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COMPARISON OF X-RAY, MILLIMETER WAVE, SHEAROGRAPHY AND THROUGH-TRANSMISSION ULTRASONIC METHODS FOR INSPECTION OF HONEYCOMB COMPOSITES

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ABSTRACT. Honeycomb composites are increasingly finding utility in a variety of environments and applications, such as aircraft structural components, flight control components, radomes, etc. In-service and environmental stresses can produce unwanted flaws that adversely affect the structural integrity and functionality of these composites. These flaws may be in the forms of disbonds, delaminations, impact damage, crushed honeycomb, moisture intrusion, internal cracks, etc. There are several nondestructive testing (NDT) methods that may be used to inspect these composites for the presence and evaluation of these flaws. Such NDT methods include X-ray computed tomography, near-field millimeter wave, shearography, and ultrasonic testing. To assess the capabilities of these methods for honeycomb composite inspection, two honeycomb composites panels were produced with several embedded flaws and missing material primarily representing planar disbonds at various levels within the thickness of the panels and with different shapes. Subsequently, the aforementioned NDT methods were used to produce images of the two panels. This paper presents the results of these investigations and a comparison among the capabilities of these methods.

Keywords: Honeycomb Composite, Millimeter Wave, Nondestructive Testing (NDT), Shearography, Through-transmission Ultrasound, X-ray Computed Tomography.
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INTRODUCTION

Honeycomb composites are widely used in various applications and industries including the aerospace industry. Components such as flight control surfaces and radome structures are two examples in which composite skin-composite honeycomb may be used. Flight control surfaces are used to control in-flight stability and motion, while radomes

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are typically designed to protect radar or communication systems from undesired environmental effects while minimally influencing the system performance. Therefore, any subsurface flaws in a honeycomb composite can significantly degrade the performance of these structures. Hence, there is a great need to inspect the honeycomb composites routinely and assess the integrity of their electrical and structural properties.

Composites with honeycomb cores and glass fiber-reinforced polymer (GFRP) skins can be inspected for subsurface flaws using a variety of nondestructive testing (NDT) methods. Such methods include X-ray computed tomography (CT), near-field microwave/millimeter techniques, shearography, and through-transmission ultrasonic testing (TTU) [1], [2].

In this paper, the detection and resolution capabilities of X-ray CT, near-field millimeter wave techniques, shearography, and TTU to inspect honeycomb-core composite panels with several embedded defects are investigated. To this end, these NDT methods were used to generate images for these panels. Based on the images and the manifestation of the detected flaws, the efficacy of each NDT method for these applications is assessed.

SAMPLES DESCRIPTION

Two honeycomb composites panels (1"-thick and 0.5"-thick) were evaluated. Each panel had one side bonded with a thin GFRP laminar skin and the other side bonded with a thin carbon reinforced (CFRP) skin. The panels appear to be produced with several embedded defects made out of thin polymer sheets (i.e., Teflon tape, plastic, paper, etc.) and missing honeycomb/skin material. The embedded defects primarily represented planar disbonds, crushed core, and delaminations at various heights within the thickness of the panels and with different shapes.

The first panel (Panel #1) is a 1"-thick honeycomb sample produced by stacking two 0.5"-thick honeycomb layers on top of one another with a mid-thickness composite septum separating the honeycomb layers. The second panel composite (Panel #2) was similarly manufactured except that it had a single layer of0.5"-thick honeycomb core.

X-RAY COMPUTED TOMOGRAPHY (CT)

X-ray CT works on the basis of conventional X-ray NDT techniques. The conventional X-ray source has a small focal spot size. Apertures at the source and detector limit the X-rays to a plane passing through the specimen. As the X-rays pass through the specimen they are attenuated by the specimen material along ray paths between the X-ray source spot and each detector element. The attenuated X-rays are detected by a linear array of detectors located on the other side of the specimen. The specimen is rotated until measurements are made throughout 180 degrees of rotation. The resulting measurements are manipulated by a computer according to a reconstruction algorithm to produce a two-dimensional map of the X-ray attenuation in the irradiated cross section. The resulting data correspond to point-by-point density values in thin cross sections of the specimen, in effect allowing three-dimensional imaging of the internal structure when successive transverse sections are produced. For this investigation, the CT slices were taken at 1 mm intervals.

