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NANOFOCUS X-RAY COMPUTED TOMOGRAPHY AND ULTRASONIC INSPECTION OF BARELY VISIBLE IMPACT DAMAGE IN CARBON FIBER REINFORCED POLYMERS

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ABSTRACT

Carbon fiber reinforced composites are often used for applications in the aerospace, defense, and automotive industries. To safely engineer these components, non-destructive inspection techniques are necessary for qualification and damage assessment. Nanofocus computed tomography was used to investigate barely visible impact damage in CFRP's and results were compared to ultrasonic inspections. Nanofocus CT inspection revealed details about delamination, matrix cracking, and extent of damage in impacted CFRP's not seen with other techniques.

Keywords: computed tomography, composites, BVID

1. INTRODUCTION

Carbon fiber reinforced polymers (CFRP's) have been the subject of intense interest in recent years for high-performance engineering applications such as those in aerospace, defense, and even automotive due in large part to their high strength-to-weight ratio [1]. However, due to the complex nature of CFRP's, non-destructive evaluation (NDE) techniques are critical to their successful implementation both for component qualification and post-damage assessment inspections [2]. Traditionally, ultrasonic testing (UT) has largely been the NDE tool used for CFRP inspection due to its portability and ability to inspect large regions across the span of the entire structure of interest in a relatively short period of time [3]. X-ray computed tomography (CT), however, offers the ability to conduct full 3D inspections at high resolution (~1-20 µm), but at the expense of portability for in-service inspections and is limited to a component that must fit within a sphere of a diameter on the order of 10's of centimeters. Because of its high resolution and ability to fully image structures both internally and externally, x-ray CT is a useful method for pre- and post-impact in-laboratory inspections of CFRP's for coupons and can serve as a validation of field-portable systems and techniques on equivalent structures.

CFRP's are highly vulnerable to impact damage, the detection of which is critical due to the subsurface damage that can cripple composite structures [1]. Slight damage induced by tool drops during manufacture or repair or other low-velocity impacts can be difficult or impossible to detect using human or machine visual inspection [4] and has consequently been termed barely visible impact damage or BVID [5]. BVID is of increasing interest due to an understanding of the sensitivity of the overall part performance to a local reduction in load capacity due to minor damage. The rapidly improving damage detection abilities of a variety of NDE techniques and the new ability to detect such damage in detail will allow technicians to make in field decisions regarding repair or replacement.

Detailed computed tomography inspection of CFRP's is valuable for validation of more traditional, but lower-resolution NDE techniques such as ultrasonic, thermographic, and vibration-based inspection. Additionally, the large amount of high-fidelity data offered by x-ray CT provides a platform for the intimate understanding of damage mechanisms in composite structures when subjected to realistic in-service impact loads. This information is critical for the accurate modeling of composites during impact damage.

In this study, nano and microfocus x-ray computed tomography inspections were conducted on two impact damaged CFRP samples. Samples were inspected using ultrasonic c-scans before and after impact and subsequently inspected using x-ray CT for a detailed impact damage assessment. Comparisons between the two inspection techniques have been made to further understand the strengths and limitations of both.

2. MATERIALS AND METHODS

CFRP specimens were manufactured with 18 plies in a $[(0/45)_4/0]_s$ layup using a 3K/6oz plain weave. Samples were manufactured in-house at Baylor University using the vacuum-assisted resin transfer method.

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2.1 Impact Damage

Specimens were impacted using a custom drop tower with a 16 mm diameter hemispherical impactor with a mass of 3.85 kg. Impacts of 7.5 J and 9.5 J were induced normal to the CFRP plane in two nominally identical specimens. All impact tests were performed in accordance with ASTM D7136-15.

2.2 Ultrasonic Inspection

Prior to impact testing, both specimens were inspected using an ultrasonic c-scan in an immersion tank equipped with a custom translation system. Scans were conducted using a 15 MHz transducer with a 38.1 mm focal length and a spatial resolution of 0.2 mm/A-scan in both the x_1 and x_2 directions. Ultrasonic waveforms were sampled at 160 MHz using a US Ultratek EUT 3600 pulser/receiver and controlled using an in-house code. Inspections were performed from the tool side of parts to minimize scatter of the ultrasound wave. Following impact testing, damaged samples were scanned using identical parameters. UT data analysis was performed in MATLAB.

