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Defect imaging in carbon fiber composites by acoustic shearography

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) composites are increasingly used in aerospace, automobile, marine and power industries due to its good mechanical strength and low material density. The defect detection in CFRP has been challenging because of their complex material configuration and various types of defects. In this paper, we reported the use of acoustic shearography imaging for defect detection in carbon fiber composite materials. CFRP specimens with different levels of defects were prepared by open-hole compression tests according to ASTM standard. These specimens were subsequently tested with acoustic shearography imaging method. It is found that acoustic shearography can successfully image various defects efficiently. By synchronizing the stroboscopic laser with the ultrasonic wave frequency, the defect imaging quality can be significantly improved. Comparison with X-ray computed tomography results shows that acoustic shearography can provide sufficiently good defect imaging results with significantly reduced imaging time.

1. Introduction

Carbon fiber reinforced polymer (CFRP) composites are widely used in aerospace, automobile, marine and power industries due to its good mechanical strength and low material density. Currently, composites account for more than 50% of aircraft weight in the latest models of aircraft by Boeing and Airbus [1]. Unlike metallic materials, composites materials have more types of defects due to its complex structures. Composite materials are usually weak in their compressive strength compared to their tensile strength due to micro-bulking of the fibers [2] and/or delamination. The drilling of holes in composite materials further reduce the compressive strength of composite materials in some applications in aerospace industry. The defect detection in composite materials is critical for both the maintenance of composite structures and the development of improved composite systems. However, the defect detection in composites is always challenging. This is not only because of the multiple constituents arranged in complex configurations but also the large span in the scales of various defects.

Many NDT methods have been used for defect detection in composite materials including ultrasound, thermography, laser shearography, eddy currents, etc. Bustamante et al. studied on hybrid air-coupled ultrasonic systems to conduct non-contact B-scans to characterize the defect size on aluminum and CFRP composites with an accuracy of more than 80% by analyzing the amplitude of ultrasonic waves propagating through the defects [3]. Morokov et al. looked into the microstructural damage caused by low-velocity impact within CFRP laminates by using high-frequency impulse acoustic microscopy, which resulted in enhanced resolution ultrasound images of various defects within the laminates [4]. For aeronautical structures that contain CFRP composite elements, Dattoma et al. evaluated the sensitivity of various ultrasonic testing methods such as contact, water stream and immersion methods that utilized ultrasonic transducers, as well as thermography for comparison. It was found that ultrasonic techniques were more reliable and faster for deep defect detection while the thermographic method was more reliable with near surface defects [5]. Zhang et al. used muti-frequency ultrasonic method for detection and characterization of delamination and rich resin in thick composites with waviness. A numerical model was established to include the fiber waviness, uneven inter-ply resin distribution and side-drilled hole (SDH)-simulated delamination. The differentiation of SDHs and rich resin in ultrasonic signals were realized with various filtering frequencies [6]. Ibrahim investigated the ultrasonic wave propagation in hybrid carbon-glass

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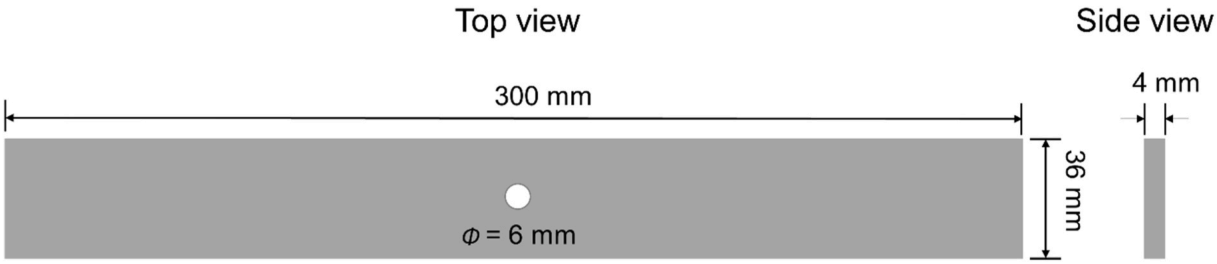

Fig. 1. Dimensions of composite specimens for OHC tests.

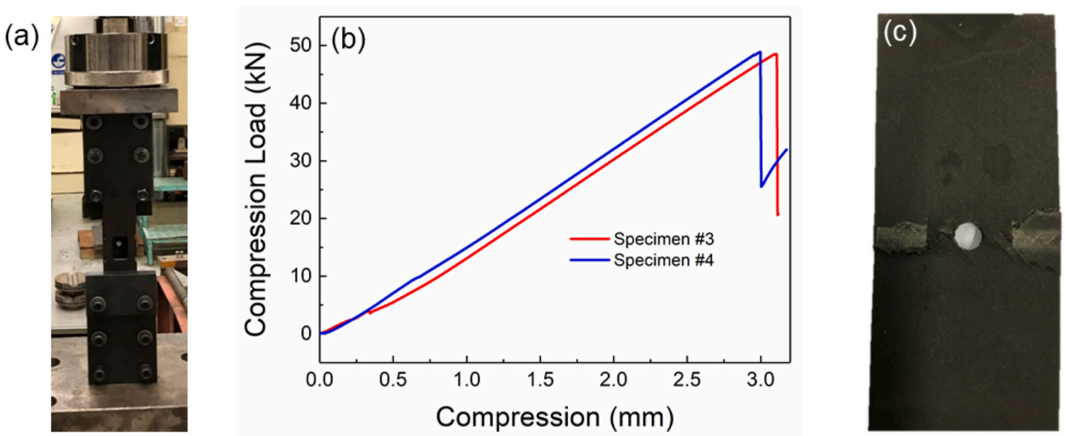

Fig. 2. (a) Setup of OHC test; (b) Load vs. compression curves for two composite specimens; and (c) (b) photography of a damaged composite specimen after the OHC test.