Figure 1 shows selected image slices of Panel #1 obtained using X-ray CT. The slices show different images as a function of depth within the panel thickness. As shown in Figure 1, there are four subsurface flaws of different shapes appearing at the upper right-hand corner of the core-GFRP skin interface slice. A rectangular flaw is detected at the upper right-hand corner of the next slice shown. The image corresponding to the slice at the middle of the core shows one additional flaw in the panel septum. Finally, the core-CFRP skin interface slice reveals two rectangular flaws around the middle of the top portion of the panel (as well as the words "NDI TEST" engraved in the honeycomb at that depth).

The X-ray CT sliced images of Panel #2 are shown in Figure 2. It is evident that most of the detected subsurface flaws are concentrated in the upper portion of the panel. The image slice corresponding to the core-GFRP skin interface shows four rectangular flaws at the upper left-hand side. Meanwhile, the middle slice indicates the presence of one flaw at the upper right hand corner. The image slice corresponding to the core-CFRP skin interface shows two additional rectangular flaws.

In summary, the X-ray CT detected at least 21 different subsurface flaws in Panel #1 and 14 subsurface flaws in Panel #2. This method is clearly well-established, capable and provides detailed information both spatially and through the panel depth. Therefore, these X-ray CT results will be used subsequently to benchmark the other NDT techniques considered herein. This is partially due to the fact that the panel schematics were not available at the time of these investigations. However, due to the high resolution capabilities of this method (in 3-D) these results are used in the place of the missing panel schematics.

NEAR-FIELD MILLIMETER WAVE TECHNIQUE

The suitability of millimeter wave method for honeycomb composite inspection stems from the fact that these composites are in the family of low permittivity and low loss materials. Consequently, millimeter wave signals easily penetrate inside these composites and interact with their interior structure [3]-[5]. In general, a flaw in the honeycomb composite is considered as a discontinuity in the dielectric properties of that medium. Millimeter wave-based NDT systems are particularly appealing for this application since these waves are sensitive to minute dielectric property discontinuities in a composite.

Panels #1 and #2 were imaged using several near-field millimeter wave reflectometers operating at frequencies from 26.5 GHz to 75 GHz (mainly Ka- and V-bands). A rectangular waveguide probe was used to irradiate the samples from the GFRP skin side and receive the reflected signal. The waveguide probe was raster scanned over the panels in one plane, the *imaging plane*, in a C-scan fashion. The images were then formed as 2D intensity maps in which the intensity is a function of the reflected signal power and/or phase at each sampling point in the imaging plane [4]. Since the panels are made of low loss dielectric materials (e.g., glass and honeycomb), the reflectometers were designed to be more sensitive to the phase variations in the reflected signal. This was accomplished by heterodyning the reflected signal with a reference signal [2].

Figures 3 and 4 show the corresponding images (raw) of Panel #1 and Panel # 2 at different frequencies in the Ka- and V-band. When comparing these images with those

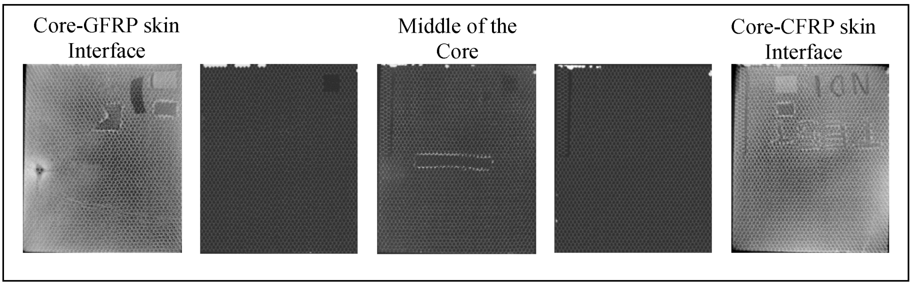

FIGURE 1. X-ray CT image slices of Panel #1.

