CHALLENGES AND PERSPECTIVES FOR NONDESTRUCTIVE INSPECTION AND STRUCTURAL DIAGNOSTICS OF COMPOSITES

Yuri Nikishkov*, Andrew Makeev, Guillaume Seon, Ekaterina Bostaph and Erian Armanios
Department of Mechanical and Aerospace Engineering
University of Texas at Arlington, Arlington, Texas, U.S.A.

Abstract

This work presents some of the most recent technology advances that lead to development of new methods for nondestructive inspection and structural diagnostics of composites. In particular, new developments in structural diagnostics include a fundamental shift in the nondestructive detection of manufacturing defects in composites to accurate 3D measurement of defect location and size with automated transition to structural finite element models. Enabling technologies to allow for such shift, based on X-ray computed tomography, are discussed. The challenges in the nondestructive inspection and structural diagnostics of composites, and the new perspectives to address such challenges at material and structural scales are presented. This work concludes with the assessment of the possibility for breaking through the current limits of X-ray Computed Tomography (CT) in order to enable high-fidelity limited-angle nondestructive inspection of large aircraft structures.

1. INTRODUCTION[1]

Aircraft composite parts are more susceptible to variations in manufacturing processes compared to metal parts. In addition to material variation in the resin content, bulk factor, and fiber alignment, part fabrication process variations such as operator skill, tooling setup, humidity fluctuation and equipment control, are common causes that contribute to variation in part quality. Consequently, the increased sensitivity of composite parts quality to material and process variations lowers their production yields. Production yields of greater than 90% remain a "hit-and-miss" target.

In particular, the effects of inadequate design method and manufacturing process used to produce Carbon/Epoxy and Glass/Epoxy composite aircraft fatigue-critical, flight-critical components, result in defects such as combinations of fiber waviness and porosity/voids, with a significant risk to impact the residual capability and the useful life of these components. Accurate measurements of manufacturing defects are essential for assessment of the effects of the defects strength and fatigue performance of composite structures.

This work presents some of the most recent technology advances that lead to development of new methods for nondestructive inspection and structural diagnostics of composites. In particular, new developments in structural diagnostics include a fundamental shift in the nondestructive detection of manufacturing defects in composites to accurate 3D measurement of defect location and size with automated transition to structural finite element models. Enabling technologies to allow for such shift, based on X-ray computed tomography, are discussed. The challenges and the new perspectives to address such challenges in the nondestructive inspection and structural diagnostics of composites at material scale and structural scale are presented.

One of the objectives of this work includes assessment of the possibility for breaking through the current limits of X-ray Computed Tomography (CT) in order to enable high-fidelity nondestructive inspection (NDI) of large aircraft structures. Currently, strict limitations related to generating X-ray projections all around the inspected object in a full CT scan, prohibit CT application to large structures. The commercial industrial CT systems utilize full 360º projection angle range for high-quality 3D reconstruction of the inspected objects. The ability of the software methods used in such systems to reconstruct the details of the inspected object often becomes unacceptable as soon as the range of projection angles decreases below 180º. Even if the flaws under investigation are small and located in the known areas of the inspected structure, the overall large size of the part can prevent the ability to generate the full range of X-ray projections. This problem also arises when scanning the objects that fit in the CT system but higher magnification of the object details is required due to the small size of defects. Figure 1 shows examples of the two cases. A high-fidelity CT inspection based on a limited, less than 180º, range of projection angles is essential for enabling CT inspection of large structures.

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* Corresponding author, e-mail: yuri@uta.edu.

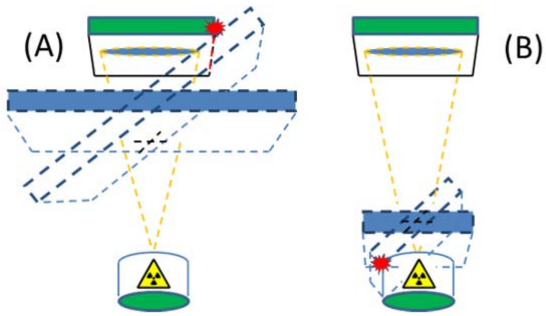

Figure 1. The inspected object can be too large to make a full scan (A) or smaller object cannot make a full scan for the selected magnification (B).

The feasibility assessment will build on the success of the state-of-the-art medical tomosynthesis systems that enhance digital radiography [1]. Specimen internal details barely recognizable in a single X-ray radiograph can be enhanced by additional X-ray projections, which are reconstructed to a stack of slices dramatically improving the depth perception. However, the slices generated in medical tomosynthesis are too thick for the industrial applications. We explore the potential for the development of reconstruction algorithms enabling higher resolution compared to the medical applications. Such algorithms will be optimized to further improve depth perception of the tomosynthesis by using iterative reconstruction methods capable of reducing noise and refining selected scan qualities. Also, the reconstruction techniques can be further expanded by the implementation of the iterative stochastic reconstruction methods capable of detecting the details (flaws) that cannot be identified by the tomosynthesis technique in relation to composite structures.

2. STRUCTURAL DIAGNOSTICS

Composite parts are susceptible to imperfections due to the variability of the manufacturing processes. For example, non-uniform curing pressure is responsible for material irregularities including a combination of fiber waviness and porosity [2, 3]. The presence of such manufacturing defects at critical locations might significantly reduce strength and useful life of composite structures [4, 5]. Moreover, addressing one type of defect may not result in overall improvement, e.g. lower curing pressure reduces the fiber waviness but increases the porosity content. An accurate characterization of defects in the structural models is key to assessing their effects on structural strength and durability. Three-dimensional nature of manufacturing defects in composite structures makes it essential to shift from just detection to accurate 3D measurement of the defect location and size [2 – 5].

