Audible Acoustics for Detecting and Locating Damage in Composite Structures

Matthew Pearson and Rhys Pullin
Cardiff University, School of Engineering
Cardiff, CF24 3AA, Wales
pearsonmr@cardiff.ac.uk

Eszter Szigeti
Airbus
Filton, BS34 7PA, UK

Abstract

Carbon fibre composites are increasingly being used for large scale load bearing structures in a variety of industries, which include aerospace and renewable energy sectors. The main benefit of composite structures over traditional metallic equivalents is the inherent strength to weight ratio. This allows for the development of more optimised and efficient structures. However, the development of these large-scale composite structures can be a very costly and time-consuming exercise. As a part of the development process extensive verification testing is undertaken, which can range from coupon specimens to full scale structural tests. Non-Destructive Testing (NDT) techniques are often employed to detect the early onset of damage and avoid catastrophic failures. This requires periodic test down time to gain access to the structure to undertake these inspections. Audible Acoustics (AA) uses an array of microphones to audibly detect the sound signatures from damage initiation and growth in composite materials. It has the potential to be used as a non-contact NDT technique, creating a quick and easy to setup damage detection system. Therefore, offering a reduction in testing downtime, avoiding unexpected failures and enabling the re-use of specimens, which will ultimately reduce time and costs. This paper explores the use of an acoustic camera to detect and locate damage in a carbon fibre specimen. An acoustic camera is an array of microphones which can be used to visualise the location of a sound source. Results showed that by using delay and sum beam forming it was possible to locate damage in the specimen.

1. Introduction

Carbon fibre composite components are being increasingly utilised for large load bearing structural components due to their performance benefits. Two such industries which are seeing the benefit of these composite structures is the aerospace and wind power industries. Composite materials have an inherent strength to weight ratio advantage over metallic equivalents.

Although there are many benefits to the use of composites their development and certification can be a time consuming and costly process. As composites are being increasingly utilised for primary safety critical structures, an extensive certification testing programme must be undertaken. This ranges from small coupons, large panels and full scale structural tests. During these programmes Non-Destructive Testing (NDT) techniques are used to monitor damage evolution in the structure. One disadvantage of conventional NDT techniques is that they require periodic access to the structure. This results in test downtime causing additional time and costs to the certification testing programme. Structural Health Monitoring (SHM) techniques are being developed to monitor certification tests on-line. However, these techniques require are large number of sensors and cabling and represent significant time prior to testing for installation. Audible Acoustics (AA) offers the potential to be used as a rapidly deployable, non-contact NDT technique for the detection and location of damage in composite structures.

AA is an emerging technology in terms of damage assessment. Farshidi et al(1) used the response from micro-electro-mechanical-system microphones to investigate the modal response of a simple aluminium cantilever beam excited by a pulsed air jet. Arora et al(2). demonstrated an acoustic damage assessment method by exciting a thin plate with a loudspeaker. A passive acoustic method of damage detection was presented by Jiang et al(3). Loud speakers were used to excite the panels and non-contact measurements were taken by positioning a microphone at various points on a grid. More recently, AA has advanced through the use of Acoustic Cameras. Acoustic Cameras comprise of an array of microphones to detect and locate audible sound emissions which are then overlaid over the video image. Acoustic cameras have typically been used to detect and analyse noise such as assessing noise from aircraft at airports(4). Aizawa et al(5) used different acoustic beamforming techniques for detecting damage in wind turbine blades and composite plates using two different microphone arrays. Measuring Lamb waves and their interaction with damage in composite aerospace structures with an acoustic camera has been studied by Pfeiffer et al(6). This paper builds on previous work(7) using an acoustic camera to detect final failure in composites materials. The aim is to explore the use of audible acoustics to detect damage initiation and propagation in a composite specimen under tensile loading and validate the results using Digital Image Correlation (DIC).

