Guided Wave Propagation and Scattering in Aerospace Composite Panels

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Abstract

Carbon fiber laminate composites, consisting of layers of polymer matrix reinforced with high strength carbon fibers, are increasingly employed for aerospace structures. They offer advantages for aerospace applications, e.g., good strength to weight ratio. However, impact during the operation and servicing of the aircraft can lead to barely visible and difficult to detect damage. Depending on the severity of the impact, delaminations can occur, reducing the load carrying capacity of the structure. Efficient structural health monitoring of composite panels can be achieved using guided ultrasonic waves propagating along the structure. The guided ultrasonic wave (A_0 Lamb wave mode) propagation and scattering at delaminations was modelled using full three-dimensional Finite Element (FE) simulations. Impact damage was induced in the composite panels using standard drop weight procedures. Ultrasonic immersion C-scans were performed to quantify the extent and shape of delamination due to the impact. The guided wave scattering at the impact damage was measured using a noncontact laser interferometer, quantified, and compared to baseline measurements on an undamaged part of the composite panel. Good agreement between experiments and FE predictions was found. The sensitivity of guided waves for the detection of barely visible impact damage in composite panels has been verified.

1. Introduction

Composite materials have good strength to weight capacity for the aerospace structures. Impacts during service can result in barely visible damage (1), requiring nondestructive testing and monitoring. Hidden impact damage such as matrix cracks, fiber damage, and delaminations can reduce the structural integrity and load bearing capacity (2). Different non-destructive testing methods for the monitoring of composite structures have been proposed (3, 4). Manufacturing defects in composites, e.g., porosity, in-plane fiber orientation, and out-of-plane ply wrinkling, have been detected with good sensitivity from ultrasonic measurements (5). Delaminations can be detected and sized accurately using ultrasonic immersion C-scans (6-8). Large structures can be efficiently monitored using guided ultrasonic waves (9), e.g., fatigue cracks in metallic and multi-layered structures (10-14). The propagation of guided waves in anisotropic materials is dependent on the direction to the fiber layup, requiring good understanding for experimental design and analysis (15, 16). For higher excitation frequencies and higher guided wave modes, in addition to complicated propagation patterns, the attenuation in composite materials is quite high, limiting their potential for defect detection. Fundamental guided wave modes at low frequencies have been found to be advantageous for most structural health monitoring (SHM) applications. Guided waves have been successfully employed to detect delaminations in composite structures [17, 18]. The scattering of the fundamental A_0 guided wave mode at impact damage was measured and compared to Finite Element (FE) predictions [19].

This contribution describes the composite specimen with barely visible impact damage, ultrasonic C-scans, and guided waves system. Experimental results for the observed guided wave scattering are compared with FE simulations for delaminations and discussed.

2. Experiments

The cross-ply composite specimen was manufactured by the Composite Systems Innovation Centre at the University of Sheffield, UK [1]. The specimen (990 mm x 110 mm) was made from 8 pre-preg layers (Cytec 977-2/ Tenax HTS) with a symmetric, cross-ply layup sequence of $[0/90]_{2s}$, having 2 mm thickness. Impact damage had been generated using standard drop weight impact (7.4 J energy, hemispherical 15 mm impactor head). Limited indentation and fiber fracture on the impacted plate was observed (Fig. 1).

Ultrasonic C-scans were performed of the area around the impact [20, 21]. A 200 mm long section was cut out of the specimen and placed in a water bath for immersion scanning. A 12 mm thick steel plate was placed 5 mm below the composite specimen in the water bath to perform double-through transmission ultrasonic C-scans, recording the maximum amplitude of the pulse reflected at the steel plate. The reflection of the ultrasonic pulse within the specimen was captured as well. The C-scan area shown was 70 mm x 35 mm (step size 1 mm). For the ultrasonic immersion measurements, an unfocused, quarter inch diameter, 10 MHz center frequency transducer was employed. The signals were recorded using a digital oscilloscope and transferred to a PC for evaluation using MATLAB.

