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Damage detection in laminated composites using pure SH guided wave excited by angle beam transducer

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) composites have been widely used in aerospace structures due to their high specific strength and stiffness, resistance to corrosion, and lightweight. However, it has posed new challenges for implementing guided wave-based structural health monitoring (SHM) techniques due to the general anisotropic behavior and complicated wave-damage interaction scenarios in composites. This paper presents a new methodology for detecting various types of composite damage such as simulated delamination and actual impact damage using pure shear horizontal (SH) wave generated by adjustable angle beam transducers. For the first time, angle beam transducers were successfully applied to excite pure SH0 wave in a 2-mm quasi-isotropic composite plate. The pure SH0 wave excitation was verified by a three-dimensional (3D) finite element (FE) simulation. SH0 wave propagation and interaction with the delamination were further investigated numerically and strong trapped waves within the delamination region were observed. Experimental validations were conducted to detect simulated delamination by Teflon insert using pure SH0 wave. A good match between the FE simulation and the experiment was achieved. Pure SH0 wave was also utilized to detect actual impact damage in the quasi-isotropic CFRP composite plate. It can be found that the SH0 wave is sensitive to both delamination and impact damage, and a significant amplitude drop is observed due to the presence of different types of damage. Both numerical and experimental results demonstrated the effectiveness of pure SH0-wave detection of various damage types in composites using angle beam transducers.

Keywords: Structural health monitoring; SH0 wave; Composite structures; Damage detection; Angle beam transducer; Delamination; Impact damage.

1. INTRODUCTION

Composite materials have been widely used in aerospace structures due to their high specific strength and stiffness, design flexibility, and lightweight. However, composite structures are prone to various types of damage [1]-[5], including debonding, delamination, and impact damage. Barely visible impact damage (BVID) from low-velocity impact is the most prevalent type of damage found in composite structures. This damage, in the form of matrix cracking, fiber breakage, and delamination, is invisible to the naked eye and is easily induced from various sources such as bird strikes, tools dropped on parts during manufacture and servicing, or runway debris encountered during the takeoff [2]. Due to the general anisotropic behavior [6] and complex damage scenarios, the successful implementation of damage detection in aerospace composite structures is always challenging.

To ensure the reliability of composite structures, various non-destructive evaluation (NDE) techniques have been developed for damage detection, including eddy current [7], X-ray, and ultrasonic C-scan. However, the use of these techniques is often labor-intensive and depends heavily on the skill and experience of the operator. Structural health monitoring (SHM) technologies offer a promising alternative [8]. Guided waves have the advantage of long-distance propagation in complex structures and low energy loss, which have been widely used in the structural health monitoring of composite structures. In general, there are two various families of guided waves in plate-like structures: Lamb waves and shear horizontal (SH) waves [1]. Among them, Lamb-wave based SHM technologies have been widely used to detect various types of damage in composite structures, including delamination [9] [10] and impact damage [11]. However, the problem for typical Lamb waves is the existence of at least two wave modes at any given frequency and the inherent dispersive nature. Therefore, the multi-modal dispersive propagation will make the wave signal complex and increase the difficulty of signal interpretations.

In recent years, adjustable angle beam transducers (ABT) have been utilized to achieve single-mode Lamb wave excitation and detection. Wang et al. [12] used the ABT pair, one transmitter ABT and one receiver ABT, to detect the disbond in a

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multilayer bonded structure using a high-order mode Lamb wave. Toyama and Takatsubo [13] employed the ABT and an acoustic emission transducer to detect impact damage in a cross-ply composite plate. In their study, the ABT was used as a transmitter to generate a pure S0-mode Lamb wave. These studies facilitate the understanding of SHM applications using single-mode Lamb waves generated by ABT.

Compared with the widely used Lamb waves, the fundamental shear horizontal (SH0) wave is relatively simpler because they are only mildly dispersive in typical composites [14]. However, SH0 wave has been less investigated for composite SHM applications. In metallic structures, the SH0 wave was usually excited by electromagnetic acoustic transducers (EMAT) [15]. ABT transducers are not usually used to excite SH0 wave in isotropic structures because they would require a shear-wave coupled transducer whereas ABT devices are usually pressure-wave coupled. However, EMAT methods are not appropriate for composites. In recent years, the convenience of SH0 wave has promoted the development of new techniques to overcome the difficulties associated with SH0 wave generation in composites. SH-wave piezoelectric transducers based on either thickness-shear (d_{15} and d_{35}) mode [16] or face-shear (d_{36} and d_{24}) mode [17] piezoelectric wafers, and piezoelectric fiber patches [18] have been developed for SH0 wave generation. However, these SH-wave transducers must be permanently bonded onto the structures to be effective. For the first time, adjustable angle beam transducers were used to excite pure SH0 wave in a thick quasi-isotropic composite plate [19]. It shows that although the ABT excitation consists of pressure waves, the generation of SH0 is possible due to the anisotropy of the quasi-isotropic composite layup.

This paper describes a new methodology for detecting various types of composite damage such as simulated delamination and actual impact damage using pure SH0 wave generated by adjustable angle beam transducers. First, the ABT tuning angle of SH0 mode was calculated from the theoretical phase-velocity dispersion curve based on Snell's law. Then, a three-dimensional (3D) finite element simulation was conducted to verify the feasibility of pure SH0 mode excitation in a 2-mm thick quasi-isotropic carbon fiber reinforced polymer (CFRP) composite plate using adjustable ABT methods. The wave interaction with delamination was also investigated. Next, a pitch-catch experiment using adjustable ABT was conducted to validate the excitation of pure SH0 mode and the detection of the simulated delamination by the Teflon insert. A good match was achieved. Finally, the SH0 mode was utilized to detect actual impact damage in the quasi-isotropic composite plate.

