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Predictive Sensing of Aerospace Composite Structures

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14. ABSTRACT A methodology for predicting the response of structural sensors in aerospace composites as a function of the structural state and/or the presence of structural flaws or damage was studied. The project involved a judicious combination of advance theoretical developments and carefully conducted experiments. An efficient hybrid global-local (HGL) approach that combines global analytical wave propagation with local FEM wave-damage interaction analysis was adopted. Computer codes for predicting guided wave propagation and interaction with damage in aerospace composites were developed. A variety of composite specimens were fabricated and tested for code validation. In consultation with AFRL colleagues, the focus was placed on detecting 1-inch impact damage in 2, 4, 6-mm quasi-isotropic composites. New experimental techniques also resulted from this project: (a) ultrasonic NDE determination of composite elastic properties; (b) selective generation of SH0 and S0 guided wave modes using angle beam transducers; etc. This fundamental research project has high relevance to USAF because it has produced a methodological framework for predicting the performance of a structural health monitoring (SHM) system to be installed on aerospace composite structures. The results of this project can be used to generate virtual data sets for testing data-driven models and for designing new SHM systems.					
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FINAL REPORT

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Predictive Sensing of Aerospace Composites

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1 INTRODUCTION

This document represents the final report for a 4-year project with the title “Predictive Sensing of Aerospace Composites”. This introductory chapter covers Project Overview, Executive Summary, and Future Work suggestions resulting from this project. The last section of this chapter discusses the organization of this report.

1.1 PROJECT OVERVIEW

1.1.1 Objective

The objective is to predict the sensor signals in composite airframes which are sensitive to structural state (e.g. pristine and damage) and insensitive to confounding factors: loads, temp., vibration, etc.

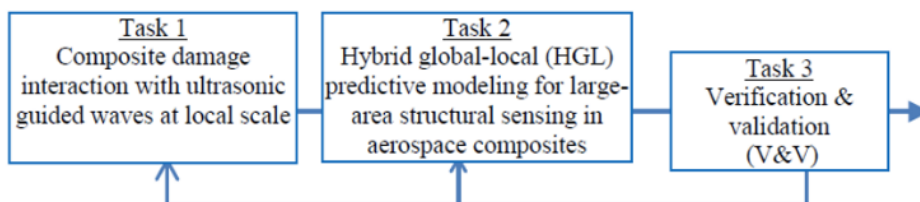
1.1.2 Approach

The project approach was organized into three main tasks:

- **Task 1:** composite damage interaction ultrasonic guided waves at the local scale
- **Task 2:** hybrid global-local (HGL) large-area prediction sensing in aerospace composites
- **Task 3** verification and validation of the developed techniques in task 1 and task 2

Project tasks scheduled over 4 years

Tasks	Year 1	Year 2	Year 3	Year 4
1. Composites damage interaction with ultrasonic guided waves at the local scale	■	■		
2. Hybrid global-local (HGL) large-area predictive sensing in aerospace composites		■	■	■
3. Verification and validation (V&V)			■	■



1.2 EXECUTIVE SUMMARY

The objective of this project is to develop efficient simulation methods to predict how guided waves propagate and interact with critical damage in composite structures (e.g., internal delaminations, matrix cracking, fiber breakage, etc. resulting from barely visible impact damage). The project involved a judicious combination of advance theoretical developments and carefully conducted experiments. The project developed new knowledge in the area of predictive sensing of aerospace composites. The results of this project may enable the development of a methodology and associated instrumentation for the in-situ on-demand evaluation of damage evolution in a critical composite component during the structural health monitoring (SHM) process.

Composite specimens for damage detection experiments were fabricated and tested in accordance with standards. Controlled impact events were applied to quasi-isotropic CFRP composite coupons of 6-in×4-in planform and increasing thickness in order to produce a specific impact-damage size of 1-inch diameter. The results demonstrate that controlled damage size is predictable in thin 2-mm laminates where a linear dependence between impact energy and damage size was found to apply. However, no such linear dependence between impact energy and damage size could be found in thicker coupons where a threshold phenomenon seems to be present. In 4-mm coupons, the threshold appeared at ~12.5 J impact energy. Below the threshold, the damage size was below 0.5 inch whereas just above the threshold energy the damage was around 1.25 inch in diameter. For the 6-mm coupons, the threshold appeared around 24 J, with <0.5-inch damage just below the threshold and ~2-inch diameter damage just above the threshold. Thus, an approximately 1-inch diameter damage could be produced in 2-mm and 4-mm CFRP quasi-isotropic coupons but not in 6-mm thick coupons where only a larger ~2-inch damage could be generated. Increasing the coupon planform from 6-in×4-in to 12-in×6-in changed the threshold energy from 24 J to 30 J but still yielded ~2-inch damage above the threshold and <0.5-inch damage below the threshold.

For guided-wave damage detection experiments, composite CFRP plates with seeded delaminations were constructed. The seeded delaminations consisted of very thin Teflon inserts of 25-mm and 20-mm diameter placed in single and double configurations with the aim of reproducing actual delamination patterns reported in the literature for actual impact damage postmortem performed by our AFRL colleagues. These CFRP plate specimens were used to validate the theoretical guided-wave SHM and NDE damage detection methods developed in this project.

A newly developed ultrasonic immersion technique was used to estimate the stiffness properties of the CFRP composite material without performing the customary destructive testing. The results demonstrated that the ultrasonic immersion technique yields a more accurate estimation of CFRP material properties for guided wave applications than the destructive testing methods.

The predictive simulation of guided-wave propagation in aerospace composites of various layups was developed using fast and efficient algorithms for generating with verified accuracy the wavespeed, group velocity, and skew angle dispersion curves as well as the associated displacement and stress modeshapes in multilayered anisotropic composites. These algorithms were based on the semi-analytical finite element (SAFE) approach which was found to be more stable and robust than the fully analytical approach preferred by other investigators. A graphical user interface (GUI) predictive code named *LAMSS-COMPOSITES* was developed and posted on the website <http://www.me.sc.edu/research/lamss/html/software.html>.

The more-difficult topic of guided-wave excitation in aerospace composites was also studied using the SAFE approach. Directionality and damping effects were included in the 2D guided-wave analysis. An accurate, efficient, and versatile predictive model for guided-wave excitation of both 1D and 2D guided waves in anisotropic composites was developed. For the first time, it was clarified and experimentally validated how material damping affects the tuning between surface-mounted transducers and guided waves in composite structures. It was established that intrinsic upper limits exist on the guided-wave excitability frequency in polymeric composites which is very important for designing efficient SHM systems.

The excitation and propagation algorithms developed in this project were tentatively combined

into a hybrid global-local (HGL) methodology for simulating an actual SHM scenario in which guided waves generated by active sensors travel into the aerospace composite, scatter from composite damage, and arrive at the receiving sensors. In the global domain, the HGL methodology relies on the newly develop predictive codes for efficient simulation of guided-wave excitation and propagation. In the local domain, the guided-wave scatter from composite damage is simulated as a secondary source using wave-damage interaction coefficients (WDIC). The scatter waves are then propagated very efficiently in the global domain until they reach the receiving sensors. A GUI based on the HGL approach was constructed and tested. This user-friendly and efficient GUI called *WFR 2D Composites* can be used to conduct fast predictive simulation and parametric studies. It was found that computational time savings of several orders of magnitude are obtained by using the HGL approach instead of full-scale multi-physics FEM simulations. It was found that the HGL approach achieves remarkable performance in terms of computational accuracy, efficiency, and versatility.

The major challenge in this work is the determination of the wave-damage interaction coefficient (WDIC). Two challenges are apparent: (a) the multitude of complicated guided-wave modes present in realistic composite structures; and (b) the impact damage complexity consisting of multiple delaminations, matrix cracking, and even fiber breakage. In this work, we addressed challenge (a) and developed an approach for predicting the WDIC through a local high-fidelity FEM analysis performed in the frequency domain followed by the WDIC extraction through projection onto the extensive modal space. This approach was tested on some simple damage cases, i.e., composite delamination. The challenge (b) related to the impact damage complexity could not be resolved in this project and remains for future work.

The predictive simulation developed in this project was also applied to analyzing how angle-beam transducers (ABT) can excite guided waves in anisotropic composites. It was discovered, for the first time, that a pressure-type ABT can be used to generate shear horizontal (SH0) guided wave which was not possible in isotropic metals where only S0 waves could be detected. This theoretical prediction was validated experimentally and made the object of an invention disclosure. This discovery opens new opportunities for composite nondestructive evaluation (NDE) because it permits rapid inspection of large composite areas for the detection of different types of manufacturing flaws and operational damage using a combination of S0 and SH0 waves. Such a guided-wave method is much more efficient than the point-by-point through-the-thickness ultrasonic scan used in conventional C-scan NDE techniques. Considerable time saving can be achieved while maintaining the ability to evaluate the various composite damage types.

The project resulted in eleven (11) peer-reviewed archival journal articles, eleven (11) conference papers, and one invention disclosure.

1.3 FUTURE WORK

The fundamental research results of this project have identified several directions in which further research should be conducted, as listed below:

- Angle-beam NDE methodology for composites
- Impact-damage predictive HGL detection
- Acoustic-emission SHM of composite
- Artificial Intelligence for aerospace composites SHM under varying operational and

- environmental conditions
- Nonlinear guided waves for damage detection in aerospace composites

1.4 ORGANIZATION OF THE REPORT

This final report is organized as follows. In chapter 2, the specimens for damage detection experiments in aerospace composites were manufactured and tested. In chapter 3, guided waves in aerospace composites were presented in detail, including ultrasonic measurements of composite material properties, prediction of guided wave propagation, and damping effect on wave propagation. In chapter 4, guided wave damage interaction in aerospace composites was discussed, including hybrid global-local (HGL) approach and angle beam NDE methodology for damage detection in composites. Chapter 5 lists the publications of this project. Summary, conclusions, and suggestions for future work are given in Chapter 6.

For ease of navigation, the TOC and the figure and table citations are hyperlinked. By clicking on a specific chapter or section in the TOC, the reader is taken directly to that specific chapter or section. By clicking on a specific figure citation or table citation, the reader is taken directly to that figure or table.

2 SPECIMENS FOR DAMAGE DETECTION EXPERIMENTS IN AEROSPACE COMPOSITES

This chapter discusses the composite specimens develop for damage detection experiments in aerospace composite structures.

2.1 IMPACT DAMAGE OVERVIEW

Impact damage is a damaging event specific to aerospace composites. Very challenging is the barely visible damage that can be created by low velocity impacts such as from a tool drop or runway debris. This type of damage was not critical in metallic airframes because a dent in a metallic airframe is easily observed and repaired as needed. In aerospace composite, low velocity impact does not produce a visible dent and thus can pass unnoticed while critically diminishing the load-carrying capacity and fatigue behavior of the composite structure. Thus, barely-visible low-velocity impact damage is currently considered one of the most challenging aspects of aerospace composites.

2.1.1 State of the art

In carbon fiber reinforced polymer (CFRP) composites, barely visible impact damage (BVID) can occur due to tool drops during manufacturing on the shop floor or low velocity impact of small and large debris during the service life of the structure. In low velocity impact events, the impactor may not penetrate the composite material but still may lead to BVID causing various types of damage such as delamination, matrix cracks and fiber fracture. BVID represents surface indentations which are too small to be seen during visual aircraft inspections and can cause the formation and growth of considerable internal damage. Under compressive loading scenarios such damage can propagate and can lead to extensive overall strength reduction of the structure.

The earliest work on impact testing of composites was conducted on unidirectional laminates in the 1970's by Butcher [1] and Toland [2] under different loading conditions to understand how an impact event affects the structural behavior of composites and how impact damage begins to propagate in composites. In the 1980's Cantwell et al. began to conduct low and high velocity

impact tests on different stacking sequence of composites materials to see the influence of varies parameters like geometry and projectile mass on impact response of composites [3]-[7] Cantwell also began to look into methods that could be used to detect impact damage [8]. Subsequently researchers began to conform to ASTM standard of drop weight impact testing [9] for conducting their impact experiments. Ishai and Shragai [10] looked at the effect of impact loads on damage and residual compressive strength of CFRP laminated beams. Stellbrink [11] looked at the fatigue behavior of impact damaged CFRP laminates. After conducting impact experiments, it became important to come up with prediction models to quantify the residual strength of a composite after impact. This work was spearheaded by Caprino [12]. Shortly after prediction models were developed, finite element methods to model impact damage began to be explored by Clark [13] and other researchers [14]-[17]. In some recent work, Schoeppner et al. [18] investigated used low velocity impact load –time histories from the AFRL database to impact load level at which impact damage will begin. Caputo et al. [19] developed numerical FEM models for impact scenarios in composites and proposed model described damage initiation and propagation of impact damage. Flores et al. [20] used 3D DIC to analyze the deformation in coupons subjected to low velocity impacts in the order of 10 J. Wallentine et al. [21] conducted serial sectioning microscopy and Ultrasonic scans to characterize BVID in unidirectional CFRP composites. Bogenfeld et al. [22] conducted a comprehensive review of impact analysis methods and discussed analytical and numerical models to predict impact damage and fiber failure. Panettieri et al. [23] conducted a benchmark low velocity impact study on thin 16-ply and 24-ply quasi-isotropic carbon/epoxy laminates and proposed a numerical-experimental approach to evaluate the effect of impact energies. Gómez-del Río et al. [24] examined the effect of temperature on low velocity impact response of CFRP composites. Sutherland et al. [25] studied the impact response of marine laminates experimentally focusing on the energy absorption mechanisms of the laminates. Sevkat et al. [26] examined the effect of low velocity repeated impacts on plain-woven hybrid composites. Amaro et al. [27] investigated the influence of single and multiple impacts on GFRP composite laminates. Olsson [28] conducted analytical predictions of critical impact loads for large mass impact damage in 2-mm composite plates and validated them. This relationship was later used by Ghajari et al. [29] for the identification and reconstruction of impact force history for composite stiffened panels.

The concept of BVID was introduced in the 1980's with respect to understanding the damage tolerance of composite laminates [30], [31]. In subsequent years, BVID became important in the inspection of composite aircraft where the damage needed to be characterized as BVID or visible impact damage (VID). BVID is defined as damage that is visible at a distance of less than 1.5 m and VID is defined as damage that is visible at a distance of 1.5 m or greater [32]. This clear distinction between BVID and VID during aircraft inspections can determine if a composite repair is needed or not. If a damage is characterized as VID it needs repairs to be conducted to the composite. However, there is a loophole to these definitions. A situation may arise where damage is characterized as BVID based on visual inspections but may have an impact damage diameter of 1" or greater. An impact damage diameter of 1" or greater may significantly deteriorate the compressive strength of the composite part (see Figure 1) and may need immediate repairs and must not be discounted despite being characterized as BVID. From Figure 1 we can also observe that in comparison to a 1" damage diameter of any damage type (delamination, porosity, open hole), an impact damage having a diameter of 1" or greater can significantly reduce the compressive strength of the composite structure. This is the significance and importance of detecting and monitoring impact damage having a diameter of 1" or greater.

