

NONDESTRUCTIVE INSPECTION OF COMPOSITE STRUCTURES: METHODS AND PRACTICE

David K. HSU
Center for Nondestructive Evaluation
Iowa State University
Ames, Iowa 50011, USA

ABSTRACT

Composite materials are widely used in a number of industrial sectors from aviation, space, to boat building, automotive, and sports goods. In recent years composite structures have seen a substantial increase of their use in the new generation of airplanes. The nondestructive testing and inspection of composite structures, both for manufacturing quality assurance and for in-service damage detection, has prompted the development and adaptation of a number of methods and techniques over the years. In this paper we review the various NDT methods for inspecting composites, especially those developed by the Center for Nondestructive Evaluation at Iowa State University in its interaction with the industrial users of composites. We will address the inspection issues of different types of composite structures including solid laminates, honeycomb- and foam-core sandwich components, and touch upon the inspection of perforated facesheets and bonded aluminum structures. The capability of various NDT methods including water- and air-coupled ultrasound, bond testing, manual and automated tap testing, thermography, and shearography will be described, with emphasis given to techniques that demonstrated benefits to the practice of composite inspection. Techniques developed by Iowa State University for performing composite inspections in the field, especially those with imaging capability, will be described.

Keywords – composites, inspection methods, field techniques

1. INTRODUCTION

The various forms of composite materials, with their advantages of light weight, design flexibility, and high specific stiffness and specific strength, are widely used as structural materials in the aviation, space, marine automobile, and sports industries. The nondestructive inspection (NDI) of composites is a crucial component in the service life cycle of critical structures on airplanes, space vehicles, and boats used in transportation [1]. Composite structures can be divided into approximately two large categories: solid laminates and bonded sandwich structures. The use of composites in the aviation industry started by employing honeycomb panels as flight control surfaces, fairings, and engine nacelles. Composite sandwiches with foam core have been used in boat building, on helicopter rotor blades, and in radomes. In recent years, thick laminates are increasingly employed as primary load-bearing structures on aircraft. Examples include the carbon fiber reinforced plastic (CFRP) tail fin of Airbus A300, and the empennage of

the Boeing 777. Some honeycomb composite structures on the aircraft, such as the composite rudder of the Airbus 300, are now considered primary structures. Most recently, the production of the Boeing 787 represents a major step toward replacing the traditional aluminum aircraft structures by composites, where the entire fuselage and the wing structures are made of composites. With the dramatic increase of composite usage in the manufacturing of airplanes, NDI requirements are becoming increasingly important in both the manufacturing of the structures and in their subsequent in-service maintenance and repair.

Due to the large variety of composite materials and the diversity of the NDI techniques, it is not possible to address all aspects of the composite NDI topic. In this paper, an attempt is made to briefly review the NDI techniques available today for composite structures used in the transportation industry and to describe a few techniques developed at Iowa State University aimed at improving the current practice of NDI in the field and providing additional capabilities not available before.

2. DEFECTS AND FLAWS IN COMPOSITES

2.1 Solid Laminates

Imperfect manufacturing conditions can lead to flaws and defective conditions of a fabricated composite part. The list of flaws and defects sometimes encountered in manufacturing includes embedded foreign objects, regions of excessive porosity, errors in ply orientation or layup sequence, ply waviness, and interlaminar delamination. Foreign objects in a laminate compromise the uniformity and act as stress concentrators under load; they may lead to disbond or delamination while in service. Porosity is a volumetric distribution of microscopic voids that occurred in the resin matrix of a fiber reinforced composite. The size and morphology of the porosity depend on the type of the laminate construction (unidirectional prepreg tape versus woven prepreg cloth, for example) and the layup design. Since the microporosities are located in the resin matrix, they tend to concentrate in the interfacial resin rich layer in a laminate. Such porosity can considerably degrade the interlaminar shear strength (ILSS) of the composite laminate. Ply orientation and layup sequence errors are more likely to occur in hand laid up parts than in parts fabricated with automated tape laying machines or fiber placement machines. Composite parts containing layup errors are rejectable because the errors can have a large effect on the strength of the part. Ply waviness refers to sinusoidal undulations of the plies; such anomalies can occur locally in both the in-plane direction and in the out-of-plane direction. The ply waviness condition is detrimental to the performance of the laminate as the wavy fibers can stretch under load, putting stress on the matrix. Finally, composites enduring large temperature excursions can develop microcracks in the direction normal to the plies.