2. Experimental procedure

2.1 Specimen Manufacture

The composite specimens were manufactured from uni-directional Hexcell M21/35%/UD268/T800S pre-preg material and cured in an autoclave at 180 °C for 2hrs. The specimen dimensions were 200 x 400 mm with a layup of $(0,60_2)_s$ resulting in a nominal thickness of 1.5mm. Two V-notches with a depth of 55 mm were introduced at the centre line of the panel in order to promote damage at a specific location. Four Steel clamping plates were used to transmit the load to the specimens using 20 mm pins. The specimen and the clamping plates used for the investigation can be seen in Figure 1. An ultrasonic C-scanner was used to determine that there were no defects in the specimens prior to testing.

2.2 Experimental Procedure

The specimen was loaded in five stages, the first increment was 0.5 kN to 10 kN, the remaining stages were increments of 10 kN to a peak load of 50 kN. The five loading stages were necessary due to the maximum recording time of the acoustic camera system at the specified sample rate. The load was held at the end of each incremental load stage while the audible data was downloaded from the acoustic camera system. After the peak load of 50 kN was reached the specimen was unloading from 50 kN to 0 kN at rate of 1.25 kN/s. Two non-contact measurement techniques were used to monitor the evolution of damage in the specimen. The first was a commercial acoustic camera system manufactured by gfai tech GmbH. The system comprises of a circular array of 48 equally spaced microphones and an optical camera at the centre of the array as seen in Figure 2. A gfai tech GmbH MC dRec acquisition system was used to record the audible acoustic waveforms at a sample rate of 192 kHz, at this particular sample rate the maximum recording duration was 43 seconds. A pre-trigger of 40 seconds was used and the system recording was triggered at the end of each incremental loading stage. The commercial Noiseimage software was used to determine audible signatures of interest and delay and sum beamforming was utilised to localise a noise source. The second monitoring technique was a DIC system, this is an optical technique that allows for the calculation of full field deformation and strain. Before testing commenced a black and white speckle pattern was applied to the back surface of the specimen using spray paint. A Dantec Q-400 DIC system with two cameras and the ISTRA 4D software package was used to monitor the specimen. A reference image was taken at zero load. Images were recorded every second throughout each incremental loading stage. The experimental set-up can be seen in Figure 2 where the Acoustic Camera and DIC systems were used to monitor different sides of the specimen.

Figure 1. Specimen with the clamping plates

Figure 2. Experimental set-up

3. Experimental Results and Discussion

3.1 DIC Experimental Results

Figure 3 shows the strain in the horizontal direction calculated using the DIC software at peak load before the specimen was unloaded to zero. The figure shows significant strain concentrations below the Left Hand Side (LHS) notch and above the Right Hand Side (RHS) notch. This corresponds to visual observation where surface splitting on both sides was present in these areas. There was also separation of the surface layers in the region of the v-notch hence the missing data in Figure 3.

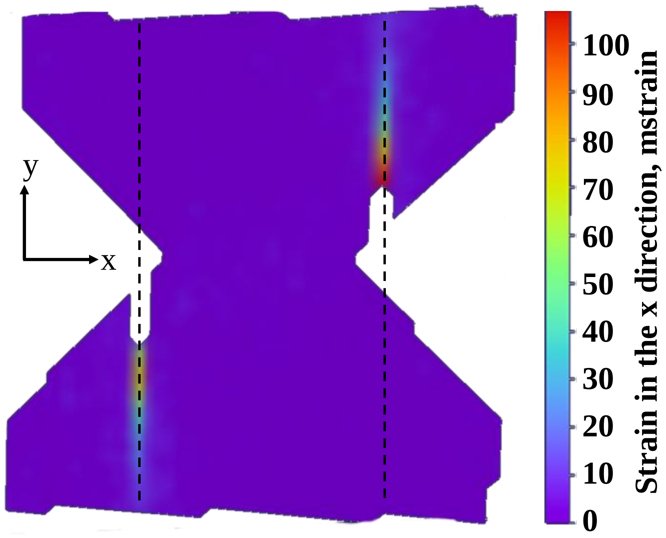

Figure 3. Strain in the x direction at peak load

Figure 4 shows the development of strain measured at incremental points on a virtual vertical line placed on the LHS and RHS high strain regions as shown by the dashed lines identified in Figure 3. This shows the development of strain throughout the loading. Figure 4 and Figure 5 show that significant strain started to occur at 120 seconds when the load was 30kN, suggesting damage started to initiate at this load. The strain than develops further along these virtual lines which corresponds to the visual observation of the surface splitting which reached the bottom and top of the area of interest on the LHS and RHS notched regions respectively (shown in Figure 3).