2. ANGLE BEAM TRANSDUCERS FOR SINGLE-MODE WAVE EXCITATION

Angle beam transducers (ABT) and wedges are generally used to excite and receive single-mode guided waves with specified mode-frequency combinations. In a practical application, the generation of a single-mode guided wave can be realized by using angle beam transducers and adjustable wedges. Let c_w be the velocity of the pressure wave in the wedge, c is the phase velocity of the desired wave mode at a selected frequency in a composite plate. θ is the ABT tuning angle, which is the incident angle of the pressure waves impinging on the structure, as shown in Figure 1. According to Snell's law, wave mode with a phase velocity of c will be enhanced through the phase-matching much more than waves of any other phase velocities if the following condition is satisfied [19]:

$$\sin\theta = \frac{c_w}{c} \tag{1}$$

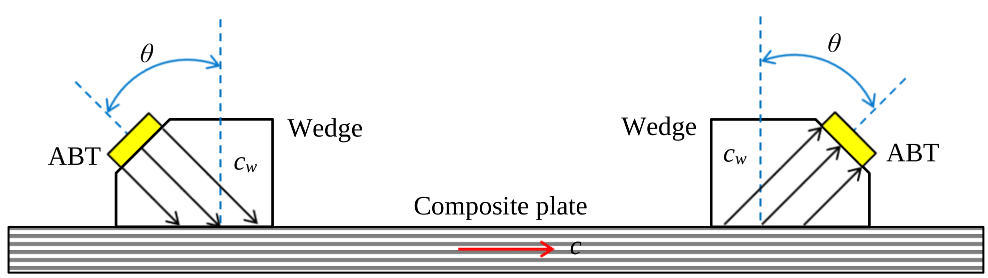


Figure 1. Single-mode guided wave excitation and detection using ABT and wedges in a composite laminate.

3. SH0 WAVE DAMAGE DETECTION IN QUASI-ISOTROPIC COMPOSITES

3.1 Composite Specimen

In this study, a 2-mm thick quasi-isotropic CFRP composite plate with simulated delamination was investigated. The stacking sequence of the composite plate is $[-45/90/45/0]_{2s}$. The dimension of the specimen is 500 mm × 500 mm × 2 mm. The IM7 12K/CYCOM 5320-1 prepreg was used to manufacture the composite specimen. The simulated delamination was created by inserting a Teflon film in the composite plate before curing in a hot press machine. A circular Teflon film (25 mm in diameter) between plies 12 and 13 was inserted to create the delamination. The delamination size was determined from the practical application, where the critical delamination size for growth monitoring is around 25-mm diameter. Figure 2 shows the schematic of the 2-mm quasi-isotropic CFRP composite plate with a purpose-built delamination.

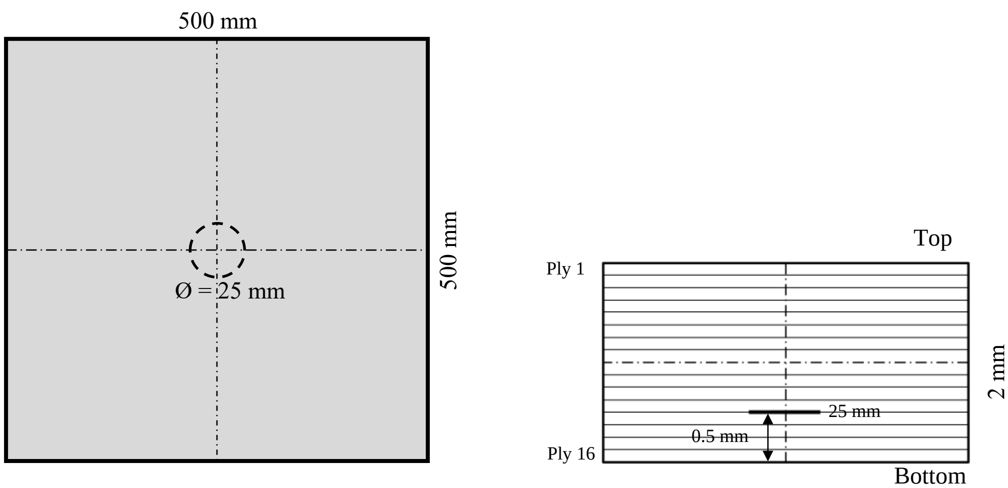


Figure 2. Schematic of 2-mm quasi-isotropic $[-45/90/45/0]_{2s}$ carbon fiber-reinforced polymer (CFRP) composite plate with delamination simulated by Teflon insert.

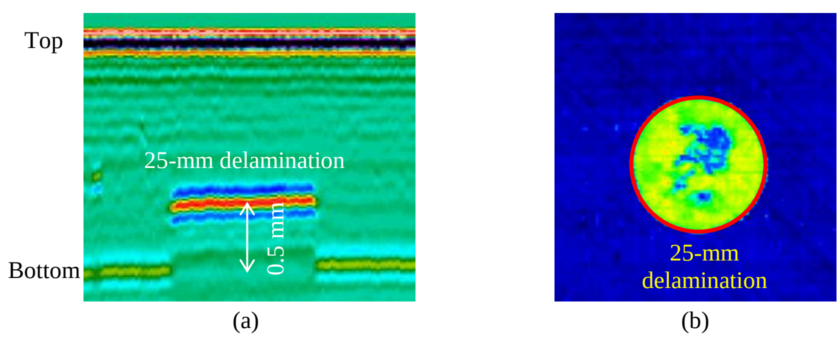


Figure 3. Ultrasonic inspection results of 2-mm quasi-isotropic composite plate with simulated delamination: (a) B-scan image; (b) C-scan image.

Ultrasonic C-scan was performed on the 2-mm thick quasi-isotropic composite plate to verify and image the simulated delamination. An ultrasonic immersion tank was used to inspect the composite specimen. In the experiment, a 10 MHz, 25.4-mm focused transducer was used. An area scan was performed to detect and image the delamination simulated by the Teflon insert. The scan area is 50 mm × 50 mm. Figure 3 shows the B-scan and C-scan images of NDE results. The depth of the simulated delamination can be determined from the B-scan image. It is around 0.5 mm from the bottom surface, which is consistent with our design. The C-scan image shows the presence of the 25-mm delamination. Therefore, the simulated delamination was successfully detected and quantified from the ultrasonic NDE inspection.

3.2 Theoretical ABT Tuning Angle

The theoretical ABT tuning angle of the 2-mm quasi-isotropic CFRP composite plate was calculated for the excitation of pure SH0 wave. The material properties of the composite specimen are given in Table 1.

Table 1. Engineering constants of the unidirectional prepreg [14].