Fig. 1. Examples of defective conditions in composite laminates: porosity, fiber waviness, and microcracking.

2.2 Adhesively Bonded Sandwich Structures

Adhesively bonded sandwich structures consist of a pair of facesheets that are usually fiber reinforced composite laminates and a composite or metallic honeycomb core or a foam core. The facesheets are adhesively bonded to the core. For facesheets made of composite laminates, defects similar to those described above may occur. The most important inspection task for bonded structures is to verify the integrity of the bond between the core and the facesheets. Although highly desirable, the strength of an adhesive bond cannot be determined by a simple NDI test. The primary focus in the inspection of bonded sandwich structures is the detection and characterization of the in-service damage.

2.3 Damage of Composite Structures

While in service, the composite structures may suffer damage from a number of natural and man-made causes. For both solid laminates and sandwich structures, the most significant damages are caused by mechanical impact. Low velocity impacts on composites often lead to non-visual damage on the surface but significant damage internally. Impact damage can result from dropped tools in a maintenance hangar or from collision with ground handling equipment. Bird strikes in flight can cause considerable damage to the radome on to the wing leading edge. The damage morphology of an impact on a composite solid laminate is well known [2,3]. The damage takes the form of a series of interlaminar delaminations that increase in size with depth. The delaminations are usually accompanied by microcracking of the matrix. For honeycomb sandwich panels, impact damage typically results in a fracture or buckling of the core, often with an upward concave profile [4,5]. The lowest point of the fracture may occur at a depth approaching one half of the core thickness. At higher impact energy, delamination or fiber breakage may occur in the facesheet. Composite components, especially the radomes on aircraft, can also be damaged by lightning strike or the discharge of static charge build-up. Such damages can produce pin holes that can then serve as path for water ingress, leading to secondary damage. Thermal degradation of composites can occur on structures near hot exhaust and chemical degradation of the adhesive bond can result from hydraulic fluid damage.



Fig. 2 Two examples of composite damage: delamination caused by impact on solid laminates and core fracture in honeycomb sandwich.

3. CURRENT PRACTICE OF COMPOSITE INSPECTION

3.1 Quality Assurance Inspection in Composite Manufacturing

Critical composite structures must pass through nondestructive inspection process before assembled onto an aircraft. The primary method used by the manufacturers is ultrasonic scanning. The inspection is typically carried out in a scan gantry with squirters in a through transmission ultrasonic (TTU) mode. Two water jets carry the ultrasonic beam from the transmitting transducer to the solid laminate or honeycomb sandwich structures, through the structure and then to the receiving transducer. The scan images produced by the ultrasonic squirter system can reveal the presence of foreign object inclusions, interlaminar delaminations, skin-to-core disbands, and regions of excessive porosity. TTU scan images of solid laminates based on the amplitude of the transmitted ultrasonic signal (or “dB drop”) are often used in the estimation of the porosity volume fraction.

Although the squirter-operated, water-coupled ultrasonic imaging using TTU scan gantries remain the prevalent method of quality assurance inspection for manufacturing of composite parts, air-coupled ultrasonic scan have become increasingly practical. Air-coupled ultrasound, being non-contact and non-contaminating, is particularly suited for



Figure 3. A multi-channel air-coupled ultrasonic scan system used by industry.

inspecting honeycomb sandwiches with perforated facesheets and other water-sensitive composite structures. Figure 3 shows an industrial setup where a multi-channel air-coupled ultrasonic system is used to scan production parts.