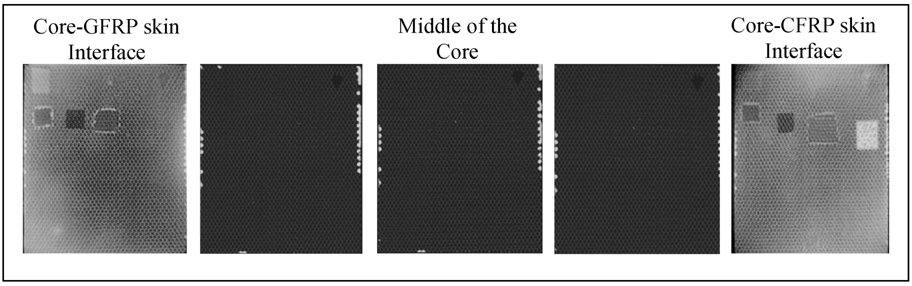

FIGURE 2. X-ray CT image slices of Panel # 2.

shown in Figures 1 and 2, respectively, it is interesting to note that specific embedded flaws are detected and their relative spatial allocations and sizes are also clearly indicated. Furthermore, flaws at different depths are detected at the same time and in the same imaging process (unlike slices in the X-ray CT images). This is an important practical issue. Additionally, some overlapping flaws were also detected in these images (e.g., the 34 GHz and 70 GHz images of Panel # 2). Generally, the V-band images show some flaws which are not a clearly indicated in the Ka-band images.

SHEAROGRAPHY

The type of Shearography used in this investigation is referred to phase stepped shearography and is based on the principles of laser speckle and optical interferometry. The images are generated by allowing the monochromatic, coherent light to interfere on the test sample and produce a reference speckle pattern [6]. When the sample is stressed, this interference will produce a fringe pattern that differs from the reference speckle pattern, which represents displacement between adjacent points. The stressed state image and reference image are subtracted to indicate material defects.

The images shown in Figures 5 - 7 were formed using different vacuum stress state values. Figure 5 shows the Shearography images of Panel #1 obtained using various vacuum pressure values applied at the GFRP skin side. Four subsurface flaws of different sizes are apparent at the top right corner of the panel. Hence, this technique detected 8 out of the 22 flaws detected in this panel. The exact shapes of the flaws, however, are not clear in the obtained image with respect to other NDT methods used in this investigation.

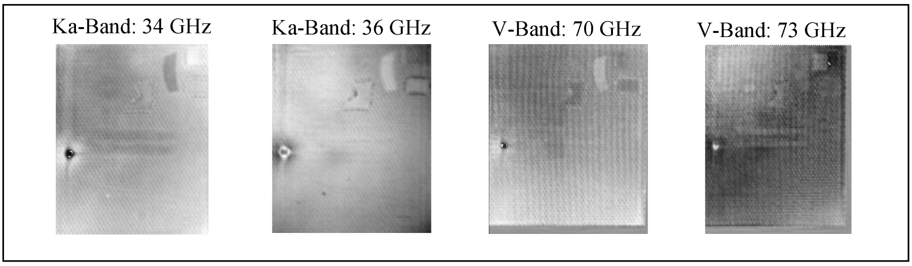

FIGURE 3. Millimeter wave images of Panel #1 obtained at 34 GHz, 36 GHz, 70 GHz, and 73 GHz.

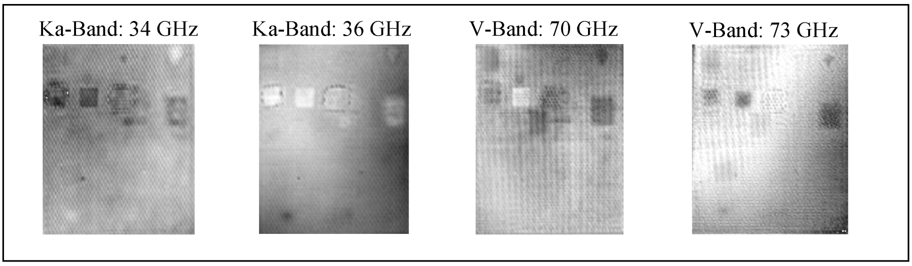

FIGURE 4. Millimeter wave images of Panel #2 obtained at 34 GHz, 36 GHz, 70 GHz, and 73 GHz.