The guided wave field was measured, covering a square scan area of 40 mm x 40 mm (step size of 1 mm) around the impact damage location. Further measurements were performed on a line across the impact location and symmetrically on an undamaged part of the composite specimen. The guided wave field was also measured on a circle (radius 30 mm) around the impact center and an undamaged part of the plate. The scattered wave field was measured using a laser interferometer, moved parallel to the specimen using a scan rig. The A_0 guided wave mode was excited using a custom-built transducer, consisting of a piezoelectric disc (diameter: 5 mm, thickness: 2 mm, polarized in thickness direction) and a bonded brass backing mass (diameter: 5 mm, thickness: 6 mm). The excitation transducer was permanently bonded to the composite specimen 100 mm from the impact damage center. The excitation signal (5-cycle Hanning windowed tone-burst, center frequency 100 kHz) was generated using a programmable function generator and amplified to approximately 200 V_{pp}. The time traces of the laser signal (proportional to out-of-plane velocity) were band-pass filtered (75 – 125 kHz) and recorded (20 averages). For the analysis using Matlab software, for each scan point, the maximum amplitude of the time trace was calculated using the Hilbert transform.

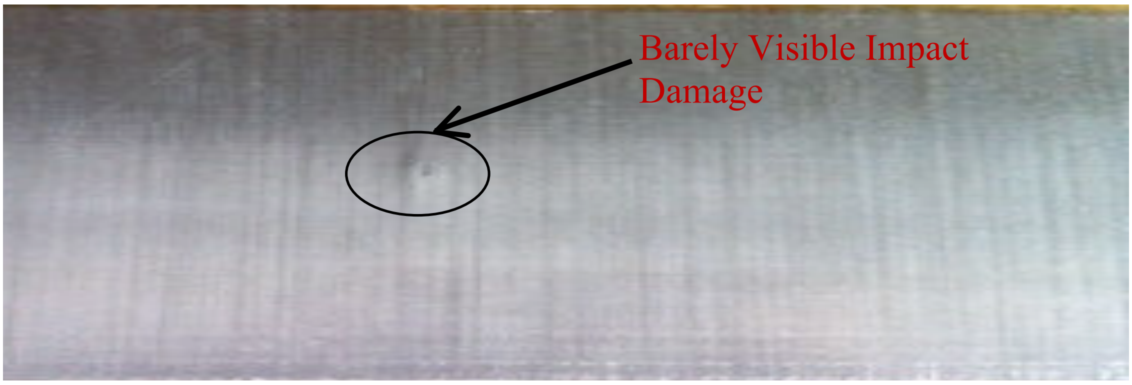

Figure 1: Composite specimen with barely visible impact damage (indent and fibre fracture) marked.

3. Finite Element Simulations

A 3D FE model of the cross-ply composite plate was developed in ABAQUS [19], in order to investigate the guided wave propagation and scattering at delaminations. The modeled composite plate consists of 8 layers through the thickness, with the same $[0/90]_{2s}$ lay-up as the specimen for the experimental, but a larger size to achieve time separation to edge reflections. The material properties for the pre-preg layers were modeled according to properties of a unidirectional composite plate, obtained from [22], with Rayleigh damping set to ß = 30 ns for wave attenuation [19]. Element size of 1 mm along the plate and 0.25 mm in the thickness direction (one element per layer) was chosen. The element type was chosen as an 8-node linear brick with reduced integration (C3D8R) and the element size and time step fulfill the stability criteria for explicit time simulation of wave propagation. The delamination was modeled with zero volume as a rectangular shape at 0.5 mm depth (quarter plate thickness). The size of the delamination (length and width) was 30 mm by 30 mm [19]. The excitation signal was the same as for the guided wave experiments, consisting of a 5 cycle sinusoidal tone burst with a center frequency of 100 kHz modulated by a Hanning window. The excitation location to generate an A_0 Lamb wave mode was placed 100 mm from the center of the delamination. The out-of-plane displacement was monitored using a line scan across the delamination and a circular scan with 30 mm radius around the delamination. Hilbert transform was used to extract the maximum of the signal envelopes for each monitoring node. Initial simulations were performed for an undamaged composite plate as baseline data.

4. Ultrasonic C-scan for Impact Damage Sizing

Figure 2 shows the images obtained from the pulse reflection (Fig. 2a) and double-through transmission (Fig. 2b) ultrasonic immersion C-scans. The center of the impact was located approximately at x = 50 mm, y = 15 mm. The resulting image for the double-through transmission (Fig. 2b) shows the delamination area (extent about 55 mm in x-direction, 25 mm in y-direction) with consistent low amplitude (dark) due the interruption of the wave propagation. In the A-scans almost no signal amplitude reflected at the steel plate was observed for this region.

