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Title: **Quantitative NDE of Composite Structures at NASA**

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ABSTRACT

The use of composite materials continues to increase in the aerospace community due to the potential benefits of reduced weight, increased strength, and manufacturability. Ongoing work at NASA involves the use of the large-scale composite structures for spacecraft (payload shrouds, cryotanks, crew modules, etc). NASA is also working to enable the use and certification of composites in aircraft structures through the Advanced Composites Project (ACP). The rapid, in situ characterization of a wide range of the composite materials and structures has become a critical concern for the industry. In many applications it is necessary to monitor changes in these materials over a long time. The quantitative characterization of composite defects such as fiber waviness, reduced bond strength, delamination damage, and microcracking are of particular interest. The research approaches of NASA's Nondestructive Evaluation Sciences Branch include investigation of conventional, guided wave, and phase sensitive ultrasonic methods, infrared thermography and x-ray computed tomography techniques. The use of simulation tools for optimizing and developing these methods is also an active area of research. This paper will focus on current research activities related to large area NDE for rapidly characterizing aerospace composites.

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INTRODUCTION

In recent years the aerospace community has increased the use of composites in aeronautic and space vehicles. As demonstrated by the Boeing 787's use of composites [1], NASA's Composite Crew Module [2] and in liquid hydrogen (LH2) cryogenic tanks [3], there is a push toward use of composites for primary structural components.

As these composite structures become larger and more complex, nondestructive evaluation (NDE) techniques capable of quantifying and fully characterizing damage are needed. The ability to quantitatively characterize damage in carbon fiber reinforced polymer (CFRP) composite components is required to enable damage progression models capable of yielding accurate remaining life predictions. For example, the depth at which delaminations occur is directly related to how damage growth progresses [4]. Therefore, a 'full' characterization of delamination damage needs to go beyond a quantitative measure of the in-plane area (size) of the damage, to also include the depth/ply at which the damage occurs. For multilayered delamination damage, a full assessment would ideally include the depth and size of all delaminations, if possible. A 'full' damage characterization for other damage types may require different damage information. Microcracking may be best characterized by a measure of microcrack density correlated to depth through the material, while fiber waviness may require a statistical measure of the affected locations and corresponding ranges in the angle of unintended in-plane or out-of-plane alignment/waviness of fibers (i.e., a 'waviness angle' range) [5, 6] .

The challenge of acquiring quantitative NDE damage characterization for aerospace composites is compounded not only by the size of the structure and complexity of the damage types occurring in composites, but also by the complex geometries of composite components required for aerospace applications. The research approaches of NASA's Nondestructive Evaluation Sciences Branch (NESB) include investigation of conventional, guided wave, and phase sensitive ultrasonic methods, infrared thermography and x-ray computed tomography techniques. The use of simulation tools for optimizing and developing these methods is also an active area of research. This paper will focus on research activities related to large area NDE for rapidly characterizing aerospace composites.

INSPECTION TECHNOLOGIES

Flash Infrared Thermography

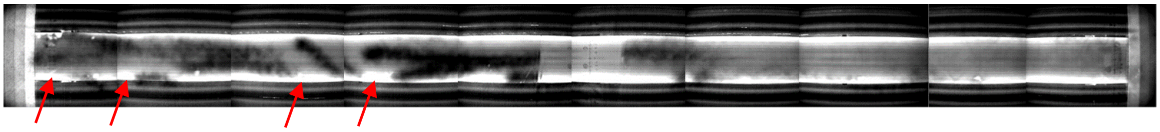
Flash infrared thermography has been used extensively as a large area rapid inspection technology for composite structures. The flash thermography system typically used by NESB is the commercially available Echotherm® system from Thermal Wave Imaging, Inc. The system features a flash hood containing a 640 x 512 element FLIR SC6000 infrared (IR) camera with two 4800-Joule xenon photographic flash tubes. The hood has dimensions of 36.8 cm wide by 26.7 cm deep by 40.6 cm tall and is configured such that the IR camera views the inspection surface directly. The flash produces an energy density of 7.15 joules per square centimeter at the mouth of the hood (based on the final temperature increase of a reference specimen and the nominal thermal properties of that reference). The flash lamps provides a uniform illumination of within 10% across an area of 24.8 cm x 32.7 cm (for a flat reference standard at the mouth of the hood as determined from measurements of the temperature rise of the reference material). The flash creates an initial temperature increase of the inspection surface of less than 10°C. A photograph of the flash thermography system is shown in figure 1.