E_{11}	E_{22}	E_{33}	v_{12}	v_{13}	v_{23}	G_{12}	G_{13}	G_{23}	ρ
140.8 GPa	11.3 GPa	11.3 GPa	0.31	0.31	0.5	5.7 GPa	5.7 GPa	3.4 GPa	1640 kg/m^3

Dispersion curves of the 2-mm quasi-isotropic CFRP composite plate were obtained using the semi-analytical finite element (SAFE) method [6]. Phase-velocity dispersion curves in the 0º direction are shown in Figure 4 (a). The wedge velocity of the adjustable wedge used in this study is 2720 m/s and the central frequency of ABT is 500 kHz. The theoretical tuning angle was calculated based on Eq. (1), as shown in Figure 4 (b). It can be found that the wave modes cannot be excited when the phase velocities are below c_w. At 500 kHz, the tuning angle of SH0 mode is about 49º. Therefore, the incident angles should be set to 49º to excite pure SH0 mode in this 2-mm quasi-isotropic CFRP composite plate. Figure 4 (c) shows the frequency-wavenumber dispersion curve, which will be used in the frequency-wavenumber analysis. In addition, the group-velocity dispersion curves are given in Figure 4 (d), and the group velocity of SH0 mode at 500 kHz 3.39 mm/μs. The group velocity will be used to validate the generated guided waves in the composite plate.

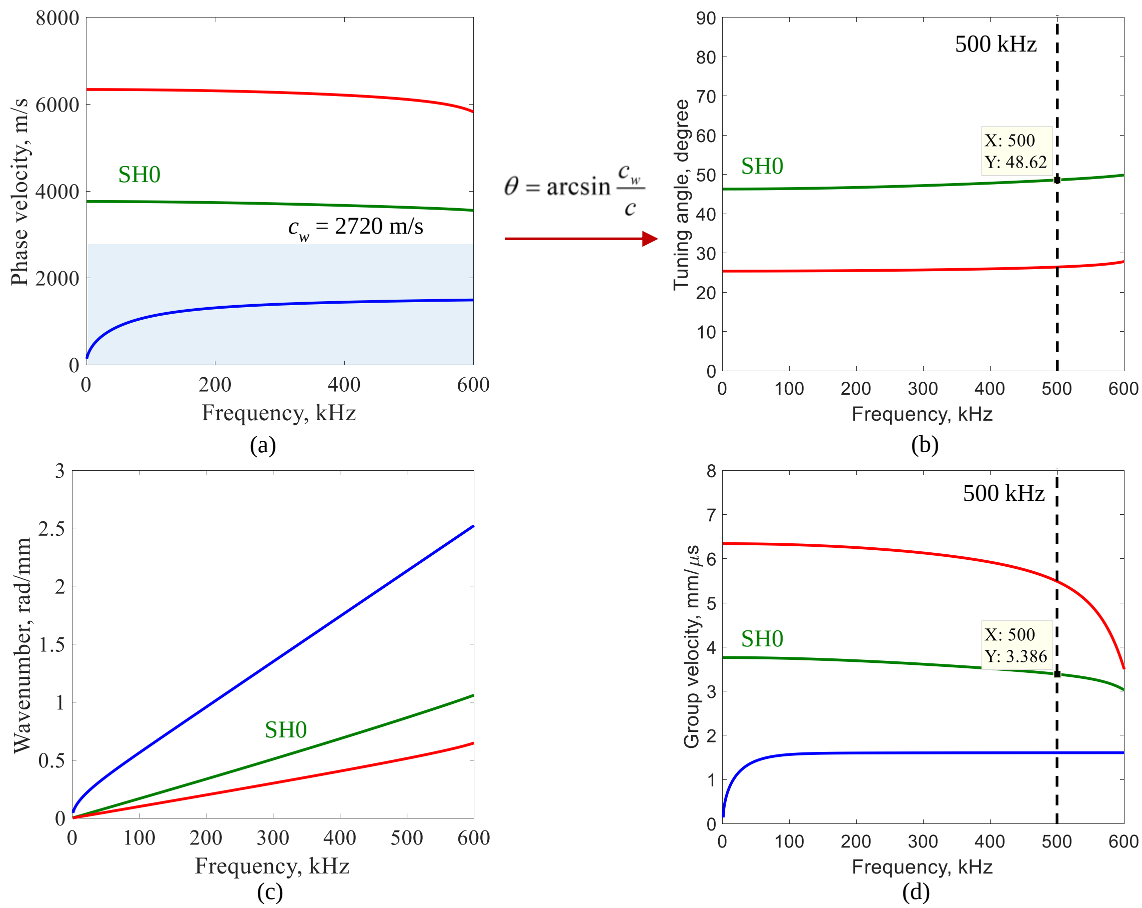


Figure 4. Dispersion curves of the 2-mm [-45/90/45/0]$_{2s}$ quasi-isotropic composite plate: (a) phase velocity; (b) ABT tuning angle; (c) wavenumber; (d)group velocity.

3.3 Finite Element Simulation

Finite element (FE) simulation has proven to be an effective and powerful tool for modeling guided wave generation and propagation in composite structures [20]. Commercial finite element package ANSYS 17.0 was used to implement three-dimensional (3D) FE models for the simulation of SH0 wave generation and interaction with delamination in the 2-mm quasi-isotropic CFRP composite plate

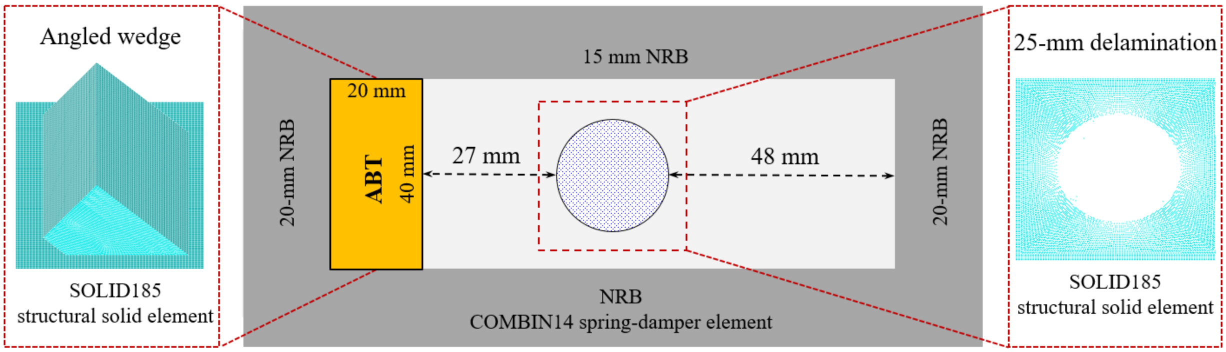


Figure 5. 3D FE model of the 2-mm quasi-isotropic CFRP composite plate with one delamination and two delaminations