The same pressure values were used to capture shearography images of Panel #2. The pressure was applied at the GFRP side first then at the CFRP side. Figure 6 and Figure 7 show the resulting images, respectively. Collectively, both images indicated the presence of 8 out of 15 flaws. Again, the shapes of the detected flaws are not well defined in these images.

THROUGH-TRANSMISSION ULTRASOUND

Through-Transmission Ultrasound (TTU) is a widely-used and traditional technique for inspecting honeycomb components for bonding defects. TTU relies on a couplant and involves the use of two piezoelectric transducers aligned coaxially on both sides of the samples. One transducer is used to transmit the ultrasonic energy through the sample, and the other transducer is used to receive or detect any ultrasonic energy that is not attenuated by the sample. For this particular investigation, the information collected by the receiving transducer was peak amplitude data only.

Figure 8 shows the TTU images of Panels #1 and #2 obtained at 5 MHz with scanning resolution of 0.01″. The image obtained from Panel #1, distinctly indicates the presence of 16 out of the 22 subsurface flaws. The flaws in the upper right hand corner are blurred and difficult to individually distinguish. Unfortunately, the sound propagation is restricted in a TTU inspection through a double layer honeycomb sample with a septum, such as Panel #1. This is due to the misalignment of the honeycomb layers through which the ultrasound energy is optimally propagated through the sample. As for Panel #2, the obtained image clearly shows 8 subsurface flaws out of possible 15. Furthermore, the shapes of the detected flaws can be readily determined in the image.

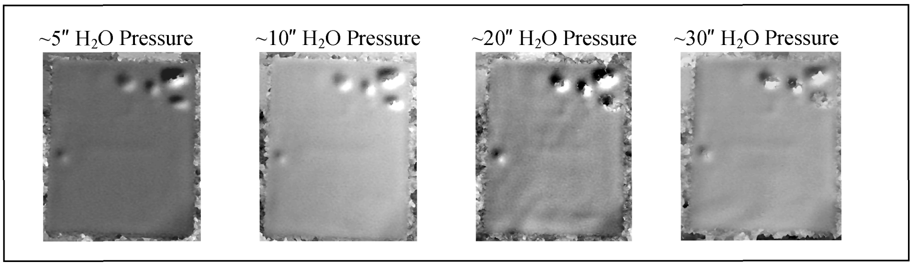

FIGURE 5. Shearography images of Panel #1 using different pressure values applied at the GFRP skin side.

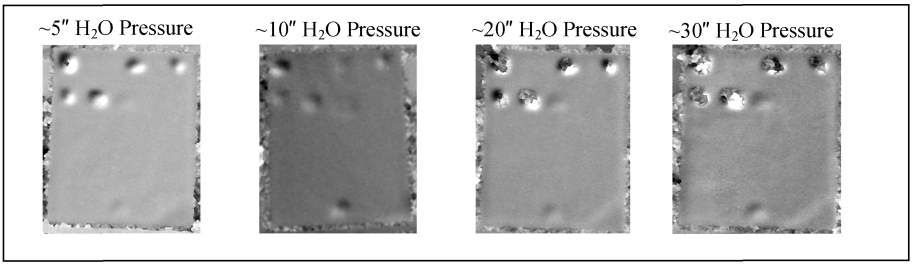

FIGURE 6. Shearography images of Panel #2 using different pressure values applied at the GFRP skin side.

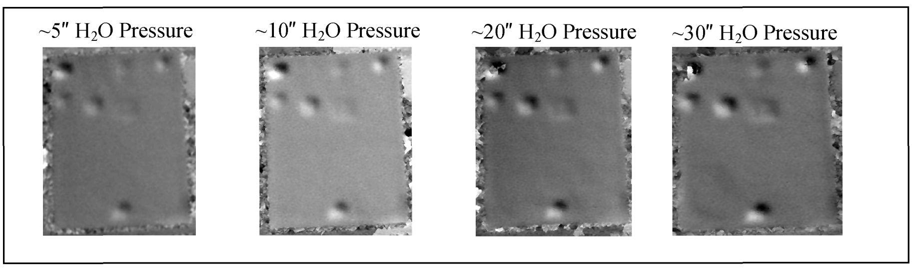

FIGURE 7. Shearography images of Panel #2 using different pressure values applied at the CFRP skin side.

FIGURE 8. Through-transmission ultrasound images of Panels #1 and #2.

