AUTOMATED DETECTION OF FOREIGN OBJECT DEBRIS IN WOVEN CARBON FIBER LAMINATE AT DIFFERENT ENVIRONMENTAL CONDITIONS

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Abstract

Carbon fiber laminates have great potential in manufacturing parts of high strength and stiffness but are lightweight because of its high strength to weight ratio. Carbon fiber laminates have other advantageous qualities like toughness, high dimensional stability, vibration damping, low coefficient of thermal expansion, etc. To get the best results from these properties, the fibers need to be aligned, straight and very well bonded. The presence of defects, specifically, foreign object debris (FOD) in the form of Teflon, Kapton films, peel-ply strips, gloving material, etc. can compromise the desirable qualities of the laminates, sometimes causing catastrophic failure. This paper presents an automated detection and sizing of FODs with the help of pulse-echo ultrasound testing outside of an immersion tank. This method uses a custom automatic edge detection technique and is highly accurate. The results in the present study show an error less than 0.025" in quantifying the critical dimension for the circular FOD and less than 0.10” for the triangular FOD. Teflon inserts of two different shapes, a nominal 0.50” diameter circle and a 3-4-5 triangle with a nominal 0.50” hypotenuse, were embedded in a woven fiber carbon fiber laminate at different depths. The samples are conditioned and investigated in several different environmental conditions ranging from 5°C to 50°C and from 10% Relative Humidity (RH) to 90% Relative Humidity (RH).

Introduction and Background

Carbon fiber composites are very attractive in manufacturing industries such as aerospace, automotive, medical instrument, marine industry, etc. due to their superior structural properties in comparison to conventional manufacturing materials (see e.g., [1]). In contrast to traditional materials, carbon fiber reinforced composite materials showcase excellent mechanical and thermal properties like high strength to weight ratio, low coefficient of thermal expansion, corrosion resistance, fatigue resistance, high toughness, high dimensional stability, renewability etc. (see e.g., [2]). Again, the woven fabric reinforced composite materials present higher drapability over contours and higher delamination and crack propagation resistance than unidirectional fiber reinforced composites, which improves the machinability and damage tolerance of the final part (see e.g., [3],[4]). The geometrical properties and weaving architecture are also very important for the material properties of the woven fiber reinforced composites [3]. On the other hand, undesirable embedded foreign object debris (FOD) like Teflon and Kapton films, tool components, peel-ply strips, release films, etc. can accidentally be placed into the composite during the manufacturing stage, in-service operations or repair process [2]. These FODs can degrade the mechanical properties and act as a stress concentration or site for crack propagation in the composite material, which can ultimately lead to disastrous failure [2]. So, for safe operation process, identifying and sizing the FODs in carbon fiber laminate is essential.

Environmental conditions can greatly influence the performance of polymer composites. Long-term exposure of high temperature, high pressure, radiation, moisture, saltwater etc. can degrade the mechanical properties of carbon fiber reinforced composites [5]. The introduction of moisture into carbon fiber laminates can weaken the fiber-matrix bond resulting in swelling, debonding and delamination [5],[6]. On the other hand, long term exposure to high temperature can cause topographical damage, chain scission, oxidation etc. and soften the polymer composite, and as a result, can degrade their performance [7],[8]. Cao *et al.* [9] showed that the tensile properties of carbon fiber composites, vastly reduces as a function of increasing temperature. Thus, the study of different environmental effects on carbon fiber laminate is essential to conduct. In addition, knowing the accuracy of any inspection method at various operating conditions as well as for samples conditioned at various operating conditions is essential for industrial acceptance of any new method of part qualification.

Different non-destructive testing methods such as ultrasound scan (UT), X-ray computed tomography (CT), eddy current, thermography, radiography, etc. have been used to detect and assess defects in carbon fiber reinforced composite [10]. Among these methods, the ultrasonic C-scan is the most popular due to its low installation and maintenance cost but at a possible reduction in accuracy [10]. Ultrasound C-scan is a volumetric inspection method which analyzes the transmitted or reflected signals to accurately detect the location and depth of the defects, in this case FODs [10]. Previous work in FOD detection has focused on the latter word, “detection”. In this study, FOD detection is coupled with automatic edge quantification technique to detect and quantify the dimensions of FODs in carbon fiber laminates in several environmental conditions.