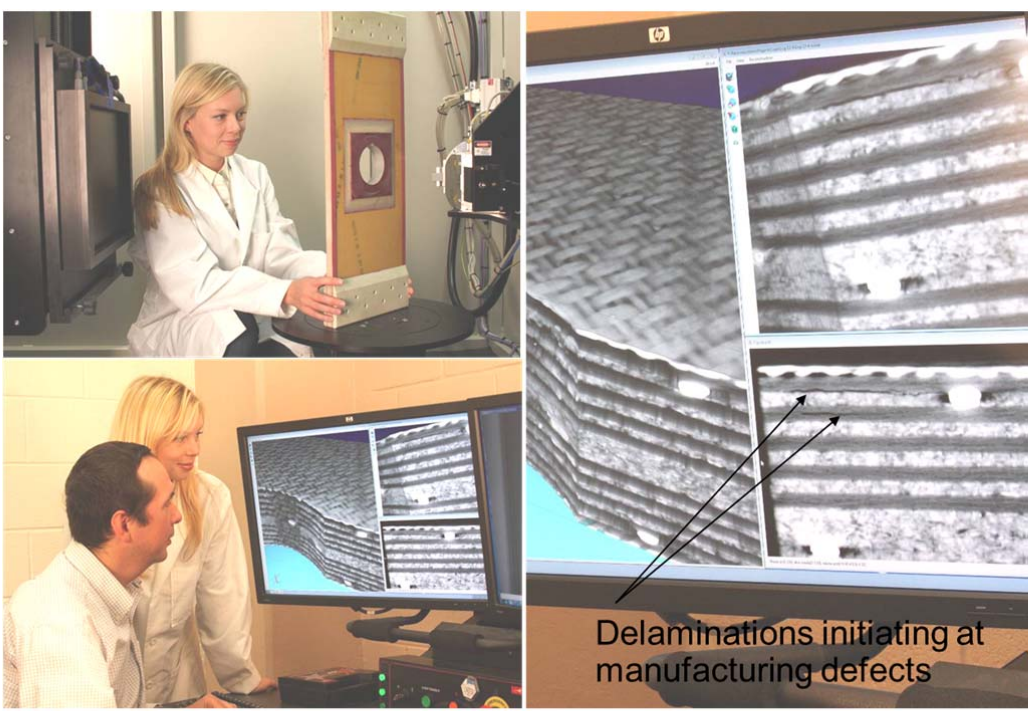

Figure 2. CT scan setup and reconstruction results for a composite element.

This section summarizes some recent advances in structural diagnostics, including a fundamental shift in the nondestructive detection of manufacturing defects in composites to accurate 3D measurement of defect location and size with a potential for automated transition to structural FEMs. In particular, technologies enabling such shift can be based on X-ray computed tomography. Micro-focus CT has been adequate for measuring manufacturing defects including fiber waviness and porosity/voids; as well as structural damage such as cracks and delaminations, in material testing coupons and composite structure articles of limited size [2 – 8]. A North Star Imaging X5000 industrial CT system with a 225 kV micro-focus X-ray tube has been successfully used at the University of Texas Arlington (UTA). Figure 2 shows a scan setup at the UTA CT facility, and reconstruction results for a composite element.

The object size limitations of industrial micro-focus CT scanners restricted pertinent efforts to the development of relatively simple test specimens that could be used across the industry for characterizing manufacturing defects in composites; and to the development of analysis techniques for capturing the effects of defects on structural performance [9]. Furthermore, stochastic methods which infer the distributions of defects large composite structures, and isolate their effects could be instrumental for understanding the effects of the defects in the large structures.

An ultimate goal of composite aircraft manufacturers is the ability to design and build a composite part to specifications the first time. Major challenges to achieving such goal include the susceptibility of composite parts to variations in the manufacturing processes, and unknown manufacturing irregularities as well as their implications. Currently, yields of greater than 90% remain a “hit-and-miss” target even at the production stage [9]. Once adequate structural diagnostics technologies integrated with the comprehensive structural analysis tools for predicting strength and life of large composite structures are available to the designers, such enabling technologies will facilitate better design and improved manufacturing through a shift from relying on the traditional time-consuming trial and error experimentation loops and empiricism in design, to efficient diagnostics and prognosis methods.

The analysis of full-scale structural components such as a composite spar or a yoke of a helicopter rotor system, is a standing challenge. The following example of a composite element shows potential for prognostics. Composite elements, more than two feet long and 0.5 in. thick, with a lay-up representative of a yoke structure, have been manufactured by Bell Helicopter Textron. The elements had a hole pattern simulating attachment to the rotor hub; and were subject to bending and shear (flapping) loads representing dynamic loading conditions. Some flapping elements had seeded flaws. Reference [5] describes the automatic structured FE-mesh generation methodology integrated with the CT based measurements of defects in the flapping elements; and provides the structural analysis details.

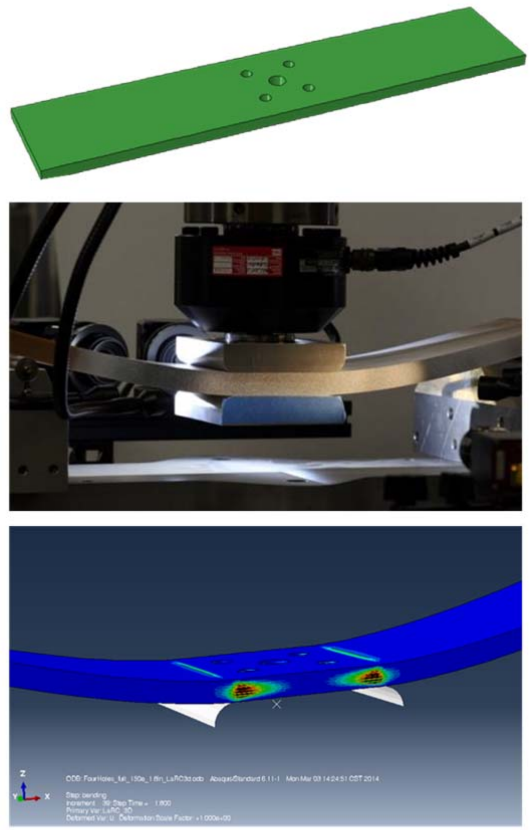

Figure 3. The flapping element test setup.