SUMMARY

X-ray CT method produced high resolution images of the embedded flaws in the considered honeycomb panels. Moreover, it provided flaw depth information. The major disadvantages of this technique are that it is slow, expensive, bulky, and not suitable for on-line real-time inspection. Furthermore, the ionizing nature of the radiation limits its use and requires strict precautions to be implemented during use.

The images obtained by the millimeter wave method revealed, with high spatial resolution, most of the subsurface flaws. The shapes of the flaws were clearly evident in the raw near-field images as well. Since the near-field probes were uncalibrated and were produced at single frequencies, it was not possible to determine the flaw depth information quantitatively. The relative signatures of the flaws in the obtained images, however, indicated the existence of flaws at different depths, i.e., overlapping flaws. Overall, the results obtained by this method were comparable to those of the X-ray CT (with the exception of flaw depth evaluation). This method is non-contact, high resolution, and through-depth detection of flaws using portable, inexpensive, and relatively small probes, which can be easily incorporated into existing scanning platforms. The millimeter wave probes do not need couplant, and they can facilitate fast and on-line real-time inspection. This method is limited by its sensitivity to the standoff distance variations and inability to penetrate through the CFRP skin.

The X-ray CT images indicated the presence of most defects in both samples, but there was an indication in each panel from the Shearography and TTU images that did not show up in the X-ray CT. These indications were interpreted as pure disbonds or delaminations because there is no apparent material density change. The Shearography method generated images much faster than any other NDI modality investigated. Shearography's high detection capability and simple equipment in addition to not requiring couplant makes it appealing for this type of application. On the other hand, the disadvantages of this method include its low lateral resolution, expensive equipment, and it requires the application of a stress to the inspected parts.

As shown by the inspection images for both panels, the TTU method offered better lateral resolution than Shearography. The advantages of the TTU include producing images with a relatively high resolution, facilitation of real-time on-line inspection, incorporation into the existing platforms, and use of simple inspection equipment. The applicability of this method, however, is impaired by the strong internal scattering by the honeycomb core. TTU is a non-contact method, but it requires couplant and access to both sides of the panel. A major disadvantage of Shearography and TTU are the defects at the same planar location but at different depths within test samples will show up as only one defect. There were many defects within these panels that were masked by others. Additionally, if inserts are well-bonded to the adjacent composite skin layers and have similar sound propagation characteristics, these flaws will not be detected by Shearography or TTU.

Based on the interpretation of the images generated from each of the techniques, there were 22 flaws in Panel #1. There appears to be three flaws (3 inserts) in the GFRP skin, five flaws (1 insert, 1 skin mill out at the skin-honeycomb interface, 3 honeycomb

TABLE 1. Summary of detection and resolution attributes of the four NDT methods.

	Detection (Number of Flaws)		Lateral Resolution
	Panel #1 (22 flaws)	Panel #2 (15 flaws)	
X-Ray CT	21	14	High
Near-Field Millimeter Wave	12	13	High
Shearography	8	8	Low
Through-Transmission UT	16	8	Moderate

hogout removals) at the GFRP-honeycomb interface, one flaw (1 honeycomb hogout) through the honeycomb layer on the side of the GFRP, one flaw (1 honeycomb hogout) at the septum, one flaw (1 honeycomb hogout) through the honeycomb layer on the side of the CFRP skin, ten defects (9 honeycomb hogouts – one for each letter in "NDI TEST", 1 insert). In addition, there was a single flaw in Panel #1 that appears to be a disbond or a delamination in the UT and the Shearography images that was not detected by X-ray CT.

There appears to be 15 flaws in Panel #2: two flaws (2 inserts) in the GFRP skin, five flaws (1 insert, 1 skin mill out at the skin-honeycomb interface, and 3 honeycomb hogout removals) at the GFRP-honeycomb interface, one flaw (1 honeycomb hogout) through the honeycomb core, five flaws (1 insert, 1 skin mill-out, and 3 honeycomb hogouts), one flaw (1 insert) CFRP skin. Like Panel #1, there was also a single flaw in Panel #2 that appears to be a disbond or a delamination in the UT and the Shearography images that was not detected by X-ray CT. The detection results from each modality are shown in Table 1.

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