Two sets of simulations were conducted: (1) pristine plate; (2) damaged plate with 25-mm delamination. Figure 5 shows the 3D FE models of the 2-mm quasi-isotropic CFRP composite plate with 25-mm delamination. The delamination was modeled using the node detachment in the delamination region. To excite the pure SH0 wave at 500 kHz, the incident angle of the angled wedge is set to 49º based on the theoretical ABT tuning angle as shown in Figure 4 (b). The pressure, a three-count Hanning window modulated tone burst with the center frequency of 500 kHz, was applied normal to the wedge top surface to simulate the ABT excitation. Non-reflective boundaries (NRB) developed by Shen and Giurgiutiu [21] can eliminate boundary reflections, and thus allow for simulation of guided wave propagation in an infinite medium with small-size models. NRB was implemented around the FE models to calculate the transient response under the ABT excitation. Structural solid elements (SOLID185) were used to mesh the composite plate and the angled wedge. COMBIN14 spring-damper elements were utilized to construct the NRB. The mesh size adopted in this study was 0.5 mm for in-plane direction to guarantee that more than 20 elements exist per wavelength and 0.125 mm for the thickness direction to ensure that each ply contains at least one element. The delamination regions were meshed with even finer elements to accommodate the high-stress gradient. The time step was set to 0.1 µs to ensure the convergence.

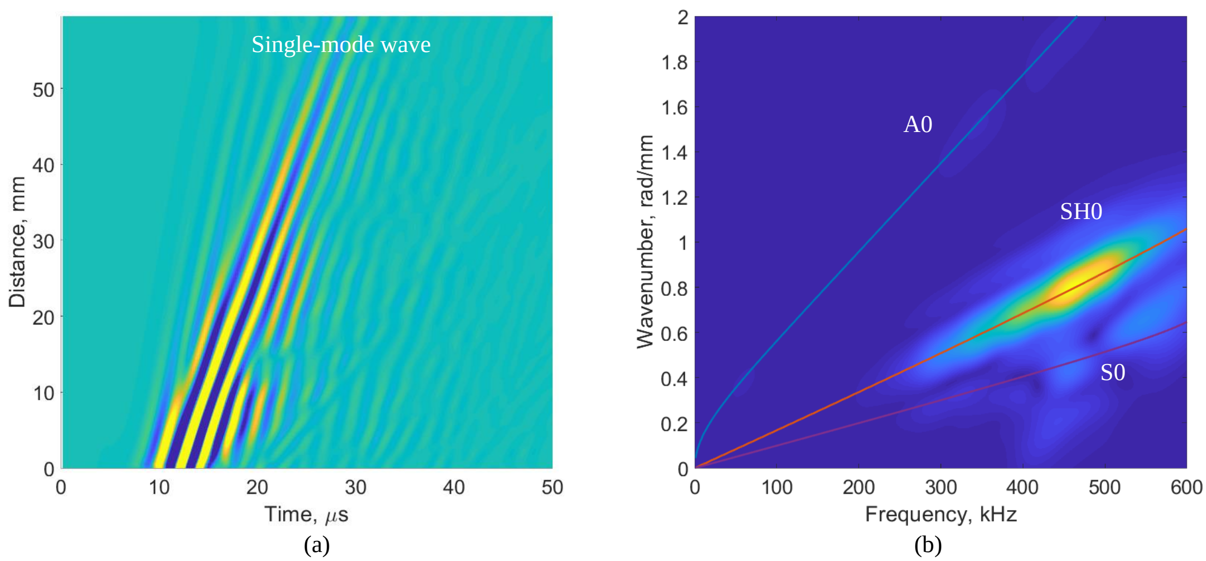


Figure 6. FEM line scan data of the 2-mm quasi-isotropic CFRP composite plate: (a) time-space wavefield of u_y at 500 kHz; (b) frequency-wavenumber spectrum showing strong SH0 mode.

First, the waveforms in terms of in-plane displacement u_y (the dominant displacement component of SH0 wave) along the horizontal centerline were extracted from the pristine FE model, as shown in Figure 6 (a). It can be found that a strong single-mode wave was generated in the quasi-isotropic CFRP composite plate. It has been demonstrated that wavenumber analysis has abundant information regarding the existence of various wave modes [22]. Therefore, the time-space wavefield was transformed into frequency-wavenumber representation using the Fourier transform (FT). The frequency-wavenumber spectrum is shown in Figure 6 (b). The solid lines are the theoretical wavenumber dispersion curves of A0, S0, and SH0 mode. It can be found that strong SH0 mode was observed in the frequency-wavenumber spectrum, which agrees well with the theoretical dispersion curve. Therefore, the FE simulation demonstrated that the pressure-wave angle beam transducers could successfully excite single-mode SH0 wave in this quasi-isotropic CFRP composite plate.

Second, the out-of-plane displacement on the top surface was extracted to visualize the SH0 wave interaction with the delamination. Figure 7 shows the comparison of the transient spatial wavefield between the pristine plate and the damaged plate with 25-mm delamination. For the pristine case in Figure 7 (a), it was found that a straight-crested wavefront was generated by the ABT excitation, strong near the wave source, and weak at the far field due to the outward propagation pattern. No strong boundary reflections were observed due to the utilization of the NRB. Figure 7 (b) shows the wave interaction with the delamination. It was found that strong trapped waves in the delamination region were observed. Previous studies have confirmed the multiple reflections within the delamination regions and a considerable amount of ultrasonic energy is trapped [9]. The direct comparison between the FEM waveforms and experimental waveforms was presented in the following section.