Sample Part Manufacturing

For this study, five circular FODs with a nominal 0.50” inches diameter and five triangular FODs of a 3-4-5 triangle with a nominal 0.50” inches hypotenuse has been implemented inside the woven carbon fiber woven composite laminate. After fabrication high resolution microscopy was used to quantify the actual FOD diameter and hypotenuse, and the dimensions were found to be, respectively, 0.497” and 0.495”. The FODs are made of a synthetic polymer called Polytetrafluoroethylene (PTFE), commonly known as Teflon. The thickness of the Teflon strips were nominally 0.002 inches. 22-layer carbon fiber 3K plain weave composites were fabricated by the Vacuum Assisted Resin Transfer Method (VARTM) process. The dimensions of each part containing the circular FOD and the triangular FOD are nominally 7 inches x 3.5 inches with a typical thickness of 0.223 inches as shown in Figure 1.

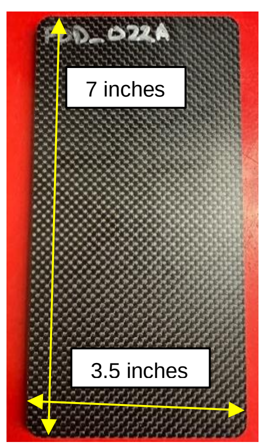

Figure 1: The sample part

After fabrication, the parts are conditioned in five different environmental conditions for a minimum of 90 days prior to inspection, and all inspections are performed in the same environment as the parts were conditioned within. The five environmental conditions are: 1. Lab environment at a nominal temperature of 22°C (72°F) and a nominal 50% relative humidity, 2. Cold-Wet with 5°C (41°F) and 90% relative humidity, 3. Cold-Dry with 5°C (41°F) and 10% relative humidity, 4. Hot-Wet with 50°C (122°F) and 90% relative humidity, and 5. Hot-Wet with 50°C (122°F) and 10% relative humidity. Conditioning was performed in one of four Lunaire environmental chambers and testing was performed in a Tenney environmental test chamber, all of which have temperature and humidity control well beyond the set points requested for the present study.

Ultrasound Scan Setup

A custom immersion C-scan system was built in house to scan the carbon fiber composites. An Olympus FOCUS PX pulser/receiver transducer, shown in Figure 2, in pulse-echo mode was used for the scans. The transducer moves in three directions, x_1, x_2, and x_3 directions, which are controlled by Velmex translation systems, shown in Figure 3. Leveling the parts is also very important to get good scan data. Here, a custom leveling structure is installed inside the immersion tank.

Figure 2: Olympus FOCUS PX system

Figure 3: Velmex system to control the movement of transducer

The full immersion tank ultrasound scan setup is illustrated in Figure 4.

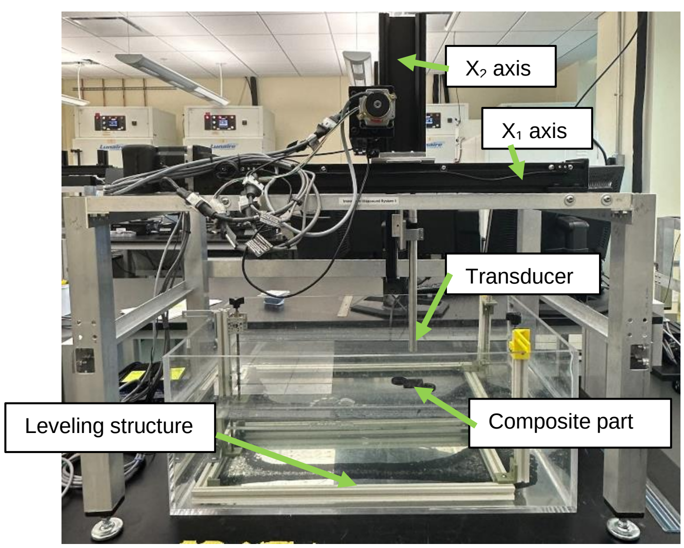

Figure 4: The immersion tank, transducer and translation of the ultrasonic system

Scans From the Ultrasound System

Ultrasound A-scan or amplitude scans are generated when a high frequency ultrasound wave passes through a part and the reflected signal is captured. The A-scan is the representation of a single pulse which is plotted as amplitude as a function of time (see e.g., [11] [12]). Figure 5 represents a plot of the average A-scan and time index, where the first significant peak represents the front wall, and the last significant peak is the back wall. The position of the FOD also can be detected from the A-scan signal, due to irregularities relative to a known signal.

