely zero in both time and frequency domains. In neat parts, complicated time response due to complex material properties, shape, and orientation of transducer focusing. Around central frequency of transducer, two different frequency peaks have been observed.

The investigations where two delamination like defect is present has shown that the two defects consist of different material properties (Fig.10). While small defect has transmitting some part of the ultrasonic wave, the big defect completely blocks the transmission of ultrasonic waves. The neat area of the sample response is similar to the previous cases, where two peaks occurs on frequency spectrum due to curvature and straight focusing.

Figure 10: C-scan image of part 2(c), along with A-scan and F-scan samples from defected (magenta small defect, black big defect) and non-defected regions (red). Top image: photo of sample and defect position (not to scale) along with C-scan correspondence.

The smallest defect has been observed in region part 2(a) has been seen in Fig.11. This defect is coinciding with the defect that is observed in Fig. 7 with pulse-echo method, and reveals the size of third dimension of the defect. A-scan and F-scan results show that there is a significant difference where the inclusion has been possibly placed and the other parts of the region even though the curvature causes big variations in ultrasonic response. It is clearly seen that there is almost no transmission of the ultrasonic wave which characterize the inclusion as not a transmitter nor a reflector (with the pulse-echo measurement results) for ultrasonic waves. Also, it is considered that the defect material...
properties might be similar to big rectangular inclusion in the previous image (Fig. 10).

Figure 12: C-scan image of T-joint contamination, along with A-scan and F-scan samples from contaminated (red and black) and non-contaminated regions (magenta). Top image: photo of sample and defect position (not to scale) along with C-scan correspondence.

Moreover, T joint area has been investigated in order to determine the presence of contamination. Through transmission pulse echo measurements has shown that there is a large rectangular area of contamination on the upper part of the T joint as seen in Fig.12. The A-scan and F-scan results show that the ultrasonic wave is barely transmitted to the receiver end of the system where defect is present. The middle dark part in C-scan image corresponds to the joining part of T-joint and triangular shapes have been observed due to clipping needed during measurement for stability of sample. All sides and parts of the sample has been investigated with ultrasonic immersion tank system. No other defect has been observed on the other parts of the sample with this through transmission and pulse-echo ultrasonic NDT technique. The advantage of the through-transmission ultrasonic immersion compared to pulse-echo is less to have attenuation and defects can be detected irrespective of defect orientation. The disadvantage of this technique is both side access of the sample needed. Also, the information such as multilayer-defect, thickness of the specimen, and the position of the defect in thickness is not possible to obtain by through transmission, however they can be obtained with pulse-echo technique. Also, system capabilities, environment, operator, alignment of transmitter to receiver (for through-transmission), alignment of the object surface to the transducer to avoid scattering as much as possible (for pulse-echo), focusing distance are main measurement aspect that might influence the reliability of immersion tank system experiments.

In this work through transmission method identify five different inclusions. Due to the very low thickness and complex surface geometry of the specimen, through transmission technique is more advantageous than pulse-echo technique for complex shaped CFRP sample.

3.4 Acoustic microscopy

Acoustic microscopy and focused transducer of 50 MHz was used for the inspection of the complex shape object. The set-up of the inspection is shown in Fig. 13.

Figure13: Set-up of the acoustic microscopy
The C-scan of inspected region 1(b) is shown along with sample photo in Fig.14.

As a result, only one biggest defect was detected using acoustic microscopy. The other two delamination like defects in region 2(c) could not be detected because of complexity to focus the signal in the region of interest and signal scattering.

The delamination like defect on the part 1(b) has been observed as multilayer defect via acoustic microscopy (Fig.15).

Figure14: C-scan image of the detected defect on the sample.

Figure15: Series of C-scans of multilayered defect
The factors which can influence the reliability of acoustic microscopy inspection are focus distance, surface alignment, attenuation, and operator. Since for Acoustic microscopy focus distance plays an important role it was difficult to set focus distance at the required position to get reasonable results. However, for the regions, where correct alignment of the ultrasonic beam with the sample is possible, high resolution C-scan images of the internal structure can be obtained via acoustic microscopy.