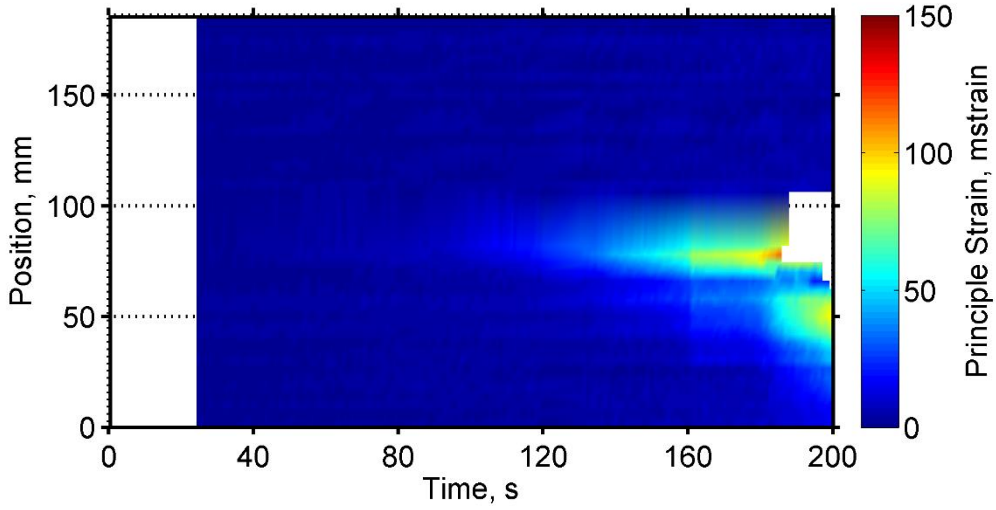

Figure 4. Principle strain along a vertical line placed at LHS high strain regions during the load regime

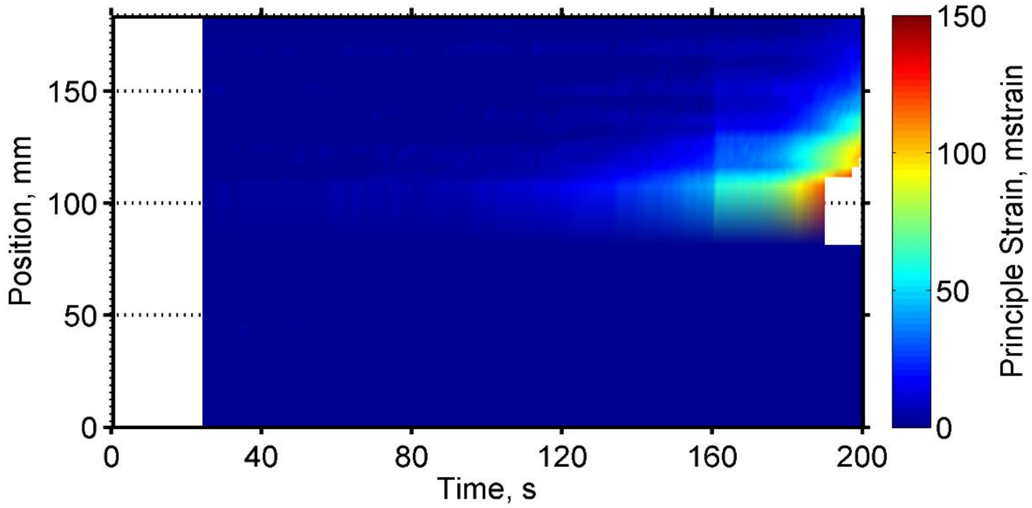

Figure 5. Principle strain along a vertical line placed at RHS high strain regions during the load regime

3.2 Audible Acoustics Experimental Results

Figure 6 shows the acoustic waveforms from each 40 second loading stage which were stitched together to form an acoustic waveform for the entire loading stage. The figure shows the ambient background noise in the laboratory was approximately 300 mPa. It is evident that contained within the waveform, higher frequency spikes occur throughout the loading period. The first spike occurred at approximately 6 seconds and was due to background noise, the other higher frequency spikes occurred during development of the increased strain at the notches. This suggest these high frequency spikes could have arisen due to damage initiation and propagation in the panel.