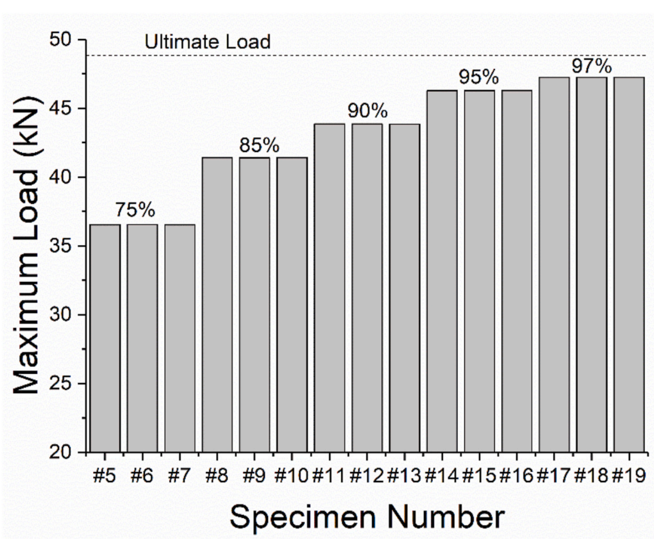

Fig. 3. Composite specimens prepared with different compression loads.

fiber polymer matrix composites. The acoustic mismatch between glass fiber and epoxy resin resulted in significant internal reflection which affected the ultrasonic penetration in deeper layers. Hidden defects in hybrid polymer matrix composites were more difficult to be detected by ultrasonic methods compared to monolithic composites [7]. In eddy current testing (ECT), Wu et al. designed a transmitter-receiver (T-R) probe which were suitable for anisotropic CFRP components. The probe design offered a boost in sensitivity and overcame the drawbacks from lift-off change which were common in ECT probes [8]. Schmidt et al. proposed the use of ECT sensor arrays to monitor the CFRP production line so as to minimize manufacturing errors and inspection time [9]. Another application of eddy current can be found in eddy current pulsed thermography (ECPT), where eddy current is used to generate heat in conductive materials through induction thermal loading. However due to the non-conductive nature of glass fiber reinforced polymer (GFRP), Xu et al. proposed a method to thermally load non-conductive materials by temporarily binding a conductive plate to the GFRP sample to transfer the thermal load onto the sample, which introduced inductive thermal loading onto non-conductive materials [10]. For thermography, heating lamps and lasers are commonly used as non-contact thermal loads. Swiderski showed the effectiveness of spot laser pulsed and laser lock-in thermography with a semiconductor laser for defect detection in materials, such as Steel and Teflon, as well as CFRP in the simulations [11]. Wu et al. suggested a solution to the long delay from switching on/off commercial heating lamps by sending a pulse-compression signal to the lamps and sync with the reference recorded step signal, which boosted the resolution of complex defect imaging in CFRP components [12]. In the field of shearography, De Angelis et al. have developed a new procedure for defect detection in metallic materials and CFRP by dynamically loading with a piezoelectric actuator to obtain the individual defects' resonance frequency through experiments. Thereafter, offset with the natural frequency obtained through simulations to calculate the depth of the circular defects [13]. De Oliveira et al. explored image fusion methods with various NDT imaging technologies such as thermography, shearography and ultrasonic B-scans to enhance the reliability of impact damage inspections of CFRP materials [14]. Burkov et al. evaluated various CFRP specimens with impact loading according to the ASTM D7136 standard with the use of shearography to determine the sensitivity towards defects that occur within CFRP materials [15]. Tao et al. investigated thermal based shearography technique for inspection of thick GFRP with flat bottom holes. The flat bottom holes are in different depths ranging from 5 to 40 mm with diameters ranging from 30 mm to 120 mm. Both simulation model and