The hood is connected to a base station which houses the system computer and power sources for the various components. Thermographic inspection is accomplished by placing the hood on the section of material to be inspected. The bottom of the hood completely surrounds or sits atop the material, depending on the dimension of the specimen. The flash lamps are triggered either by operator controls on the hood or by the computer. Thermographic images of the specimen are captured by the IR camera for a predetermined amount of time and stored in the computer for further analysis. The camera's noise equivalent temperature difference, cited by the manufacturer, is 0.025°C. The detector array operates in the 3 to 5 micrometer wavelength range. External optics, consisting of a wide-angle lens (25mm focal length), using germanium optical elements, are used to increase the system field-of-view to 21.7º horizontally and 17.5º vertically.

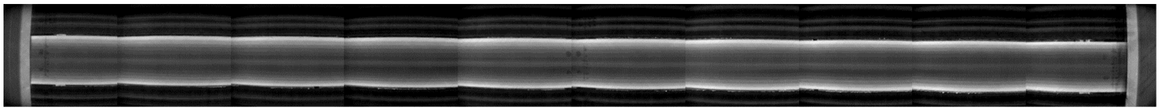
Figure 1b shows an implementation of flash thermography for large area composite inspection. The test specimen is a composite cylinder 10m in diameter and 4m in height, built as 5 panels connected with bonded joints. Inspection of the cylinder required approximately 10 hours per side (interior and exterior) and yielded 250 GB of thermal data. The thermal system is translated over the entire surface of the specimen using a custom scanning rail system that follows the curvature of the cylinder. Data acquisition consists of positioning the camera and hood, triggering the flash heating, collecting data for 15s after the heating, storing the data and indexing the scanner to the next inspection location. Total inspection time per location is approximately 45s. Data analysis was performed using Principal Component Analysis (PCA) with model derived eigenvectors [7, 8]. This approach reduced the processing time per data set (~250 MB) to less than 1s, which is less than the time required to move the camera and hood to the next inspection location. As an example of typical results figure 2 shows a PCA processed mosaic of the inspections results from one of the joints on (2a) the inner mold line of the specimen and the same joint imaged from (2b) the outer mold line of the specimen. The dark regions of figure 2a appear to be areas of excess resin in the joint, while the light regions (a few of which are indicated by arrows) are consistent with areas of poor bonding. The outer mold line results of figure 2b indicates a defect free joint.

(a) (b)

Figure 1. (a) Photograph of the flash thermograph system. (b) System configured for large area inspection of a composite test article.



(a)



(b)

Figure 2. Mosaic images showing PCA processed thermal results for joint number 2 from (a) the inner mold line and (b) the outer mold line.

Line Scan Thermography

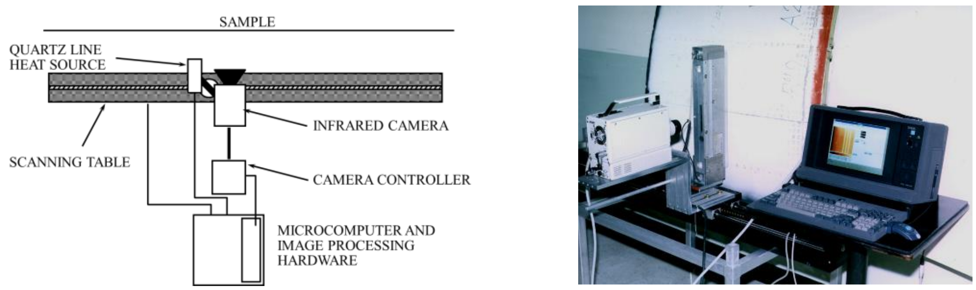
A variation of flash thermography that has shown considerable promise as a large area inspection technique is the Thermal Line Scanner (TLS), a NASA Langley developed quartz thermographic inspection system [9, 10]. This system utilizes a line heat source, typically a commercially available 3000W quartz tube mounted in front of an elliptical mirror which is used to focus the light to a width of 0.6 cm. The heat source and an IR imager (described above) are attached to a commercial linear scanning bridge and translated at a constant velocity while the position of the specimen remains fixed. Quantitative time based analysis requires synchronization between the IR imager, the heat source and the scanning apparatus. This synchronization is achieved by computer control of the application of heat, motion of the scanner and data acquisition.