3.2 In-Service Inspection of Composite Structures

The service record of critical composite structures on aircraft over several decades has been generally very good. The inspection requirements recommended by the manufacturers and required by the aviation regulatory agencies have rarely gone beyond visual inspection and manual tap test. Considering the large size of the aircraft structures, it is not impractical, nor is it necessary to contact large area inspection scans without a clear cause justified by prior incidences. In exceptional cases, advanced NDI beyond that of visual inspection and tap test have been recommended for primary composite structures. A recent example was the repetitive ultrasonic inspection and other checks recommended for the composite rudders on Airbus A300/310 reported in the news media. [6] This inspection was prompted by the in-flight rudder separation of an Air Transat A310 plane over the Caribbean in 2005 [7]. Earlier in 2001, the loss of the composite tail fin on AA587 in Bell Harbor, New York was probably the worst airline disaster associated with a critical composite structure on an aircraft [8]. The recent reported requirement of advanced NDI of the composite rudder would be quite significant in view of the fact that two major airplane manufacturers in the world, Boeing and Airbus, are both replying increasingly on the use of composites in their new generation of airliners in order to achieve fuel efficiency and maintenance economy.

4. NDI TECHNIQUES FOR COMPOSITES

4.1 Presently Available NDI Techniques for Composites

Of the many NDI techniques beyond visual inspection and manual tap test, ultrasonic testing (UT) probably comes to mind first. However, contact mode, “A-scan” type point-to-point measurements have limited capability, especially in the inspection of honeycomb sandwiches. A number of ultrasonic systems capable of doing C-scan imaging in the field have been developed, although the enhanced capabilities came with the associated greater complexity (higher training requirement), reduced portability, and higher costs. There are two non-contact modes of ultrasonic inspection, one is laser generated and detected ultrasound, and the other is air-coupled ultrasound. The former has matured to a degree that industrial implementations are in place, and the latter is also finding increased applications.

Two recently developed technologies, the acoustography and the ultrasound camera (acoustocam), may hold the potential for providing large area ultrasonic images in real time or near real time without the need for performing a C-scan. The acoustography [9] employs a stress sensitive liquid crystal material that converts the ultrasonic field intensity containing flaw indications into an optical gray scale image. The acoustocam

[10] is based on a piezoelectric readout multiplexer that operates like a CCD array and provides a visual image of the ultrasonic field at the video rate. Both the acoustography and acoustocam require water coupling of the ultrasound to the composite part.

The two optically-based, non-contact NDI methods capable of large area scan at a rapid rate are the thermal wave imaging technique and the laser shearography. Going beyond conventional infrared thermography, thermal wave imaging [11,12] applies a heat pulse to a composite surface with a flash lamp and then captures the surface temperature profiles as a function of time. Analytical methods and software have given the technique deep penetration and quantitative flaw characterization capabilities. The other high speed, area inspection technique, laser shearography [13], detects subsurface defects by measuring the minute difference in surface deformation over a good region and over a defective region when the composite part is slightly stressed. A shearography instrument detects the difference as a shift in the phase-separated optical images of the reflected laser light. The technique has superior sensitivity for detecting subsurface flaws.

4.2 Development of Tap Test Method

Aside from visual inspection, manual, hearing-based, tap test is arguably the most practiced inspection technique on composites, especially on bonded sandwich structures. Because of its wide use, a real improvement of the tap test method will have a significant impact on the NDI of composites. Over the years there have been three developments of instrumented tap test; all eliminated the human factor of reliance on operator hearing. These instrumented tap testers are the Woodpecker developed by Mitsui Heavy Industries, the Rapid Damage Detection Device (RD3) developed by the Boeing Company and licensed to WichiTech, and the Computer Aided Tap Tester (CATT) developed by the Iowa State University.

The CATT was developed to obtain meaningful engineering parameters from the instrumented tap tester and to generate scan images using the parameter [14]. The CATT uses an accelerator of known mass as the tapping instrument. The associated electronic circuit measures the time duration τ that the tapping mass remains in contact with the surface of the composite part. Based on a simple grounded spring harmonic oscillation model, the contact time τ is related to the local stiffness (spring constant) k by the simple formula $k = m(\pi/\tau)^2$. The value of k at different points on the part, in units of Newton per meter, can then be plotted as a stiffness image of the composite structure. Figure 4 shows such an image for a 5 ft x 2.5 ft outboard spoiler of a Boeing 767 airplane. Laboratory tests showed that the stiffness deduced from the tap test was in good agreement with that determined by load-displacement experiments on a mechanical testing system.