3.5 X-ray tomography

X-ray computed tomography is the technique to visualize interior features of the object and to obtain digital information of their 3-D geometries and properties of the material [11].

To investigate the CFRP sample the high-resolution computed tomography Rayscan 250 E was used. Characteristics of settings used for the inspection are presented in Table 2.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Number of projections</td>
<td>2 970</td>
</tr>
<tr>
<td>2 Averaging</td>
<td>12</td>
</tr>
<tr>
<td>3 Integration time</td>
<td>666 ms</td>
</tr>
<tr>
<td>4 Voltage</td>
<td>200 kV</td>
</tr>
<tr>
<td>5 Current</td>
<td>600 mA</td>
</tr>
<tr>
<td>6 Voxel size</td>
<td>150 um</td>
</tr>
</tbody>
</table>

The dimensional analysis was carried out with VGStudio MAX 3.3 (Volume Graphics GmbH, Germany). The resulting 3 D tomography image is shown in Fig. 16.

Table 2: System settings.

Figure16: 3-D tomography image of inspected sample

Different cross-section views of the defected regions are shown in Fig.17.

As a result, defective region absorbs X-ray radiation differently. This is because of density variation of defected areas comparing to not defective. Three defects were found using CT technique. The dimension of defects were measured using instruments in the software VGStudio and presented in Table 3.

<table>
<thead>
<tr>
<th>Defects</th>
<th>Length, mm</th>
<th>Width, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Defect in region 1(b)</td>
<td>19.93</td>
<td>20.46</td>
</tr>
<tr>
<td>2 Defect 1 in region 2(c)</td>
<td>12.95</td>
<td>12.95</td>
</tr>
<tr>
<td>3 Defect 2 in region 2(c)</td>
<td>6.85</td>
<td>6.76</td>
</tr>
</tbody>
</table>

Factors affecting the defect detectability in the case of CT are as follows: X-Ray source, detector and mechanical axis properties and stability, operator settings, environment, surface roughness, penetration depth (attenuation), dimension, geometry, material composition and defect material and type.

4. Discussion on reliability and cost analysis

As a result, different number of defects were detected using various NDT techniques. All five inclusions were detected with ultrasonic immersion tank system by using through-transmission mode. The lowest capability to detect inclusions was in the case of visual inspection and acoustic microscopy. The reason behind this limitation is penetration of visual light and non-transparent material in the case of visual inspection. In the case of acoustic microscopy, the complex geometry of the sample is the reason of signal scattering and complexity to focus it in the required depth. Each technique has advantages and disadvantages due to different physical phenomenon. Considering safety, cost and reliability, according to required results the NDT technique should be selected and adjusted. Also, the material properties, geometry, defect type and dimension...
of the structures plays a significant role in the decision making process. 

In Table 5 the detectability of five inclusions, cost of the measurement equipment and the time spent on the measurement and analysis has been shown. The cost estimation for the equipment’s has been done through previous purchases of Ultrasound Research Institute. The overall performance analysis of NDT techniques has been done based on weighted averaging with different aspects of their performance. While the weight of each aspect might change for different industries or research institutes, this table clarifies the important aspects when choosing appropriate technique in order to investigate complex shaped composite structures. Therefore, two different weighted averaging techniques, for research and industry, has been applied to calculate the performance of different NDT techniques. The weight of each variable has been selected as given in Table 4. The formula calculated to find the performance percentage values is given in Equation (1).

\[ P_i(\%) = \frac{w_i \times p_{vi}}{\sum_{i=1}^{n} w_i \times p_{vi}} \]  

(1)

Where the \( P_i \) stands for performance percentage for each NDT technique, and \( i \) is representing each NDT technique, \( w_i \) is the weight of the selected aspect changing from 0 to 1, and \( p_{vi} \) is the percentage values for detectability, cost, and time spent. The sum of weights (\( w_i \)) is equal to one.