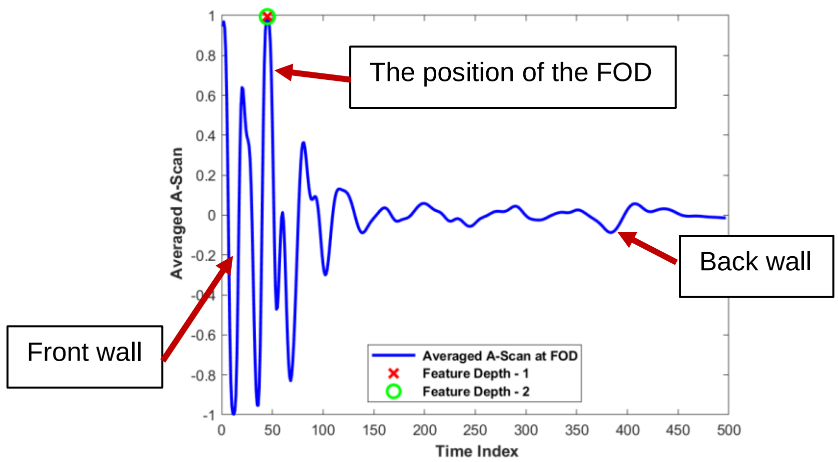

Figure 5: Representative average A-Scan data

Ultrasound B-scan and C-scans are also generated to interpret the material as a function of depth. For example, the amplitude signal at the backwall can be one indication of the FOD dimensions as shown in Figure 6. The depth, size and shape of the FODs can be characterized from, respectively the A-scan for the depth and C-scans for the size and shape. As seen from Figure 6, from the ultrasound data for the detected front and back walls each of the eight embedded FODs can be distinguished. And an approximate estimation of the depth can be identified from the thickness plot shown in the figure. Notice the image shown in Figure 6 has 8 different FOD components embedded. In the present study, only a single circular FOD and a singular triangular FOD is utilized in the analysis, and the remaining data will be part of a future study.

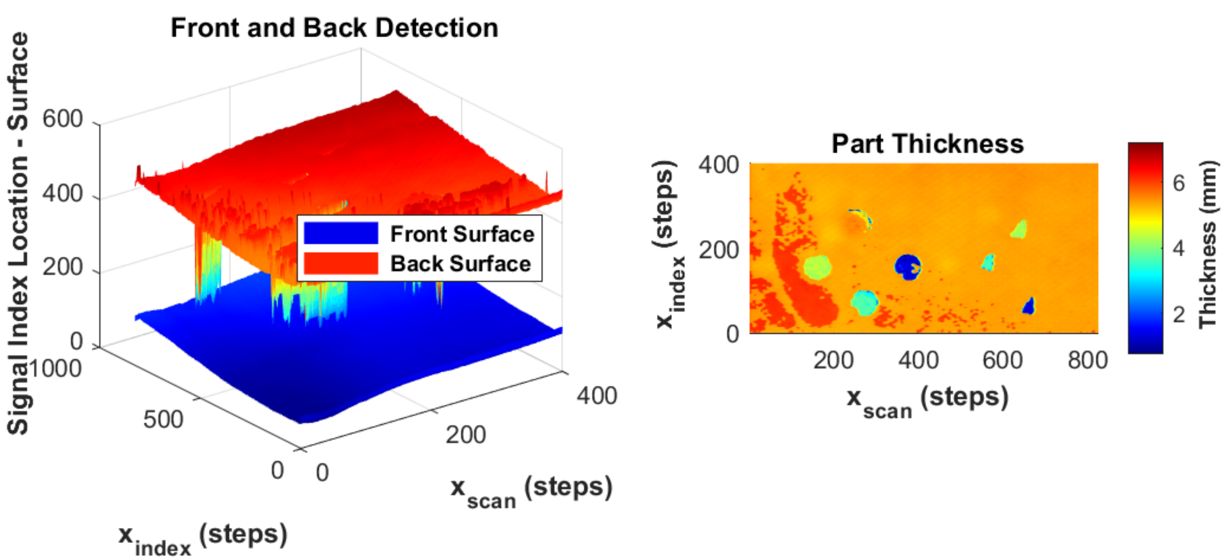

Figure 6: Front wall, back wall and FOD detection

Area Detection of FODs

The area detection of FOD is done by analyzing the reflected ultrasound signals at the depth identified from the average A-scan. The raw ultrasound data is trimmed to extract the approximate subregion containing the FOD as shown in Figure 7. Next the raw data is shifted to a 3D array data as shown in Figure 8 to remove any potential curvature of the part or the inspection system itself.