It was discovered recently [15] that the load-displacement data of a damaged composite honeycomb sandwich exhibited pronounced hysteresis. The load and unload curves were both nonlinear and combined to form a hysteresis loop. In contrast, the load versus displ-

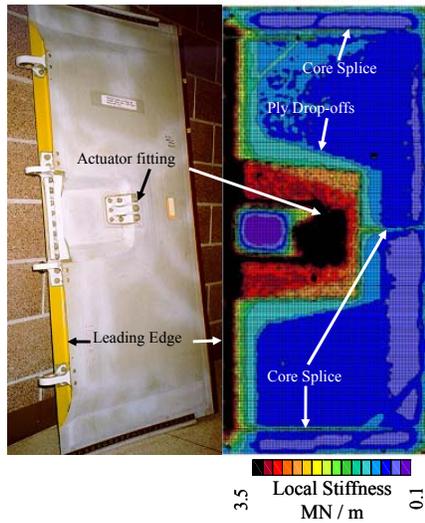


Fig. 4. A stiffness image of a Boeing 767 outboard spoiler generated by tap test using an accelerometer as the tapping mass.

acement curve of an un-damaged panel was nearly linear and had almost no hysteresis. The average slope of the load-displacement curve (stiffness) of the undamaged panel was higher than the damaged one. It was further demonstrated that the area enclosed by the hysteresis loop (i.e., the energy dissipation due to the friction of the internal damage) showed good correlation with the impact energy that caused the damage. Figure 5 shows the test results obtained on a honeycomb sandwich with impact damages. To exploit this correlation as a practical means for evaluating the damage severity of a composite structure, one must be able to conduct the test with only a single-sided access and do the test at a fast rate. An effort was therefore spent to deduce a dynamic hysteresis loop from the tap test response.

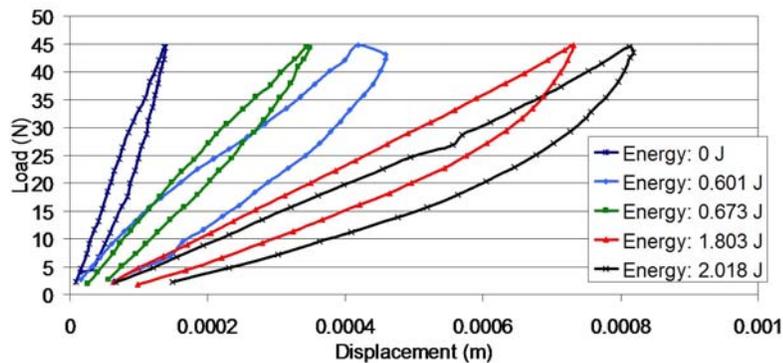


Fig. 5. Hysteresis loops in load-displacement measurement results of a CFRP/Nome sandwich panel containing damage sites caused by different impact energy.

The voltage output of the accelerometer during a tap on the composite surface is a function of time and can be converted into an acceleration curve $a(t)$ using the known sensitivity of the accelerometer (for example, 10 mV/g). This $a(t)$ curve can then be integrated twice to obtain the displacement of the surface as a function of time $d(t)$, as shown in Fig. 6. Using $F=ma$, $a(t)$ can be converted to the force of contact between the probe and the surface: $F(t)$. Having obtained $F(t)$ and $d(t)$, a load-displacement curve can then be plotted. Experiments showed that this dynamic hysteresis curve was in good agreement in terms of shape and slope with the static hysteresis loop obtained on a load frame, as shown in Fig. 7. In the process of deducing the hysteresis curve from the tap test data, the presence of noise can lead to errors in the determination of the two constants of integration using boundary conditions. Work is still underway to improve the robustness of the integration constants determination.