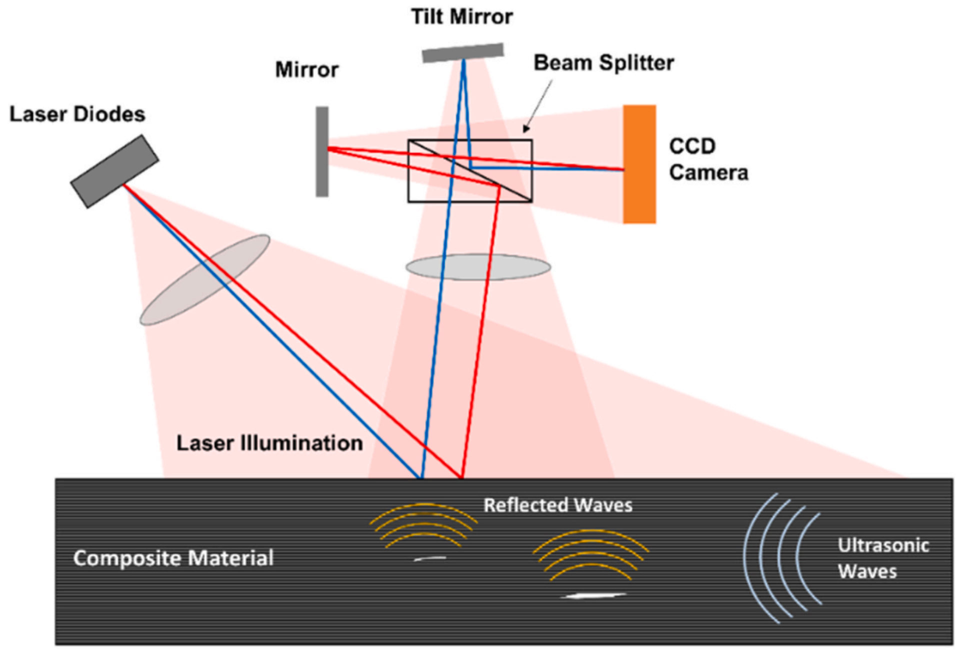

Fig. 4. Illustrative of acoustic shearography for defect detection in composites.

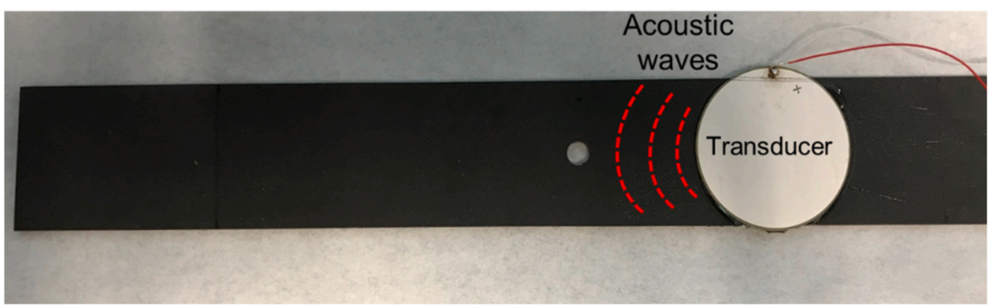

Fig. 5. Setup of acoustic shearography testing.

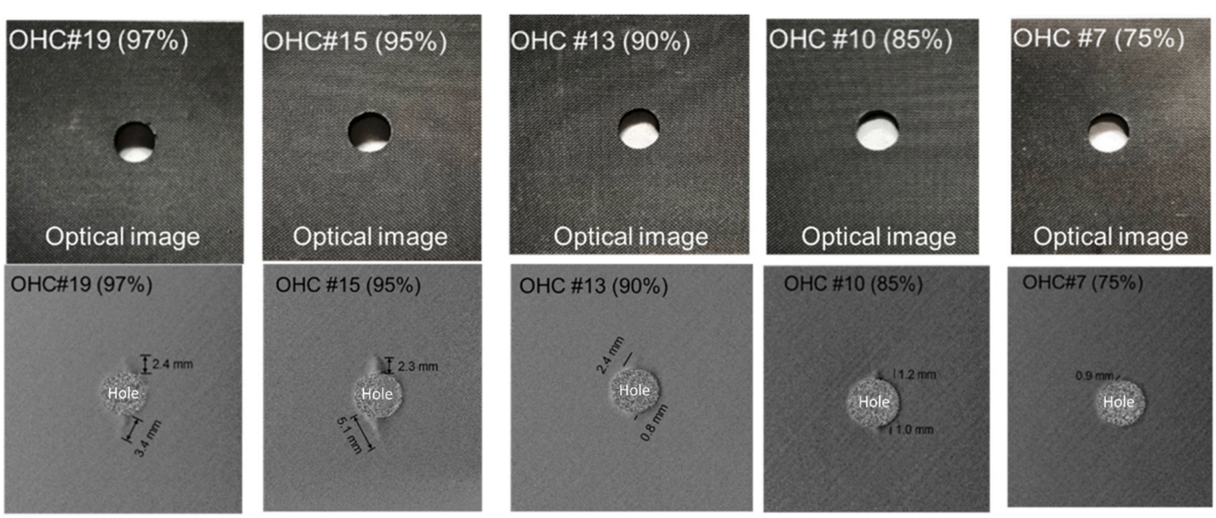

Fig. 6. Acoustic shearography imaging of composite specimens prepared by OHC tests.

experimental tests show that thermal-based shearography is a promising technique for inspection of thick composite structures [16].