With the increasing occurrence of BVID in composites, detection methods needed to be developed to characterize the impact damage size and shape accurately. Ultrasonic testing was one of the first methods to be used for impact damage inspection and detection [8], [33], [34]. Guided wave propagation in composite laminates has been widely used as a structural health monitoring technique to observe the interaction of waves with impact damage over large propagation distances [35]-[38]. Eddy current methods have been explored by researchers to detect manufacturing flaws and operational damage such as impact damage in CFRP composites [39]-[41]. Researchers have also explored microwave nondestructive evaluation techniques to investigate low velocity and high velocity impact damage in composites due to environmental effects [42]-[45]. Infrared thermography is also being explored by scientists as a viable option of detecting impact damage in a rapid manner [46]-[48]. X-ray computed tomography is also being used by researchers to give a 3D assessment of impact damage in composite structures [49]-[50]. Advanced guided wave methods [51]-[54] are currently being explored by authors of this work for rapid, reliable and large area assessment of composite structures subjected to controlled impact damage. The authors of this work are also exploring the use of in-situ acoustic emission methods [55] for the ascertainment of extensive damage occurrence in impacted composites.

2.1.2 Objectives of the Current Work

One of the objectives of this work is to conduct controlled impact events in CFRP composite coupons of increasing thicknesses to produce a specific size of impact damage i.e. 1". Such impacted CFRP coupons with controlled damage diameter would serve in the future for validation of SHM and NDE damage detection methodology. ASTM D7136 standard of impact testing has been used to conduct impact experiments on 6" x 4" quasi-isotropic coupons having a thickness ranging from 2-mm to 6-mm. The goal of the impact experiments was to identify a combination of mass, energy, and momentum of the impactor for which a controlled damage of 1" can be produced. Ultrasonic testing and X-ray micro-CT was used to visualize the size and extent of impact damage that was produced in each experiment. Surface profilometry was used to examine the impacted surface of the composite coupon as well as the rear surface of the composite coupon. The results demonstrate that controlled damage is much easier to be obtained in thin laminates compared to thicker laminates [56]. Currently, to validate SHM and NDE detection methods, embedded simulated delaminations are employed in between layers of laminated composite materials by using thin sheets of Teflon or Mylar [57]. Our approach gives us an opportunity to create a specific size of real impact damage as compared to simulated damages for effective and accurate SHM and NDE validation.

2.2 TEFLON INSERT SPECIMEN FABRICATION AND TESTING

Teflon-film inserts are used to simulate hidden delaminations in an aerospace composite structures. Specimens with small Teflon-film inserts were fabricated to simulate the delaminations produced inside a barely visible impact damage site. These simulated-delamination specimens were then subjected to ultrasonic inspection and guided-wave evaluation as described later in this report.

2.2.1 2-mm quasi-isotropic CFRP with a single 25-mm Teflon insert

CYCOM 5320-1/IM7 12K prepreg was used to manufacture the composite specimen. The simulated delamination was introduced 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 thickness of Teflon film is 50 μm . The depth of

the Teflon insert was based on the experimental results in [8]. 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 composite plate with purpose-built delamination.

Ultrasonic nondestructive testing (NDT) was conducted on the composite plate to verify and image the simulated delamination. An ultrasonic immersion tank was used to inspect the specimen. In the experiment, a 10 MHz, 25.4-mm focused transducer was used. First, a full specimen NDT inspection was conducted and there were no other manufacturing defects other than the simulated delamination. Then, a small-area scan was performed to detect and image the simulated delamination. The scan area is 50 mm × 50 mm. After an initial scan with the focus on the top surface of the sample, the transducer was refocused at the depth of Teflon film for a clearer C-scan image. Figure 3 shows the B-scan and C-scan images of NDT results. The C-scan image shows the presence of simulated delamination in the composite plate. The depth of the delamination can be observed from the B-scan image, which is 0.5 mm away from the bottom surface. From the C-scan image, the size and shape of the delamination can be clearly observed. Therefore, the simulated delamination can be detected and quantified from the NDT detection, which is consistent with the design.

2.2.2 3-mm quasi-isotropic CFRP with two different Teflon inserts

In this study, a 3-mm thick in-house quasi-isotropic carbon fiber-reinforced polymer (CFRP) composite plate with a stacking sequence of $[-45/90/45/0]_{3s}$ was investigated. The IM7 12K/CYCOM 5320-1 prepreg was used to manufacture the composite specimen. Two different delamination scenarios, one and two delaminations, were generated by inserting Teflon films during the ply layup process.

Figure 4 shows the schematic of the 3-mm thick quasi-isotropic CFRP composite plate with purpose-built multilayer delaminations. One delamination was created by inserting a circular Teflon film (25 mm in diameter) between plies 20 and 21. Two delaminations were generated by inserting two Teflon films of different sizes at various depths. First, a large circular Teflon film (25 mm in diameter) was inserted between plies 20 and 21, which is the same size and depth of one delamination. Then, an additional small circular Teflon film (20 mm in diameter) was inserted between plies 16 and 17. The thickness of Teflon film is 50 microns. The depth of the Teflon insert was based on the experimental results. The delamination size was determined from the practical application, where the critical delamination size for growth monitoring is around 25-mm diameter. After the ply layup, the specimen was placed in a hot-press machine for curing.

Ultrasonic nondestructive testing (NDT) was conducted to verify and image the simulated delaminations in the quasi-isotropic CFRP composite plate. An ultrasonic immersion tank was used to inspect the specimen. In the experiment, a 10 MHz, 25.4-mm focused transducer was utilized. First, a full specimen inspection was performed, and it was found that there were no manufacturing defects other than the simulated delaminations. Then, small-area C-scans were conducted to verify and image the simulated delaminations. The scan area is 100 mm × 100 mm. Figure 5(a) shows the ultrasonic C-scan results of the pristine area. It can be found that no manufacturing defects and the quasi-isotropic layup were observed. Figure 5(b) and (c) give the C-scan results of one delamination. In this case, ultrasonic C-scans were conducted on both bottom surface (bottom scan) and top surface (top scan). It can be seen that one 25-mm delamination was clearly noted from both bottom and top scans. From the C-scan images, the size and shape of the

delamination can be clearly observed.

The NDT inspection results of two delaminations are shown in Figure 6. First, the ultrasonic C-scan was conducted on the bottom surface which is close to the large 25-mm delamination. Figure 6(a) shows the C-scan result of the bottom scan. It can be found that only a 25-mm delamination was observed because the large delamination is close to the bottom surface, which blocks all the ultrasonic waves to penetrate. Therefore, the hidden small delamination cannot be detected from the bottom surface and this may happen in the practical applications when only single-sided access is available.

In order to detect the small delamination, the top scan with different focusing was performed. First, a 20-mm delamination was noted in Figure 6(b) when the focus was conducted at the depth of the small delamination, while a 25-mm delamination was also observed when the focus was performed at the depth of the large delamination as shown in Figure 6(c). A 20-mm shadow was clearly observed in Figure 6(c), which is the small delamination at a different depth, and it blocks the ultrasonic wave to penetrate. Therefore, the simulated multilayer delaminations were successfully detected and quantified from the ultrasonic NDT detection, which is consistent with the design.

2.3 IMPACT-SPECIMEN FABRICATION AND TESTING

To make the coupons for impact testing, composite plates were manufactured using the CYCOM® 5320-1 epoxy resin system with the Hexcel IM7 12K fiber in a compression molding (hot press) machine with the manufacturer's cure cycle. To manufacture quasi-isotropic composite plates with different thicknesses an appropriate stacking sequence with the appropriate number of layers had to be chosen. The quasi-isotropic stacking sequence was chosen based on the work done by previous researchers [19], [20]. A $[-45/90/+45/0]_{2S}$ stacking sequence was chosen for manufacturing the 2-mm composite plate with 16 layers. To manufacture a 4-mm composite plate, a $[-45/90/+45/0]_{4S}$ stacking sequence with 32 layers was chosen and to manufacture a 6-mm composite plate a $[-45/90/+45/0]_{6S}$ stacking sequence with 48 layers was chosen. After the manufacturing process in the compression molding machine, the thickness of the manufactured plates was a little higher than anticipated, i.e. the 2-mm plate had an average thickness of 2.14 mm, the 4-mm plate had an average thickness of 4.15 mm and the 6-mm plate had an average thickness of 6.28 mm. The plates that were manufactured were cut into 6" x 4" coupons to conduct impact tests conforming to the ASTM D7136 standard of impact testing. The cure cycle, compression molding machine and one of the manufactured composite plates is displayed in Figure 7. From the large composite plates, the 6" x 4" standard size coupon for the ASTM D7136 testing was cutout as displayed in Figure 7 (c).

2.3.1 EXPERIMENTAL PROCEDURES

2.3.1.1 ASTM D7136 DROP WEIGHT IMPACT TESTING

A drop tower with low friction guide rails is used to induce collision between a mass of known weight (impactor) and a fixed composite coupon of dimensions 6" x 4". The controlled impact event is recorded by a piezoelectric load cell which can accurately record data of the applied impact force, energy absorbed by the coupon and the displacement of the coupon during the event. Using variable impact heights, data is collected that shows how the coupon behaves under impacts of varied magnitude, and these impact tests can be conducted in sequence to see how damage forms in the coupon over repeated impacts. This data can then be used to predict future behavior of the material such as crack propagation and other damage formation. These tests are particularly useful

when studying composite materials. Since composites are designed to distribute damage throughout the volume of a material, damage formation and the propagation of cracks can be difficult to predict accurately through theory and simulation alone. Also, difficulties in predicting important properties such as stiffness of the material and the amount of energy it is capable of absorbing before experiencing failure make drop weight impact testing a valuable process in material science

Before the test is conducted, it is important to make sure that the impact carriage and conveyor is secured safely above the clamping platform. The sample is placed on top of the support fixture centering it on top of the 5" x 3" cut-out and the assembly is clamped into place. A protective cover is placed over the coupon to prevent accidental damage. After this the conveyor is slowly raised or lowered using the hoist control to the desired distance above the sample and is fastened into place using the shaft collars. This distance is measured using the laser height indicator and determines the drop height. All the equipment is checked to ensure that the data acquisition system is recording the data properly and then it is engaged; also checked is that the sample cover is removed. The trigger mechanism is then activated, initiating the drop impact event. The impactor can be caught safely after rebounding from the coupon to avoid secondary impact. It is also possible to avoid secondary impact if the drop weight impact testing machine has an anti-rebound device or stop block. The data is saved and the impact carriage is lifted away from the sample and is locked back into place on the conveyor. The sample cover is placed over the coupon to ensure no further damage to it as the conveyor's shaft collars are unlocked and the hoist mechanism is used to lift the carriage away from the clamping assembly. The entire experimental setup is displayed in Figure 8.

2.3.2 ULTRASONIC NDE OF IMPACTED COUPONS

Ultrasonic testing (UT) scans were conducted using the RollerFORM inspection and also in the ultrasonic immersion tank on the CFRP composite coupons before and after impact to obtain the B-scan and C-scan images and compare a pristine coupon with a coupon that underwent impact damage and to see the size and shape of the impact damage. In the case of the RollerFORM inspection, a thin layer of water is sprayed on the composite coupons to be inspected and a phased array wheel probe is moved along the composite coupon and the B-scan and C-scan images of the scanning area are displayed on the OmniScan system. In the case of the immersion tank inspection, a 10 MHz, 1" focused, 0.375" diameter ultrasonic transducer was used in the pulse-echo mode for conducting the UT scans. Post-processing of the data obtained from the ODIS software interface is able to give us a clear C-scan image, B-scan image, and A-scans in the pristine and impacted coupons. The experimental setups for these inspection techniques are displayed in Figure 9.

2.3.3 X-RAY MICRO COMPUTED TOMOGRAPHY OF IMPACTED COUPONS

To visualize some of the internal features of the impact damage that were not clearly visible using the ultrasonic NDE technique, X-ray micro-CT (computed tomography) technique was used. The Quantum GX microCT imaging system from PerkinElmer as displayed in Figure 10 was used for imaging the impacted 2-mm, 4-mm and 6-mm CFRP coupons. Different sizes of sample beds can be used to accommodate different size of specimens. The impacted 6" x 4" coupons can also be accommodated. However, to image the impacted area more clearly with a smaller field of view and a smaller voxel size, representative impacted coupons with desirable impact damage were cut into smaller sizes for better resolution of images.

2.3.4 SURFACE PROFILOMETRY OF IMPACTED COUPONS

When a CFRP structure undergoes a BVID, the changes in surface profile are not apparent. In addition to visualizing the internal damage inside the composite structure, it is important to look at the changes in the surface profile of the structure as well. In order to do this, a Veeco Dektak 3ST surface profiler as displayed in Figure 11 was used to conduct profilometry scans on impacted coupons. These profilometry scans were useful in determining the dent depth of the top surface i.e. impacted surface of the coupons as well as determining the pushout depth of the back surface of the coupons. The surface profile also elucidates the shape of the impactor tup which is hemispherical as can be seen from the shadowgraph image as displayed in Figure 12.

2.3.5 ANALYSIS OF IMPACT TESTING DATA

Behavior of a sample during the impact event can be observed in the data that is recorded from the load cell. The impact force-time history is converted from the load cell output voltage. Following ASTM D7136 [9], the impact velocity is calculated by:

$$v_i = \frac{w_{12}}{(t_2 - t_1)} + g \left(t_i - \left(\frac{t_1 + t_2}{2} \right) \right) \quad (1)$$

Where w_{12} = distance between flag prongs, t_1, t_2 = time first and second flag prong passes detector, g = acceleration due to gravity, and t_i = time of initial contact.

The velocity and displacement history of the impactor is calculated by:

$$v(t) = v_i + gt - \int_0^t \frac{F(t)}{m} dt \quad (2)$$

$$\delta(t) = v_i t + \frac{gt^2}{2} - \int_0^t \left(\int_0^t \frac{F(t)}{m} dt \right) dt \quad (3)$$

Where v_i = impact velocity, t = time, F = impact force, and m = mass of impactor. Furthermore, the energy absorbed by the coupon can be calculated using:

$$E_a(t) = \frac{m(v_i^2 - v(t)^2)}{2} + mg\delta(t) \quad (4)$$

This data provides insight into how the sample performs under the stresses applied by the impact weight and can preview how the sample absorbs energy and how damage propagates. Questions about how brittle the sample is and whether it was destroyed during the impact event can be indicated by the force-time curve.

2.3.6 EXPERIMENTAL RESULTS

2.3.6.1 IMPACT TESTS CONDUCTED ON 2-MM QUASI-ISOTROPIC COUPONS

Impact tests were conducted on various 6" x 4" coupons having the stacking sequence of [-45/90/+45/0]_{2s} which had thickness in the range of approximately 2-mm. The details of the impact tests are given in Table 1. This table indicates that 2 coupons were used for the same potential energy with an impactor mass of 3.06 kg. Coupons B and C were impacted with 5.85 J, coupons D and E were impacted with 9.66 J, coupons F and G were impacted with 14.05 J and coupons H and I were impacted with 16.04 J. All the energies were incremental and were estimated to try and obtain 1" impact damage diameter in the 2-mm thick coupons in an iterative process. In coupons H and I with impactor energy of 16.04 J we were able to obtain 1" impact damage diameter.