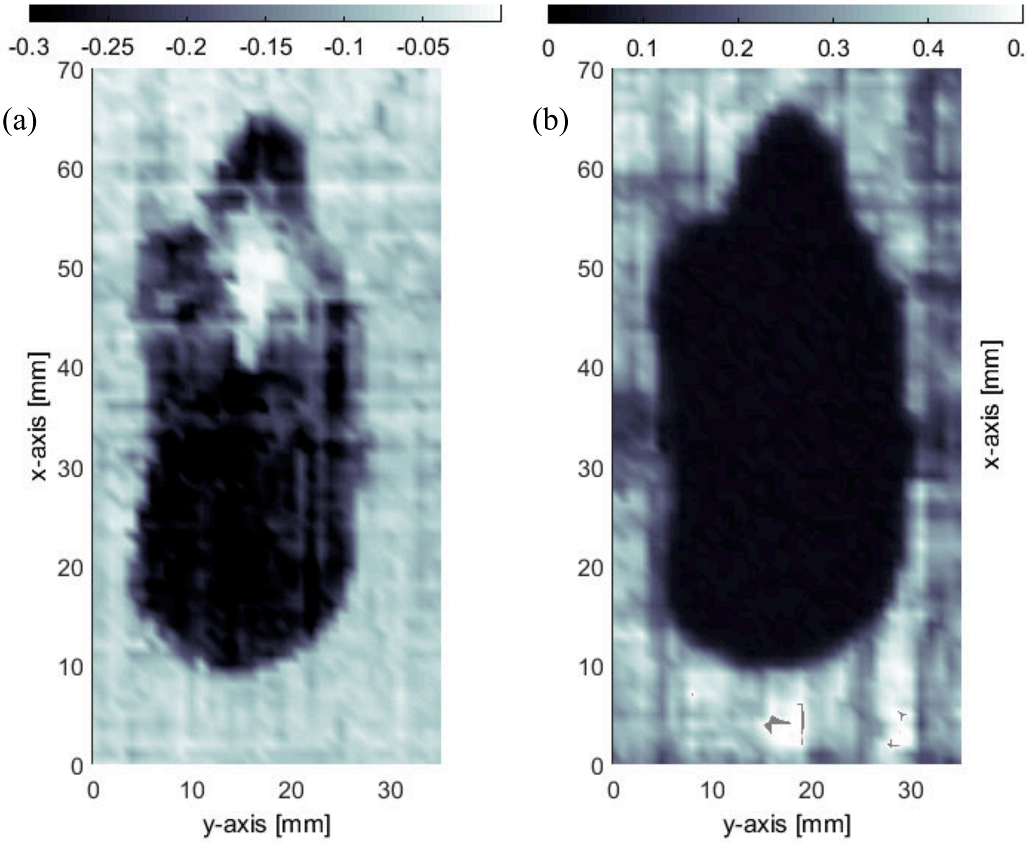

Figure 2: Ultrasonic immersion C-scan of damaged composite specimen (scan area: 70 mm x 35 mm, step size: 1mm); amplitude of ultrasonic signal, 10 MHz unfocussed immersion transducer: (a) pulse reflection; (b) double-through transmission.

In the image for the amplitude of the reflection C-scan (Fig. 2a) the delamination area can be seen as the increased reflected signal (dark, negative amplitude), matching the double-through transmission C-scan (Fig. 2b). The small, visible surface impact damage (Fig. 1) corresponds to lower reflected amplitude (around x = 50 mm, y = 15 mm, not at center of delamination area). For both the double-through transmission and reflection C-scans some pattern in the area around the delamination can be observed, which corresponds to imperfections of the composite structure, either due to manufacturing or impact damage. The transducer frequency (10 MHz) was too low to allow resolution of individual ply layers in the thickness direction.

5. Guided Wave Defect Imaging

Figure 3 shows the amplitude of the guided wave field scattered at the barely visible impact damage. The excitation transducer was placed to the left, with the incident wave propagating left to right. At the location of the visible, small indent and delamination, the guided wave field shows an irregular area and pattern of high amplitudes.