Among all the NDT techniques, X-ray radiography and computed tomography inspection are still one of the most reliable ways of defect detection. Pathak et al. were able to detect micro-cracks in tensile loaded CFRP laminates by utilizing X-ray Talbot-Lau interferometry (TLI) to

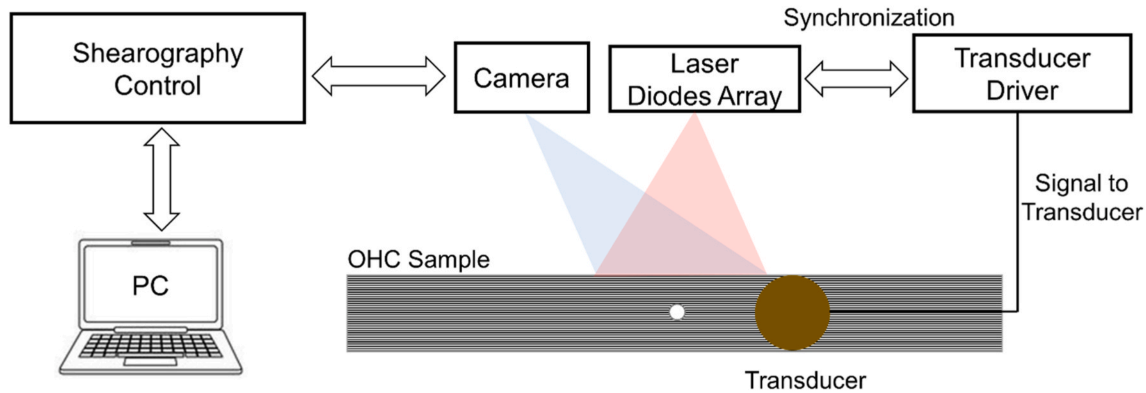

Fig. 7. Experimental setup of stroboscopic acoustic shearography.

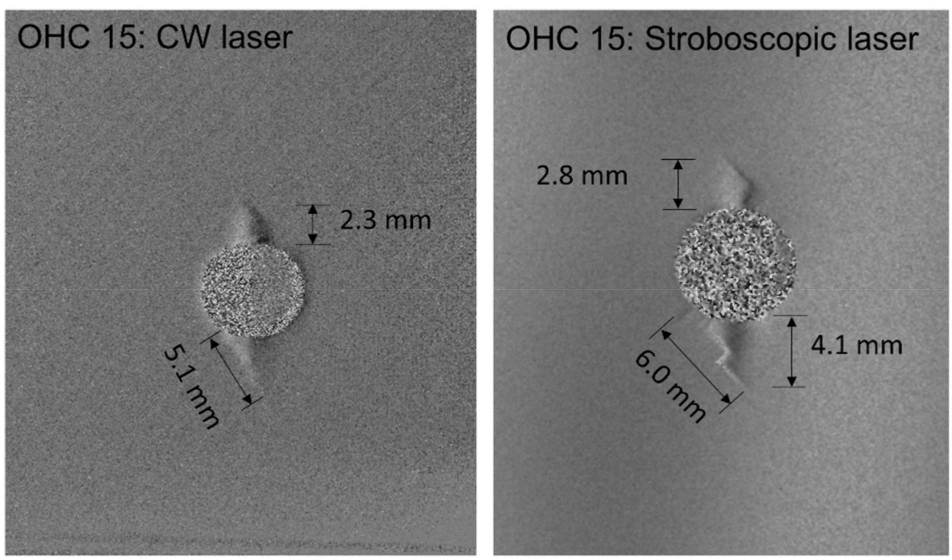

Fig. 8. Improvement of defect imaging by using synchronized laser light. Left image: acoustic shearography image with CW laser light and right image: acoustic shearography image with stroboscopic laser light.

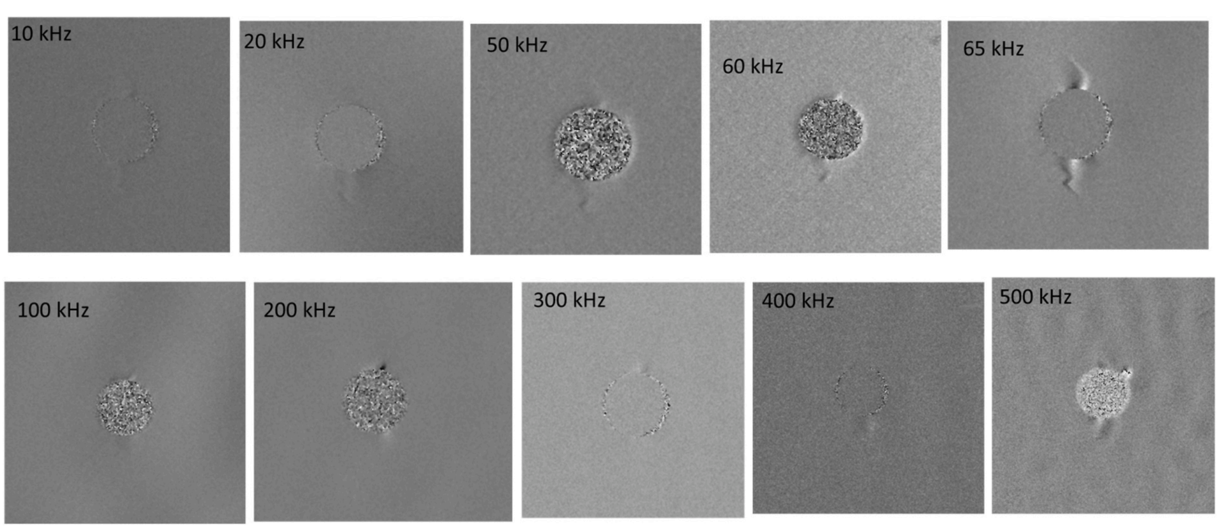

Fig. 9. Acoustic shearography images with varied frequencies.