The force-time history of the impacts is given in Figure 13. The load curve shows peaks at certain maximum load and is parabolic in shape. When the load curve is symmetric, its shape indicates that the impact energy is primarily deflected and little or no damage has occurred in the coupon. When there are irregularities in the parabolic shape of the load curve this indicates that the coupon has undergone extensive damage.

The velocity-time history of the impact events in the 2-mm coupons begins from being positive initially as the impactor is dropped towards the coupon then it becomes zero upon contacting the coupon and becomes negative as the impactor rebounds from the coupon and moves upwards. The negative velocity indicates the upward rebounding of the impactor after impacting the coupon. The displacement-time history of the coupons begins from zero and becomes maximum upon contacting with the impactor and then goes back to zero as the impactor is rebounded upwards as can be clearly observed in Figure 14. We can clearly observe that the maximum displacement is obtained in coupons H and I for an impact energy of 16.04 J. which causes an internal delamination size of 1".

The energy-time plots given in Figure 15 are taken from the force-time curves through integration of the data. The energy-time plots better describe the peak energy experienced and energy absorbed by the coupons. Here, the energy absorbed is the difference between the value at the end of the plot and the initial value. The difference between the peak energies observed and the energy absorbed can be used to determine the efficiency of energy absorption by the material. Furthermore, the energy-time history clearly is able to demonstrate the percentage of impact energy that is absorbed by the coupon to create the irreversible process of damage. For coupons H and I where 1" delamination is formed, over 65% of the impact energy is absorbed by the coupons.

After performing two impact tests per energy/ drop height, the data obtained was further extrapolated to obtain a linear relationship between maximum impact force and potential energy of impactor. A linear relationship was also obtained between delamination size and potential energy of impactor. Similarly, a linear relationship was also obtained between the absorbed energy and potential energy of impactor. These relationships are displayed in Figure 16. From these impact experiments, we can also infer the effect of impact energy and impact momentum on delamination size and penetration of damage across the thickness of these coupons as indicated in Figure 17. Hence a mass, height and energy combination of the impactor was obtained to initiate a 1" size impact damage in a $[-45/90/+45/0]_{2S}$ 2-mm thick quasi-isotropic coupon.

Ultrasonic immersion tank scans were conducted to obtain the B-scan and C-scan images of the impact damage to observe its shape and size. From the B-scan, it can be seen that although, the center of the damage area undergoes permanent deformation similar to a dent, it does not have a delamination as a clear reflection from the center of the damage can be seen in the B-scan. From the C-scan image, we can clearly see the fiber cracking and pushout in the -45° fiber direction and this can be seen by looking at the rear surface of the coupon. A quad plot of coupon I, displaying the force-time history, the energy time history, The B-scan and C-scan is observed in Figure 18.

X-ray micro-CT imaging was conducted to obtain slices of the impact damage as it propagates from the top surface of the coupon to the bottom surface in a "rotating fan" phenomenon. The C-scan image (X-Y plane) at one of the bottom layers is displayed in Figure 19 (a) along with the green dashed line and the blue dashed line which are the locations along which the B-scan images have been produced. The B-scan images of both the Z-X plane (Figure 19 (b)) and the Y-Z plane (Figure 19 (c)) can also be observed. From the B-scan images in can be observed that the center

of the impact damage has a pyramidal shape and is composed of many matrix cracks and small delaminations in the form a staircase like transition.

Profilometry scans of coupon I which produced a 1" damage were conducted using a Veeco Dektak 3ST surface profiler to observe the profile of the top and bottom surface after impact. The profilometry images are displayed in Figure 20. Using the top surface scan we were able to estimate that the dent depth is approximately 54 μm and using the bottom surface scan we were able to estimate the pushout height as 80 μm . Some of the irregularities in Figure 20 (b) can be attributed to the rough bottom surface of the composite. This roughness appears due to the fact that the caul plates used to manufacture this coupon were not smooth and the impressions on the surfaces of the caul plates were imprinted on the coupon thereby making it rough with irregularities. This roughness was fixed in subsequent manufacturing of the composite plates. It is also interesting to observe that the dent profile seems hemispherical with a small dimple. The dimple is attributed to the tup which was used for the impact and was not ground well.

2.3.6.2 IMPACT TESTS CONDUCTED ON 4-MM QUASI-ISOTROPIC COUPONS

Similar to the previous section, impact tests were conducted on various 6" x 4" coupons having the stacking sequence of $[-45/90/+45/0]_{4s}$ which had thickness in the range of approximately 4-mm. The details of the impact tests are given in Table 2. This table indicates that all coupons were impacted with an impactor mass of 3.06 kg. Coupons A, B, K and L were impacted with 16.04 J, coupons C and D were impacted with 10.53 J, coupons E and F were impacted with 13.46 J, coupons G and H were impacted with 14.75 J, coupon I was impacted with 11.71 J and coupon J was impacted with 14.05 J. All the energies were incremented/decremented based on the previous tests and were estimated to try and obtain 1" damage diameter in the 4-mm thick coupons. There seems to be a threshold phenomenon occurring where a very narrow range of energy exists where the damage diameter significantly increases with a small change in height for the same mass. This threshold phenomena could be attributed to the fact that some of the matrix cracks create the onset of larger than 1" impact damage diameter. In coupons A, B, K and L with impactor energy of 16.04 J we were able to obtain approximately 1.3" delamination size which was closest to 1".

The force-time history of the impacts is given in Figure 21. The load curve shows peaks at certain maximum load and is parabolic in shape. When the load curve is symmetric, its shape indicates that the impact energy is primarily deflected and little or no damage has occurred in the coupon. When there are irregularities in the parabolic shape of the load curve this indicates that the coupon has undergone extensive damage. These irregularities can be observed in force-time plots of coupons A, B, K and L and they seem to be very consistent. This can also be seen for coupon H which is clearly an outlier.

The velocity-time history of the impact events in the 4-mm coupons begins from being positive initially as the impactor is dropped towards the coupon then it becomes zero upon contacting the coupon and becomes negative as the impactor rebounds from the coupon and moves upwards. The displacement-time history of the coupons begins from zero and becomes maximum upon contacting with the impactor and then goes back to zero as the impactor is rebounded upwards as can be clearly observed in Figure 22. We can clearly observe that the maximum displacement is obtained in coupon G for an impact energy of 14.75 J. Coupon H was an outlier as the same energy did not create any significant damage in coupon G. If we look at the force curves of coupons G and H we will observe that they have almost the same maximum force but their damage mechanisms are different due to their difference in strength which is anomalous.

The energy-time plots given in Figure 23 is taken from the force-time curve through integration of the data. The energy-time history clearly is able to demonstrate the percentage of impact energy that is absorbed by the coupon to create the irreversible process of damage. For coupons A, B, K, L and G (outlier) where 1.3" delamination is formed, over 76% of the impact energy is absorbed by the coupons.

After performing these impact tests, the data obtained was further extrapolated to obtain a linear relationship between maximum impact force and potential energy of impactor. Similarly, a linear relationship was also obtained between the absorbed energy and potential energy of impactor. An exponential relationship was obtained between damage size and potential energy of impactor. These relationships are displayed in Figure 24. From these impact experiments, we can also infer the effect of impact energy and impact momentum on damage size and penetration of damage across the thickness of these coupons as indicated in Figure 25. Here we can see a clustering effect where coupons impacted with the same energy have similar characteristics. Hence a mass, height and energy combination of the impactor was obtained to initiate a 1.3" size delamination in a [-45/90/+45/0]_{4s} 4-mm thick quasi-isotropic coupon which was closest to 1" damage.

Ultrasonic immersion tank scans were conducted to obtain the B-scan and C-scan images of the impact damage to observe its shape and size. From the B-scan, it can be seen that although, the center of the damage area undergoes permanent deformation similar to a dent, it does not have a delamination as a clear reflection from the center of the damage can be seen in the B-scan and it aligns with the bottom surface of the coupon. In addition, it can also be observed that the impact damage has propagated all the way through the thickness of the composite similar to the 2-mm coupon. From the C-scan image, we can clearly see that there is a small fiber pushout in the -45° fiber direction, and this can be seen by looking at the rear surface of the coupon as well. A quad plot of a representative coupon, displaying the force-time history, the energy time history, The B-scan and C-scan is observed in Figure 26.

X-ray micro-CT imaging was conducted to obtain slices of the impact damage as it propagates from the top surface of the coupon to the bottom surface in a "rotating fan" phenomenon. The C-scan image (X-Y plane) at one of the bottom layers is displayed in Figure 27 (a) along with the green dashed line and the blue dashed line which are the locations along which the B-scan images have been produced. The B-scan images of both the Z-X plane (Figure 27 (b)) and the Y-Z plane (Figure 27 (c)) can also be observed. From the B-scan images in can be observed that the center of the impact damage has a pyramidal shape and is composed of many matrix cracks and small delaminations in the form a staircase like transition.

Profilometry scans of the coupon were conducted similar to the previous section to observe the profile of the top and bottom surface after impact. The profilometry images are displayed in Figure 28. Using the top surface scan, we were able to estimate that the dent depth is approximately 87 μm and using the bottom surface scan we were able to estimate the pushout height as 97 μm. As can be observed, the bottom surface of this coupon in Figure 28 (b) has much lesser the irregularities when compared to the bottom surface of the 2-mm coupon in Figure 28 (b). It is also interesting to observe that the dent profile seems a little flatter compared to the 2-mm coupon with a small dimple. The flatness in the surface profile is attributed to the additional 45° and -45° laminas in the 4-mm coupon which increases the flexural stiffness of the composite and therefore the coupon resist the bending due to impact.

2.3.6.3 IMPACT TESTS CONDUCTED ON 6-MM QUASI-ISOTROPIC COUPONS

Impact tests were conducted on various 6" x 4" coupons having the stacking sequence of $[-45/90/+45/0]_{6S}$ which had thickness in the range of approximately 6-mm. The details of the impact tests are given in Table 3. This table indicates that coupon Q-6-A was impacted 6 times with different mass and heights, coupon Q-6-B and coupon Q-6-C were impacted twice, and coupons Q-6-D, Q-6-E and Q-6-F were impacted only once. Multiple impacts were conducted to try and obtain 1" damage diameter in the 6-mm thick coupons. Despite numerous attempts there seems to be a threshold phenomenon occurring where the damage diameter significantly increases from less than 0.5" to more than 1.7" after multiple impacts. This threshold phenomena seems to be appearing in 6-mm coupons when they are subjected to multiple impact. The first impact creates a small size impact damage diameter of less than 0.5" along with some matrix cracks. Upon the second impact on the same coupon, these matrix cracks widen uncontrollably and lead to the onset of an impact damage diameter of more than 1.7".

The force-time history of the impacts are given in Figure 29, Figure 30 and Figure 31. The force-time curve shows peaks at certain maximum load and is parabolic in shape. When the load curve is symmetric, its shape indicates that the impact energy is primarily deflected and little or no damage has occurred in the coupon. When there are irregularities in the parabolic shape of the load curve this indicates that the coupon has undergone extensive damage. These irregularities can be observed in all coupons at the final impact where the damage significantly increases in the coupons.

The velocity-time history of the impact events in the 6-mm coupons is similar to the behavior described for the 2-mm and 4-mm coupons. The displacement-time history of the coupons also has a similar trend as displayed by previous coupons and can be clearly observed in Figure 32, Figure 33 and Figure 34.

The energy-time plots given in Figure 35, Figure 36 and Figure 37 is taken from the force-time curve through integration of the data. The energy-time history clearly is able to demonstrate the percentage of impact energy that is absorbed by the coupon to create the irreversible process of damage. Similar to the 4-mm plate, there seems to be a threshold phenomenon occurring where if the absorbed energy is more than 79 %, it creates a delamination of 1.7" or more in the 6-mm plate.

From these impact experiments, we can also infer the effect of impact energy and impact momentum on delamination size and penetration of damage across the thickness of these coupons as indicated in Figure 38. Hence a mass, height and energy combination of the impactor was obtained to initiate a 1.8" or greater size damage in a $[-45/90/+45/0]_{6S}$ 6-mm thick quasi-isotropic coupon.

Ultrasonic immersion tank scans were conducted to obtain the B-scan and C-scan images of the impact damage to observe its shape and size similar to the previous two sections. From the B-scan, it can be observed that the impact damage has not propagated all the way through the thickness of the composite coupon which did occur in the case of the 2-mm coupon and the 4-mm coupon. From the C-scan image, we can clearly see that the damage diameter is 1.79" which was the damage diameter that was closest to 1" that could be obtained. It can also be observed from the C-scan that the maximum damage is now in the 90° fiber direction as opposed to the -45° fiber direction in the 2-mm and 4-mm coupons because the damage had propagated through the thickness for the 2-mm and 4-mm coupon and has not propagated through the thickness for the case of the 6-mm coupon. A quad plot of a representative coupon, displaying the force-time history, the energy time history, The B-scan and C-scan is observed in Figure 39.

X-ray micro-CT imaging was conducted to obtain slices of the impact damage as it propagates from the top surface of the coupon to the bottom surface in a “rotating fan” phenomenon. The C-scan image (X-Y plane) at one of the bottom layers is displayed in Figure 40 (a) along with the green dashed line and the blue dashed line which are the locations along which the B-scan images have been produced. From the C-scan image, we can clearly observe a large delamination on the right-hand side of the impacted region. The B-scan images of both the Z-X plane (Figure 40 (b)) and the Y-Z plane (Figure 40 (c)) can also be observed. From the B-scan images it can be observed that the center of the impact damage has a pyramidal shape which is more sporadic than the scenarios of the 2-mm and 4-mm coupons and is composed of many matrix cracks and small delaminations in the form of a staircase like transition.

Profilometry scans of the coupon were conducted similar to the previous section to observe the profile of the top and bottom surface after impact. The profilometry images are displayed in Figure 41. Using the top surface scan we were able to estimate that the dent depth is approximately 119 μm and using the bottom surface scan we were able to estimate the pushout height as 93 μm . As can be observed, the bottom surface of this coupon in Figure 41 (b) does not cover the entire damage since it is greater than 1" and the scanning area is also limited by the bounds of the surface profiler when compared to the bottom surface of the 2-mm coupon in Figure 20 (b) and 4-mm coupon in Figure 28 (b). It is also interesting to observe that the dent profile seems flatter in Figure 41 (a) compared to the 2-mm and 4-mm coupon with a small dimple. The flatness in the surface profile is attributed to the additional 45° and -45° laminas in the 6-mm coupon compared to the 2-mm and 4-mm coupons which increases the flexural stiffness of the composite and therefore the coupon resists the bending due to impact. This is an interesting observation and has not been reported before in literature. From this observation, we can assume that as the thickness of the impacted coupons increases, the profile of the impacted surface becomes flatter and less hemispherical.

