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AZIMUTHALLY SCANNED ANGLE-BEAM PULSE ECHO ULTRASOUND FOR CHARACTERIZATION OF IMPACT DAMAGE IN COMPOSITES

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ABSTRACT

Characterization of barely visible impact damage (BVID) in polymer matrix composites (PMCs) is necessary to use slow crack growth damage tolerance models and evaluate remaining life of PMC components. Azimuthally scanned angle-beam pulse echo ultrasound is investigated as a complimentary technique to normal incidence ultrasound inspection of BVID in PMCs to characterize delamination fields. It is found that there is a correlation between signals present in the azimuthally scanned angle-beam pulse echo ultrasound C-scans and transverse matrix cracks seen in X-ray computed tomography inspection. These transverse matrix cracks are not readily identifiable as transverse matrix cracks in normal incidence C-scan inspection.

Keywords: ultrasound, X-ray computed tomography, composites

NOMENCLATURE

AFRL	Air Force Research Laboratory
AZ	azimuthal angle
BVID	barely visible impact damage
INC	incidence angle
NDE	nondestructive evaluation
PMC	polymer matrix composite
RAM	random access memory
USAF	United States Air Force
UT	ultrasonic testing
XCT	X-ray computed tomography

1. INTRODUCTION

For the past several years, AFRL has explored methods to characterize BVID (impact damage that leave little to no visible indication on the surface) in PMC structures using single sided inspection and field level NDE tools. The motivation for this research is to develop characterization capabilities that assist damage tolerant lifing approaches, which are already used by the USAF for metallic structures [1-3]. One approach that has been investigated is angle-beam (a.k.a, oblique angle) pulse echo ultrasound [3-6]. While characterization of the delamination substructure is a primary input for progressive damage models, detecting and characterizing other defects for inclusion in the models, such as matrix cracks, would also improve the model's fidelity.

This work leverages work in ultrasonic polar scan in composites [7, 8] and backscattered ultrasound in composites [9]. Martin and Andrews were the first to recognize the angular dependence of defects in composites using backscattered UT in an azimuthal scan configuration. They imaged a single point as a function of azimuthal angle and plotted the data as a B-scan [10]. To date all the previous work has looked at responses from a single point [7-10] or a single azimuthal angle C-scan [3-6]. This work presents results of characterizing a BVID delamination field with multiple C-scans as a function of azimuthal angle at a constant incidence angle in order to identify and locate defects over a spatial area.

2. MATERIALS AND METHODS

A flat laminate PMC panel was used in this work (Fig. 1). It was fabricated from unidirectional prepreg of IM7 carbon fiber and 977-3 epoxy using a stacking sequence of $[-45_3/90_3/45_3/0_3]_S$. This layup was chosen because there would be fewer impact delaminations, and the delamiantions would be spaced farther apart in the thickness direction than a more typical quasi-isotropic layup, like $[-45/90/45/0]_{3S}$. This was done to make it easier to discriminate the individual delamination and crack

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signals from each other. The panel dimensions were 100 mm x 150 mm x 3.2 mm. BVID was induced in the panel with a 10 J drop impact. Small drops of epoxy were used as fiducial marks. These drops were placed on the top surface of the specimen to ensure the UT and XCT data sets could be registered.

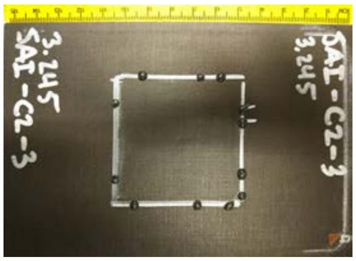

FIGURE 1: PHOTOGRAPH OF THE CFRP PANEL AFTER TESTING SHOWING AN EPOXY DOT AND SILVER MARKER STENCIL PATTERN THAT IS USED FOR COLLECTION AND REGISTRATION OF UT AND XCT DATA SETS.

2.1 X-ray Computed Tomography

XCT was performed using a commercial system (Zeiss Xradia Versa 520). The detector has a resolution of 2000 x 2000 pixels, and 1601 projections per tomograph were collected with a tungsten filament source at 130 kV and 8 W. The stitching features of the system were used enabling 4 tomographs to be collected and stitched together (2 tomographs in the horizontal direction and 2 tomographs in the vertical direction) into 1 final tomograph. The final tomograph was 3768 x 3808 x 3322 pixels and 91 GB. On a workstation with 40 threads and 64 GB of memory the entire tomograph could not be opened without cropping it down first in a pre-processing step. The cropped data set of just the volume of interest was 3768 x 3322 x 365 pixels with a voxel edge length of 15.328 µm resulting in a final volume of 57.76 x 50.92 x 5.59 mm. The exported image stack in 16-bit TIFF file format is 8.5-11.6 GB depending on whether the x-y, x-z, or y-z image stack is saved. Dragonfly Pro (Optical Research Systems) was used for the pre-processing tomograph cropping and TIFF image stack export.

2.2 Ultrasonic C-scans

UT was performed using a custom 5-axis (x, y, z, transducer incident angle, specimen rotation angle) ultrasonic scanning system. The specimen was held in a custom fixture to maintain an air back wall condition, and this fixture is described in [6]. C-scans were performed with a 2.25 MHz, 6.35 mm diameter, 50 mm nominal focus transducer. The inspections were performed in pulse-echo configuration with a 24° incident angle. C-scans were taken at azimuthal angles from 0°-360° in 45° increments resulting in 9 C-scans as a function of azimuthal angle. A C-scan using normal incidence pulse-echo UT was also performed with the same transducer. The transducer position was adjusted to focus on the front wall. Each C-scan contains 16-bit amplitude values in 5120 time point A-scans in a 500 x 500 pixel spatial grid, with a spatial resolution of 0.2 mm and time resolution of 0.004 µs. This produced a 100 mm x 100 mm x 20.48 µs UT data set for each C-scan collected that was 2.5 GB in size when stored as a binary file.