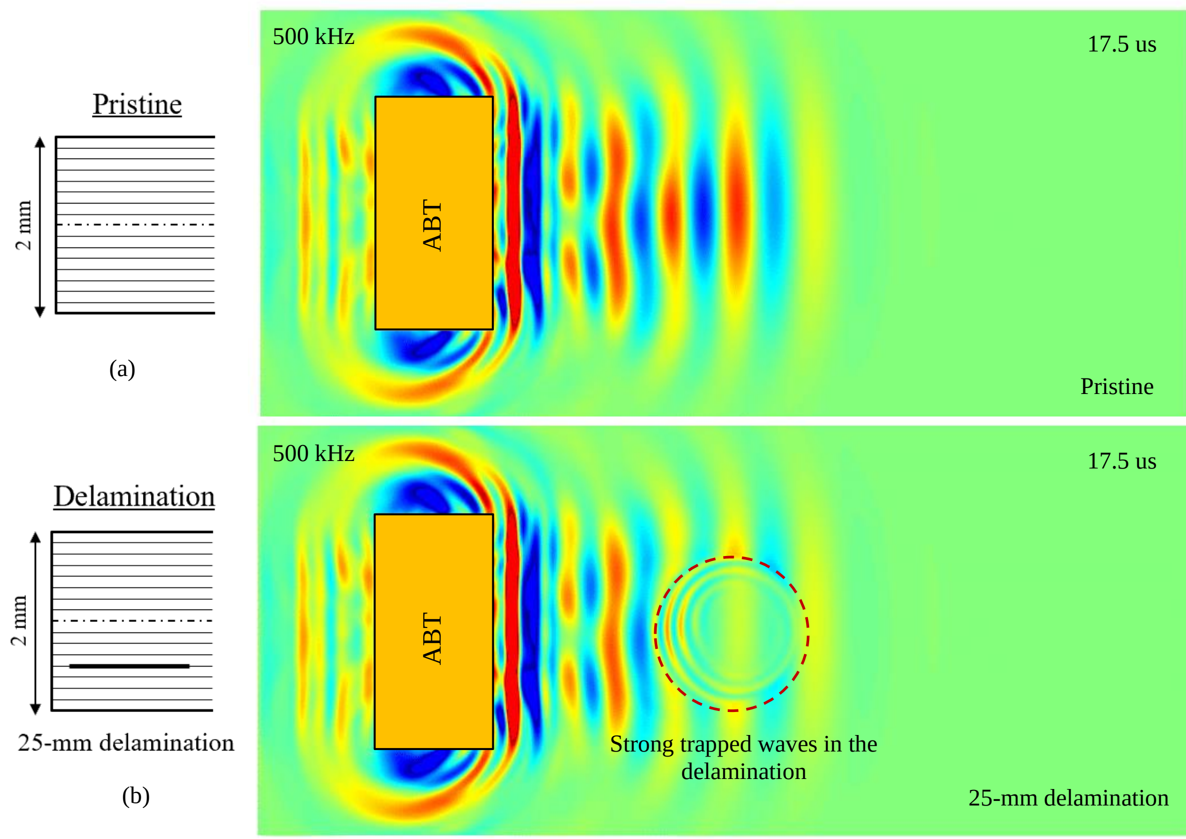


Figure 7. Comparison of the transient spatial wavefield in the 2-mm quasi-isotropic CFRP composite plate: (a) pristine plate; (b) damaged plate with 25-mm delamination.

4. EXPERIMENTAL VALIDATIONS

4.1 Pure SH0 Wave Excitation

The adjustable ABT pair was used to generate pure SH0 mode in the 2-mm quasi-isotropic CFRP composite plate. Broadband angle beam transducers tuned at 500 kHz (Olympus A413S-SB) mounted on adjustable wedges (Olympus ABWX-2001) were used as the transmitter and the receiver. For the excitation of pure SH0 mode at 500 kHz, the incident angle of the wedge was set to 49º based on Snell's law. The excitation signal applied to the transmitter ABT was a narrow-band three-count tone burst at the central frequency of 500 kHz. To validate the generated guided wave, response signals at five different locations were measured by moving the receiver ABT with a constant interval of 10 mm. The received signals at various locations are plotted in Figure 8 (a) showing strong and non-dispersive waves. The TOF of the direct wave packet was determined for each location and plotted as a function of distance, as shown in Figure 8 (b). Linear regression was used to estimate the group velocity, yielding a value of 3.41 mm/μs, which agrees well with the theoretical SH0-mode group velocity of 3.39 mm/μs at 500 kHz. Therefore, the generated wave in the 2-mm thick quasi-isotropic composite plate is pure SH0 mode as expected.

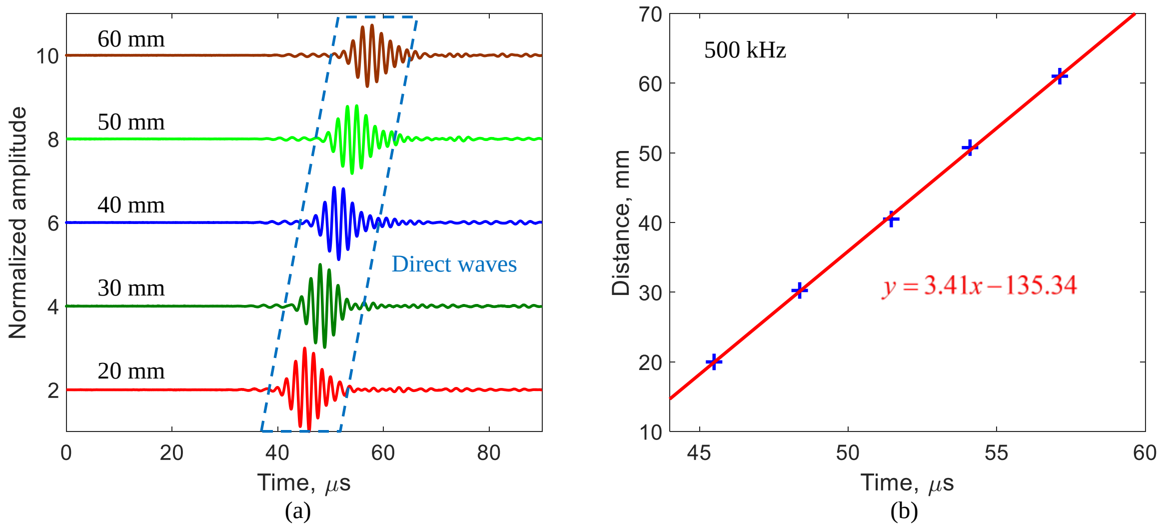


Figure 8. Experimental group-velocity measurement for SH0 mode excitation in the 2-mm quasi-isotropic CFRP composite plate: (a) waveforms at various locations; (b) correlation between distance and time of flight.