2.3.6.4 MODIFIED EXPERIMENTAL SETUP FOR DROP WEIGHT IMPACT TESTING

After having some difficulties in obtaining the mass, height and energy combination to obtain 1" delamination size in the 4-mm and 6-mm thick coupons, it was assumed that due to the thickness of the coupons being more than 2-mm, the in-plane dimensions (aspect ratio) needed to be increased so that the coupon could be bent more in flexure upon impact. Since the ASTM D7136 fixture has maximum in-plane dimensions of 12" x 6", the coupon dimensions will be changed from 6" x 4" to 12" x 6" (since that is the in-plane dimension of the fixture). Two rectangular frames have been constructed that will hold the larger coupon and be clamped to the D7136 fixture to conduct impact tests on the same drop tower. These tests will not conform to ASTM D7136 standards. The modified experimental setup is displayed in Figure 42. These tests will be conducted in the future to try and obtain close to 1" impact damage diameter in thick composite coupons. Guided-wave based methods will also be explored to detect impact damage of different sizes and distinguish impact damage from a simulated delamination. The use of X-ray computed tomography will also be explored as an impact damage detection technique in addition to the aforementioned methods.

2.3.6.5 IMPACT TESTS CONDUCTED ON 12" X 6", 6-MM QUASI-ISOTROPIC COUPONS

Using the modified experimental setup, impact tests were conducted on various 12" x 6" coupons having the stacking sequence of $[-45/90/+45/0]_{6S}$ which had thickness in the range of

approximately 6-mm. The details of the impact tests are given in Table 4. In Section 2.3.6.3 the impact tests conducted on 6" x 4", 6-mm thick coupons designated as Q-6-A, Q-6-B, etc. were discussed. In this section, the 12" x 6", 6-mm thick coupons will be designated as QL6A, QL6B, etc. The data in Table 4 indicates that coupon QL6A, QL6B and QL6C were each impacted 2 times with the same mass but different heights to try and obtain close to 1" impact damage diameter. Coupon QL6D was impacted only once. Double impacts were conducted to try and obtain 1" impact damage diameter in the 6-mm thick coupons. Despite numerous attempts there seems to be a threshold phenomenon occurring where the damage diameter significantly increases from less than 0.45" to more than 2" after double impacts. A similar threshold phenomenon was observed in the 6-mm coupons of having a standard size of 6"x 4".

The force-time histories of the double impacts conducted on coupons QL6A, QL6B and QL6C are displayed in Figure 43. The force-time curves show peaks at certain maximum load and are parabolic in shape. When the load curve is symmetric, its shape indicates that the impact energy is primarily deflected and little or no damage has occurred in the coupon. When there are irregularities in the parabolic shape of the load curve this indicates that the coupon has undergone extensive damage. The first impacts as indicated by the plots on the left-hand side show little or no irregularities indicating that there was little to no internal damage in the coupons. Some irregularities can clearly be observed in the three coupons at the second impact where the damage significantly increases in the coupons. For coupon QL6D, it can be observed from its force-time history in Figure 44 that even with the impact energy comparable to the second impact on coupon QL6C which created 2" impact damage diameter in it, there is only a damage of 0.37" created in coupon QL6D which indicates the threshold phenomena described earlier.

The velocity-time history of the impact events in these 6-mm coupons is similar to the behavior described in the previous sections. The displacement-time histories of the double impacts conducted on coupons QL6A, QL6B and QL6C are displayed in Figure 45 where the second impact clearly create a larger displacement as compared to the first impacts. The displacement-time history of coupon QL6D is displayed in Figure 46 and indicates a displacement value comparable to the second impacts of the previous coupons but creates a fraction of the impact damage size.

The energy-time plots of the double impacts conducted on coupons QL6A, QL6B and QL6C are displayed in Figure 47 and clearly able to demonstrate the percentage of impact energy that is absorbed by the coupon to create the irreversible process of damage. For the first impact we can observe that the absorbed impact energy is only 50% of the impact energy and for the second impact more than 68% of the impact energy is absorbed by the coupons. The energy-time history of coupon QL6D is displayed in Figure 48. In this coupon although the impact energy is comparable to the second impact conducted on coupon QL6C, it only absorbs 50% of the impact energy which is similar to the first impacts on the previous coupons. Similar to the previous sections, there seems to be a threshold phenomenon occurring where if the absorbed energy is more than 68 %, it creates a delamination of 2" or more in the 12" x 6", 6-mm coupons.

From these impact experiments, we can also infer the effect of impact energy and impact momentum on delamination size and penetration of damage across the thickness of these coupons as indicated in Figure 49. In these plots, the first impacts and the second impacts have the numbers "1" and "2" before the symbols indicating the impacts. From these impact experiments, a mass, height and energy combination of the impactor was obtained to initiate a 2" or greater size impact

damage in a $[-45/90/+45/0]_{6s}$ 6-mm thick quasi-isotropic coupon having a coupon size of 12" x 6".

Ultrasonic immersion tank scans were conducted to obtain the B-scan and C-scan images of the impact damage to observe its shape and size similar to the previous three sections. From the B-scan, it can be observed that the impact damage has not propagated all the way through the thickness of the composite coupon which is similar to the previous section where the 6" x 4", 6-mm coupons was examined. This phenomenon did occur in the case of the 2-mm coupon and the 4-mm coupon. From the C-scan image, we can clearly see that the damage diameter is approximately 2" which was the damage diameter that was closest to 1" that could be obtained. It can also be observed from the C-scan that the maximum damage is now in the -45° fiber direction even though the damage has not propagated through the thickness of the 6-mm coupon. A quad plot of a representative coupon QL6B, displaying the force-time history, the energy time history, The B-scan and C-scan is observed in Figure 50.

3 GUIDED WAVES IN AEROSPACE COMPOSITES

3.1 ULTRASONIC MEASUREMENT OF CFRP MATERIAL PROPERTIES

Several ultrasonic methods can be used to estimate the stiffness properties of a composite material without destructive testing [58]. The essence of the method is to send an ultrasonic beam through a composite specimen at various angles of incidence and measure how the propagation time changes with the incidence angle. In addition, advantage can be taken by the simplifications introduced by wave propagation in planes of symmetry [59] and by the direct formulae offered by the critical angles [60]. A recent development and implementation of this methodology is presented in ref. [61], [62] as discussed next.

3.1.1 Experimental setup

The specimen used in this process is a small coupon of unidirectional composite plate as shown in Figure 51. The x_1 axis is aligned with fiber direction, the x_2 axis is transverse to the fiber direction, and the x_3 axis is pointing outward from the plate (Figure 51). Typical dimensions are length (along x_1) = 150 mm and width (along x_2) = 64 mm. The thickness (x_3) should preferably be larger than 2 mm to allow good separation between the faster quasi-pressure wave and the slower quasi-shear wave.

The experiment is conducted in a water tank equipped with a linear scanning gantry and a rotational scanning turntable (Figure 52). The specimen is mounted in a fixture (Figure 53a). The fixture allows for in-plane positioning of the specimen by a polar angle ϕ (Figure 53b). The fixture is mounted in the turntable and thus can perform spin scanning by angle θ (Figure 53c).

3.1.2 Enabling theory

The following enabling principles are used. These enabling principles are based on the bulk wave theory in orthotropic composites.

1. Pressure wave propagation directly across the thickness of the specimen depends only on one stiffness component, C_{33}
2. For wave propagation in a plane of material symmetry, the critical angle value can be used to determine the wavespeed of the wave that is in a critical condition, i.e., is changing from a propagating wave into an evanescent wave

3. Wave propagation in planes of material symmetry depends only on a reduced set of stiffness components
4. Wavespeed and refraction angles can be extracted from time delay information
5. Transversely isotropy of unidirectional composites can be used to further simplify the calculation

These principles are detailed next.

3.1.2.1 Propagation across the thickness of the specimen

If a pressure wave is propagated directly across the thickness of the specimen, i.e., in the direction of the x_3 axis, then the only stiffness component used in calculating its wavespeed is the C_{33} component and hence one can determine C_{33} as

$$C_{33} = \rho v_{33}^2 \quad (5)$$

3.1.2.2 Calculation of wavespeed using the critical angle

When wave propagation takes place in a plane of material symmetry, the shear horizontal (SH) wave is decoupled from the pressure (P) and shear vertical (SV) waves. If the wave propagation is generated by a fluid pressure wave that impinges obliquely on the specimen surface, then two refracted waves are generated into the specimen, a P wave and an SV wave. The refraction angle is calculated in accordance with Snell's law, i.e.,

$$\theta_r = \sin^{-1} \left(\frac{v}{v_f} \sin \theta_i \right) \quad , \quad v > v_f \quad (6)$$

Since $v > v_f$, the refraction angle θ_r is always greater than the incidence angle θ_i . As the oblique incidence angle θ_i increases, the refraction angle θ_r also increases. Eventually, a value will be reached when the argument of the sine function becomes equal to 1 and hence $\theta_r = 90^\circ$. This is the critical angle because no further refracted waves will be generated beyond this value of incidence angle θ_i . If the critical angle, θ_{cr} , is known, then one can find the refracted wavespeed as

$$v = \frac{v_f}{\sin \theta_{cr}} \quad (\text{wavespeed calculate from critical angle}) \quad (7)$$

At the critical angle, the refracted wave travels at an angle $\theta_r = 90^\circ$, i.e., parallel to the specimen surface (Figure 54).

3.1.2.3 Oblique propagation in a plane of material symmetry

As shown in ref. [59], if wave propagation takes place in plane of material symmetry, then only a reduced number of stiffness components participate in the wave propagation process. Figure 55 shows that wave propagation in the x_1 - x_3 plane of material symmetry depends only on C_{11} , C_{33} , C_{55} , C_{13} , whereas propagation in the x_2 - x_3 plane of symmetry depends only on C_{22} , C_{33} , C_{44} , C_{23} .

3.1.2.4 Transverse isotropy

Unidirectional composites are transversely isotropic and their stiffness matrix has only five

independent components C_{11} , C_{33} , C_{55} , C_{13} , C_{23} , i.e.,

$$\mathbf{C} = \begin{bmatrix} C_{11} & C_{13} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{33} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} = (C_{33} - C_{23})/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{55} \end{bmatrix} \quad (8)$$

Thus, under the assumption of transversely isotropic composite, only five stiffness components need to be found, specifically, C_{11} , C_{33} , C_{55} , C_{13} , C_{23} .

3.1.3 Data collection

Data collection consists of preliminary steps to be followed by ultrasonic signal collection at a range of (θ, y) values.

3.1.3.1 Preliminary steps

The preliminary steps consist of establishing the wavespeed in the water tank and of finding the true zero of the spin angle θ , i.e.,

- use the T and R transducers to perform pitch-catch through the tank fluid in order to establish the fluid wavespeed v_f
- use only the T transducer to perform pulse-echo through the specimen with the fixture spin angle θ scanning a small $\pm 5^\circ$ zone in order to establish the true $\theta=0^\circ$ location by search for the maximum echo signal. Store the $\theta=0^\circ$ signal in the database for further processing.

3.1.3.2 Collection of ultrasonic scanning data

Set the transmitter (T) and receiver (R) transducers sufficiently far apart to accommodate the specimen fixture between them as shown in Figure 56b. Move the T-R pair sideways until outside the specimen area and perform pitch-catch between them to establish the fluid time of flight t_f .

Perform rotational and translational scanning as follows. Use a range of spin angles θ from -60° through $+60^\circ$ in small steps of 0.1° (Figure 56a). For each spin angle value θ , perform lateral scanning along the y axis from -25 mm through $+25$ mm with increments of 0.025 mm (Figure 56b). Record the ultrasonic signal for each (θ, y) pair. The (θ, y) scanning is repeated for several values of the in-plane specimen position angle ϕ , e.g., $\phi=0^\circ$, $\phi=90^\circ$, or another arbitrary position ϕ . In this way one generates a (θ, y, ϕ) database of ultrasonic signals that are subjected to further processing. Also recorded in this process is signal for the fluid time of flight t_f that was measured by moving outside the specimen zone.

3.1.4 Data processing

3.1.4.1 Processing of the thickness-wise pulse-echo signal to calculate C_{33}

From the pulse-echo measurement at $\theta=0^\circ$, one uses the signal envelope to determine the signal

peaks and extract the time-of-flight difference Δt_0 between the first and second peaks (Figure 57). This value Δt_0 is used to determine the wavespeed in the thickness direction (h), i.e.,

$$v_{33}=2h/\Delta t_0 \quad (9)$$

This value is used in Eq. (5) to calculate the stiffness component C_{33} .

3.1.4.2 Calculation of time shift Δt at all (θ, y) points

The collected (θ, y) data is first processed such that the angle θ and position y ranges have maximum signal strength at the $(\theta=0, y=0)$ center. After recentering, the (θ, y) data is processed to calculate the time of flight for each (θ, y) by locating the largest peak in the signal envelope (Figure 58). The time shift Δt is calculated from the signal time of flight by subtracting the fluid time of flight t_f . The time shift Δt and the peak amplitude are stored in the database for each (θ, y) . This database needs to be collapsed such that for each θ value only one value of Δt is retained, i.e., the true Δt corresponding to the center spot of the refracted beam. This is done as follows.

The peak amplitude database is used to generate a surface plot of the peak amplitude in the signals recorded for each incidence angle θ and location y (Figure 59). To identify the location of the beam spot on the y axis, keep constant the incidence angle θ and search in the data along the y axis for the maximum value of the plotted signal peak amplitude. The index of the maximum peak amplitude along the y axis is used to pick up the corresponding Δt from the database at that θ value. The resulting Δt value can now be plotted against the incidence angle θ as shown in Figure 60a.

3.1.4.3 Calculation of wavespeed and refraction angle

The wavespeed and refraction angle are calculated with the formulae given in ref. [58]. For a fluid pressure wave impinging on a specimen at an incidence angle θ_i , the calculation of wavespeed v refracted into the specimen and of the refraction angle θ_r is done with Eqs. (3.17), (3.18) of ref. [58], i.e.,

$$v = \sqrt{\frac{1}{v_f^2} - \frac{2\Delta t \cos \theta_i}{hv_f} + \frac{\Delta t^2}{h^2}} \quad (\text{refracted wavespeed}) \quad \text{Eq. (3.17) of ref. [1]} \quad (10)$$

$$\theta_r = \sin^{-1} \left(\frac{v}{v_f} \sin \theta_i \right) \quad (\text{refraction angle}) \quad \text{Eq. (3.18) of ref. [1]} \quad (11)$$

where h is the specimen thickness, v_f is the fluid wavespeed, and Δt is the time shift, i.e., the difference between the time of flight measured with and without the specimen between the transmitter and the receiver.