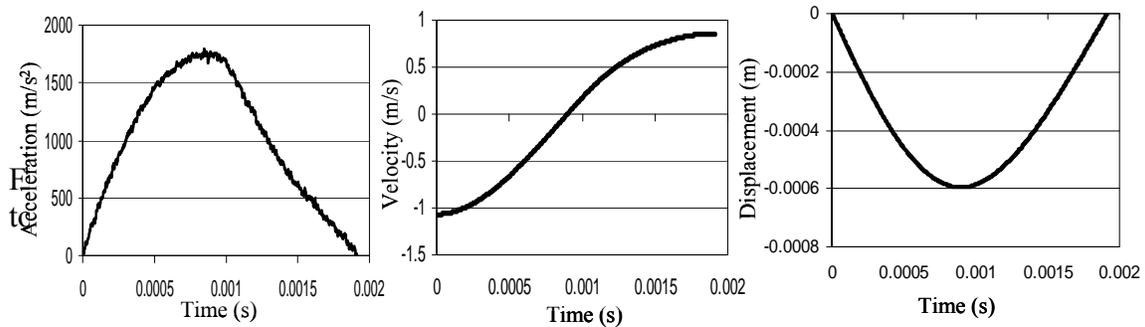


Fig. 6. Voltage output of an accelerometer used as a tapping mass is integrated to obtain the displacement versus time data

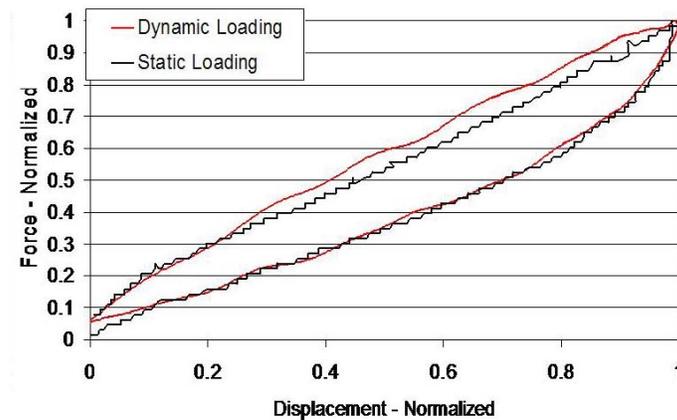


Fig. 7. Normalized static and dynamic hysteresis loops showing agreement in shape and in slope.

4.3 Development of Air-coupled Ultrasound for Field NDI

When ultrasonic NDI is performed on composite structures in a maintenance environment or in the field, a couplant-free test procedure is highly desirable. Air-coupled ultrasound would satisfy this requirement, but has some intrinsic limitations. The primary challenge for using air-coupled ultrasound for NDI of composites is that the severe mismatch of acoustic impedance between that of air and that of a solid composite leads to an extremely inefficient transfer of the ultrasonic energy at the air-solid interface. Approximately only 0.04% of the incident sound energy in air is transferred into the composite. The same impedance mismatch problem must also be overcome in the making of piezoceramic based air-coupled ultrasonic transducers. Despite the difficulties, it is possible to inspect solid laminate and honeycomb sandwich structures with air-coupled ultrasound although only in the transmission in an industrial setting [16]. In Fig. 8, a pair of gas matrix piezoceramic (“GMP”) transducers was driven by a Panametrics Epoch-4 flaw detector, with the aid of an external preamp, in the detection of a disbond in a honeycomb panel.



Fig. 8. Detection of disbond in honeycomb sandwich panel with simple air-coupled ultrasonic setup.