Figure 3 shows the flapping element test setup; Figure 4 shows the topography of the seeded flaws determined from a CT scan; and Figure 5 compares the FEM-based fatigue failure predictions with fatigue test data for a carbon/epoxy composite flapping element.

Delamination failure location has been captured for static and fatigue IM7/8552 carbon/epoxy composite flapping elements. The failure load prediction has been 99% accurate for a static flapping element without seeded flaws, and 95% accurate for a static element with the flaws included in the structural simulation. Cycles to failure prediction has been 80% accurate for another flapping element with flaws, tested at constant amplitude fatigue loads with a 0.1 load ratio.

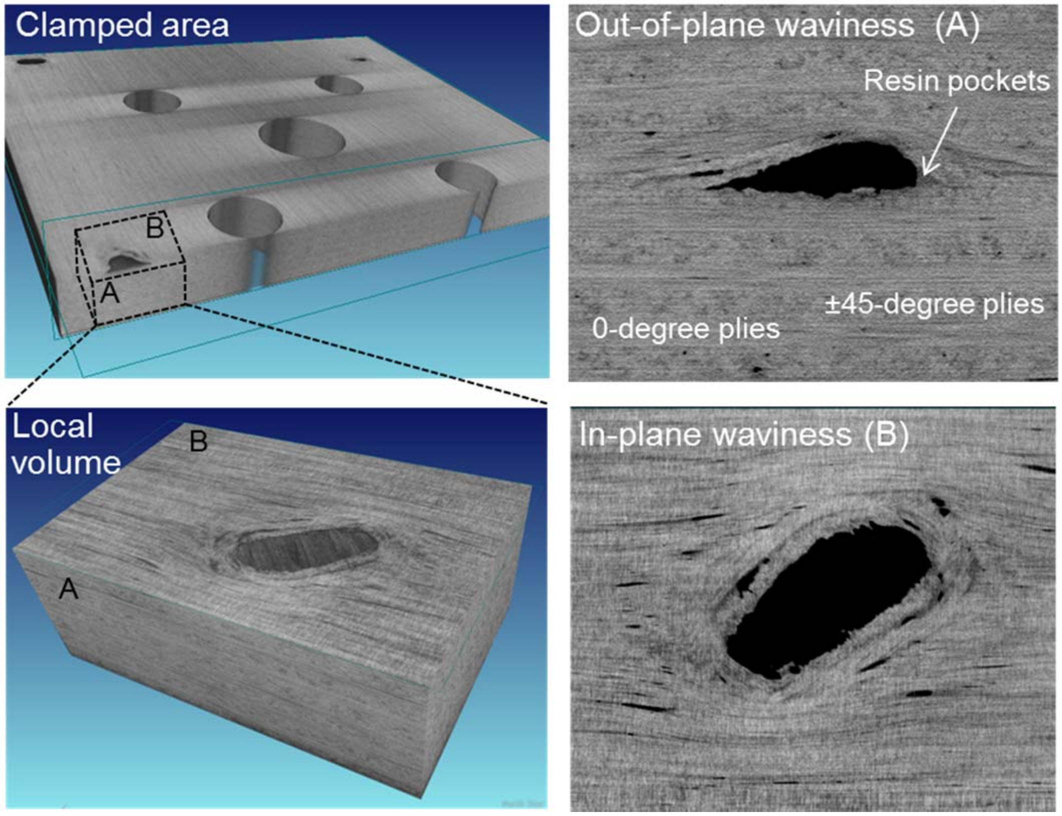

Figure 4. Topography of the seeded flaws.

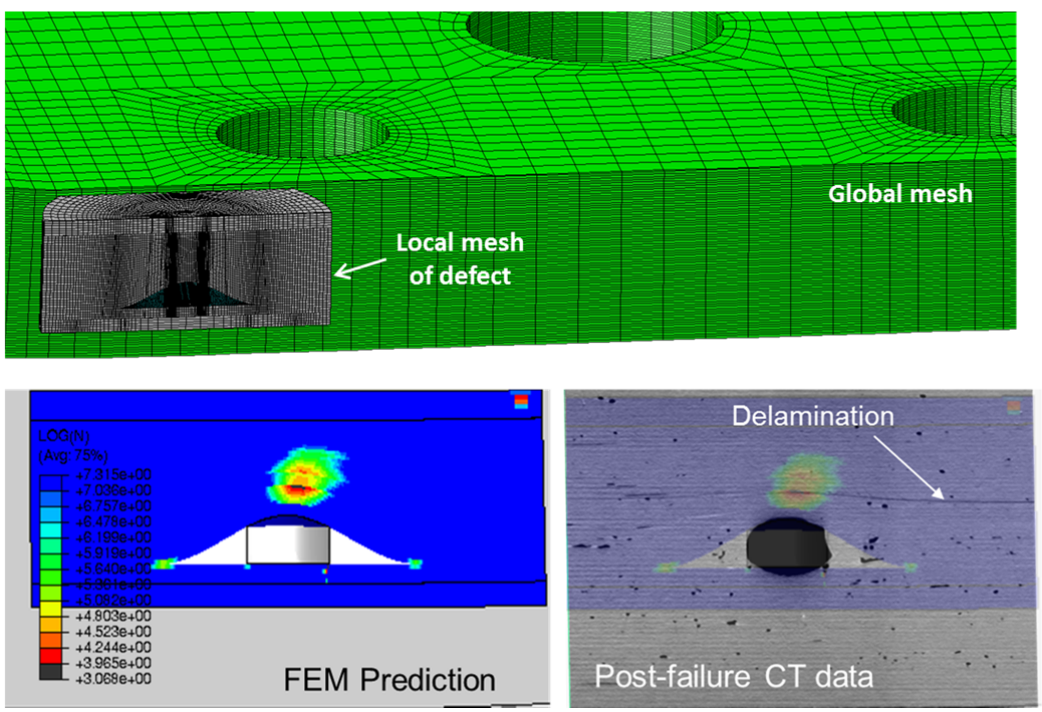

Figure 5. Comparison of the FEM predictions and fatigue test data.