This implementation enables the rapid inspection of large composite structures. From the output of the IR camera, an image is reconstructed which yields the induced temperature changes at fixed distances behind the line heat source. Because the heat source is a narrow line that is moving, each region of the specimen (corresponding to the width of the line) is only heated for a brief period of time. Since the velocity of the camera is constant during the inspection interval, the fixed distances are equivalent to fixed times after heating and are analogous to data acquired via flash thermography.

This method has several distinct advantages over conventional flash thermography. First, since the IR heater is held close to the object of interest, a more efficient coupling of the energy into the specimen is possible, thus the power requirements are reduced while preserving sensitivity. This method also enables very high inspection rates, for example in graphite/epoxy composites, continuous speeds of 5-10 cm/s can be achieved. An additional advantage is that for some applications a linear array of detectors can replace the IR camera, significantly reducing the cost of the system and the data acquisition and storage requirements.

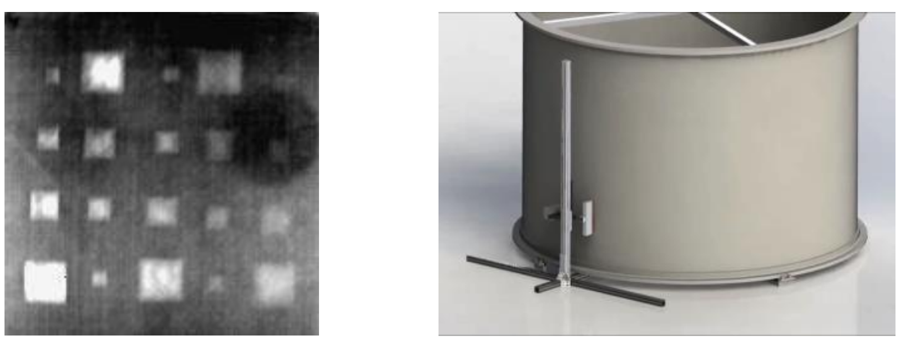
Figure 3 shows a schematic diagram and the laboratory implementation of the TLS scanning an aircraft fuselage specimen. Figure 4a shows the typical results of performing TLS on a 10-ply, 30.5 cm x 30.5 cm graphite-epoxy composite plate with square delaminations at various depths. The size of defects ranged from 3.81 to 1.27

cm. The shallowest subsurface defects were between plies 1 and 2 while the deepest defects were between plies 5 and 6 [11]. Finally, figure 4b shows an artist's conception of the implementation of TLS on the composite cylinder discussed previously. It is estimated that using TLS to perform the inspection of this cylinder could reduce the inspection time by 85% to 90 minutes per side.



(a) (b)

Figure 3. (a) Block diagram of thermal line scanner experimental setup and (b) photograph of laboratory implementation.



(a) (b)

Figure 4. (a) Typical results of inspection of a graphite-epoxy specimen using TLS and (b) an artist's conception of TLS on a large composite cylinder described previously.