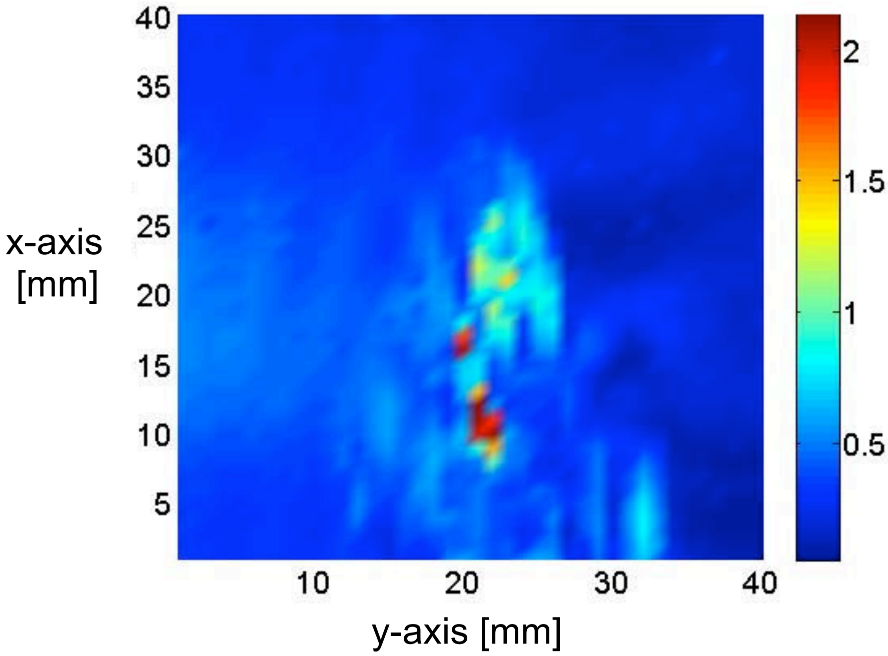

Figure 3: Guided wave image of area around impact damage; A_0 guided wave mode, 100 kHz excitation frequency; 1 mm step size; maximum amplitude of time trace (Hilbert transform).

The area of increased amplitude corresponds reasonably well with the delamination area observed from the ultrasonic immersion C-scans. A significant drop of the amplitude of the guided wave field behind the impact damage compared to the incident amplitude can be seen. This can be correlated to the scattering of the incident guided wave at the impact damage, with limited transmission beyond the defect.

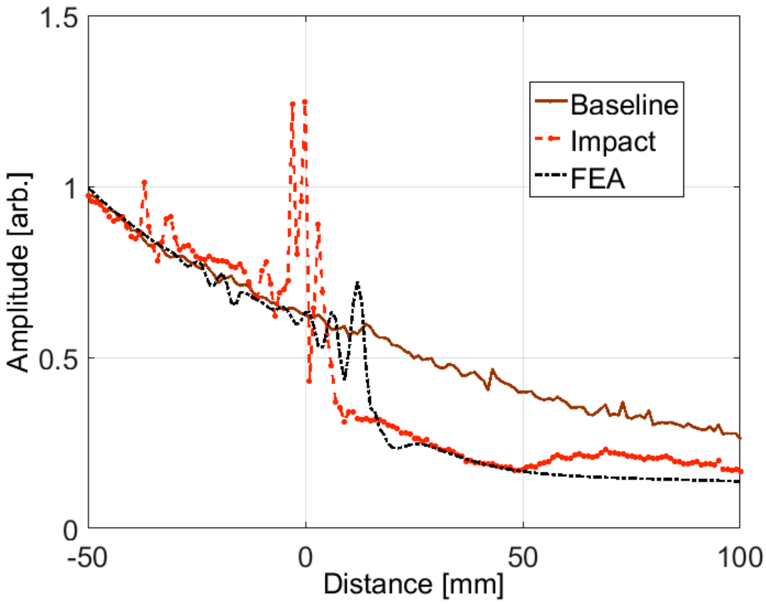

Figure 4: Guided wave amplitude on line across defect; A_0 guided wave mode, 100 kHz excitation frequency; baseline measurement (solid, brown), measurement across impact damage (dashed, red), FE simulation for delamination (dash-dot, black).