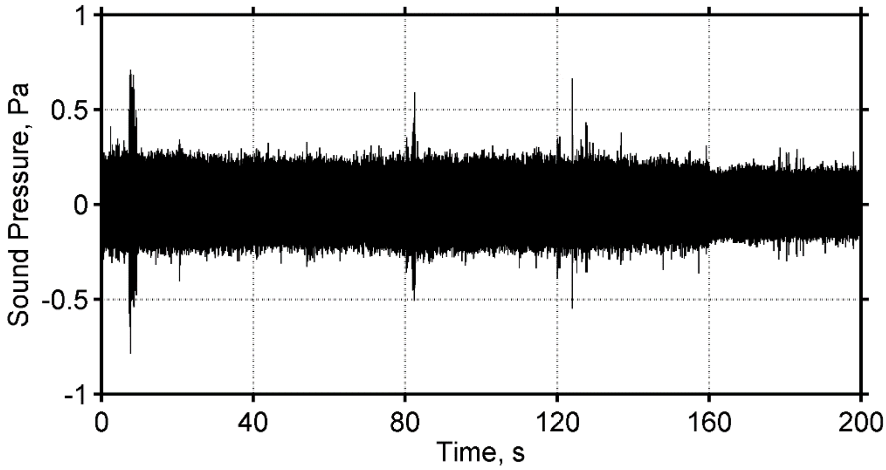

Figure 6. Resulting acoustic waveform from the start of the loading to peak load

In order to locate the sound sources a two second window of the acoustic waveform was chosen and then a short time FFT was calculated. High frequency components were identified in this window and delay and sum beam forming was applied in the frequency domain. This procedure was repeated for the entire 200 second acoustic waveform. Figure 7 shows an example result of the delay and sum beam forming in the frequency domain performed in the Noiseimage software for an event occurring at 182 seconds into loading regime. The dotted line in the figure represents the edge of the composite specimen. The figure shows the sound level of the spatially located source which corresponds to the RHS notched at the elevated strain levels seen in Figure 5 and its most likely due to damage propagation in the specimen.

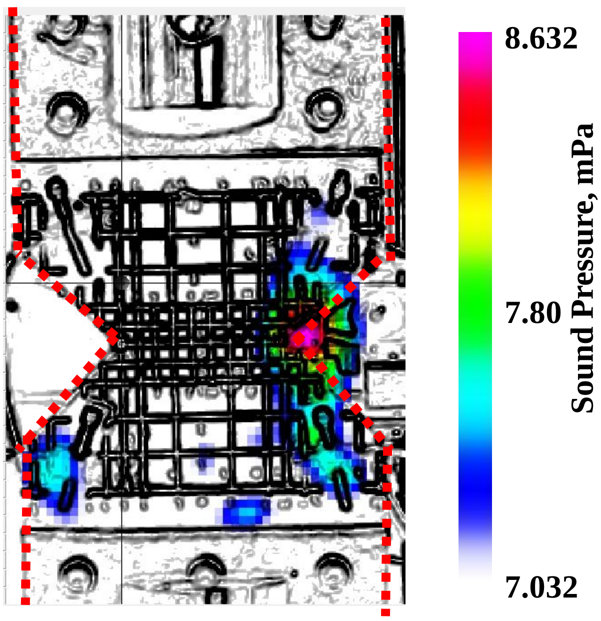

Figure 7. Located Acoustic source at 182 seconds

Figure 8 shows results of the number of located acoustic events and the corresponding cumulative sound pressure of these located sources. Relatively significant levels of acoustic events occur at 80 seconds at the start of the 20-30 kN loading stage. Between 130 and 160 seconds there is a significant increase in the rate of located events and pressure level, this corresponds to the increase in strain seen in Figure 4. At the start of the 40-50 kN loading stage (160 seconds), the rate of acoustic events and pressure levels that were recorded decreases. This corresponds to no significant propagation of the damage due to very little increase in the strain levels. At approximately 180 seconds there is an increase in the cumulative sound pressure rate which again corresponds to increasing strain over the final 20 seconds of the loading test. This suggest the rate at which the located audible events correspond to the increasing strain levels and the propagation of damage in the panel.