It is worth noting that the fidelity of the nondestructive inspection (NDI) needed to quantify the smallest defects that would impact structural performance is key to structural diagnostics of aircraft composite parts. However, the fidelity of NDI required to understanding manufacturing of production composite parts is not yet adequate. Current work on smaller structural details is useful in identifying technology gaps and motivating the development of the higher-resolution NDI technology appropriate for large structures [9]. In particular, recent improvement in computing power and advances in X-ray CT reconstruction make it possible to develop high-resolution limited-angle CT technology breaking through the object size limits of X-ray CT in order to develop high-fidelity NDI of large composite aircraft structures. A focused R&D effort, starting with the development and demonstration of the algorithms and software required for enabling high-resolution partial CT capability to handle large composite structures, has a strong potential for enabling much needed efficient and accurate NDI products, and better understanding of the manufacturing processes and failure mechanisms.

3. LIMITED ANGLE TOMOGRAPHY

Photon transmission tomography problem has been extensively studied since 1970s. A historical review on the research in the field can be found in [10]. Presently, the CT reconstruction methods are typically divided in the two categories: analytical and iterative. Analytical methods are superior in terms of performance and are most commonly used for commercial transmission tomography systems, both medical and industrial. Iterative methods are capable of higher quality reconstructions due to more precise modeling of the tomography problem but at the significant performance penalty. However during the last decade, due to improvements in both computer hardware and reconstruction methods, iterative and statistical methods have started to gain more prominence and their implementations are now marketed in X-ray Computed Tomography systems by GE Medical and Siemens [11]. Limited angle tomography (LAT) based on combination of analytical and iterative reconstruction methods is implemented in medical devices [1, 12].

Tomographic reconstruction from limited projection angles was recognized as important problem from the 1980s. In principle, perfect reconstruction from an infinite set of limited angle tomographic data is possible [13]. In practice, due to being extremely ill-posed, LAT reconstructions are very sensitive to noise in measurements. Recent advances in X-ray systems such as increased detector resolutions may help to improve noise sensitivity by allowing high number of projections in LAT reconstructions.

The first practical proposals [13] were based on completing missing data in the projection (sinogram) space and using variations of filtered backprojection (FBP) algorithm to reconstruct the object. For the FBP-type algorithms it has been shown [10] that the minimum number of viewing angles required for the full reconstruction is 180 degrees for the parallel projection system and 180 degrees plus cone angle for the cone beam projection system. These methods were shown to successfully reconstruct low frequency contents of the scanned object but not the sharp boundaries between the phases (high frequency contents). In 1993 Quinto has shown that sharp discontinuity is reliably recoverable only if available projections contain rays tangent to the curve that represents a discontinuity [14]; otherwise the discontinuity cannot be reconstructed by any algorithm based on the projection data only.

Non-local transforms define the requirement for the range of views for the analytical methods. When smaller number of viewing angles is used, the analytical reconstruction methods show quick deterioration of reconstruction quality. Analytical methods are derived in the assumption of ideal properties of tomography system such as point source, uniform detector response, and white (unspecific) noise in projections. Any specific knowledge on the system properties as well as knowledge on the data properties is not easy to incorporate in the solution as most of this knowledge cannot be expressed as convolution operator in Fourier space.

Statistical reconstruction methods brought new interest to LAT due to improved ability to include system knowledge, noise approximations and prior knowledge on the scanned data. Statistical inversion based on total variation prior was shown to yield more realistic and sharp reconstructions for limited angle dental CT scans as compared with tomosynthesis slices [15]. Methods based on wavelet expansion and statistical inversion [16] and curvelet expansion with technique for sparse regularization [17] allowed improved reconstructions of discontinuities in LAT. The latter method concentrated on optimization of the technique by excluding discontinuities unobservable by Quinto. Finally, a method of nonnegative modeling of X-ray attenuation as equilibrium solution of a nonlinear evolution equation analogous to the equations used in level set methods has shown smaller reconstruction error and better performance comparing to FBP and algebraic methods in dental tomography application [18].

A reconstruction of the arbitrary object with a limited number of projection angles cannot be always accomplished with the adequate quality. In fact, the general reconstruction method (i.e. a method that does not use prior knowledge of the scanned object) has well known limitations in reconstructed features given the limited number of viewing angles [19]. Therefore, a successful reconstruction method for limited angle tomography must use as much prior knowledge on the reconstructed data as possible; and include data modeling that is especially targeted for special combinations of scanned object geometries and material compositions.

4. IMPROVED RESOLUTION OF FAILURE DETAILS IN FALPPING ELEMENTS

The flapping element structures introduced in section 2, made of Glass/Epoxy and Carbon/Epoxy materials, were considered for the LAT scan application. For both materials, the general 360° scan of the clamped hole area of the specimen was accomplished after structural test to determine the location of delamination surface with respect to seeded voids. The 360° scan with higher magnification (close-up, Figure 6A) was then performed for the seeded defect that led to failure.

By taking advantage of the fact that the seeded void was located at the edge of the specimen, we placed the specimen on the rotating table such that the seeded void was at the minimum possible distance from the X-ray source. Since the seeded void is located close to the specimen edge, the flapping element can make a rotation of 180° during the scan (Figure 6B). As noted in section 3, for the cone beam system configuration, the rotation of 180 degrees constitutes the LAT scan. Such setup allowed increasing the geometric magnification to 23.5x for the Glass/Epoxy specimen which is 2.4 times higher compared to the geometric magnification of the close-up 360° scan of the seeded void and almost 8 times higher than the magnification of the overall scan of the clamped area. The geometric magnification of the LAT scan of the Carbon/Epoxy specimen turned out to be even higher because of the smaller dimensions of seeded void. The area of interest was zoomed in by 46x versus 9.5x in the close-up 360° scan. Tables 1 and 2 show X-ray scanning technique parameters for the full and LAT scans of the flapping elements for glass/epoxy and carbon/epoxy respectively.