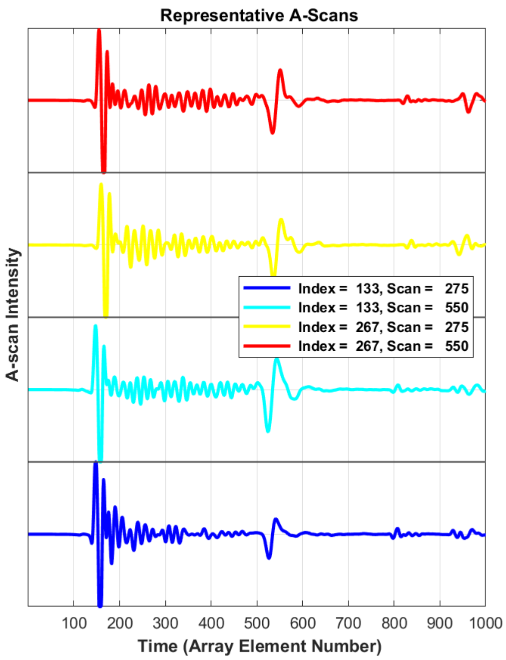

Figure 7: Trimming of raw data

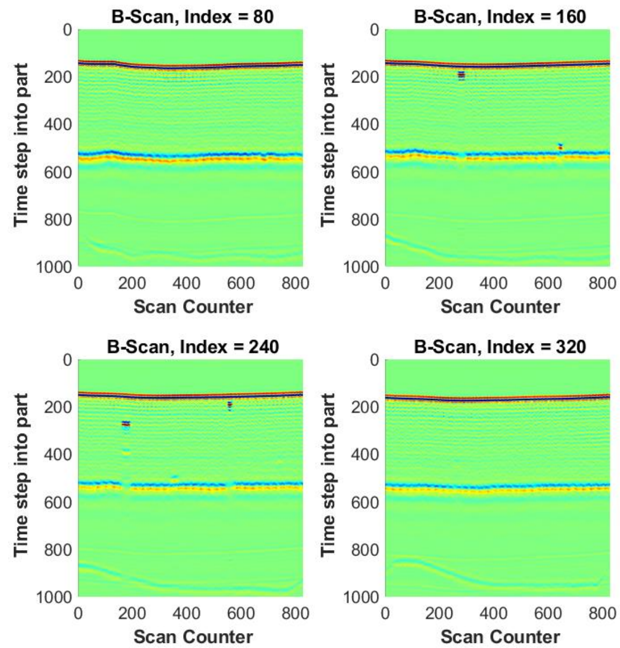

Figure 8: Shifting from raw data to a 3D array

Next, the depth of the FOD relative to the front wall, taken from the differential identified from the average A-scan is shown in Figure 9, where the plane of the FOD is shown in three orthogonal axis for easy visualization of the FOD relative to the part depth. Next the region of interest without and with the FOD is selective, as shown in Figure 10. This differential will be used to specify the depth along with a baseline signal to extract from the FOD region for easier differentiation between noise, such as from the woven fabric, and the FOD itself.

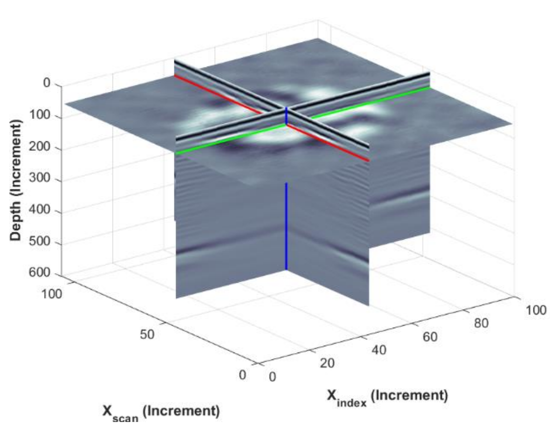

Figure 9: Detecting FOD depth

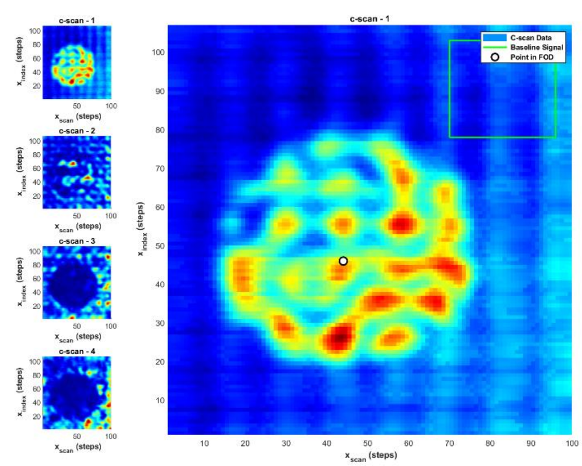

Figure10: Detecting FOD region

The signal for the depth at which the FOD occurs is then filtered as shown in Figure 11. After filtering, the image is binarized and the surface is closed and filled. Finally, the effective area and the effective diameter or hypotenuse is calculated from the binarized data as shown in Figure 11.