Using piezoceramic air-coupled transducers, the inspection of composites is typically carried out in the 50 kHz to 500 kHz range. In thin laminates of composites, flaws as small as 3 mm (1/8”) diameter can be detected by imaging using a focused beam of air-coupled ultrasound. In thick laminates, the transmission coefficient strongly depends on the thickness due to a resonance behavior. The transmission coefficient is high at the frequencies corresponding to the mechanical resonances where the thickness of the composite equals to an integral multiple of the half-resonance. For the inspection of honeycomb sandwich structures, the frequency of 100 kHz has proven to be a good compromise between resolution and sensitivity. Honeycomb sandwich panels several inches thick can be readily scanned with air-coupled ultrasound for the detection and imaging of skin-to-core disbond, facesheet delamination, and damage of honeycomb core.

The good performance of air-coupled ultrasound for inspecting honeycomb composite structures, including thick panels with adhesively bonded multi-core of different cell

sizes, and panels with perforated facesheets, showed good promise for using air-coupled ultrasound as a viable NDI technique in field applications. Possible candidate structures for air-coupled ultrasonic inspection include most flight control surfaces with two-sided access. Certain semi-enclosed box-like honeycomb structures, such as rudders, radomes, and nacelles are also candidates for air-coupled inspection using the magnetically attracted transducer holders developed by Boeing [17]. In a large scale round robin experiment organized by the Sandia Laboratories to evaluate and compare the various NDI techniques for honeycomb sandwiches, the probability of detection (POD) of air-coupled ultrasound was found to be among the highest ones of the techniques investigated [4].

4.4 Image-Based NDI for Composite Inspection

The modalities used in the NDI of composite structures, especially polymer matrix composites, include visual inspection, tap test, low frequency bond test, ultrasonic test, thermography, and laser shearography. Of these methods, thermography and shearography are inherently image-based, as are the acoustography and acoustocam. The usefulness of the last two devices will increase considerably when the viewing area is made larger. Ultrasonic inspection, when implemented with mechanized, automated scanners, generates scan images and is widely used in the laboratories and for the inspection of manufactured composite products. When used in the field or in a maintenance hangar, ultrasonic inspection is typically carried out with a flaw detector and does not lead to an image. Low frequency bond testing and tap test are not image-based techniques. In the inspection of composite structures, the advantage of an image-based technique cannot be over emphasized. By having the inspection results presented in an image form, a complete coverage of the inspected area is ensured. The image also allows the inspectors to differentiate between flaws and normal internal features in making their calls. A scan image can reveal the size and shape of the flaw or damage more accurately; such information is valuable for planning the repair of a composite structure. Driven by the desire to improve the capabilities for composite inspection, especially in an maintenance environment or in the field, Iowa State University has devoted a number of years to the development of image-based inspection techniques and instrument that are portable, simple to operate, and cost effective.

The generation of an image by the computer aided tap tester, as described in Sec. 4.2, was based on the use of a grid template and an assumed encoding approach. The software in a PC was informed of the scan size such as 40 by 30 taps. A recently developed approach for making manual, image-based “C-scans” using ultrasound, eddy current, and low frequency bond testing (mechanical impedance analysis) exploits the existence of off-the-shelf, low cost, commercial products with position encoding capability. The NDI output, such as the amplitude or time-of-flight of an ultrasonic signal, is combined with the position information by software in the generation of the scan image. A schematic diagram of this approach is shown in Fig. 9. The position encoding device can be a handwriting capture device, such as the Pegasus PC

NotesTaker, conference room device for capturing writings or drawings on a whiteboard or flip chart, such as the Mimio FlipChart or Digital Meeting Assistant, or a magnetic position and attitude recorder used in virtual reality and medical applications (the “Flock of Birds” by Ascension Technology). By merging the position data from such devices with the digital or analog data output of the NDI instrument in a PC, an inspector can manually inspect an area with no changes to the existing procedure while ending up with an image of the inspection results that can be further processed when necessary.