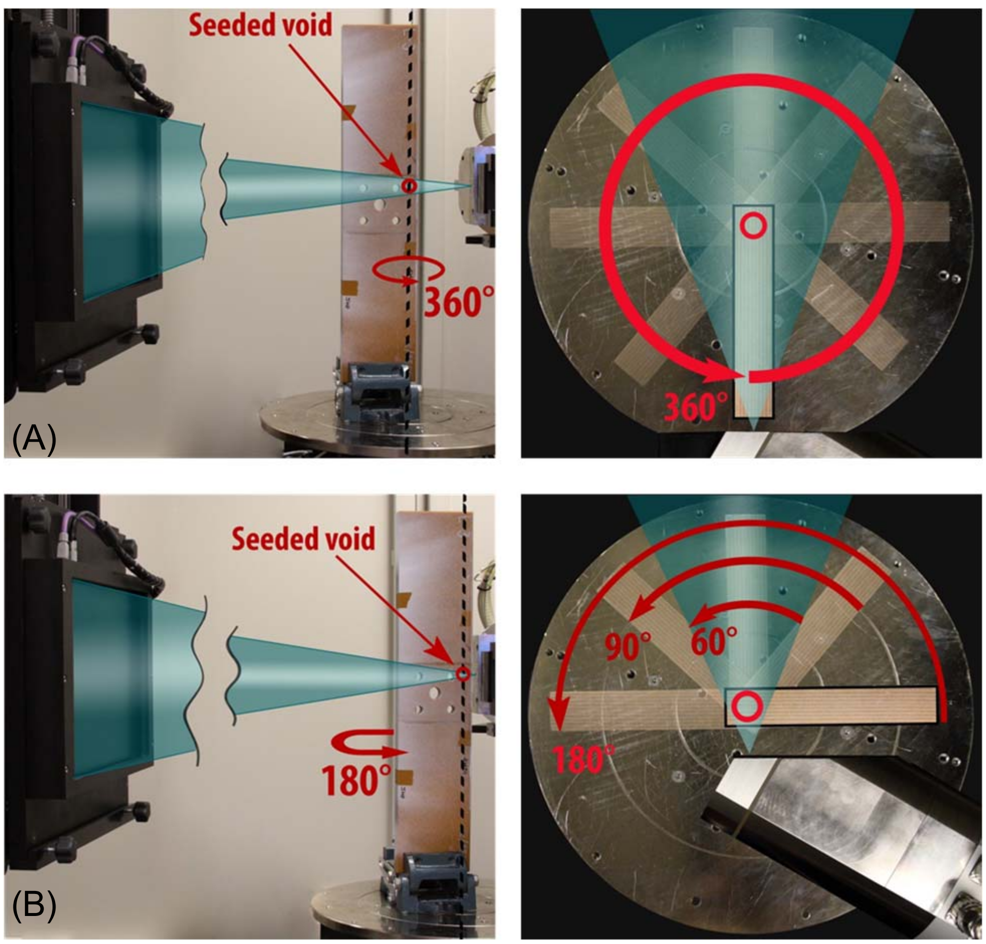

Figure 6. The close-up scan of a seeded void in a glass/epoxy flapping specimen is performed for a full 360° rotation (A) and for a 180° range (B). Magnification of the 180° scan is 2.4 times higher than of the 360° scan.

Table 1. Parameters of the full and LAT scans of Glass/Epoxy flapping element

Flapping Element Glass/Epoxy	Tube voltage, kV	Target current, μA	Speed, frame/sec	Magnification	Voxel resolution	Step, deg	Number of projections
Full scan 360° range	180	139	2	9.8x	0.51×10^{-3} inch (13 μm)	1/4	1440
LAT scan 180° range	180	139	1.2	23.5x	0.21×10^{-3} inch (5.4 μm)	1/6	1080

Table 2. Parameters of the full and LAT scans of Carbon/Epoxy flapping element

Flapping Element Carbon/Epoxy	Tube voltage, kV	Target current, μA	Speed, frame/sec	Magnification	Voxel resolution	Step, deg	Number of projections
Full scan 360° range	180	139	2	9.5x	0.53×10^{-3} inch (13 μm)	1/4	1440
LAT scan 180° range	180	139	1.2	46x	0.11×10^{-3} inch (2.8 μm)	1/6	1080