3.1.4.4 Calculation of C_{11} , C_{22} from critical angles

Using Eq. (10) and the Δt data shown in Figure 60a, one calculates and plots the wavespeed (aka phase velocity) vs. incidence angle as shown in Figure 60b. Examination of Figure 60 reveals the critical angle phenomenon. At an incidence angle value of $\pm 27.3^\circ$, the curves in Figure 60 have a sharp discontinuity. The physical explanation for this discontinuity is that the curves before and after the discontinuity belong to different wave types. The wave in the center of the plot is the P

wave for propagation in the x_2 - x_3 plane of material symmetry. However, as the angle of incidence increases, the critical incidence is reached beyond which the P wave becomes evanescent and no longer appears in the refracted signal. What appears now is the refracted SV wave which has a much slower wavespeed as indicated in Figure 60b. Thus it is determined that the critical angle for P-wave propagation in the x_2 - x_3 plane of material symmetry is $\theta_{cr}^{22} = 27.3^\circ$. This θ_{cr} value can now be used in Eq. (7) to calculate the wavespeed associated with P-wave propagation in the x_2 - x_3 plane of material symmetry. The P wavespeed v_{22} is constant for all θ values in the x_2 - x_3 plane because the unidirectional composite is transversely isotropic (see x_2 - x_3 polar plots in Chapter 6 of this book). This fact is apparent in Figure 60b where the P wavespeed has a value $v_{22} \approx 3000$ m/s. The speed v_{22} of the refracted wave at the critical angle is calculated with Eq. (7) comes out also $v_{22} \approx 3000$ m/s. Using v_{22} , one can calculate C_{22} as

$$C_{22} = \rho v_{22}^2 \quad (12)$$

Note that v_{22} propagates parallel to the specimen surface in the x_2 direction, hence this P wave is a pure wave and Eq. (12) is appropriate.

A similar process in the x_1 - x_3 plane gives a very small value for the critical angle $\theta_{cr}^{11} = 8.1^\circ$. The corresponding P wavespeed in x_1 - x_3 plane is calculated with Eq. (7) as $v_{11} \approx 10,000$ m/s. This v_{11} propagates parallel to the specimen surface in the x_1 direction; hence this P wave is a pure wave in the x_1 direction and the wavespeed can be used to calculate the C_{11} stiffness component, i.e.,

$$C_{11} = \rho v_{11}^2 \quad (13)$$

So far, we have calculated C_{11} , C_{22} , C_{33} . However, since the material is transversely isotropic, the transverse constants C_{22} , C_{33} should be equal, or at least nearly equal. (If only nearly equal, then the average of the two values should be calculated and retained as $C_{22}=C_{33}$.) What is left to calculate are the remaining three constants C_{55} , C_{13} , C_{23} .

3.1.4.5 Calculation of C_{55} , C_{13} , C_{23} from wavespeed plots

The calculation of C_{55} , C_{13} , C_{23} is done through an optimization process in which measured wavespeed-angle plots are used as input data and the stiffness components are adjusted to predict wavespeed-angle plots that fit the input data. The optimization is aimed at minimizing the absolute value of the difference between the measured and predicted wavespeed-angle curves. Details of this optimization process and numerical results are given in ref. [61].

3.1.5 Experimental validation of extracted CFRP material properties

In this section, experiments were conducted to validate the extracted CFRP material properties. These material properties will be used in the FEM simulation and analytical modeling for corresponding composite plates.

3.1.5.1 NASA thick IM7G-8552 unidirectional CFRP plate

In this section, the hybrid PWAS-SLDV system was used to obtain the frequency-wavenumber dispersion curves for a thick IM7G-8552 unidirectional CFRP composite plate. The plate thickness is 16.4 mm and the stacking sequence is $[0]_{96}$. The stiffness matrix of the CFRP plate was measured

using the proposed ultrasonic immersion technique. The stiffness matrix $\mathbf{C}$ is given by Eq. (14) and the corresponding engineering elastic properties are given in Table 5.

$$\mathbf{C} = \begin{bmatrix} 172.6 & 3.9 & 3.9 & 0 & 0 & 0 \\ 3.9 & 15.2 & 5.2 & 0 & 0 & 0 \\ 3.9 & 5.2 & 15.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 6.17 & 0 \\ 0 & 0 & 0 & 0 & 0 & 6.17 \end{bmatrix} \text{GPa} \quad (14)$$

In this experiment, the SLDV line scans in the 0° and 90° directions are used to measure the out-of-plane velocity of guided waves propagating in the CFRP plate. Then the experimental frequency-wavenumber dispersion curves can be obtained. First, the SLDV line scan in the 0° direction was conducted. To obtain higher order wave modes in the experiment, the PWAS is excited using a three-count tone-burst signal at a central frequency of 120 kHz, the peak-to-peak voltage is 140 volt after amplification. Figure 61 shows the schematic of hybrid PWAS-SLDV system. The 15.5-mm IM7G-8552 unidirectional CFRP plate is shown in Figure 62.

The time-space wavefield of the CFRP composite plate is shown in Figure 63. It can be noted that several wave modes are generated in this thick plate. Then the time-space signals are converted to the frequency-wavenumber domain using 2D FFT. The experimental results are employed to compare with the predictions of SAFE approach.

For the predictions, SAFE approach was used to calculate the frequency-wavenumber dispersion curves. The comparison between experimental and predicted frequency-wavenumber dispersion curves in the 0° direction is shown in Figure 64. The SAFE predictions are in good agreement with the experimental data. Due to the excitation frequency of 120 kHz, the A0 mode is the dominant mode, this behavior is validated by the experiment. It is important to notice that due to the thickness of the composite plate, higher-order wave mode (S1, A1) in this high frequency-thickness domain (1860 kHz-mm) are excited.

Second, the SLDV line scan in the 90° direction was performed. Figure 65 shows the schematic of the hybrid PWAS-SLDV system. The 15.5-mm unidirectional IM7G-8552 CFRP plate used for the validation in the 90° direction is shown in Figure 66. The time-space wavefield in the 90° direction is shown in Figure 67. It can be noted that several wave modes are generated in the composite plate. Then the time-space signals are converted to the frequency-wavenumber domain using 2D FFT.

The comparison between the experiment and prediction in the 90° direction is shown in Figure 68. The SAFE predictions are in good agreement with the experiment. It is important to notice that due to the thickness of the composite plate, higher-order mode (S1, S2, A1, and A2) in this high frequency-thickness domain (1860 kHz-mm) are excited.

3.1.5.2 In-house unidirectional CFRP composite plate

First, a 1.8-mm thick in-house unidirectional CFRP composite plate with a stacking sequence of $[0]_8$ was examined. The material properties of the unidirectional CFRP composite plate were measured experimentally using the ultrasonic immersion technique. The stiffness matrix $\mathbf{C}$ is

given by Eq. (15) and the corresponding engineering elastic properties are given in Table 6.

$$\mathbf{C} = \begin{bmatrix} 145.3 & 7.2 & 7.2 & 0 & 0 & 0 \\ 7.2 & 15.3 & 7.9 & 0 & 0 & 0 \\ 7.2 & 7.9 & 15.3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5.7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 5.7 \end{bmatrix} \text{ GPa} \quad (15)$$

In this experiment, the same CFRP composite plate was examined. To excite guided waves in the unidirectional CFRP composite plate, a circular PWAS (Steminc SM412, 9-mm-diameter disk, and 0.5 mm thick) was bonded on the top surface as the excitation source. A scanning laser Doppler vibrometer (SLDV) was adopted to measure the out-of-plane velocity of the plate. Thus, a hybrid SLDV-PWAS system was established to measure the guided wave propagation in the composite plate.

Figure 69 shows the experimental setup on the 1.8-mm thick CFRP composite plate. The excitation signal is a three-count tone-burst at the central frequency of 90 kHz. Under electrical excitation, the PWAS will generate guided waves propagating in the composite plate. The guided waves propagate with an out-spreading pattern, undergo dispersion, experience attenuation, and are finally picked up by SLDV.

To validate the SAFE approach, a comparison between experimental frequency-wavenumber dispersion curves and the predictions was conducted. Figure 70 shows the schematic of the hybrid PWAS-SLDV system. In this experiment, the time-space guided wave data was obtained from the SLDV line scan. To obtain the experimental frequency-wavenumber dispersion curves, the measured time-space data $u(t, x)$ was transformed into the frequency-wavenumber domain by applying a two-dimensional (2D) fast Fourier transform (FFT).

$$U(f, \xi) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} u(t, x) e^{-i(\xi x - 2\pi f t)} dt dx \quad (16)$$

where $U(f, \xi)$ is the resulting frequency-wavenumber representation in terms of the frequency variable f and the wavenumber variable ξ .

The theoretical frequency-wavenumber dispersion curve was calculated using the material properties of Eq. (15) and our SAFE formulation. The comparison between experiments and predictions in the 0° and 90° directions are shown in Figure 71 (a) and (b), respectively. Because of the tuning effect on the out-of-plane velocity response of S0 mode, measurements of S0 mode could be made only in the 90° direction. The red and white lines are the frequency-wavenumber dispersion curves for A0 and S0 modes calculated by our SAFE approach. A good match between the experiment and the prediction can be observed in both directions. In addition, a larger A0 wavenumber in the 90° direction and a smaller one in the 0° direction due to the influence of anisotropy can be observed.

The group velocities in different propagation directions were also measured using the hybrid PWAS-SLDV system. Figure 72 shows the directivity plot of the measured and predicted group velocities for A0 mode in the CFRP composite plate at 90 kHz. A good match between the

experiment and the prediction was achieved.

The curve represents the spatial wave propagation pattern. It can be observed that A0 mode has the highest group velocity along the fiber direction at 0° and 180°, whereas in the transverse direction at 90° and 270° the group velocities are much lower. Thus, if the guided waves were excited by a point source, then an elliptical wave crest would be obtained.

3.1.5.3 2-mm in-house unidirectional CFRP with the same prepreg for quasi-isotropic CFRP

In this section, a 2-mm thick in-house unidirectional CFRP composite plate was examined. The material properties of the unidirectional CFRP composite plate were measured experimentally using the ultrasonic immersion technique. The stiffness matrix $\mathbf{C}$ is given by Eq. (17)

$$\mathbf{C} = \begin{bmatrix} 157.8 & 6.6 & 6.6 & 0 & 0 & 0 \\ 6.6 & 11.8 & 6 & 0 & 0 & 0 \\ 6.6 & 6 & 11.8 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.9 & 0 & 0 \\ 0 & 0 & 0 & 0 & 6.9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 6.9 \end{bmatrix} \text{ GPa} \quad (17)$$

The material properties of the in-house composite plate were measured experimentally using the ultrasonic immersion technique proposed in Ref. (Barazanchy et al. 2018). The retrieved engineering elastic constants are given in Table 7. To validate the retrieved material properties, a comparison between the experimental frequency-wavenumber dispersion curve and the theoretical dispersion curve was conducted. In this experiment, the time-space guided wave data was obtained from the SLDV line scan in the 0° direction on the pristine area. The quantity measured by the SLDV is the out-of-plane velocity of surface particle motion. The excitation signal applied to the PWAS transducer is a linear sine wave chirp from 50 kHz to 900 kHz.

The theoretical frequency-wavenumber dispersion curve was calculated using the measured material properties and the SAFE approach. For the SAFE approach, 48 one-dimensional (1D) quadratic elements across the thickness direction were utilized to ensure the convergence of the solution. The comparison between experimental and theoretical frequency-wavenumber dispersion curves in the 0° direction is shown in Figure 73. The dotted lines are the theoretical frequency-wavenumber dispersion curves for all the wave modes in the quasi-isotropic CFRP composite plate. A good match between the experiment and the prediction of measured material properties was achieved. Besides the fundamental A0, S0, and SH0 modes, high-order modes such as A1, SH1, and SH2 were successfully generated in the 3-mm quasi-isotropic composite plate. It can be found that the A0 mode has a strong out-of-plane velocity at low frequency (below 250 kHz).

3.2 PREDICTION OF GUIDED WAVE PROPAGATION IN LAMINATED COMPOSITES

In this chapter, a semi-analytical finite element (SAFE) approach is presented to calculate guided-wave dispersion curves in composites. The theoretical derivative of group velocity and skew angle is introduced. The SAFE framework is formulated using the finite element method (FEM) to describe the material variation across the thickness direction and assuming an analytical solution along the wave propagation direction. As with any finite element approach, the convergence study is first performed to ensure the accuracy of the SAFE approach. Then, numerical verifications with

existing reference data are conducted to assess the performance of the SAFE approach. Dispersive curves are obtained in terms of phase velocity, group velocity, and the skew angle between them. Finally, experimental validations are conducted using the pitch-catch experiment and the scanning laser Doppler vibrometer (SLDV) measurements in unidirectional carbon fiber reinforced polymer (CFRP) composite plates.

3.2.1 Dispersion curve calculation of composites

the following homogeneous wave equation in FEM form is obtained

$$\left[\mathbf{K}_1 + i\xi\mathbf{K}_2 + \xi^2\mathbf{K}_3 - \omega^2\mathbf{M} \right] \mathbf{U} = 0 \quad (18)$$

Eq. (18) can be written in an equivalent equation

$$\mathbf{A}\mathbf{Q} = \xi\mathbf{B}\mathbf{Q} \quad (19)$$

where $\mathbf{A}$, $\mathbf{B}$, $\mathbf{Q}$ are given in Eq. (20)

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{K}_1 - \omega^2\mathbf{M} \\ \mathbf{K}_1 - \omega^2\mathbf{M} & i\mathbf{K}_2 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{K}_1 - \omega^2\mathbf{M} & \mathbf{0} \\ \mathbf{0} & -\mathbf{K}_3 \end{bmatrix}, \quad \mathbf{Q} = \begin{bmatrix} \mathbf{U} \\ \xi\mathbf{U} \end{bmatrix} \quad (20)$$

Eq. (19) is an eigenvalue problem. If M is the dimension of the original vector $\mathbf{U}$, then the dimension of $\mathbf{Q}$ is $2M$. At each frequency ω , one obtains $2M$ eigenvalues ξ_m , $m=1,2,\dots,2M$. Eq. (19) accepts $2M$ left eigenvectors $\mathbf{v}_m^L$ ($1 \times 2M$ vector) and $2M$ right eigenvectors $\mathbf{v}_m^R$ ($2M \times 1$ vector).

$$\mathbf{A}\mathbf{v}_m^R = \xi_m\mathbf{B}\mathbf{v}_m^R, \quad \mathbf{v}_m^L\mathbf{A} = \xi_m\mathbf{v}_m^L\mathbf{B}, \quad m=1,2,\dots,2M \quad (21)$$

Group velocity is the key information for the signal interpretation as it reveals the types of wave modes traveling in the structures. One common way to calculate group velocity is $c_g = d\omega/d\xi$, where ω and ξ are angular frequency and wavenumber, respectively. However, the differential operation is prone to numerical errors, especially when the phase velocity dispersion curves are calculated using a large frequency increment. An alternative way of calculating group velocity is using each (ω, ξ) solution obtained from the SAFE approach as follow:

$$c_g = \frac{\partial\omega}{\partial\xi} = \frac{\mathbf{v}_L^T (i\mathbf{K}_2 + 2\xi\mathbf{K}_3) \mathbf{v}_R}{2\omega\mathbf{v}_L^T \mathbf{M} \mathbf{v}_R} \quad (22)$$

Based on the group-velocity formula, it can be calculated for each individual solution (ω, ξ) of the dispersion curves independently.