4.2 Delamination Detection Using Pure SH0 Wave

The pure SH0 mode generated by the ABT pair was utilized to detect the simulated delamination by Teflon insert in the 2-mm quasi-isotropic composite plate. The experimental setup was shown in Figure 9. A 100-mm distance was ensured between the transmitter ABT and the receiver ABT using a rigid frame. A narrow-band three-count tone burst excitation at the central frequency of 500 kHz was used as the input signal for the transmitter ABT. In the experiment, the measurements were conducted by placing the ABT pair on the pristine area and delamination region, respectively.

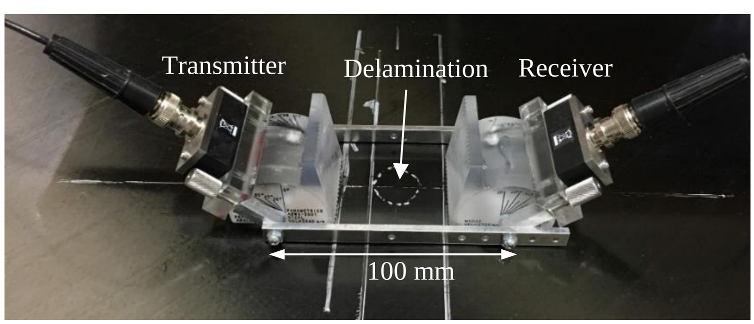


Figure 9. Experimental setup for delamination detection using ABT on a 2-mm quasi-isotropic composite plate.

The experimental signal comparison between the pristine and the delamination is shown in Figure 10. It can be found that strong and non-dispersive wave packets were observed in the response signals, as shown in Figure 10 (a). The amplitude drop can be noted due to the presence of delamination. Similarly, amplitude drop can be observed in the frequency spectrum, as given in Figure 10 (b). Therefore, delamination simulated by Teflon insert was successfully detected using the pure SH0 mode generated by ABT.

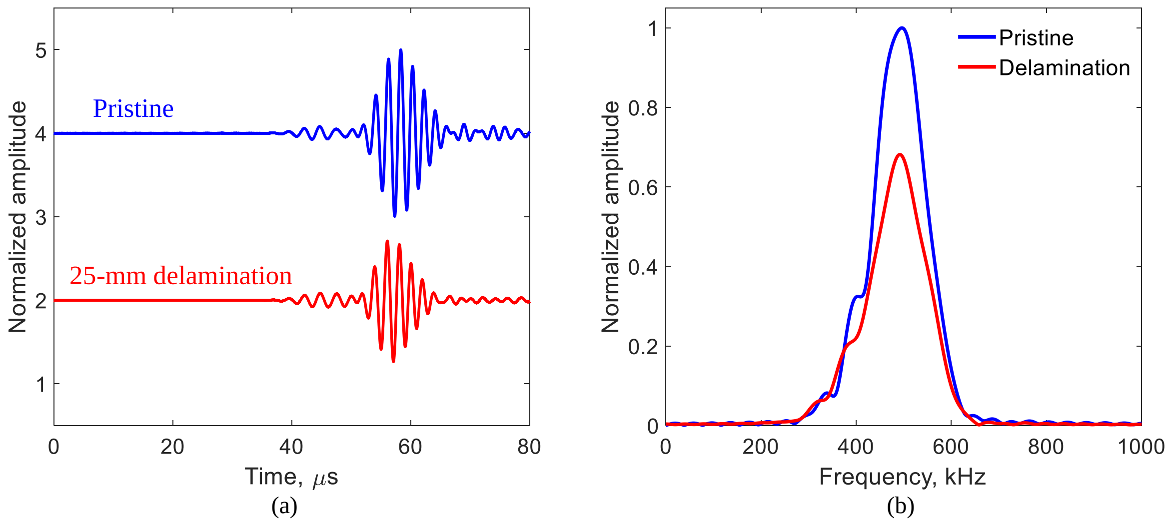


Figure 10. Experimental signal comparison between pristine and the delamination using the pure SH0 mode generated by angle beam transducers: (a) measured signals; (b) FFT results.

To verify the experimental results in Figure 10, the numerical waveforms were extracted from the FE simulation results in section 3.3. Figure 11 shows the direct comparison between FE results and the experimental waveforms. The FE waveforms were normalized by the maximum absolute amplitude of the pristine signal, as shown in Figure 11 (a). The normalized experimental waveforms were presented in Figure 11 (b).

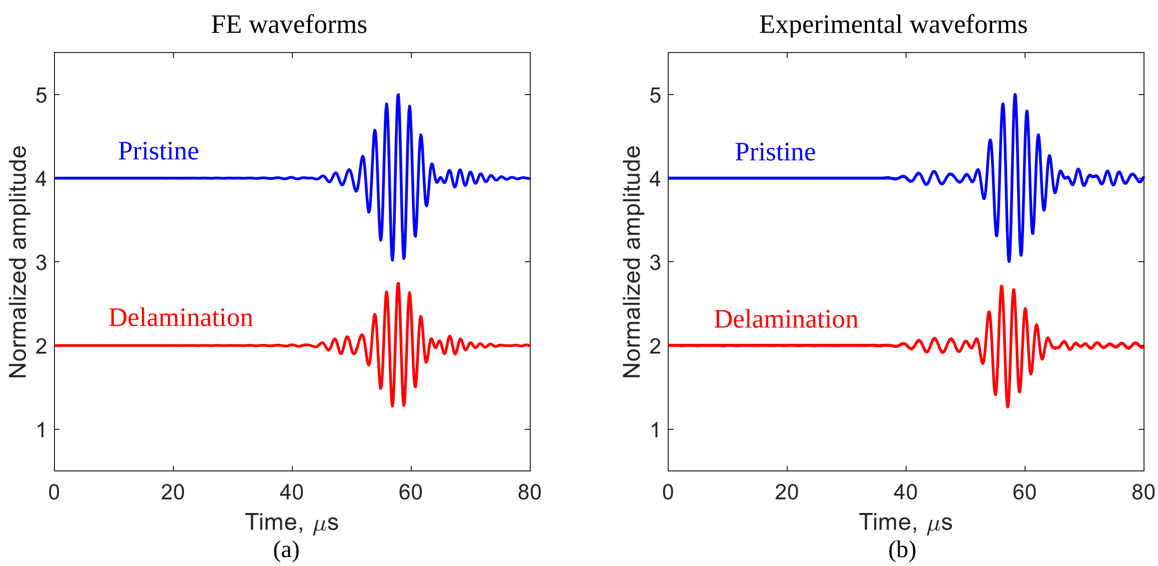


Figure 11. Comparison between FE simulation and the experiment: (a) FE waveforms; (b) experimental waveforms.