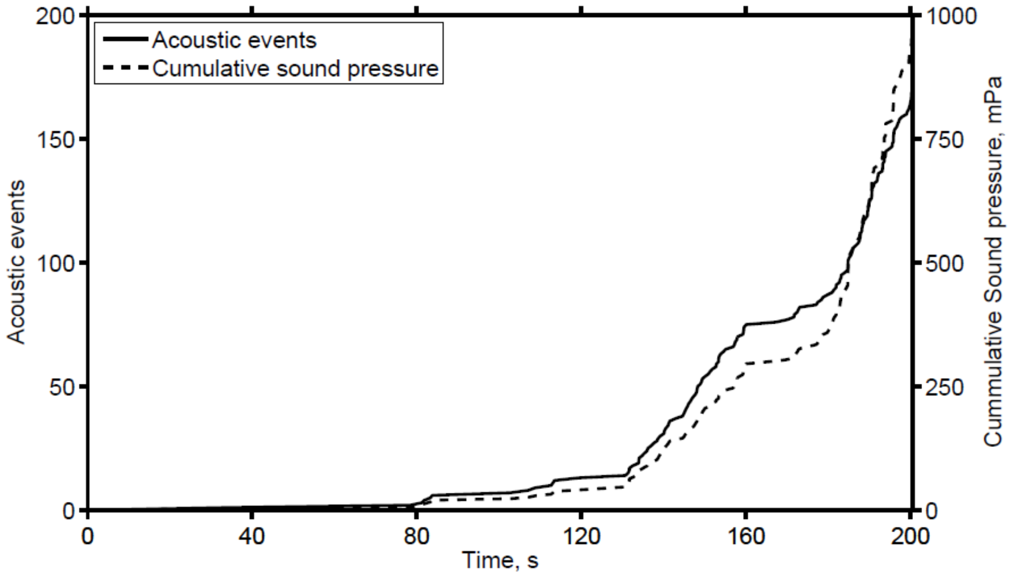

Figure 8. Rate of acoustic events and the corresponding cumulative pressure level

3. Conclusions

An investigation into the use of DIC and an acoustic camera to track and locate damage introduced into a composite tensile specimen was undertaken. Although damage was introduced in the specimen, complete failure of the specimen had not occurred at the end of the loading stage. A commercial acoustic camera system was used to locate the high frequency components of the acoustic waveform, using delay and sum beamforming. The located sources corresponding to the damage regions was verified by the DIC system. The rate at which located sources increased with the observed strain at the notches. This demonstrates the potential of audible acoustics as a NDT technique for composite materials, creating a non-contact damage detection system.

Acknowledgements

The authors would like to acknowledge Airbus for the loan of the acoustic camera system.

References

1. R Farshidiet al., '*Non-contact experimental modal analysis using air excitation and a microphone array',*. Measurement, Vol **43, No** 1, pp 755-765, 2010.
2. V Arora et al, '*Acoustic-based damage detection method.* Applied acoustics', Vol 80, pp. 23-27,2014.
3. H Jiang et al, '*Material damage modelling and detection in a homogeneous thin metallic sheet and sandwich panel using passive acoustic transmission',*. Structural Health Monitoring, Vol 5, No 4, pp 373-387,2006.
4. R Merino-Martinez et al, '*Determination of aircraft noise variability using an acoustic camera*'. ICSV23, 2016.
5. K Aizawa et al, '*An acoustic-array based structural health monitoring technique for wind turbine blades'* SPIE Proceedings. Vol 9437, 2015
6. H Pfeiffer et al, '*Identification of impact damage in sandwich composites by acoustic camera detection of leaky Lamb wave mode conversions'*. 2013.
7. M Pearson et al, *'Damage Detection in Composite Materials using Airborne Acoustics'*, Key Engineering Materials, Vol 569-570, pp 72-79,2013.