3.2.1.1 Convergence Study

As in conventional FEM applications, convergence study has to be considered to guarantee the simulation accuracy. In SAFE approach, 1D FEM mesh is used to discretize the thickness direction. Therefore, the accuracy of SAFE approach will depend on the number of elements used in the thickness direction. To perform the convergence study, dispersion curves in terms of phase velocity have been computed for various discretization.

We conducted a case study of wave propagation in isotropic materials, where, the exact analytical

solution for dispersion curves exists. The comparison between SAFE and analytical solutions for a 1-mm aluminum 2024-T3 plate was conducted. The material properties of 2024-T3 aluminum are given in Table 8. The effect of the element number through the thickness on the convergence of SAFE approach was investigated. Figure 74 compares the SAFE results with the results obtained by a unified analytical method as reported in ref. [63]. In the SAFE approach, we use a 1D quadratic isoparametric element, which is comprised of three nodes per element. The results of convergence study are shown in Figure 74. It can be noted that several wave modes are not retrieved when the number of element is insufficient (one element), as shown in Figure 74 (a). When we increase the number of element as shown in Figure 74 (b) and (c), it can be observed that high-order modes are retrieved. However, the accuracy of the solution remains unsatisfactory. When the number of element is increased to 15, satisfactory results are obtained for all the high-order modes.

3.2.1.2 Verification of Group Velocity and Skew Angle Calculation

To verify the applicability of the SAFE approach, numerical verifications are conducted to calculate dispersion curves in terms of group velocity and skew angle for the composite plate in the ref. [64]. The stiffness matrix $\mathbf{C}$ of the 3.6-mm CFRP composite plate is given in Eq. (23). The material density is 1560 kg/m^3 .

$$\mathbf{C} = \begin{bmatrix} 86.6 & 9 & 6.4 & 0 & 0 & 0 \\ 9 & 13.5 & 6.8 & 0 & 0 & 0 \\ 6.4 & 6.8 & 14 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.72 & 0 & 0 \\ 0 & 0 & 0 & 0 & 4.06 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4.7 \end{bmatrix} \text{ GPa} \quad (23)$$

In reference, an analytical method was used to calculate the dispersion curves of group velocity and skew angle. For our SAFE approach, we use 1D quadratic element and 30 elements across the thickness.

Figure 75 shows the comparison of the calculation of group velocity and skew angle in the 60° direction (along the phase-velocity direction) for symmetric modes. It can be noted that a good agreement between the two different methods is obtained. The skew angle is not zero due to the anisotropic characteristics of composites and it depends on the frequency and wave modes. Similarly, the group-velocity and skew-angle comparison of anti-symmetric modes are given in Figure 76. Our SAFE approach matches well with the analytical method used in the reference, which means that the proposed SAFE approach is reliable, robust, and efficient in solving dispersion curves of composites.

3.2.2 GUI Development: LAMSS-COMPOSITES

In this section, a graphical user interface (GUI) ‘LAMSS-COMPOSITES’ is developed to retrieve and display the dispersion curves from guided wave database. We use the combination of a unified analytical method [63] and the SAFE approach to generate the database for different materials and layups. Cross-checking between the two methods is employed to ensure the accuracy of the database.

In the GUI, three isotropic materials, four carbon fiber reinforced polymer (CFRP) laminates with different layups, and one woven glass fiber reinforced polymer (GFRP) laminate are selected to generate the database. The database for new materials and layups can be further extended as required. The main interface of LAMSS COMPOSITES is shown in Figure 77. The database contains the phase and group velocities, the skew angle between them, and the modeshape across the thickness. As shown in Figure 77, the top left figure is the phase velocity. The top right figure shows the group velocity. The bottom left has the polar plot for phase velocity and modeshape for wave mode of the selected frequency. The bottom right is skew angle. The GUI will automatically load the guided wave database in the database folder. The user can select the database from the Material-Layup pop-up menu in the control panel, as shown in Figure 78.

The user can click the ‘Property’ button to display the detailed material properties (stiffness matrix, stacking sequence, and material density) for the material selected from the database. Figure 79 shows material properties for the selected crossply CFRP [0/90]_{2s}. The user can view the material properties of each layer from the Layer number pop-up menu.

In addition, the user can change the direction by typing the value (0 - 360) in the textbox or moving the direction slider. The GUI will update all the figures for this specific direction. To display the modeshape of a certain wave mode at a specific frequency, the user can click the red dot in the phase velocity figure. The red dots on other figures will update automatically. The top right of figures will display the values for the phase velocity, group velocity, and the skew angle between them.

3.2.3 1D guided wave propagation and excitation in composites

For 1D (straight crested) guided wave propagation, which is a y -invariant problem, guide wave propagation takes place in the x direction, as shown in Figure 80. They are excited by external tractions $\mathbf{t}$.

$$\begin{aligned}
 \mathbf{u}(x, \omega) &= i \sum_{m=1}^M \text{Res}\{\xi_m\} = i \sum_{m=1}^M \frac{N(\xi_m)}{D'(\xi_m)} \\
 &= i \sum_{m=1}^M \frac{\mathbf{V}_m^L \mathbf{P} \Phi_m e^{i\xi_m x}}{-\mathbf{V}_m^L \mathbf{B} \mathbf{V}_m^R} \\
 &= -i \sum_{m=1}^M \frac{\mathbf{V}_m^L \mathbf{P} \Phi_m}{\mathbf{V}_m^L \mathbf{B} \mathbf{V}_m^R} e^{i\xi_m x}
 \end{aligned} \tag{24}$$

Based on the strain-displacement relation, the expression for normal strain in the x direction is given as follow

$$\begin{aligned}
 \varepsilon(x, \omega) &= \frac{d\mathbf{u}(x, \omega)}{dx} \\
 &= \sum_{m=1}^M -i(i\xi_m) \frac{\mathbf{V}_m^L \mathbf{P} \Phi_m}{\mathbf{V}_m^L \mathbf{B} \mathbf{V}_m^R} e^{i\xi_m x} \\
 &= \sum_{m=1}^M \xi_m \frac{\mathbf{V}_m^L \mathbf{P} \Phi_m}{\mathbf{V}_m^L \mathbf{B} \mathbf{V}_m^R} e^{i\xi_m x}
 \end{aligned} \tag{25}$$

To simulate the guided wave propagation due to the excitation by a surface-mounted PWAS, the component of $\mathbf{P}$ in Eqs. (24) and (25) should be written as

$$\mathbf{P} = \begin{bmatrix} \mathbf{0} \\ \mathbf{F} \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} a\tau_a(-2i\sin\xi_m a) \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (26)$$

The flow chart of time domain simulation for 1D guided wave propagation is given in Figure 81. In this section, a unidirectional CFRP composite plate was used to validate our SAFE approach for the simulation of 1D guided wave propagation. To assess the applicability of SAFE approach for composite plates, pitch-catch guided wave experiments were conducted on the 1.8-mm unidirectional composite plate used in chapter 3. Five 9-mm circular PWAS disks (Steminc SM412, 9-mm-diameter disks, and 0.5-mm thick) were installed on the front side of the plate in various angular directions (0° , 30° , 45° , 60° , and 90°) to perform guided wave propagation analysis. The distance between R-PWAS and T-PWAS is 100mm. The PWAS network is shown in Figure 82. Five-count tone-burst excitation signal is applied to the T-PWAS at the central frequency of 90 kHz. Figure 83 shows the tuning curves of strain response and displacement response in the 0° and 90° directions for this unidirectional composite plate.

It can be observed that the strain and displacement responses have obvious differences in the 0° and 90° directions due to the anisotropic behavior of this unidirectional composite plate. The material in the 90° direction is dominated by the polymeric matrix, which is softer, whereas the material behavior in the 0° direction is dominated by the much stiffer fibers. For the strain response of S0 mode in the 0° direction, there is only one peak around 450 kHz, whereas several peaks exist for S0 mode in the 90° direction.

Figure 84 shows the comparisons between the experiment and SAFE prediction in the 0° and 90° directions at 90 kHz excitation. Figure 84 (a) is the comparison result in the 0° direction, a relatively good agreement between the experiment and prediction can be observed for the S0 and A0 modes. In addition, the experimental measurement has some boundary reflections. Similarly, the comparison results in the 90° direction are described in Figure 84 (b). It can be noted that the S0 mode matches well the experiment, whereas A0 mode has a slight difference.

4.2.5.1 Woven Composite Plate

A large number of PWAS disks (Steminc SM412, 9-mm-diameter disks, and 0.5-mm thick) were used for guided wave propagation analysis. The PWAS network bonded on the woven CFRP plate is shown in Figure 85. The specimen under investigation is a plate consisting of a carbon fabric substrate combined with an epoxy resin system. The plate dimension is $350 \times 350 \times 2 \text{ mm}^3$. The plate plies have the orientation $[0/45/45/0]_s$. Three-count tone-burst excitation signal was performed, at a central frequency of 90 kHz, using T-PWAS as actuator and R-PWAS as sensors.

The engineering constants are given in Table 9, and the stiffness matrix $\mathbf{C}$ is given as

$$\mathbf{C} = \begin{bmatrix} 65.7 & 6.4 & 1.0 & 0 & 0 & 0 \\ 6.4 & 68.4 & 2.7 & 0 & 0 & 0 \\ 1.0 & 2.7 & 8.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 5.0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5.0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 5.0 \end{bmatrix} \text{ GPa} \quad (27)$$

Figure 86 shows the tuning curves of strain response and displacement response in the 0° and 45° directions for the 2-mm woven composite plate.

It can be observed that the strain and displacement responses are similar in the 0° and 45° directions due to the quasi-isotropic assumption for this woven composite plate. For the strain response of S0 mode, there is only one peak around 320 kHz, whereas several peaks exist for A0 mode.

Figure 87 shows the comparisons between the experiment and SAFE prediction in the 0° and 90° directions at 90 kHz. Figure 87 (a) is the comparison result in the 0° direction, it can be observed that the S0 and A0 modes match well with the experimental result, while there are some differences in the zone between S0 mode and A0 mode. In addition, the experimental measurement has some boundary reflections. Similarly, the comparison result in the 45° direction is described in Figure 87 (b). It can be noted that both A0 and S0 modes agree well with experimental measurements.

3.2.4 2D guided wave propagation and excitation in composites

Considering an infinite composite plate as shown in Figure 88. To model guided wave propagation in this composite plate, we are going to use the semi-analytical finite element (SAFE) approach in which the guided waves propagate analytically in the r, ϕ directions while in the thickness direction z the domain is being discretized with the finite element method (FEM). The harmonic term $e^{i(\xi_x x + \xi_y y - \omega t)}$ is used to describe the guided wave propagation, where x and y are the wave propagation directions, ξ_x, ξ_y are the corresponding wavenumbers, ω is the angular frequency, and t is the time term.

The far-field approximation of integral is calculated using the stationary phase method [65]. The displacement $\mathbf{u}(r, \phi, \omega)$ calculated at a reasonably far distance from the wave source ($r/h \gg 1$, h is the thickness of the plate) can be expressed as

$$\mathbf{u}(r, \phi, \omega) = -i \sum_{m=1}^M \frac{\xi_m(\theta_m)}{\sqrt{2\pi r b(\theta_m)}} \frac{\mathbf{V}_m^L \mathbf{P}}{\mathbf{V}_m^L \mathbf{B}(\theta_m) \mathbf{V}_m^R} \Phi_m e^{i[r \xi_m(\theta_m) \cos(\theta_m - \phi) + \pi/4]} \quad (28)$$

where

$$\theta_m = \phi + \arctan \frac{\xi'_m(\theta_m)}{\xi_m(\theta_m)} \quad (29)$$

$$b(\theta_m) = [\xi_m''(\theta_m) - \xi_m(\theta_m)] \cos(\theta_m - \phi) - 2\xi_m'(\theta_m) \sin(\theta_m - \phi) \quad (30)$$

3.2.4.1 Coupling between PWAS and the Host Structure

PWAS transducers are convenient enablers for generating and receiving guided waves in structures for SHM applications [66]. Figure 89 (a) shows the interaction between the PWAS and the host structure. In this study, a circular PWAS transducer is used as the guided-wave excitation source. The effect of the actuator on the substrate can be accurately represented by shear tractions along the edges of the transducer on the substrate's surface. In the case of ideal bonding, the shear stress in the bonding layer is assumed to be concentrated at the ends and the pin-force model is utilized to represent the PWAS excitation.

To simulate the guided wave propagation due to the excitation by a surface-mounted circular PWAS in composite plates, the component of $\mathbf{P}$ in Eq. (28) should be written as

$$\mathbf{P} = \begin{bmatrix} \mathbf{0} \\ \mathbf{F} \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} -ia\tau_0 J_1(\xi_m a) \cos \theta_m \\ -ia\tau_0 J_1(\xi_m a) \sin \theta_m \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (31)$$

4.3.4.1 Validation in a Unidirectional Composite Plate

In this experiment, the same 1.8-mm thick in-house unidirectional CFRP composite plate with a stacking sequence of $[0]_8$ was examined.

To excite guided waves in the unidirectional composite plate, a circular PWAS (Steminc SM412, 9-mm-diameter disks, and 0.5-mm thick) was bonded on the top surface as the excitation source. A laser vibrometer (Polytec PSV-400-M2) was adopted to measure the out-of-plane velocity of the plate. Thus, a hybrid SLDV-PWAS system was established to measure guided wave propagation. Figure 90 shows the experimental setup of the hybrid SLDV-PWAS measurements. Under electrical excitation, the PWAS generate guided waves in the composite plate. The guided waves propagate with an out-spreading pattern, undergo dispersion, and are finally picked up by SLDV.

Figure 91 shows the SLDV area-scan setup for the measurement of 2D guided wave propagation pattern in the composite plate. The excitation signal is a three-count tone-burst at the central frequency of 90 kHz.

To demonstrate the capability of our SAFE approach, the comparison between the experiment and SAFE prediction is presented in Figure 92. The wave propagation patterns of 90 kHz were plotted. A relatively good match between experimental and predicted wave pattern can be observed. It shows that SAFE prediction can depict the outward spreading wave propagation pattern with spatial dispersion. The elliptical wave propagation patterns match quite well. However, the difference appears in the 90° direction, where the wave amplitude is much more diminished due to material damping. The damping effect will be included in a later chapter using damping model

for composites.

Due to the anisotropic behavior of the composite plate, the elliptical wave propagation pattern can be observed and it is different from the isotropic case which is a circular wave propagation pattern. For the unidirectional composite plate, the material in the 90° direction is dominated by the polymeric matrix, which is softer, whereas the material behavior in the 0° direction is dominated by the fibers which are much stiffer.

3.3 2D GUIDED WAVE PROPAGATION WITH INTERNAL DAMPING IN COMPOSITES

3.3.1 Damping effect on PWAS tuning

There are two commonly used models: Maxwell damping model, where a spring is in series with a dashpot, and Kelvin-Voigt damping model, where a spring is in parallel with a dashpot [67]. In this study, the Kelvin-Voigt damping model based on the frequency-dependent damping coefficient, which is more applicable to the frequency-dependent attenuation of Lamb waves [68] is adopted to investigate the effect of structural damping on the tuning between PWAS and Lamb waves.