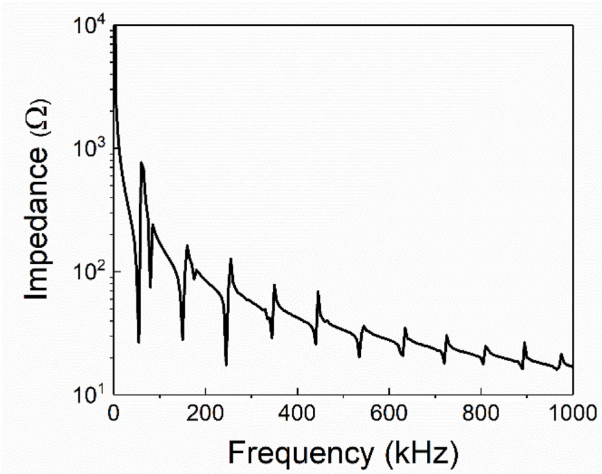

Fig. 10. Impedance of piezoelectric transducer used in frequency sweeping showing multiple intrinsic transducer resonances.

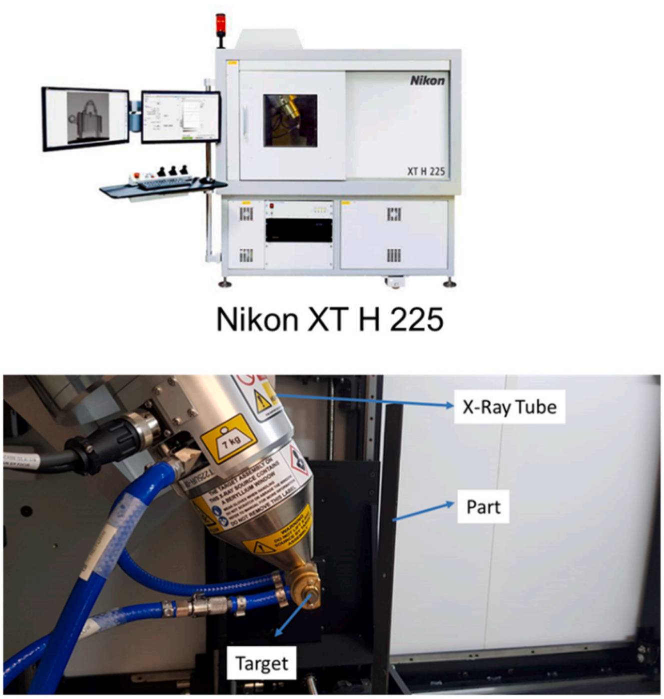

Fig. 11. X-ray equipment and setup for cross-validation.

capture attenuation contract (AC), differential phase contrast (DPC) and dark-field contract (DFC) images in a single shot. Among all the images captured, DFC images had the highest resolution of micro-cracks in CFRP components [17]. Dilonardo et al. reported the use of X-ray computed tomography (X-CT) to capture porosity within CFRP elements with further analysis in the characteristics of the pores and other the various defects [18]. To improve the manufacturing of CFRP, Stamopoulos et al. have trained an artificial neural network using various scenario of CFRP defect images captured using XCT with inputs such as temperature and pressure to enhance the consistency of the CFRP production line [19].

Wave-based acoustic shearography is a new hybrid method by combining ultrasonic excitation with shearography optical imaging. The method is based on the wave-defect interactions which can significantly increase the detection depth and therefore the detection sensitivity of shearography testing compared to conventional shearography with vacuum, thermal or vibration as loadings. The acoustic shearography relies on generation of high-intensity ultrasonic waves to excite defects of various sizes. In contrast to vibration-based shearography where acoustic excitation needs to sweep over a frequency range [20,21], the wave-based acoustic shearography does not need to sweep in a frequency range. Instead, a single fixed frequency which is the major resonant frequency of the transducer is used. This eliminates the need for frequency sweeping and increases the detection reliability. A variation of the technique, directed acoustic shearography [22], is based on high-power phased array transducer to focus and direct ultrasonic waves at different spatial locations for defect imaging. The directed acoustic shearography can image deeper defects. The acoustic shearography method has demonstrated to be capable of detecting deep subsurface defects in metallic materials in a rapid (in a few seconds) and effective manner [22,23]. To apply acoustic shearography for defect imaging in composites, the frequency needs to be kept low to minimize the loss due to wave attenuation. In addition, the wave intensity needs to be larger compared to that in metallic samples to compensate the energy loss due to wave attenuation. Lastly, as composites have more types of defects of various length scales, the defect detection in composites is more challenging. Improvement on acoustic shearography method is needed. In this paper, we evaluate the acoustic shearography method for the defect detection in carbon fiber composite materials. Firstly, CFRP specimens with different levels of defects were prepared by conducting open-hole compression (OHC) tests of different maximum loads. These specimens were subsequently tested with acoustic shearography imaging method. Piezoelectric transducers are used in the acoustic shearography testing to generate ultrasonic waves in the composite specimens. Shearography imaging system is used to capture the changes of optical pattern due to wave-defect interactions. The acoustic shearography imaging was done at different ultrasonic wave frequencies which could be used for classification of defects. To validate the acoustic shearography imaging results, X-ray 2D radiography and X-CT were conducted. Comparisons between X-ray radiography, X-CT and acoustic shearography imaging results show that acoustic shearography can provide sufficiently good defect imaging with much reduced imaging time.