6. Guided Wave Scattering

Figure 4 shows the amplitude of the guided wave across the defect location and a symmetric, undamaged location on the specimen as a baseline. Similar to Fig. 3, increased amplitude at the impact location (distance: 0 mm) and a significant amplitude drop behind the defect can be seen. The amplitude drop is well predicted from a FE simulation for a delamination. Further variations of the delamination depth and size can lead to changes in the amplitude pattern [19].

Similarly, the guided wave amplitude on a circle around the center of the impact and an undamaged part of the composite specimen was measured. For the undamaged part of the specimen, good agreement of the predicted and measured guided wave amplitude pattern can be seen in Fig. 5a. The incident wave again propagates from left (180 degree) to right with high amplitude along the composite fiber direction. The drop in amplitude is due to the attenuation, which is reasonably well modelled by the assumed level of Rayleigh damping. Some variation of the measured amplitude indicates imperfection in the composite material or potentially reflections at the edge of the specimen.

For the case of a delamination, the FE simulations predict a significant drop in the amplitude of the guided wave pulse propagating past the defect, in line with the above results and literature [19]. This is matched quite well by the observed reduction in amplitude of the experimental measurement. The measured amplitude curve is not symmetric (unlike the FE simulation), with significantly higher amplitude observed in the 90 degree direction. This could likely be linked to the asymmetric shape and location of the delamination observed from the ultrasonic C-scans (Fig. 2), where the impact center is not at the center of the observed delamination.

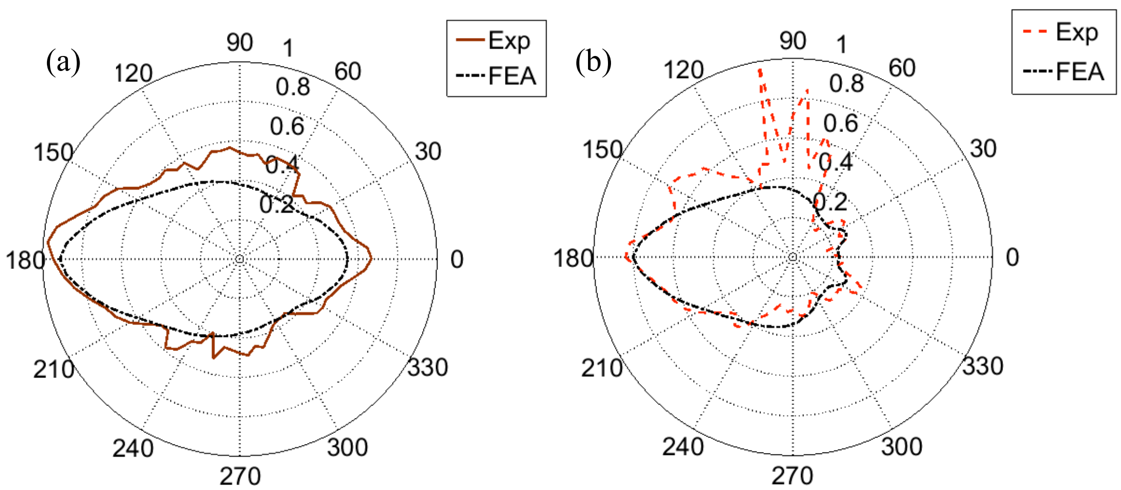

Figure 5: Guided wave amplitude on circle around defect; A_0 guided wave mode, 100 kHz excitation frequency; (a) baseline measurement (solid, brown), FE simulation without defect (dash-dot, black); (b) measurement around impact damage (dashed, red), FE simulation for delamination (dash-dot, black).

7. Conclusions

A cross-ply composite specimen containing barely visible impact damage was experimentally tested using guided waves and ultrasonic C-scans. Impact damage leads to a range of defects in composite structures, ranging from delaminations to matrix and fiber cracking. The ultrasonic immersion C-scans provided clear information about the size and shape of the delamination. The guided wave measurements showed significant scattering and increased amplitudes in the damage area, allowing the localization of the impact damage, but providing limited information about the exact damage shape. From a comparison to FE simulations for a rectangular delamination, reasonably good agreement of the amplitude patterns was observed. Based on a systematic comparison, approximate information on delamination size might be extracted, but it must be considered that actual impact damage is typically of a complicated shape.

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