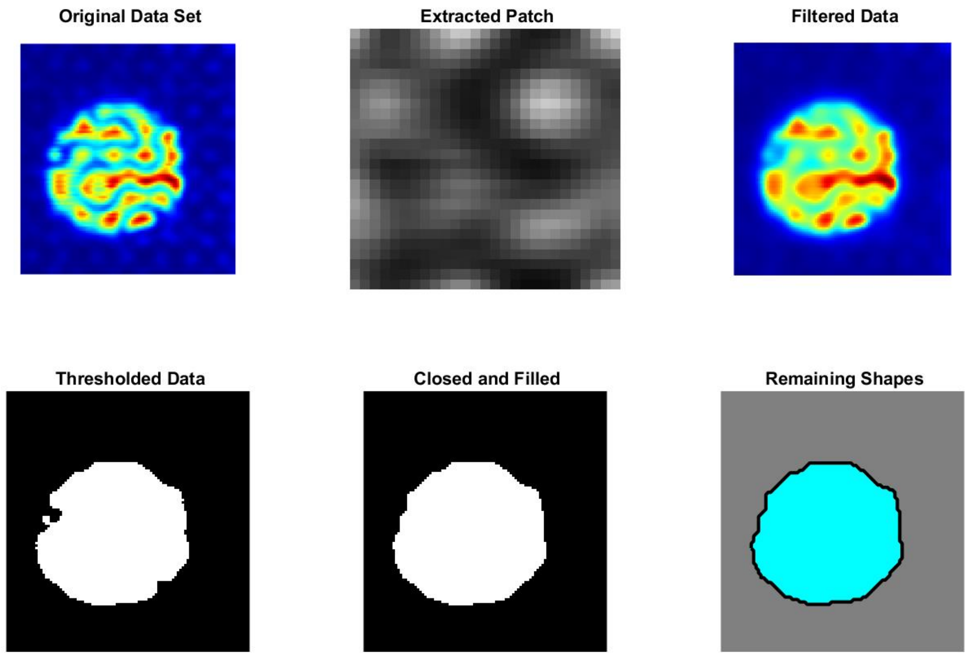

Figure 11: Filtering, binarizing and calculating FOD area

Result

In Table 1 the effective radii of the circular FODs are presented and in Table 2 the effective hypotenuse dimensions are presented. These values are compared against the actual radius (0.25") and the actual hypotenuse (0.5"). Notice that for the circular FOD the error is less than 0.025", whereas standard inspections are focused on detectability. Similarly, the triangular FOD has errors that range from 0.030" to 0.100". The reason for this discrepancy will be investigated in a future study. It is worth noting that the results are all considered acceptable for all environmental conditions. It is interesting to note that the results for the laboratory and the elevated temperature conditions appear to be better than for the cold temperature range, and a future study will investigate this dependence over a larger sample set.

Table 1: Circular FOD in woven carbon fiber laminate

Environmental condition	Area (in^2)	Effective Radius (in)	Absolute error for effective radius (in)
Lab	0.227	0.269	0.019
Clod-Temperature Dry	0.235	0.274	0.024
Clod-Temperature Wet	0.201	0.254	0.004
Elevated-Temperature Dry	0.198	0.251	0.001
Elevated-Temperature Wet	0.196	0.250	0.000

Table 2: Triangular FOD in woven carbon fiber laminate

Environmental condition	Area (in^2)	Effective Hypotenuse (in)	Absolute error for hypotenuse (in)
Lab	0.068	0.533	0.033
Clod-Temperature Dry	0.084	0.590	0.090
Clod-Temperature Wet	0.086	0.599	0.099
Elevated-Temperature Dry	0.074	0.554	0.054
Elevated-Temperature Wet	0.073	0.550	0.050

Conclusion and Future Work

Different environmental conditions can greatly change the mechanical and structural properties of carbon fiber laminates, thus needing extensive research on the effects. Also, the existence of FODs in the composite part can cause catastrophic failure and lead to dangerous operational environment. Pulse echo ultrasound technique can very accurately detect the location, depth, size, and shape of the FODs. The current study presented results from a novel method to automate the feature extraction from the extracted ultrasonic waveforms, and for the circular FOD panels all characterized results yielded a geometry to within 0.025" for the 0.497" diameter features. For future work, a more detailed study for FOD identification as a function of depth as well as over a range of operation temperatures will be studied.

Acknowledgements

Special thanks to Verifi Technologies for funding and supporting this research.

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