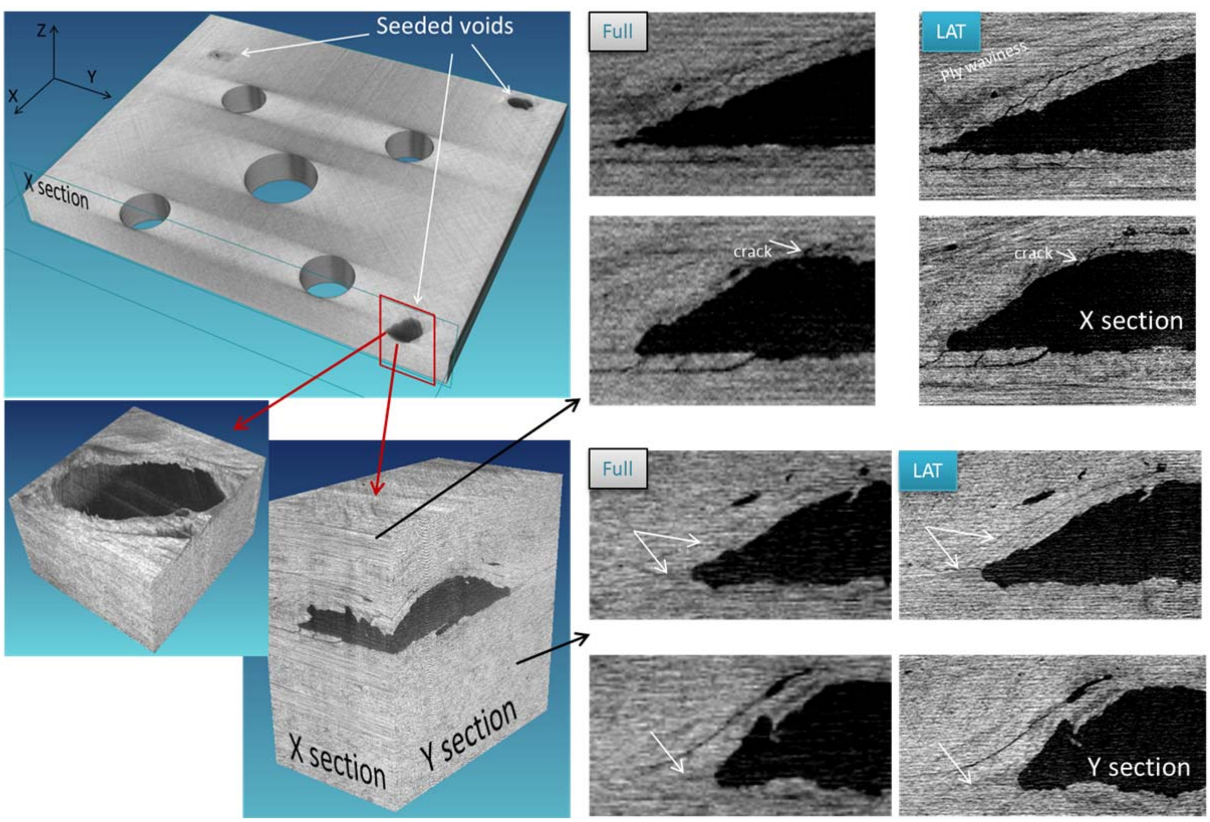

Figure 7. Glass/Epoxy flapping element. 3D view of the clamped area and close-up cross sections of the seeded void and X/Y sections of close-up 360° and LAT scans.

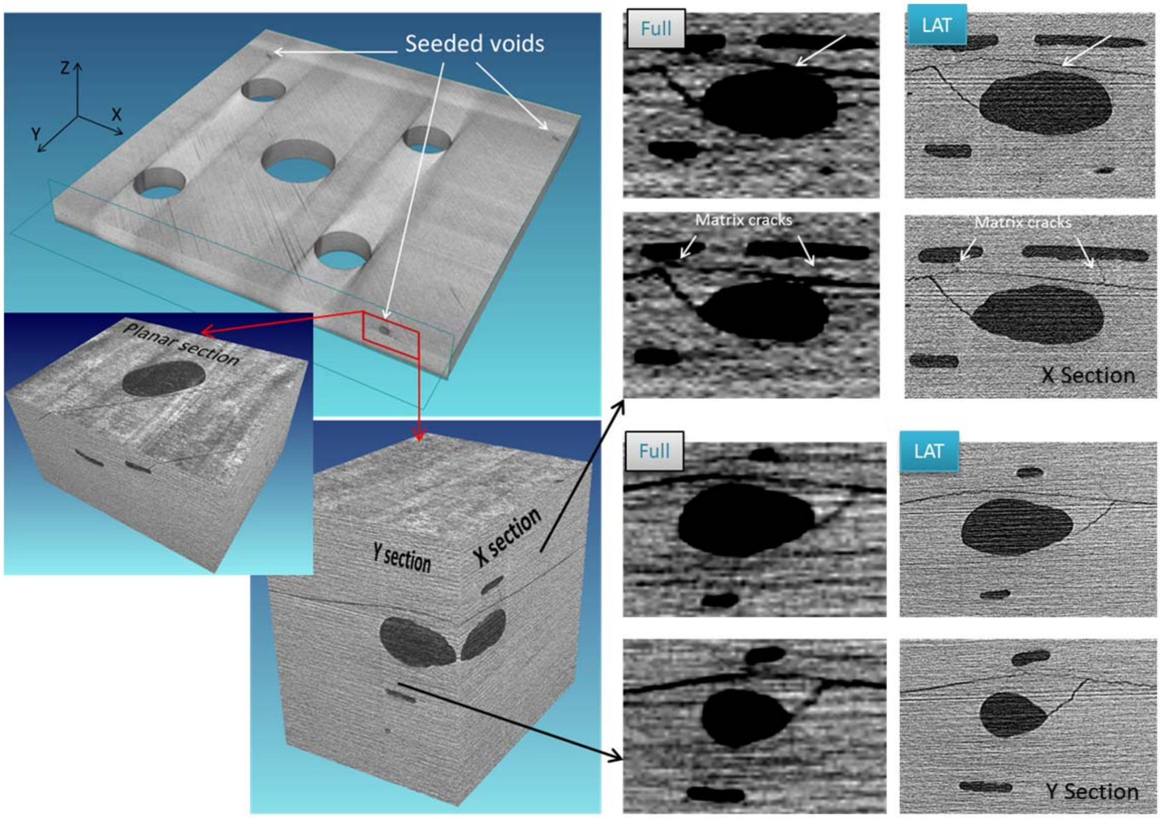

Figure 8. Carbon/Epoxy flapping element. 3D view of the clamped area and close-up cross sections of the seeded void and X/Y sections of the close-up 360° and LAT scans.

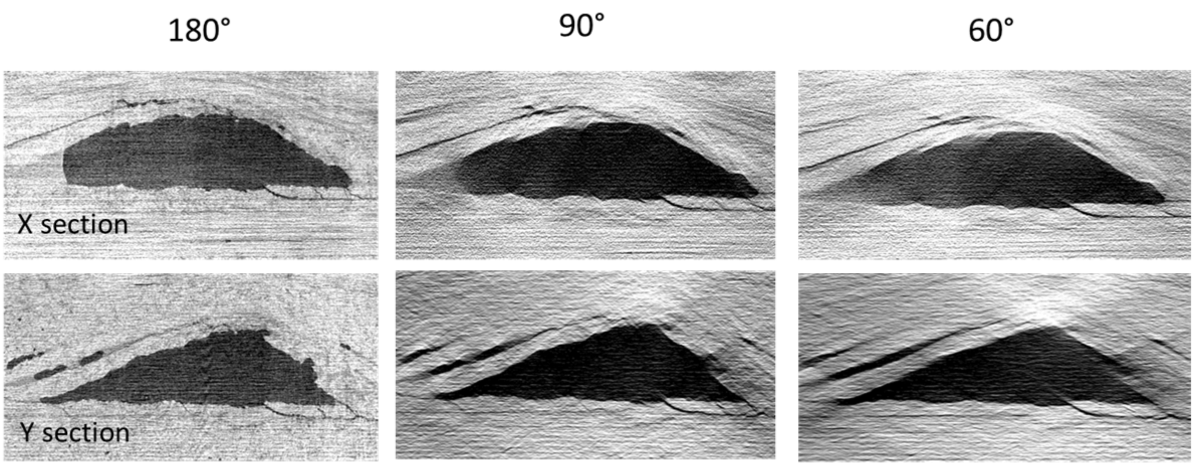

Figure 9. Glass/Epoxy flapping element. X/Y sections of the close-up LAT scans.