| Table 4: Weighted averages of aspects that determines NDT performance. |
|-----------------|-----------|-----------|
| Aspects         | Research  | Industry  |
| Detectability   | 0.8       | 0.5       |
| Cost            | -0.1      | -0.4      |
| Time Spent      | -0.1      | -0.1      |

The results show that the overall performance for immersion TecScan ultrasonic system outperform the other techniques for both research and industrial weighted averages. It should be noted that the cost of the X-ray tomography makes it very disadvantageous in industrial applications. While visual inspection has higher values than acoustic microscopy, technique is very disadvantageous considering it only allows surface defects to be detected. However, one can propose another calculation that considers other aspects of the NDT techniques.

| Table 5: Performance of different NDT techniques. |
|-----------------|-----------|-----------|-----------|-----------|-----------|
| NDT technique   | Inclusions / sizes | Cost of equipment (k=1000x) | Time spent (~hour) | Overall (%) |
|                 | 1(b)       | 2(c)big   | 2(c)small | 2(b)T-joint | research   | Industry  |
| Visual Inspection | \( \checkmark \) | \( \times \) | \( \times \) | \( \times \) | \( \sim 2.8 \text{k€} \) | 2          | 1          | 7.7        | 18        |
| PAUT            | \( \checkmark \) | \( \checkmark \) | \( \checkmark \) | \( \times \) | \( \times \) | \( \sim 12\text{k€} \) | 6          | 5          | 22.4       | 46        |
| Immersion       | \( \checkmark \) | \( \checkmark \) | \( \checkmark \) | \( \checkmark \) | \( \checkmark \) | \( \sim 500\text{k€} \) | 10         | 20         | 37.8       | 67        |
| Acoustic microscopy | \( \checkmark \) | \( \times \) | \( \times \) | \( \times \) | \( \times \) | \( \sim 155\text{k€} \) | 2          | 0.5        | 7.3        | 9         |
| X-ray Tomography | \( \checkmark \) | \( \checkmark \) | \( \checkmark \) | \( \times \) | \( \times \) | \( \sim 1500\text{k€} \) | 12         | 10         | 24.4       | -42       |

5. Conclusions

This paper represents the results of 'student challenge' complex shaped CFRP specimen investigation with different NDT techniques, mostly focusing on ultrasonic inspection. The detectability of defects, along with the size measurements and position has been reported. Five different defects have been detected. Different NDT techniques has been compared considering their detection performance in parallel to cost analysis.

In conclusion, using through-transmission ultrasonic immersion with 15 MHz frequency focused transducers, all four inclusions and contamination in T-joint were detected. Visual inspection results give additional information surface defects such as cracks and impact damage. Using PAUT and X-ray tomography it was possible to detect three inclusions in region 1(b) and 2(c). Therefore, the ultrasonic immersion tank inspection with through transmission of focused transducers is the most reliable technique that was used for investigation of complex shape CFRP sample.

The cost analysis results shows that the importance of interests can affect the calculated performance of NDT techniques. For research field where detectability of defects plays more important role the ultrasonic immersion through-transmission inspection has a higher performance comparing to other methods (Table 5). The following most effective techniques are X-ray tomography and PAUT. In industrial field performance calculations, immersion TecScan inspection has a higher performance as well. The next more effective method is using PAUT. However, X-ray tomography is the worst possible option due to high cost of instrument.

For future task in order to increase the detectability of defects for such complex shape components the immersion ultrasonic through-transmission or pulse-echo inspection in the immersion tank can be improved by developing the system which aligning the surface to transducer by rotating
the sample and inspecting sample at the same time. The surface tracking algorithm has to be developed to control this kind of system. In case of PAUT, surface alignment ultrasonic (SAUL) electronic scan can be implemented in order to improve signal to noise ratio. Also, the C-scan analysis can be obtained by using the encoder for scanning what can give more promising results.

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References