One way to manage the analysis of such large data sets is to utilize memory mapping, a technique in which a map is created to locations in the file on the disk that, in this context, allows operating system-level loading and caching of data while appearing to the user as being completely loaded into memory. This is ideal, since only small chunks of the file are worked with at any given time, but quick and seamless access to data throughout the entire file is needed. Care must be used to ensure the analysis tool, in this case MATLAB (Mathworks, Inc.), does not attempt to copy large segments of the file into memory from the memory map, as this operation by default will create copies using a double floating point data type, which significantly increases the amount of memory required. Furthermore, performance is generally worse than working with the entire data set while stored in memory. However, memory mapping enables fairly efficient data analysis on computers with smaller amounts of available RAM. Development of an automated scheme for segmenting the UT data is on-going.

3. RESULTS AND DISCUSSION

Example amplitude C-scan images are shown in Fig. 2. The normal incidence C-scan, Fig. 2(a), shows the typical petal-spiral shape of impact delamination field in a PMC. Figures 2(b)-(d) show angle-beam pulse-echo UT amplitude C-scans as a function of azimuthal angle. The images in Fig. 2(a)-(d) have been rotated so that the damage fields are in the same orientation for easy comparison. This is also the same orientation as the specimen photograph in Fig 1.

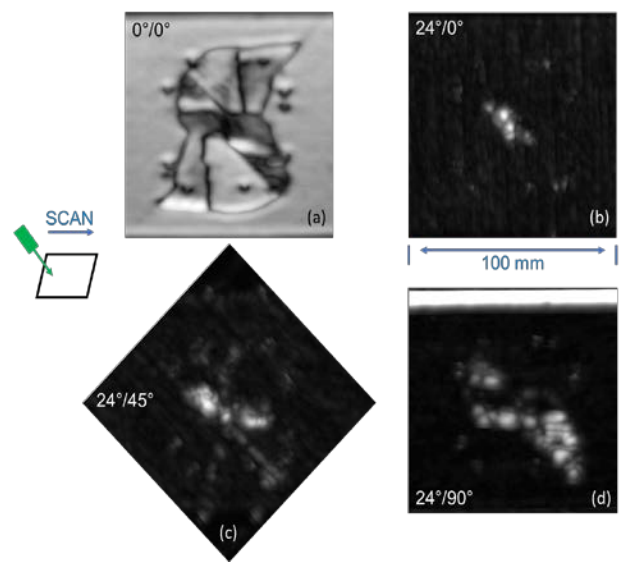

FIGURE 2: EACH C-SCAN IS 100 MM SQUARE. A SCHEMATIC SHOWS THE UT SCAN DIRECTION AND TRANSDUCER ORIENTATION RELATIVE TO IMAGES. (a) NORMAL INCIDENCE C-SCAN, (b) 24° INC/0°AZ, (c) 24° INC/45°AZ, (d) 24° INC/90°AZ

It can be seen qualitatively in Fig. 2(a) that the normal incidence amplitude C-scan detects the interfaces of the delaminations very well. As expected, these planar defects do not appear in the angle-beam pulse echo UT amplitude C-scans. While strong signals from the delamination edge would be expected, these are not present and the reason for this is an open question [6]. The signals that are present correlate to various subregions of the entire delamination field. These isolated signals are likely indications of matrix cracks that travel between lamina connecting a delamination at one ply interface to a delamination on another ply interface. Correlation of the UT signals to the transverse matrix cracks seen in the XCT data is on-going. An example of transverse matrix cracks in the specimen seen in XCT is shown in Figure 3. Delaminations are the dark gray horizontal line features, and the transverse cracks are the dark gray diagonal line features running between the delaminations in the light gray rectangle of the specimen.

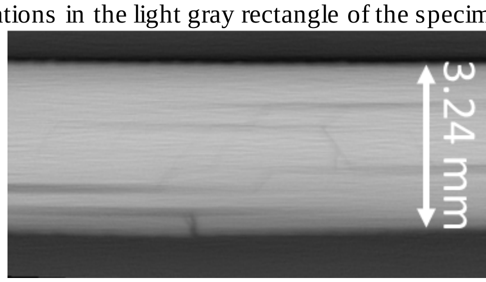

FIGURE 3: XCT IMAGE, X-Z SLICE, SPECIMEN IS LIGHT GRAY RECTANGLE, DELAMINATIONS ARE HORIZONTAL DARK GRAY LINES, TRANSVERSE CRACKS ARE DIAGONAL DARK GRAY LINES

4. CONCLUSION

Angle-beam pulse echo UT as a function of azimuthal angle shows the potential for providing additional information to normal incidence UT C-scans for characterizing BVID in PMCs, specifically information on the presence and location of transverse matrix cracks. While this method was pursued initially to detect and characterize delaminations hidden to normal incidence pulse echo UT inspections, it appears better suited to detection of transverse matrix cracks, another defect of interest to damage prognosis modeling. Combining the information of several angle-beam pulse-echo UT C-scans performed at various azimuthal angles with a normal incidence pulse echo UT C-scan appears to be a readily implementable solution to characterize BVID in PMCs. The ability to characterize BVID delamination fields would enable slow crack growth damage tolerance models to be used to predict remaining component life, and this life prediction capability would eliminate unnecessary repair and replacement of PMC structures.

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