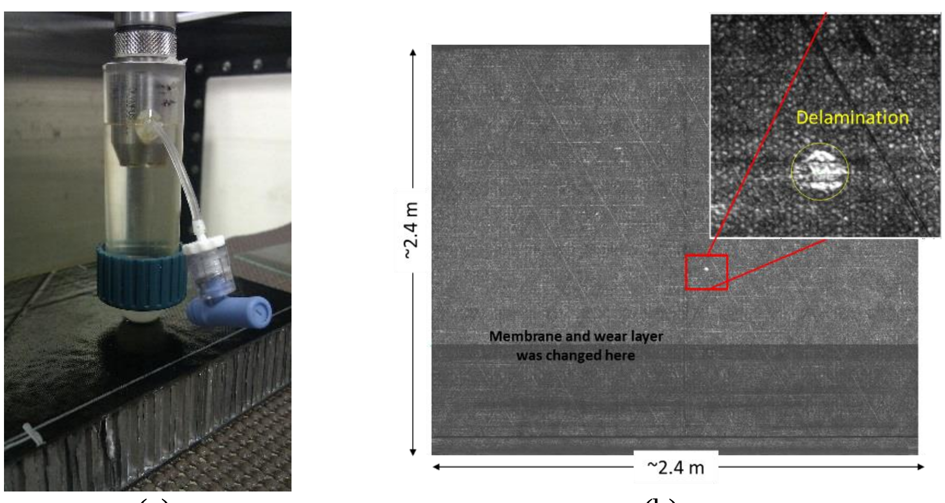
Large Area Ultrasonics

Ultrasound is a valuable technology for the nondestructive inspection of aerospace structures. In the majority of situations, an ultrasonic probe must be coupled to the structure by physical contact. A fluid medium promotes complete coupling of the acoustic wave into the material. Often, solid coupling devices such as stand-offs or wedges provide time delay and incident angle control of the sound waves into the part. Solid stand-offs and wedges can be shaped to match planar and fixed curvature surfaces.

However, ultrasonic coupling problems occur when surfaces deviate from the shape of a solid coupling device. Furthermore, the ultrasonic beam from a contact probe is typically in the near field of the transducer and unfocused. In a given application, the lateral resolution obtained may be inadequate for the required measurement. Therefore, for large area, high speed applications NASA Langley has chosen to implement a captive water column coupling approach. This provides coupling that is similar to an ultrasonic water squirter system without requiring a mechanism for delivering and capturing the constant stream of water

Figure 5a shows a photograph of a single-element transducer with a captive water column. The transducer is sealed into a water-tight probe housing. Water is captured in the probe housing with a flexible membrane selected to produce very little ultrasonic reflection. The membrane is pressed directly against the inspection surface and mechanically scanned. Usually, a mist of water is required to wet the surfaces and promote ultrasonic coupling. A large area, high speed, computer controlled scanning system allows for automated inspections of large specimens. Scanning speeds are a maximum of 2 m/s (typical scan speed are 0.3 – 0.6 m/s) with full waveform capture (16-bit) of the ultrasonic signal every 0.25mm.

Figure 5b shows an example of pulse-echo C-scan results from the inspection of a large composite specimen, approximately 2.4 m x 2.4 m in size. The test article is a composite sandwich structure with 6-ply graphite/epoxy face sheets and an aluminum honeycomb core. The inset image is a close up, high resolution scan, of a delamination between the face sheet and the core. Total acquisition time for the captive water column ultrasonic inspection was approximately 45 minutes per side.



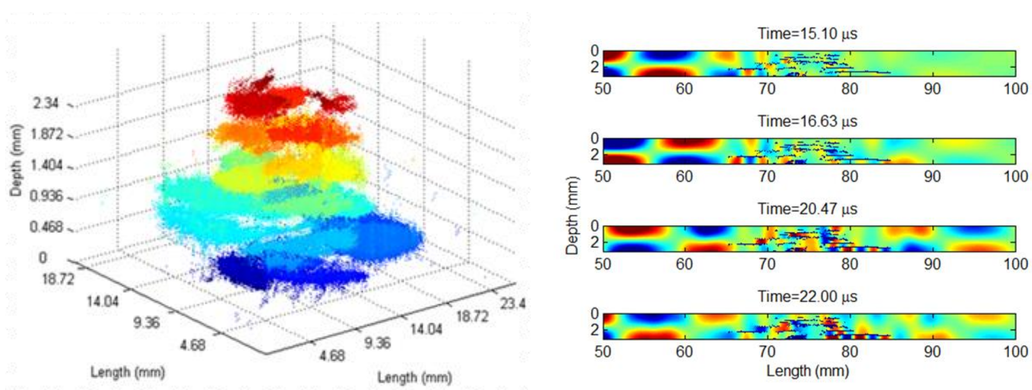
(a) (b)

Figure 5. (a) A photograph of a single-element transducer with a captive water column and (b) C-scan results from the inspection of a large honeycomb sandwich composite specimen with an inset showing a skin-to-core delamination.

COMPUTATIONAL NDE

Simulation tools have the potential to create a cost-effective method for developing and optimizing damage characterization techniques for composites. Such tools enable a method for predicting inspectability of advanced composite components during the design stage. For example, simulation tools could be used to establish confidence in an NDE technique's ability to inspect complex joints, hard to reach locations, characterize complex damage and/or to inspect large areas [12].