The reconstruction of the LAT scan in a 180° angular range demonstrates very fine details due to significant increase in magnification. Sharp details of crack geometry around the void, resin pockets and matrix cracks that were either undetectable or unclear in the local full scan are fully visible in the LAT scan. For example, a horizontal crack that goes through the void at Y section in Figure 7 is not visible in the close-up 360° scan but appears in the LAT scan. Ply waviness can be well detected in the through-the-thickness (X) section of the LAT scan while 360° lacks resolution and contrast required for reliable waviness detection. Delamination crack that follows wavy plies is clearly seen in the X section of the LAT scan (Figure 7) together with matrix cracks that connect it to the surface of the void. The cracks in the LAT scan appear sharply-defined as compared to the lower magnification 360° scan that lacks pixel resolution to clearly resolve the crack geometry.

The LAT scan of the Carbon/Epoxy specimen shows significant improvement in details over the lower magnification close-up 360° scan. Cracks in the LAT scan are sharply defined while in the 360° scan cracks are thicker and sometimes discontinuous. In the 360° scan (Figure 8) the X section shows that the crack goes through the void but the corresponding section in the LAT scan clarifies that the crack is only bypassing it. The 360° scan has some darker areas around small voids that are not observed in the LAT scan due to the LAT scan's improved resolution.

Figure 9 shows LAT scans with further decreasing angular range, as shown on Figure 6, from 180 degrees to 60 degrees. Smaller angular range scans show decreasing sharpness and increasing cross-like artifacts. While overall structure of the void and defects is still visible even on 60-degree scan, fidelity of the details becomes much lower due to increasing artifacts. For instance, automatic reconstruction for 90-degree and lower angular range scans does not seem feasible due to much lower reliability of detail boundaries.

We conclude that the LAT scans for the two flapping elements enabled significantly improved resolution in the reconstruction of the failure details around seeded void. Using LAT scans improves understanding of the complex nature of failure in composite laminates.

5. CLOSE-UP SCAN OF IMPACT DAMAGE IN 12-PLY CARBON/EPOXY PLATE

12-ply Carbon/Epoxy 0.08 inch (2 mm)-thick $[0°/90°]_{3S}$ laminate plate shown in Figure 10 was subjected to an impact load that resulted in the complex sub-surface damage all laminate plies. The purpose of this study is to achieve maximum magnification of the impacted area and demonstrate whether resolving the damage in a structure with large in-plane dimensions compared to the out-of-plane dimension can be improved due to the LAT scan at higher magnification.

First, a full 360°scan was performed. The starting position of the specimen was edge on towards the source of X-ray; after 90° of rotation the plate would be parallel to the detector. The radiographs were taken at each ¼ of a degree resulting in 1440 radiographs for the full rotation. Geometric magnification of the scan was 13X and the 3D reconstruction of the specimen had pixel resolution of approximately 0.37×10^{-3} inch (9.4 μm). The 360° scan is able to resolve the details of the damage that occurred in the part: through-the-thickness matrix cracks and delaminations between the plies. Table 3 shows X-ray scanning technique parameters for the full and LAT scans.

Figure 10 shows the setup of the 360° scan. Larger plate dimensions lead to lower magnification of the impacted area scan, which in turn results in decreased level of detail. An angular range α for the LAT scan that is smaller than 180° enables closer placement of the plate to the X-ray source. The goal of the LAT reconstruction is to increase geometric magnification while maintaining the quality of reconstruction.

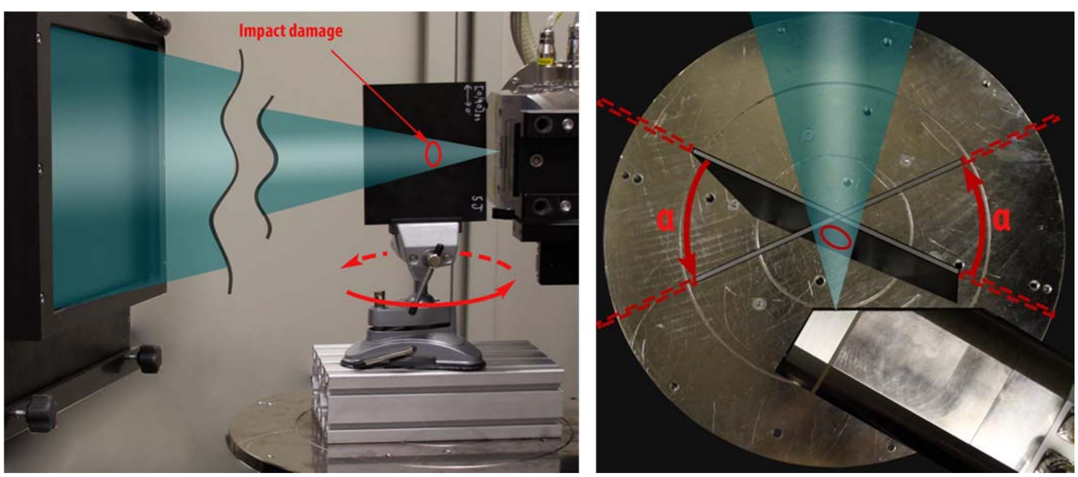

Figure 10. Full (360°) scan setup and area of interest in the center of the plate specimen (image on the left); LAT scan (image on the right): specimen rotation in the angular range α was examined.