It can be found that a good match between the simulation and the experiment was achieved. Amplitude drop due to the SH0 wave interaction with delamination was observed in both the simulation and the experiment. Note that, compared with the results of the FE simulation, a small time-of-flight shift of the delamination signal was observed in the experiment. It is expected that this is due to the differences between Teflon insert for the simulated delamination in the experiment and the node detachment used in the simulation. Both numerical and experimental results confirmed that the SH0-mode amplitude decreased when delamination exists through the composite thickness, this is due to the strong trapped waves within the delamination region after the wave-delamination interaction.

5. IMPACT DAMAGE DETECTION USING PURE SH0 WAVE

5.1 Impact Testing and Ultrasonic Nondestructive Inspection

A small coupon was cut from the 2-mm quasi-isotropic CFRP composite plate and was used to conduct the impact testing. A drop-weight impact tower was utilized to induce a low-velocity impact on the composite coupon, as shown in Figure 12.

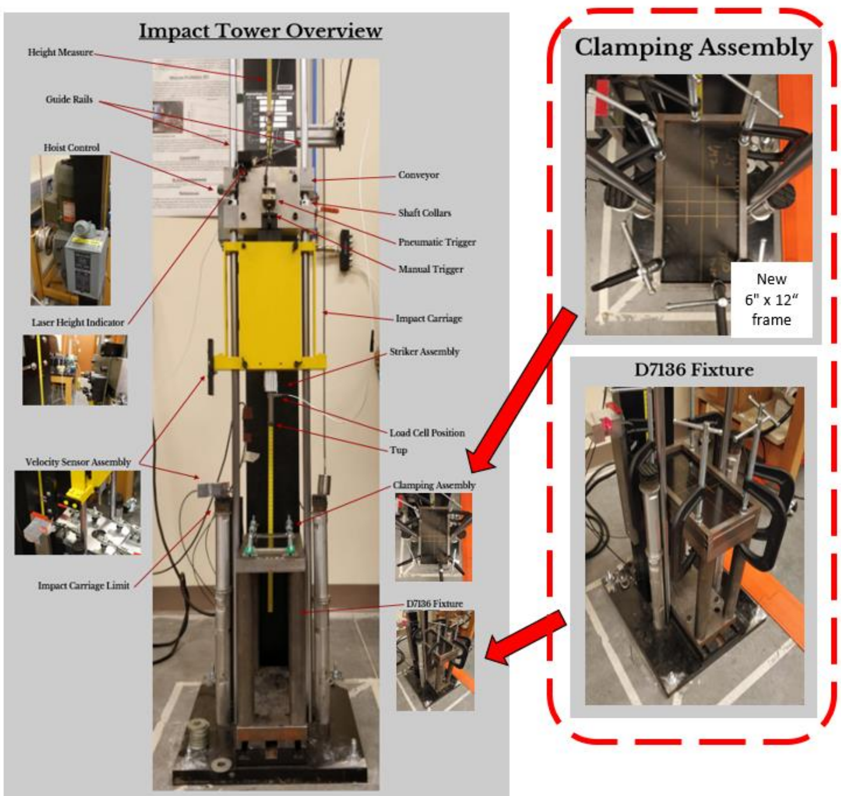


Figure 12. Dynatup 8200 drop-weight impact tower for impact testing with the modified fixture.

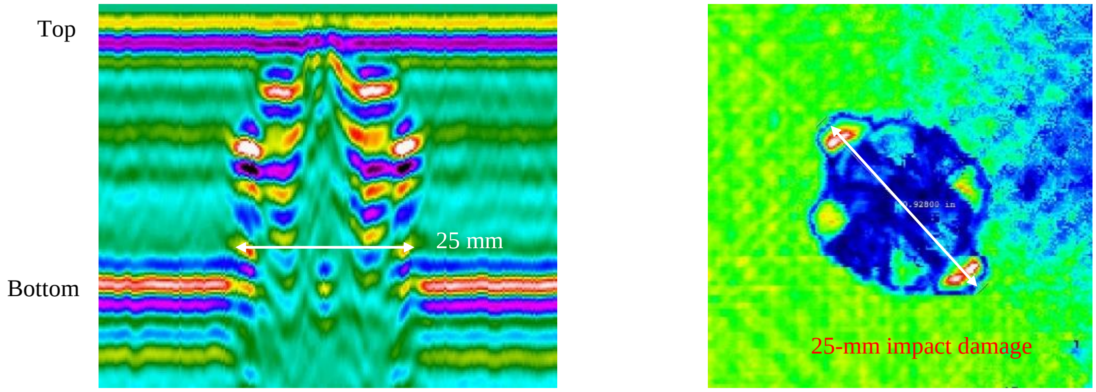
In this study, the coupon dimensions were changed from 150 mm × 100 mm (ASTM D7136 standard dimension) to 150 mm × 300 mm. Note that the in-plane area of the coupon was thrice the area of ASTM D7136 standard to make the panel size more realistic for guided wave propagation. The details of the impact testing are given in Table 2. It indicates that the coupon was impacted using a 3.06-kg impactor with the potential energy of 16.69 J. This energy was chosen from engineering judgment to try to obtain a 25-mm impact damage size in the 2-mm thick quasi-isotropic composite coupon.

Table 2. Impact testing conducted on a 2-mm quasi-isotropic composite coupon.