2. .Composite materials and defect preparation

2.1. *Composite materials*

The composite materials studied are carbon fiber composites with a layup of $[-45/45/90/0]_{4s}$, which were provided by Hexcel Composites, UK. The composite specimens were prepared according to the ASTM D6484 standard for OHC tests. The sample dimensions are 300 (L) x 36 (W) x 4 mm (T) with hole diameter of 6 mm, as shown in Fig. 1.

The OHC test is a method to generate natural and controlled defects in composite materials. A total of 20 specimens were prepared for the OHC tests.

2.2. *OHC testing*

OHC is a test that can evaluate the structural performance of composites in the aerospace industry. The complex stress state arising from the hole in combination with the anisotropic plies arranged at different angles, gives rise to a range of different defects and failure mechanisms such as fiber micro-buckling, tensile fracture, matrix microcracking, intralaminar splitting and delamination. To prepare specimens with different levels of defects, OHC tests are performed following ASTM standard. The OHC composite specimens were loaded to different maximum stress levels, which results in composite specimens with different levels of damage for subsequent tests and examinations. An initial reference test was first done to determine the breaking load for this type of specimens. Tests loaded to different stress levels could then be assigned a % value corresponding to the fraction of load with respect to the reference specimen.

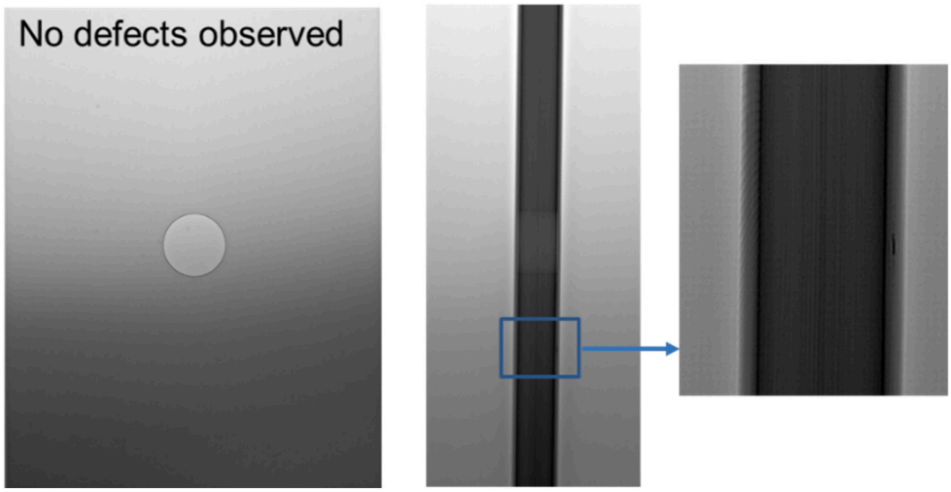

Fig. 12. X-ray radiography of an OHC sample.