The complex Young's modulus E^* at a generic frequency, f , can be obtained by scaling the damping coefficient at the reference frequency f_0 :

$$E^* = E' \left(1 - i\eta_0 \frac{f}{f_0} \right) \quad (32)$$

The Kelvin-Voigt damping model results in a small attenuation below f_0 , and a larger attenuation above f_0 . The complex Young's modulus in Eq. (32) can be used to modify the analytical solutions of tuning by introducing the effect of structural damping.

In the case of viscoelastic fiber reinforced polymer composites, one of the main complexities involved in the use of Lamb waves is the attenuation caused by structural damping. This is essentially due to viscoelastic properties of the fiber and matrix constituents [69] [70]. In this section, damping effects on Lamb-wave tuning for composite plates were investigated.

The pitch-catch Lamb-wave experiments between T-PWAS and R-PWAS on a woven composite plate were conducted to investigate the damping effect on Lamb-wave tuning. The specimen under investigation is a woven carbon fiber reinforced polymer composite plate. The plate dimension is 350×350×2 mm³ and the layup is [0°, 45°, 45°, 0°]_s.

A large number of PWAS transducers (Steminc SM412, 9-mm-diameter, and 0.5 mm thick) were installed on the top surface of the plate, as shown in Figure 94. Three-count tone burst excitation signals were applied to the T-PWAS. The frequency range from 10 kHz to 2000 kHz in steps of 10 kHz was explored. The response signals were collected from the R-PWAS 1, 2, and 3 in the 0° direction and R-PWAS 4 in the 45° direction. The distances between T-PWAS and R-PWAS 1, 4 are 100 mm. The interval of the R-PWAS 1, 2, and 3 is 20 mm. Since Lamb waves have a much stronger attenuation in composite plates, a power amplifier (NF Corporation HSA4014) was used to amplify the excitation signal to 140 Volt peak-to-peak. At each frequency, the wave amplitudes of A0 and S0 modes were extracted using the Hilbert transform to generate the experimental tuning curves.

Experimental Lamb-wave tuning curves of A0 and S0 modes at 100 mm in the 0° direction are shown in Figure 95. A similar pattern can be observed from the 2D tuning curves, where the first maximum of the A0 mode happened at around 80 kHz, at which the amplitude of S0 mode is very small. The first minimum of the A0 mode was found around 210 kHz. At this frequency, the S0 mode amplitude placed on an increasing curve, which means that the S0 signal is dominant. It should be noticed that the S0 maximum happened at 300 kHz. Moreover, it can be noted that the amplitudes at higher frequencies (850 kHz to 2000 kHz) were reduced significantly due to the structural damping of the woven composite plate.

To capture the effect of structural damping, the improved analytical model of 2D tuning was used to predict the theoretical tuning curves. Based on the assumption of quasi-isotropic material for this woven composite plate, the theoretical tuning curves can be calculated using the effective Young's modulus and Poisson's ratio from ref. [71]. This is because the woven composite with the layup is quasi-isotropic, which possesses the same material properties in all the directions. Gresil and Giurgiutiu [71] performed pitch-catch experiments to measure group-velocity curves in different propagation directions (0°, 30°, 45°, 60°, and 90°) on the woven composite plate and found that the quantities were the same in all the directions.

To validate the quasi-isotropic assumption of the woven composite plate, experimental 2D tuning curves obtained from R-PWAS 4 in the 45° direction were compared with the results in the 0° direction, as shown in Figure 96. It can be found that the tuning curves in the two various directions are almost the same. It means that the specimen considered is a quasi-isotropic plate, which possesses the same material properties in all the directions.

To determine the reference frequency f_0 and the damping coefficient η_0 of the Kelvin-Voigt damping model, the same procedure used in section 5.3.1 was employed. Eventually, we found that the most appropriate values for the damping coefficient η_0 and the reference frequency f_0 are 12% and 1.5 MHz, respectively.

The comparisons between experimental and theoretical 2D Lamb-wave tuning curves of A0 and S0 modes are shown in Figure 97. A good match between experimental measurements and theoretical predictions with damping was achieved. It should be noted that the theory also predicts that the S0 maximum would happen at 300 kHz, A0 maximum would happen at 80 kHz, and the rejection of the A0 would occur at 210 kHz; these predictions were validated by the experiments. On the other hand, it can be observed that the damping coefficient of the woven composite plate ($\eta_0 = 12\%$) is larger than that of the aluminum plate ($\eta_0 = 8\%$), which means that the woven composite plate has a much stronger damping effect. It can be concluded that both experiment and prediction demonstrate that the structural damping of the woven composite plate can significantly change the tuning curves, both through peak shifts and through drastic diminishing of the amplitude at higher frequencies.

3.3.2 Damping effect on 2D wave propagation in composite

3.3.2.1 Damping Models for Composite Materials

In the theoretical SAFE formulation, the stiffness matrix may be real or complex. For composite materials, damping attenuation of guided waves is caused by the viscoelastic nature of the polymeric matrix and wave scattering from the fibers and matrix inhomogeneities. Damping can be modeled by assuming a complex frequency-dependent stiffness matrix [72]. This section

reviews the linear viscoelastic models that may be used in SAFE approach. Linear viscoelasticity can be modeled by allowing complex components in the material stiffness matrix, i.e.,

$$\tilde{\mathbf{C}} = \mathbf{C}' - i\mathbf{C}'' \quad (33)$$

where $\mathbf{C}'$ is the storage matrix corresponding to the elastic behavior and $\mathbf{C}''$ is the loss matrix corresponding to the dissipative behavior. Two damping models, hysteretic and Kelvin-Voigt, which are well established in ultrasonic NDE, are considered in this study. In the hysteretic damping model, the loss matrix is independent of frequency i.e., $C''_{pq} = \eta_{pq} C'_{pq}$, where $0 \leq \eta_{pq} \leq 1$ is the loss coefficient. Eq. (33) can be written as

$$\tilde{C}_{pq} = (1 - i\eta_{pq}) C'_{pq}, \quad p, q = 1, \dots, 6 \quad (\text{hysteretic damping model}) \quad (34)$$

However, in the Kelvin-Voigt damping model, the loss matrix is frequency-dependent. If a reference frequency f_0 is specified, then the loss matrix at a generic frequency, f , can be scaled as $C''_{pq} = f\eta_{pq} C'_{pq} / f_0$ and Eq. (33) becomes

$$\tilde{C}_{pq} = \left(1 - i \frac{f}{f_0} \eta_{pq} \right) C'_{pq}, \quad p, q = 1, \dots, 6 \quad (\text{Kelvin-Voigt damping model}) \quad (35)$$

It is apparent that, at the reference frequency f_0 , both models predict the same damping attenuation.

In the case of unidirectional composites, the loss coefficient matrix $\boldsymbol{\eta}$ contains only diagonal terms and the damping effects in different directions are decoupled when the lamina orientation coincides with the global coordinates or with the loading axis [73]. Hence, the loss coefficient matrix $\boldsymbol{\eta}$ for unidirectional composites becomes

$$\boldsymbol{\eta} = \begin{bmatrix} \eta_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & \eta_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & \eta_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \eta_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \eta_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \eta_{66} \end{bmatrix} \quad (\text{unidirectional composites}) \quad (36)$$

In general, $\eta_{11} \neq \eta_{22} = \eta_{33}$ (related to dilatational/extensional damping) and $\eta_{44} \neq \eta_{55} = \eta_{66}$ related to distortional/shear damping).

3.3.2.2 Verification of Damping Models Using Literature Data

To verify the damping models, a CFRP composite plate studied in ref. [64] is examined and the corresponding comparisons are made with original results obtained from an analytical model in ref. [64]. The specimen is a 3.6-mm thick plate and the material density is 1560 kg/m³. The storage matrix and loss coefficient matrix are given as

$$\mathbf{C}' = \begin{bmatrix} 86.6 & 9 & 6.4 & 0 & 0 & 0 \\ 9 & 13.5 & 6.8 & 0 & 0 & 0 \\ 6.4 & 6.8 & 14 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.72 & 0 & 0 \\ 0 & 0 & 0 & 0 & 4.06 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4.7 \end{bmatrix} \text{ GPa} \quad (37)$$

$$\boldsymbol{\eta} = \begin{bmatrix} 8.66\% & 3.33\% & 9.37\% & 0 & 0 & 0 \\ 3.33\% & 4.44\% & 3.67\% & 0 & 0 & 0 \\ 9.37\% & 3.67\% & 2\% & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.67\% & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.95\% & 0 \\ 0 & 0 & 0 & 0 & 0 & 5.95\% \end{bmatrix} \quad (38)$$

The hysteretic damping model investigated in reference is utilized to calculate damping attenuation coefficients.

The comparisons between results in ref. [64] and our SAFE predictions for the damping attenuation of S0, SH0, and A0 modes are shown in Figure 98 and Figure 99, respectively. Our predictions are in very good agreement with reference. These polar plots represent the damping attenuation as a function of the phase-velocity direction θ . It can be noted that the material damping effect in the composite plate is anisotropic.

To obtain the results shown in Figure 100, we had to iteratively adjust the loss coefficient matrix of Eq. (36). This adjustment was done through an iterative updating of the loss coefficient components in Eq. (36) while trying to best match the fitted experimental data. Since the material in a unidirectional composite plate is transversely isotropic, the loss coefficient matrix contains only diagonal terms made up of four independent values (η_{11} , $\eta_{22} = \eta_{33}$, η_{44} , and $\eta_{55} = \eta_{66}$). In the iterative updating process, these loss coefficients were initially taken as 1% (recall that loss coefficients in stiff solids are usually small, $\eta_{pq} < 5\%$). These values were then iteratively adjusted to bring the predicted damping attenuation closer to the experimentally measured damping attenuation. This process was done manually. (An automated optimization process could be devised in the future, but this did not make the object of the present investigation.) Eventually, we found the most appropriate values for the Kelvin-Voigt loss coefficient matrix $\boldsymbol{\eta}$ as

$$\boldsymbol{\eta} = \begin{bmatrix} 0.03\% & 0 & 0 & 0 & 0 & 0 \\ 0 & 2.4\% & 0 & 0 & 0 & 0 \\ 0 & 0 & 2.4\% & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.1\% & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.5\% & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.5\% \end{bmatrix}, \quad f_0 = 250\text{kHz} \quad (39)$$

Note that the η_{22} and η_{33} are equal since the material is transversely isotropic. These two elements

are also much larger than η_{11} because the damping in the transverse directions x_2 and x_3 is dominated by the polymeric matrix, which is viscoelastic, whereas the material behavior in the x_1 direction is dominated by the fibers which are much stiffer and much less lossy.

3.3.2.3 Model-experiment Comparison

To demonstrate the improvement of our extended SAFE approach, the comparison between experiment and SAFE prediction with damping effect is presented in Figure 100. Kelvin Voigt damping model using the obtained loss coefficient matrix was utilized to capture the anisotropic damping effect. The wave propagation patterns of 90 kHz in the composite plate were plotted. A good match between experiment and predicted wave pattern can be observed. The elliptical wave propagation patterns match quite well; some small discrepancies still exist along the fiber direction (0° and 180°). This may be due to thickness variation in the composite plate.

The waveform comparison between experiment and prediction at 100 mm away from PWAS in the 0° and 90° directions is shown in Figure 101. In the 0° direction (the fiber direction), strong A0 mode can be observed, while the wave amplitude of S0 mode is very small. On the other hand, in the 90° direction, much stronger S0 amplitude was measured. The S0 and A0 wave packets are clearly separated.

Predicted waveforms by the SAFE approach with Kelvin-Voigt damping model achieved a good agreement with experimental measurements. This shows that the extended SAFE approach can successfully capture the anisotropic damping effects in the composite plate.

4 GUIDED-WAVE DAMAGE INTERACTION IN AEROSPACE COMPOSITES

4.1 HYBRID GLOBAL-LOCAL (HGL) APPROACH

4.1.1 Overview of HGL

Guided wave generation, propagation, damage interaction (scattering, mode conversion), and detection are modeled using the semi-analytical finite element (SAFE) approach, while the wave damage interaction coefficients (WDIC) to describe damage effect are extracted from the harmonic analysis of local small-size FEM models with non-reflective boundaries (NRB) [74]. Figure 102 shows the HGL approach for the simulation of 2D guided wave interaction with damage in composites.

HGL approach couples the global SAFE method with the local small-size FEM solution through WDIC. It combines the virtues of both SAFE and numerical methods: the SAFE approach provides high calculation efficiency, a wide parameter exploration capability, and applicability for isotropic and composite structures, while FEM models have the ability to simulate the damage with complicated geometries.

Figure 103 shows a typical active sensing procedure via the PWAS and scanning laser Doppler vibrometer (SLDV) approach. Under electrical excitation, the PWAS transducer generates guided waves into the host structure. They propagate along the structure, interact with damage, undergo scattering and mode conversion, and are finally picked up by SLDV.

In the predictive framework, the received signal is comprised of two parts: (1) direct incident waves from the PWAS; (2) scattered waves from damage. Thus, damage can be modeled as a

secondary wave source. The total wavefield W_{TOTAL} is the superposition of the incident wavefield W_{IN} and the scattered wavefield W_{SC} from the damage.

$$W_{TOTAL} = W_{IN} + W_{SC} \quad (40)$$

The frequency and direction dependent complex-valued WDIC were utilized to model the scattering and mode conversion phenomena of wave-damage interaction. These WDIC are capable of describing the scattered waves amplitude and phase as a function of frequency and direction.

The notations of WDIC are as follows: two letters are used to describe the interaction phenomena, with the first letter denoting the incident wave mode, and the second letter standing for the resulting wave mode. For instance, SS (symmetric-symmetric) means the incident symmetric waves are scattered as symmetric waves, while SA (symmetric-antisymmetric) means incident symmetric waves are scattered and mode converted into antisymmetric waves. Thus WDIC $C_{SS}(\omega, \theta, \phi)e^{-i\varphi_{SS}(\omega, \theta, \phi)}$ denotes the scattered symmetric mode generated by incident symmetric mode with amplitude ratio $C_{SS}(\omega, \theta, \phi)$ and phase shift $\varphi_{SS}(\omega, \theta, \phi)$. Similarly, $C_{SA}(\omega, \theta, \phi)e^{-i\varphi_{SA}(\omega, \theta, \phi)}$ represents the scattered antisymmetric mode generated by incident symmetric mode with amplitude ratio $C_{SA}(\omega, \theta, \phi)$ and phase shift $\varphi_{SA}(\omega, \theta, \phi)$. ω is the wave component frequency and θ represents the scattering angle with respect to the incident wave direction ϕ . These coefficients are determined by damage features and are calculated from the local small-size FEM harmonic analysis, which will be introduced later.

4.1.2 Methodology and framework

Figure 104 shows the predictive framework flowchart. The computational model was constructed in the frequency domain based on the global SAFE approach for 2D guided wave propagation in the following steps:

STEP 1: Perform Fourier transform of the time-domain excitation signal $V_T(t)$ to obtain the frequency domain excitation spectrum $\tilde{V}_T(\omega)$.