2.3 Computed Tomography Inspection

In order to more thoroughly understand the nature of BVID in CFRP's and the damage mechanisms associated with impact damage of composite, x-ray CT inspections were conducted. Samples were prepared for CT inspection by cutting 30 mm x 30 mm samples containing the damage-afflicted zone using a low-speed diamond saw, which was used to minimize damage to the material during the cutting operation. Samples were cut to this size to maximize CT scan resolution and minimize aspect ratio-related artifacts during CT inspection, a significant challenge in composite CT inspection.

CT scans were conducted using two systems. The first is a Zeiss Xradia 520 Versa nanofocus system achieving a resolution of 4.37 µm and the second is a custom NorthStar microfocus system achieving a resolution of 23.6 µm. Prefiltering was used to remove low energy x-ray energy emission and thus decrease beam hardening artifact interference as well as increase the signal-to-noise ratio of the scans in the microfocus system. CT inspection parameters are summarized in Table 1. CT data analysis was performed using Volume Graphics VGSTUDIO MAX 3.2.

TABLE 1: CT INSPECTION PARAMETERS

	Microfocus CT	Nanofocus CT
Number of Projections	2500	3200
Accel. Voltage (kV)	220	80
Voxel Side Length (µm)	23.6	4.37
Prefilter	0.3 mm Cu	None
Scan Time (hr)	1.25	10.75

3. RESULTS AND DISCUSSION

3.1 Ultrasonic Inspection

A comparison of pre- and post-impact ultrasonic inspection results can be seen in Figure 1 at approximately 0.551 mm into the ~3 mm thick specimen, as seen from the tool side.

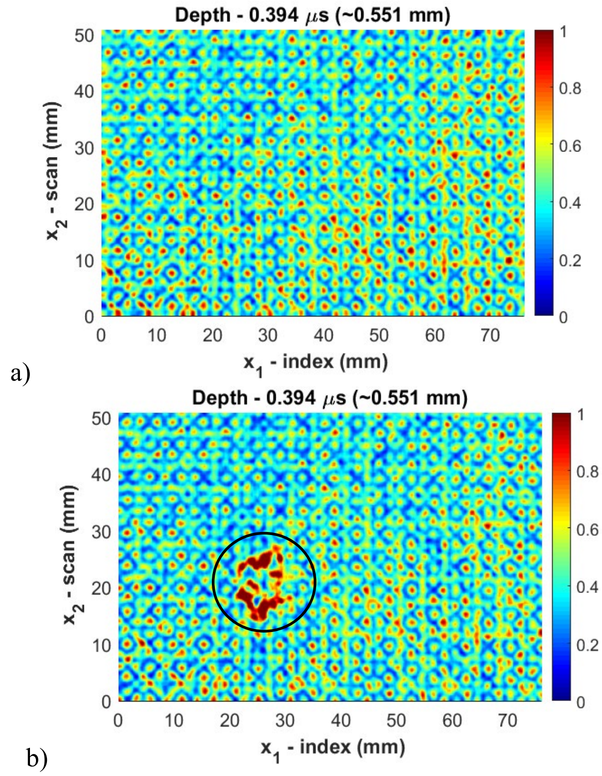
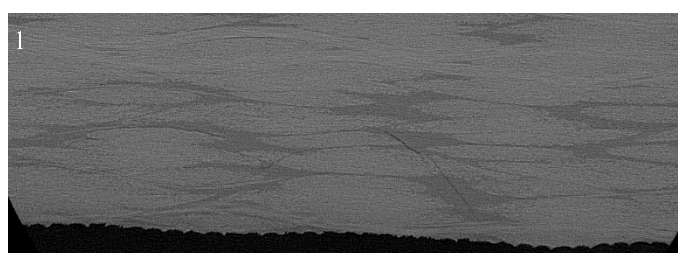


FIGURE 1: A) PRE-IMPACT ULTRASONIC C-SCAN. B) POST-IMPACT ULTRASONIC C-SCAN WITH IMPACT AREA CIRCLED

It is visually apparent that there is impact damage detected in the post-impact ultrasonic c-scan, as highlighted in Figure 1b. Damaged region area was calculated throughout the c-scan for each image and damage areas were calculated for each ply. Ultrasonic damage analysis was conducted in MATLAB.