To demonstrate the capability of simulating complex damage in a composite material, a 26-ply quasi-isotropic IM7/8552 composite laminate coupon was fabricated at NASA Langley to be used for the purpose of growing enclosed impact-like delamination damage. The composite coupon is 152 mm by 65 mm by 3.23 mm. Details of the damage growth setup can be found in a prior paper by Rogge and Leckey [13]. The damaged sample was scanned at a resolution of 23.4 μm using microfocus x-ray computed tomography (microCT). Figure 6a shows the microCT results scaled such that only the delamination is visible. The interaction of guided ultrasonic waves with the delamination damage defined by the microCT was then modeled using custom developed 3D anisotropic elastodynamic finite integration technique (EFIT) software [14]. For straight-forward one-to-one mapping of the damage into the simulation, and to capture all details of the delamination damage, the EFIT simulation used a step size that is equal to the microCT data resolution (23.4 μm). Figure 6b shows a 2D representation of a through-thickness slice from the EFIT simulation results at four different time steps and demonstrates that the complex geometry of the damage must be taken into account in order to capture the scattering and mode conversion that occurs as guided waves interact with the delaminated region. Modeling such a complex delamination as a simple circular void would not accurately capture this behavior. Analysis of the simulation results has led to an approach for the detection of hidden multilayer delaminations [15].



(a) (b)

Figure 6. (a) MicroCT results showing the complex nature of impact damage in a composite specimen and (b) simulation of guided ultrasonic wave in the presence of complex delamination damage.

Finally, these simulation tools can also be used to develop new rapid and quantitative methods to analyze NDE data. For example, PCA has been used extensively for the reduction of flash IR thermography data. Typical application of PCA to the reduction of transient thermographic data consists of calculating the principal components of the temporal data through singular value decomposition (SVD) of the experimental data itself. For example, Rajic [16, 17] and Valluzzi [18] both use PCA as a contrast enhancement technique for defect detection. Genest [19] and Vavilov [20] provide comparisons between PCA and various other data reduction techniques for defect sizing. Zalameda [21] discusses PCA's use for temporal compression of the thermal data. PCA was used to analyze thermal "flying-spot" data by Hermosilla-Lara [22] for detection of open cracks in metallic specimens. Finally, Marinetti [23] suggests the use of an experimentally derived training set to calculate the principal components.

While this technique is quite effective in reducing thermal data, the singular value decomposition require for PCA can be computationally intense especially with large three-dimensional arrays of thermal data typically produced during an inspection. Additionally, PCA can experience problems when very large defects are present (defects that dominate the field-of-view). The first vector accounts for as much of the variability in the data as possible therefore if defective material dominates the field of view, the first eigenvector may reflect the response of the defect, not the "good" material. If material responses captured by the first eigenvector are considered to be nominal material response, this results in a misclassification of the defect region. To increase the processing speed and eliminate issues arising from the presence of large defects, an alternative method of PCA is being pursued where a fixed set of eigenvectors, generated from an analytic model of the thermal response of the material under examination, is used to process the thermal data from composite materials. Either a one dimensional multilayer analytic model or a 2D finite element model is used and a set of eigenvectors are then numerically generated from this array of responses [7, 8]. Figure 2, discussed earlier, shows the results achieved using this model based analysis approach. In this example, calculation of each PCA image (each mosaic of figure 2 contains 10 images) using the model derived eigenvectors took less than 1sec. in Matlab®, whereas a full SVD calculation of the eigenvectors and back projection on the same data can take more than 1min.

CONCLUSIONS

This paper reviewed ongoing NDE inspection research and simulation tool development within the NASA NESB at Langley Research Center. The paper gave an overview of a few of the technologies under development for rapid, large-area inspection of complex composite structures. Examples were given of how those technologies are being applied to characterize the state of composite structures. Additionally, a discussion of the potential impact of realistic simulation tools for NDE was presented, including examples incorporating realistic composite damage and model based data analysis for faster, more reliable results. A number of other techniques are also being explored by NESB for quantitative characterization of composite structures which were not discussed in this paper. For example current research includes the use of fiber optic, wireless surface acoustic wave and acoustic emission sensors for structural health monitoring (SHM) of large composite components, eddy current inspection of high temperature ceramic composites as well as terahertz and microwave inspection of non-conducting composite materials. Finally, NESB is investigating how data from multiple NDE and/or SHM techniques applied to the same structure could be combined to provide a fuller understanding of the overall health of component under inspection.

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