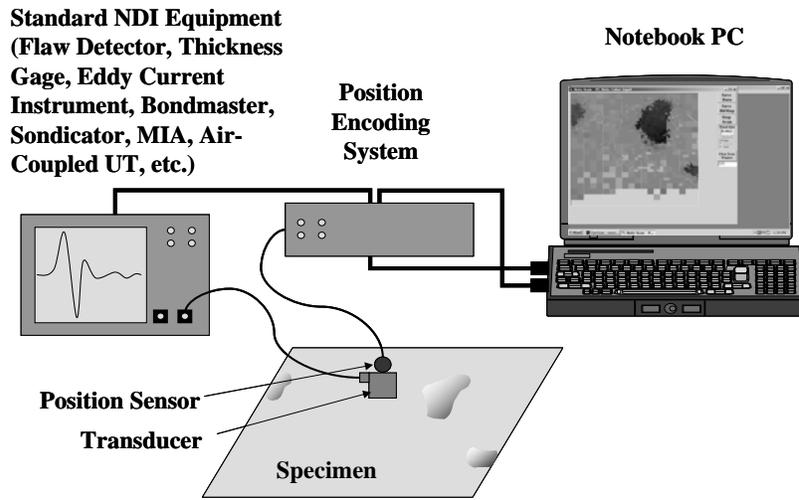


Fig. 9. Schematic diagram of the components and configuration of the Generic Scanner (“GenScan”) for producing manual scan images in various NDI modalities.

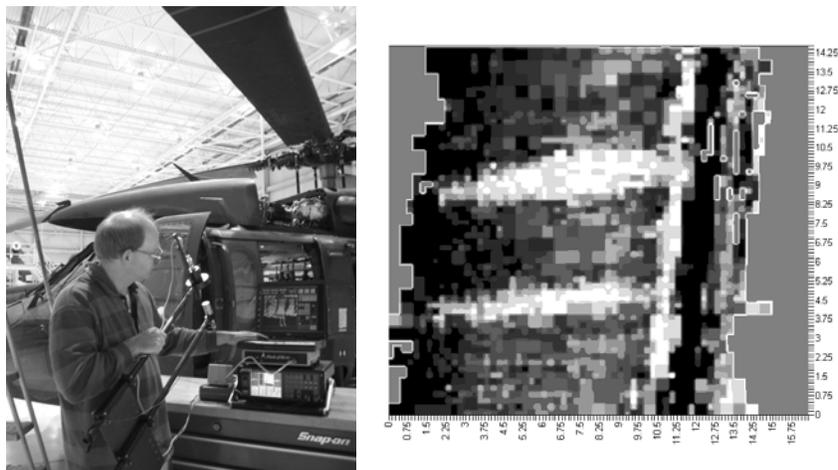


Figure 10. A manual “GenScan” image showing damages in a helicopter rotor blade as revealed by the amplitude of transmitted air-coupled ultrasound.

The simple generic manual scanner, coming to be known as the "GenScan" system, is applicable to a number of NDI modalities, and has given the imaging capability to a number of conventional point-by-point manual tests such as the contact mode ultrasonic testing, air-coupled ultrasonic testing, eddy current inspection, and MIA bonding testing [18]. The PC NotesTaker has been combined with a Panametrics Epoch-4 flaw detector for the generation of thickness images of aluminum skins in corrosion inspection. Both the Mimio FlipChart and the Flock-of-Birds have been used in the generation of air-coupled ultrasound scan images of honeycomb sandwiches. Figure 10 shows an example of a field application of the GenScan system on helicopter rotor blades where crushed core damages were mapped out manually using the transmitted amplitude of air-coupled ultrasound [19]. The position encoding was based on the Flock of Birds instrument.

5. CONCLUSIONS

As the use of composite increases, especially in the next generation of airplanes, there will be a greater need for nondestructive inspection procedures for quality assurance by the manufacturers. The challenges will include efficient inspection of thick primary structures. Specific field inspection needs of the new generation of composite-intensive airplanes may not arise until they are in service for a number of years. More bonded structures are now classified as primary structures and will receive more inspection attention. The use of foam-cored sandwiches is also on the rise, with the accompanying NDI needs. Since the disposition of a composite structure depends on the nature and severity of the detected flaw or damage (for example, a certain degree of core damage may be tolerable in a sandwich structure but a core-to-facesheet disbond may not be), the ability to nondestructively characterize the detected flaws or damage will continue to be in demand.

6. ACKNOWLEDGMENT

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