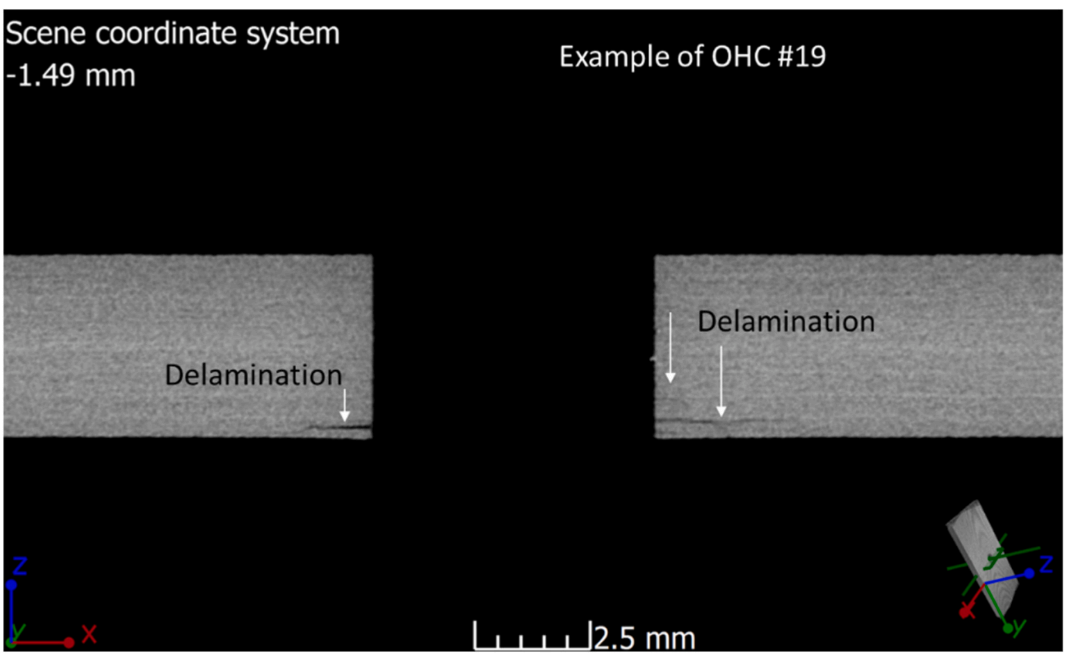

Fig. 13. An X-CT image showing cross-section of an OHC sample.

The OHC fixture was used in the tests as shown in Fig. 2(a) following the ASTM standard D6484. Two OHC specimens, #3 and #4 were tested till their failures to determine the ultimate load of the specimens. Fig. 2(b) shows the load displacement curves for the two specimens. Fig. 2(c) shows a photo of the specimen after the compression failure. According to Fig. 2(b), the average ultimate compression load for the two specimens is found to be 48.7 kN. Based on this ultimate load, 5 load points, i.e. 75%, 85%, 90%, 95% and 97% of the ultimate compression load were selected and 3 specimens for each load point were prepared as shown in Fig. 3.

3. Acoustic shearography method

Shearography is a full-field optical imaging method suitable for fast defect inspection [24]. Shearography is based on the subtraction of two interferometric images obtained when a testing object is under stress loading and without stress loading. Unlike conventional shearography techniques which use stress loadings by vacuum, thermal and vibration excitations, acoustic shearography takes use of the stress loading generated from ultrasonic waves. The technology has the advantages of fast inspection speed and large penetration depth, which is suitable for high-efficient defect characterisation of materials and structures.

In acoustic shearography testing, coherent laser lights are used to illuminate on the sample surface to generate interferometry pattern via shearography optics as shown in Fig. 4. The changes of the interferometry pattern due to stress loading of ultrasonic waves are captured by a camera in reference to the pattern without stress loading. Both surface and subsurface defects are detectable in nearly real time. The shearography sensor used in this study is a SE2 sensor (isi-sys GmbH, Germany).

Systematic shearography tests with piezoelectric ultrasonic transducers were conducted for the defect detection of the composite specimens. The detectability of defects in composite materials is a key aspect to be investigated. Based on the types of the defects, ultrasonic waves of various frequencies are generated by using piezoelectric transducers in the acoustic shearography tests.

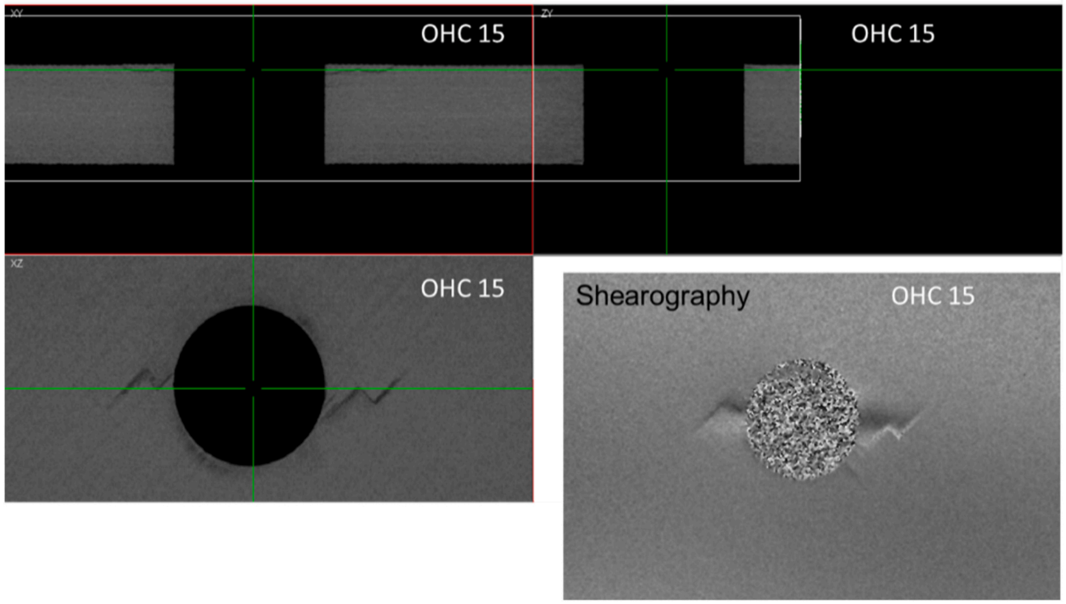

Fig. 14. Comparison of X-CT image with shearography image.