3.1 Computed Tomography Inspection

Analysis of the collected CT inspection data revealed the presence of delamination and matrix cracking in the impacted CFRP's. Figure 2 shows parallel slices from damage induced in specimen 2. Delaminations are horizontal cracks separating tows of fibers from the resin matrix. Matrix cracks are vertical cracks in the resin matrix. Microcracking shown in Figure 2 could be detected on the Nanofocus CT system but not the microfocus system, emphasizing the challenges present in accurately measuring and inspecting BVID in composites.



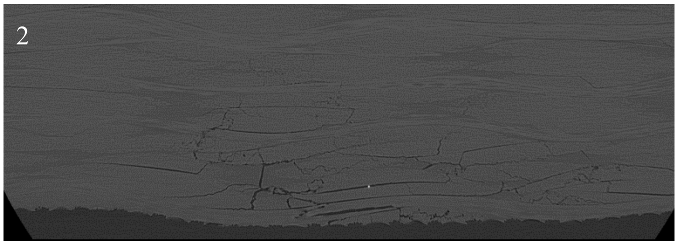


FIGURE 2: SAMPLE 2 NANOFOCUS COMPUTED TOMOGRAPHY SLICES FROM SAMPLES 1 AND 2 SHOW DELAMINATION AND MATRIX CRACKING.

Indent depth, an important measure in composite impact damage, was measured by comparing a virtual plane to the damaged plane of the CT scan. The plane was calculated by using several distributed fit points from un-impacted areas on the surface of the CT data sample. Results are shown in Figure 3 where positive deviations are in excess of nominal geometry and negative deviations are indentations. Figure 3a shows the impact indent to be predominantly circular and 0.088 mm deep at the deepest point. Figure 3b shows positive deviations in red due to surface cracks extending from the impacted area.

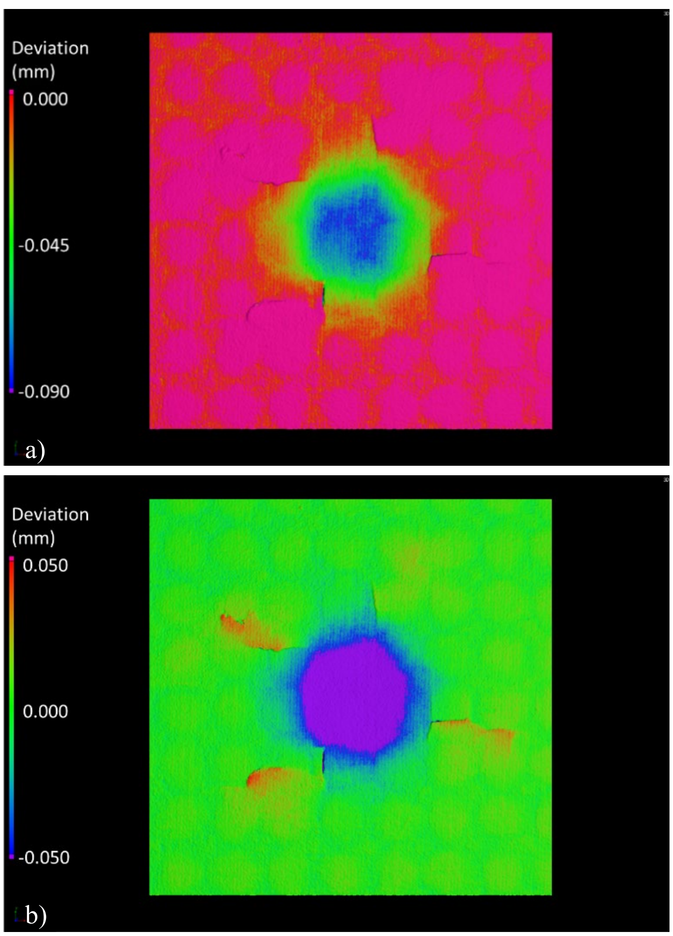


FIGURE 3: DAMAGED REGION DEVIATION MAPPING OF SAMPLE 2. A) SCALED TO SHOW INDENT DEPTH. B) SCALED TO SHOW SURFACE CRACKS

4. CONCLUSION

Through pre- and post-impact ultrasonic inspection and nanofocus computed tomography inspected of damaged CFRPs, both qualitative and quantitative information about the nature of impact damage in carbon fiber reinforced polymers has been determined. Nanofocus CT inspection was leveraged to achieve ultra-high-resolution imaging of barely visible impact damage and provide a detailed understanding of CFRP impact damage as well as providing validation of ultrasonic techniques useful for in-service, large-area inspections of composite structures.

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