Table 3. Parameters of the full and LAT scans of 12-ply Carbon/Epoxy plate

12-Ply Carbon/Epoxy Plate	Tube voltage, kV	Target current, µA	Speed, frame/sec	Magnification	Voxel resolution	Step, deg	Number of projections
Full scan 360° range	40	600	0.7	13.4x	0.37×10^{-3} inch (9.5 µm)	1/4	1440
LAT scan 180° range	40	600	0.5	19.8x	0.25×10^{-3} inch (6.4 µm)	1/6	540

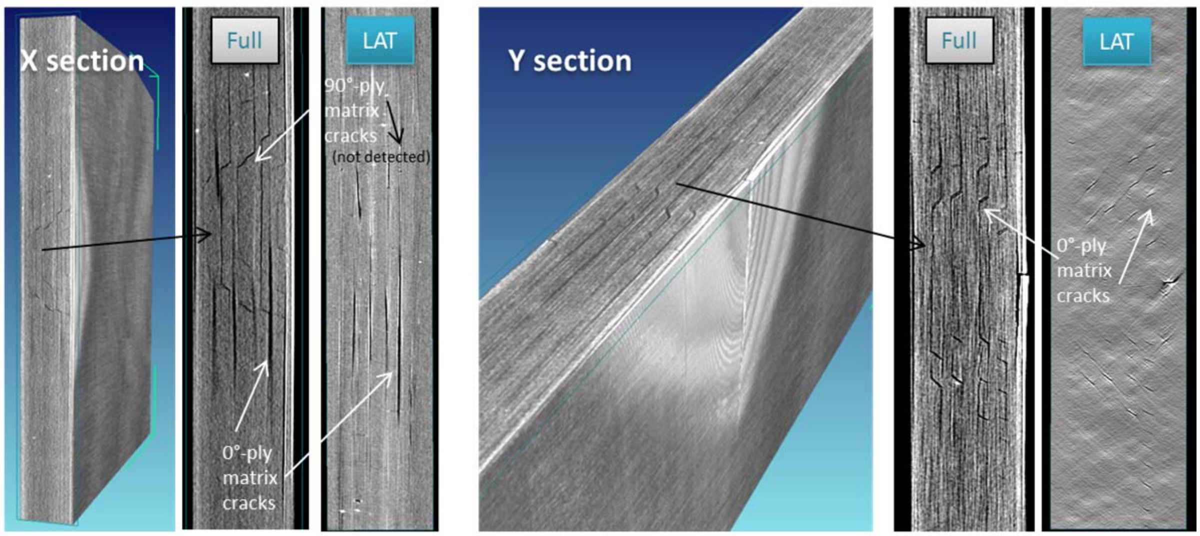

Figure 11. X/Y-section views for the full and LAT scans of the plate with impact damage.

Figure 11 shows reconstructed 3D volume of the scanned area with impact damage. The laminate is oriented such that zero-degree plies are along Y direction and 90-degree plies are along X-direction. While decreasing the angular ranges of the LAT reconstruction it was observed that ply delaminations in Y section and matrix cracks in Z section become undetectable after angle α becomes less than 180°. Smaller range angle α leads to difficulties in interpretation of details and dimensions of the damage. For example, the 3D volume reconstructed from the 160°-scan radiographs of [10°, 170°] angular range does not show 90-degree ply matrix cracks in Z section and delaminations in Z and Y sections while the other cracks are consistent with the full scan. At the 60°-scan angular range [60°, 120°] distortion in Z direction becomes prevalent; zero-degree ply matrix cracks in Y section are still visible, but it's hard to identify their through-the-thickness location. The zero-degree cracks in X and Z section remain visible even at very short angular range.

Based on these observations a 90° LAT scan in the range of specimen rotation from 45° to 135° was performed. The plate was positioned closer to the source as shown in Figure 10. The radiographs were taken at each 1/6 of a degree resulting in 540 projections. Geometric magnification of the new LAT scan was 19.8X, which was 1.46 times higher than the full scan and the 3D reconstruction of the specimen had pixel resolution of approximately 0.25x10-3 inch (6.4 µm). Comparison of the full (360°) and LAT (90°) scans of the impact damage is summarized in the following:

X-section: What appears as good detection of delaminations in the LAT scan, are in fact the zero-degree cracks distorted in thickness (Z) direction. As opposed to delaminations in the 360° scan that remain in the same thickness locations, the vertical lines on the X-section move in thickness direction when the section location is changed. Therefore, the X-section of the 90° LAT scan shows that delaminations and 90-degree cracks are not detectable.

Y-section: Delaminations are not visible in the LAT scan. Zero-degree ply matrix cracks are in good agreement with the full scan. Dimensions in Z direction are distorted leading to difficulties in estimation of precise location of the cracks.

The radiographs of the LAT scan contained significantly more noise, as compared with the full scan. The noise pattern consisted primarily of contrasting vertical and horizontal lines. The above comparison of the full and LAT scans demonstrated that while matrix cracks oriented within the LAT scan angular range can benefit from the increased magnification, the other defects may not be detectable or appear largely distorted. The application of the LAT scan in case of plate geometry therefore requires improved reconstruction algorithms that can utilize the knowledge of the particular damage patterns observed in such specimens.

6. CONCLUSIONS

High-resolution CT-based NDI, enabling the shift to 3D measurement of defect location and size in composite structure, allows for better understanding of the manufacturing processes and failure mechanisms, including the effects of defects.

The results demonstrated in this work increase our confidence in the ability to break through the current limits of X-ray CT in order to enable a high-fidelity NDE of large aircraft structures. Currently, strict limitations related to generating X-ray projections all around the inspected object in a full CT scan, prohibit CT application to large structures. A software technology that uses limited (less than half rotation) number of angular projections can provide accurate X-ray CT capability essential for enabling CT inspection of the large structures. The algorithms used in the existing commercial CT reconstruction software need to be improved by using iterative stochastic reconstruction methods and physics-based system modeling. Efficient and reliable reconstruction software technology is the missing link to high-fidelity limited-angle CT as medical hardware technologies can be expanded to large structures once the appropriate software has been developed.

Enabling technology presented in this work has a strong potential for providing the basis for a reliable and cost-effective structural design methodology for aircraft.

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