Mass (kg)	Drop height (cm)	Velocity (m/s)	Energy (J)
3.06	55.61	3.3	16.69

After the impact testing, an ultrasonic NDE inspection was conducted using a 10 MHz transducer. The NDE inspection results are shown in Figure 13. The B-scan results are given in Figure 13 (a) showing multiple impact-induced delaminations across the thickness, which is much more complicated than the simulated delamination by the Teflon insert.

Figure 13 (b) shows the C-scan results. It was found that the maximum size of the impact damage obtained is around 25 mm.



(a) (b)

Figure 13. Ultrasonic NDE inspection results of the impact damage: (a) B-scan image; (b) C-Scan image.

5.2 Impact Damage Detection Using Pure SH0 Mode Guided Wave

After the impact testing, a 25-mm barely visible impact damage (BVID) was introduced in the small composite couple. BVID due to low-velocity impact is the prevalent type of damage found in aerospace composite structures. This damage in the form of matrix cracking, fiber breakage, and interlaminar delamination, will cause a noticeable decrease in the load-carrying capability of composite structures, and such damage can develop progressively, leading to a catastrophic failure. Therefore, it is of great importance to detect BVID. In this section, the adjustable ABT pair was used to generate pure SH0 wave and detect the actual impact damage in the 2-mm quasi-isotropic CFRP coupon. A spacing of 100 mm was ensured between the transmitter ABT and receiver ABT using a rigid frame, as shown in Figure 14.

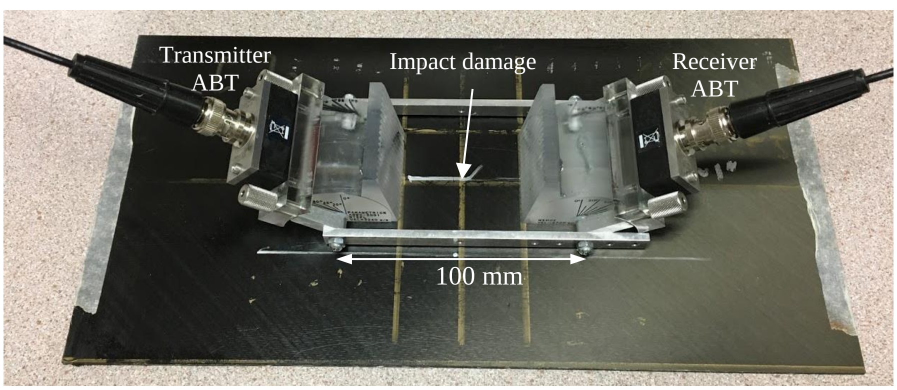


Figure 14. Experimental setup for the impact damage detection using adjustable ABT pair.

Experimental signal comparison between the pristine and actual impact damage is shown in Figure 15. Strong response signals with a high signal-to-noise ratio were observed for both cases, as shown in Figure 15 (a). An obvious amplitude drop was noted due to the presence of actual impact damage. Therefore, the impact damage was successfully detected using the pure SH0 wave generated by angle beam transducers. Similarly, an amplitude drop was also noted in the frequency spectrum, as given in Figure 15 (b). The experimental results demonstrated that pure SH0 wave generated by angle beam transducers can successfully detect the actual impact damage in the 2-mm quasi-isotropic composite plate, which means that this method has great potential for a quick inspection of various damage types in composite structures.

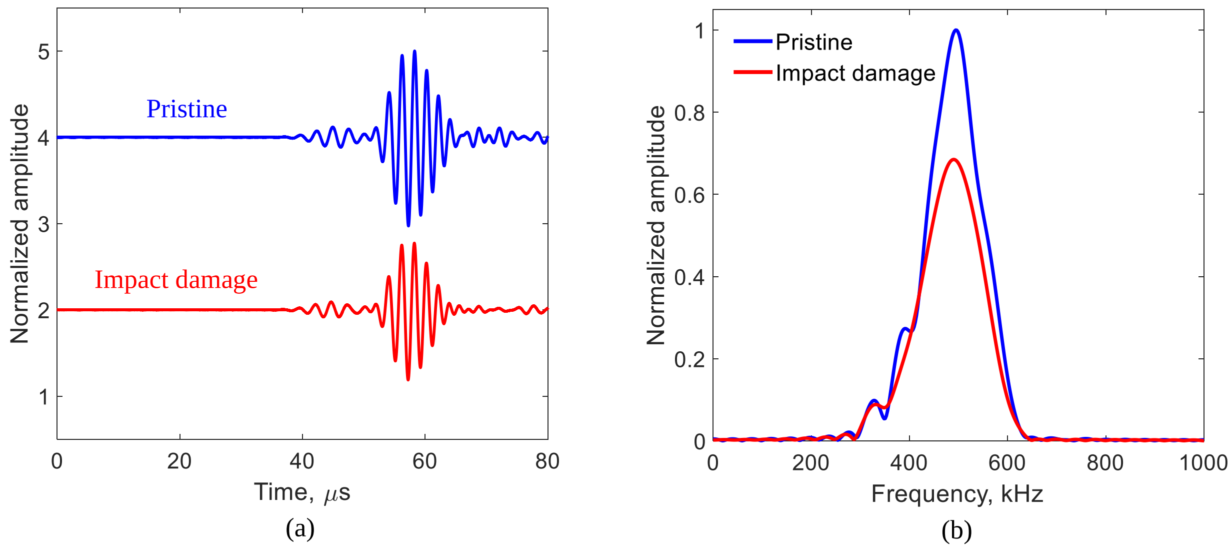


Figure 15. Experimental signal comparison between the pristine and actual impact damage in the 2-mm quasi-isotropic CFRP composite plate: (a) signals; (b) FFT results.

6. CONCLUSIONS

This paper has demonstrated the possibility of the excitation of pure SH0 mode in a 2-mm quasi-isotropic composite plate, a fact that is not possible in isotropic plates. The method can be used to detect various types of composite damage including simulated delamination and actual impact damage. It was found that all the measured signals maintained a high signal-to-noise ratio even in the presence of damage and the considerable attenuation in composites. A significant amplitude drop was observed due to the various damage types. The proposed method of simply measuring the change in the amplitude and frequency spectrum is simple, reliable, and suitable for the quick and large-area inspection. In this method, no baseline measurement was required, which is important in practical applications. An invention disclosure [23] covering our novel findings has been filed. For future work, an imaging method should be developed to visualize the damage in composite structures.

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