4. Results & discussions

4.1. Acoustic shearography imaging results

Acoustic shearography tests were conducted on the composite specimens with different damage levels. As shown in Fig. 5, a piezoelectric disc transducer was bonded on the composite specimen by wax. The diameter of the transducer is 40 mm and the thickness is 0.5 mm. The center of the transducer was located at 50 mm from the center of the hole. Electrical potential was applied to the transducer and the transducer was excited at its first resonant frequency at around 50 kHz. The total electrical power to the transducer is around 30 W.

Fig. 6 shows the acoustic shearography for specimens which underwent OHC tests. It is evident that defects in the OHC composite specimens were imaged successfully. For OHC specimens which had undergone 97% and 95% of ultimate compression load, large area of defects was imaged in shearography images. These area type defects could be delamination in the composites given its areal nature. The minimum feature identified from the shearography images is around 0.8 mm.

The above acoustic shearography imaging is based on time-averaging measurement method where the laser light in the shearography system is continuous wave (CW) and the final acoustic shearography images are results of cumulative exposure over a period, e.g., 5–10 s. As the ultrasonic waves used in the shearography testing are periodic waves with fixed frequency, it is possible to freeze the wave motion by synchronizing the frequency of ultrasound with that of the illumination laser, i.e., the frequency of laser flashing is the same as that of ultrasonic wave/transducer frequency. The laser diodes used in the current setup can generate stroboscopic light with an external trigger signal. The experimental setup for the stroboscopic acoustic shearography is shown in Fig. 7.

Fig. 8 shows the comparison of acoustic images obtained with CW laser light and stroboscopic laser light. It is obvious that with the synchronization between laser illumination and wave frequency, the defect imaging quality is significantly improved. When using the CW laser light, the laser light is always on. Shearography images of various times are accumulated and averaged leading to a less distinct defect image. When using the stroboscopic light which is synchronized with the ultrasonic frequency, shearography images at a specific wave phase are captured and accumulated. Thus, clearer defect features are captured in the shearography image with stroboscopic laser light.

As the frequency of the acoustic waves are controllable through external electric signals, it is feasible to conduct a frequency sweep in the acoustic shearography imaging. The purpose of the sweeping is to explore the feasibility of exciting defect resonances. As different types of defects may have different resonances, the defect resonance is potentially a tool for classification of different types of defects. Fig. 9 shows the acoustic shearography images obtained at different wave frequencies. For this frequency sweeping test, a square shape transducer with dimensions of 35 mm × 35 mm x 1 mm was used. The transducer's first resonance was 65 kHz. At transducer resonance, the acoustic shearography images shows most of the defects as the wave intensity is the maximum. At other frequencies, for example from 10 kHz to 500 kHz, the defects imaged are different. A general trend is that at lower frequency, the defects imaged are mainly large area defects indicating possible delamination. With the increase of frequency, the defects are localized in selected small regions. This reflects the frequency characteristics of different types of defects which are related to their sizes, depths and local stiffnesses.

However, as the frequency response of the piezoelectric transducer is not flat for the frequency range of 10 kHz–500 kHz as shown in Fig. 10, the interpretation of the results is not straightforward. The acoustic shearography images obtained at different frequencies are the combined effects of transducer resonances, structural resonances of whole specimens and defect resonances. More detailed analysis and experimentation are planned in the future.

4.2. Results validation by X-ray CT

After obtaining the acoustic shearography images of OHC composite specimens, X-ray radiography and computed tomography have been conducted for cross-validation of the results. In the X-ray based validation method, Nikon XT-H 225 was used for the experiment as shown in Fig. 11.

Fig. 12 shows the 2D radiography images for the major surface and cross-section. It is evident that no defects were observed when X-ray was projected normal to the major surface of the sample. When the X-ray is projected through the side of the sample, a defect was observable as shown in the zoon-in figure in Fig. 12. X-CT was subsequently conducted for the same composite sample to obtain more details of the defects. As shown in Fig. 13, the defects are much clearer in the X-CT image.

Fig. 14 shows the comparison of X-CT image with acoustic shearography image. It is evident that the features captured by the acoustic shearography match well with the X-CT results. This indicates that the acoustic shearography method can provide sufficiently good defect imaging for characterization of composite materials. In contrast to the hours-long scanning process of X-CT, acoustic shearography imaging was completed within1–2 s.

5. Conclusions

In this paper, we reported the use of acoustic shearography imaging for defect characterization in carbon fiber composite materials. Composite specimens with different levels of defects were prepared by OHC tests according to the ASTM standard. These specimens with defects were tested with acoustic shearography imaging method. It was found that the acoustic shearography can successfully image various defects in one short. By synchronizing the stroboscopic laser with the ultrasonic wave frequency, the defect imaging quality can be significantly improved. The minimum defects detected is around 0.8 mm based on the current setup. The acoustic shearography imaging results agree well with the X-CT imaging results. The results show that acoustic shearography can provide sufficiently good defect imaging results with significantly reduced imaging time.

CRediT author statement

Lei Zhang: Conceptualization, Methodology, Writing - Original Draft. **Zi Wen Tham:** Investigation, Validation. **Yi Fan Chen:** Investigation. **Chin Yaw Tan:** Investigation. **Fangsen Cui:** Investigation. **Bisma Mutiargo:** Investigation. **Lin Ke:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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