STEP 2: Calculate structural transfer function.

Detailed derivation of 2D guided wave propagation generated by a circular PWAS is given in Ref. [75]

$$u_z^S(\omega, r, \phi)|_{z=d} = -i \sum_{m=1}^M \frac{\xi_m^S(\theta_m^S)}{\sqrt{2\pi r b(\theta_m^S)}} \frac{\mathbf{V}_m^L \mathbf{P}}{\mathbf{V}_m^L \mathbf{B}(\theta_m^S) \mathbf{V}_m^R} \Phi_3 e^{i[r \xi_m^S(\theta_m^S) \cos(\theta_m^S - \phi) + \pi/4]} \quad (41)$$

$$u_z^A(\omega, r, \phi)|_{z=d} = -i \sum_{m=1}^M \frac{\xi_m^A(\theta_m^A)}{\sqrt{2\pi r b(\theta_m^A)}} \frac{\mathbf{V}_m^L \mathbf{P}}{\mathbf{V}_m^L \mathbf{B}(\theta_m^A) \mathbf{V}_m^R} \Phi_3 e^{i[r \xi_m^A(\theta_m^A) \cos(\theta_m^A - \phi) + \pi/4]} \quad (42)$$

where ϕ is the group-velocity direction and r is the distance between the point of interest and PWAS. The superscripts S and A refer to symmetric and antisymmetric guided wave modes. In this study, only the two fundamental modes, S0 and A0, are present.

STEP 3: Multiply the structural transfer function by the frequency-domain excitation signal to obtain the direct incident waves at the sensing location, where the distance R_{IN} from PWAS up to sensing location is used. Similarly, multiply the structural transfer function up to the damage location by the frequency-domain excitation signal to obtain the interrogating waves arriving at the damage, where the distance R_D from PWAS up to the damage location is used.

$$u_{IN}(\omega, R_{IN}, \phi_{IN}) = \tilde{V}_T(\omega) \left(G^S(\omega, R_{IN}, \phi_{IN}) + G^A(\omega, R_{IN}, \phi_{IN}) \right) \quad (43)$$

$$u_D(\omega, R_D, \phi_D) = \tilde{V}_T(\omega) \left(G^S(\omega, R_D, \phi_D) + G^A(\omega, R_D, \phi_D) \right) \quad (44)$$

It can be noticed that the direct incident wavefield is the superposition of S0 and A0 wave modes.

STEP 4: Scattered wave source at the damage location is obtained by modifying incident waves at the damage with the WDIC obtained from local FEM analysis.

$$u_N^S = C_{SS}(\omega, \theta, \phi_D) e^{-i\varphi_{SS}(\omega, \theta, \phi_D)} u_D^S + C_{AS}(\omega, \theta, \phi_D) e^{-i\varphi_{AS}(\omega, \theta, \phi_D)} u_D^A \quad (45)$$

$$u_N^A = C_{SA}(\omega, \theta, \phi_D) e^{-i\varphi_{SA}(\omega, \theta, \phi_D)} u_D^S + C_{AA}(\omega, \theta, \phi_D) e^{-i\varphi_{AA}(\omega, \theta, \phi_D)} u_D^A \quad (46)$$

where u_N^S and u_N^A represent the S0 and A0 damage generated wave sources, respectively. These scattered waves are transferred from damage up to the sensing point. The 2D guided wavefield radiating from a point source takes the following solution [76]:

$$u_r = \sum_{n=1}^{\infty} a_n(z) H_0^{(1)}(\xi_n r) e^{-i\omega t} \quad (47)$$

where $a_n(z)$ is the thickness dependent modeshape of wave mode number n . Since the amplitude relationship between the interrogating waves and the scattered waves is enclosed in the WDIC, the transfer function from the damage up to the sensing point is simply $H_0^{(1)}(R_{SC}\xi)$, where R_{SC} is the distance from the damage up to the sensing location. Thus, the scattered waves arriving at the sensing point can be calculated.

$$u_{SC}^S = u_N^S H_0^{(1)}(R_{SC}\xi^S); \quad u_{SC}^A = u_N^A H_0^{(1)}(R_{SC}\xi^A) \quad (48)$$

STEP 5: The total wavefield at the sensing location is the superposition of the direct incident waves calculated from Eq. (43) and the scattered waves calculated from Eq. (48).

$$u_z^{TOTAL} = u_{IN} + u_{SC} \quad (49)$$

It should be noted that the total wavefield obtained in Eq. (49) is the out-of-plane wave displacement. Since laser vibrometer measures the out-of-plane particle velocity, this displacement needs to be converted into velocity.

STEP 6: The out-of-plane velocity was calculated by differentiating the out-of-plane displacement with respect to time. Through this differentiation, the wave amplitude will be modified by a factor of $-i\omega$ as shown in Eq.(50).

$$u = U_0 e^{-i\omega t}, \quad \frac{\partial u}{\partial t} = \frac{\partial (U_0 e^{-i\omega t})}{\partial t} = -i\omega u \quad (50)$$

Thus, the solution for out-of-plane velocity in frequency domain can be obtained in the following form.

$$\dot{u}_z^{TOTAL}(\omega, R_{IN}, R_D, R_{SC}, \theta, \phi_{IN}, \phi_D) = -i\omega u_z^{TOTAL} \quad (51)$$

STEP 7: Perform inverse Fourier transform to obtain the time-domain sensing signal.

$$\dot{u}_z^{TOTAL}(t, R_{IN}, R_D, R_{SC}, \theta, \phi_{IN}, \phi_D) = IFFT \left[\dot{u}_z^{TOTAL}(\omega, R_{IN}, R_D, R_{SC}, \theta, \phi_{IN}, \phi_D) \right] \quad (52)$$

In this study, we focused our attention on fundamental modes (S0 and A0), which find the widest application in the guided wave based SHM. However, higher-order modes (S1, A1, S2, A2, etc.) and shear horizontal (SH) modes from wave-damage interaction may also exist. The framework can be easily extended to consider these aspects under the same principle.

4.2 LOCAL FEM ANALYSIS TO EXTRACT WAVE-DAMAGE INTERACTION COEFFICIENTS (WDIC)

4.2.1 WDIC extraction methodology

Non-reflective boundaries (NRB) developed in ref. [74][72] can eliminate boundary reflections, and thus allow for simulation of guided wave propagation in an infinite medium with small-size models. This NRB application was employed to analyze harmonic responses, to calculate the steady-state response under sinusoidal loads. NRB are used in the FEM harmonic analysis to simulate continuous harmonic waves that are incident to a region of interest, as well as waves scattering from arbitrary damage. This analysis can be performed for any specific frequency of interest.

The steady-state amplitude and phase information facilitates the extraction of WDIC $C_{AB}(\omega, \theta, \phi) e^{-i\varphi_{AB}(\omega, \theta, \phi)}$. In order to extract WDIC for a certain wave mode, a pair of harmonic analyses needs to be conducted: a pristine case and a damaged case. Since this study focused on fundamental S0 and A0 wave interaction with damage, two pairs of (a total of four) harmonic analyses need to be performed. Figure 105 shows the small-size FEM pair designed for a 2.032-mm thick aluminum plate. Each model is 100-mm long, 100-mm wide, and 2.032-mm thick, with a 30 mm wide NRB covering each boundary. A 6-mm-diameter through-thickness hole is introduced in the damaged plate.

Figure 105 also shows the loading nodes and the sensing nodes. The loading nodes are aligned to create a straight crested harmonic incident wavefield, which is a good approximation when the damage is located far away from the excitation source. In the pristine model, a circle of sensing nodes and one center sensing point are designed to collect the structural harmonic response. The center sensing point records the incident waves arriving at the damage location. In the damaged case, only a circle of sensing nodes, with the same location as the pristine model, are used to collect the response data. The design of the circular positioned sensing nodes allows us to extract

information for all the directions of interest. We imposed wave mode excitation through nodal forces by evaluating integrals of stress modeshape components on the loading nodes. The stress modeshapes were obtained for each calculation frequency. Then, the stress modeshapes were converted to nodal forces through boundary integration on each element along the loading line. The detailed procedure can be found in ref. [77].

A simple through-thickness hole is shown in Figure 105. The geometry is kept simple to ensure consistent FEM and experimental models, but complex enough to represent general wave-damage interaction phenomena, which have many mode conversion possibilities. It should be noted that different types of damage would have different scattering characteristics; this will require a corresponding local damage model for WDIC extraction.

When guided waves arrive at damage, they will be scattered and mode converted. The scattered wavefield, by its nature, can be regarded as the superposition of waves generating from distributed point sources around the damage contour. The constructive or destructive interference among these waves is the cause of scattered wavefield directionality and phase lead or delay. We used frequency and direction dependent complex-valued WDIC to represent the wave scattering phenomena.

Figure 106 shows the schematic of the sensing region from the small-size FEM for the extraction of WDIC. The out-of-plane displacements at the sensing nodes are used. According to Eq.(40), the scattered wavefield can be obtained by the subtraction of the incident waves from the total waves.

$$W_{SC} = W_{TOTAL} - W_{IN} \quad (53)$$

The data of sensing nodes in the pristine model is the incident wavefield, while the data from the damaged model represents the total wavefield containing both incident and scattered waves. Thus, the subtraction of the data between these two models provides the scattered wavefield in all directions. Using Eq. (53) and a transformation from Cartesian to polar coordinate system, we calculated the scattered wave displacements at the top and bottom surface sensing nodes in the out-of-plane direction (u_z^T and u_z^B). We can separate and selectively represent each wave mode as follows:

$$u_{SC}^{S0} = \frac{u_z^T - u_z^B}{2}; \quad u_{SC}^{A0} = \frac{u_z^T + u_z^B}{2} \quad (54)$$

The incident wave arriving at the damage location is recorded by the center sensing point and denoted as u_{IN} . The relationship between the incident wave arriving at the damage and the scattered wave picked up on the sensing boundary can be formulated as:

$$u_{IN}^M e^{-i\varphi_{IN}^M} C_{MN}(\omega, \theta, \phi) e^{-i\varphi_{MN}(\omega, \theta, \phi)} H_0^{(1)}(\xi^N r) = u_{SC}^N(\theta) e^{-i\varphi_{SC}^N(\theta)} \quad (55)$$

where $u_{IN}^M e^{-i\varphi_{IN}^M}$ is the M mode incident wave recorded by the center sensing node with amplitude and phase information; $C_{MN}(\omega, \theta, \phi) e^{-i\varphi_{MN}(\omega, \theta, \phi)}$ is the WDIC, containing mode conversion (M mode to N mode), direction dependency, amplitude ratio, and phase relationship information. The first kind Hankel function of order zero, $H_0^{(1)}(\xi^N r)$, represents the outward propagating 2D wavefield of the resulting scattered wave mode N for the out-of-plane motion [76]. $u_{SC}^N(\theta) e^{-i\varphi_{SC}^N(\theta)}$ is the resulting scattered waves recorded on the sensing circle with scatter angle, amplitude, and

phase information.

The harmonic analysis of the small-size FEM can provide the incident and scattered wave amplitude-phase information in Eq. (55), with $C_{MN}(\omega, \theta, \phi)e^{-i\varphi_{MN}(\omega, \theta, \phi)}$ left as the only unknown term. Upon rearrangement, Eq. (55) becomes

$$C_{MN}(\omega, \theta, \phi)e^{-i\varphi_{MN}(\omega, \theta, \phi)} = \frac{u_{SC}^N(\theta)}{u_{IN}^M} \frac{1}{H_0^{(1)}(\xi^M r)} e^{-\Delta\varphi_{MN}(\theta)}; \quad \Delta\varphi_{MN}(\theta) = \varphi_{SC}^M(\theta) - \varphi_{IN}^N \quad (56)$$

By identification, the amplitude coefficient and phase coefficient can be extracted.

$$C_{MN}(\omega, \theta, \phi) = \left| \frac{u_{SC}^N(\theta)}{u_{IN}^M} \frac{1}{H_0^{(1)}(\xi^N r)} \right| \quad (57)$$

$$\varphi_{MN}(\omega, \theta, \phi) = \Delta\varphi_{MN}(\theta) - \left[\angle \frac{1}{H_0^{(1)}(\xi^N r)} - \angle \frac{1}{H_0^{(1)}(0^+)} \right]$$

4.2.2 WDIC of hole and delamination in unidirectional CFRP

In this section, the harmonic analysis of small-size FE models was extended to extract WDIC for composites. Similarly, a pair of harmonic analyses needs to be conducted: a pristine case and a damaged case. Figure 107 shows the schematic of through hole for a 1.8-mm-thick unidirectional carbon fiber reinforced polymer (CFRP) composite plate with stacking sequences of $[0]_8$. The stiffness matrix $\mathbf{C}$ and material density of the unidirectional prepreg are given by Eq. (58).

$$\mathbf{C} = \begin{bmatrix} 145.3 & 7.2 & 7.2 & 0 & 0 & 0 \\ 7.2 & 15.3 & 7.9 & 0 & 0 & 0 \\ 7.2 & 7.9 & 15.3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5.7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 5.7 \end{bmatrix} \text{ GPa; } \rho = 1640 \text{ kg/m}^3 \quad (58)$$

In this FEM simulation, a 10-mm through hole is introduced in the damaged plate. The dimension of the FE models is 100 mm × 100 mm × 1.8 mm. 3D solid elements (SOLID185) were employed to mesh the composite plate. COMBIN14 spring-damper elements were used to construct the NRB. A Rayleigh damping ($\beta = 3 \times 10^{-8}$) was considered to simulate the damping effect of the composite material. The stiffness proportional damping coefficient β introduces damping proportional to the strain rate, which can be thought of as damping associated with the material itself. Similarly, we imposed wave mode excitation through nodal forces by evaluating integrals of stress modeshape components on the loading nodes. The stress modeshapes were obtained for each calculation frequency using the semi-analytical finite element (SAFE) method.

4.2.2.1 WDIC of Through Hole in the Unidirectional Composite Plate

Figure 108 shows a WDIC example of A0 wave interaction with the through hole at 120 kHz in the unidirectional CFRP composite plate. The first row shows the amplitude coefficients and the second row shows the phase coefficients. It can be observed that the interaction between the incident A0 wave and the through hole only involves scattered A0 wave, no mode conversion can be found for this symmetric through-thickness hole.

The WDIC pattern is symmetric with respect to the 0° direction. The amplitude and phase coefficients are different for each scattering direction, i.e., they are heavily direction-dependent. It can be seen that the scattering energy is mainly concentrated in the fiber directions (0° and 180°). This is due to the anisotropic behavior of the unidirectional composite plate. The material behavior in the 0° and 180° directions are dominated by the fibers, which are much stiffer compared to the polymeric matrix in the transverse directions (90° and 270° directions). Figure 109 shows an example of S0 wave interaction with through hole at 120 kHz in the composite plate. The amplitude and phase coefficients are plotted. Similar scattering without mode conversion and direction-dependency phenomena can be noticed in the coefficient patterns.

Figure 110 shows the WDIC amplitude coefficient of A0 wave interaction with the through hole in the unidirectional composite plate at various frequencies. It can be observed that WDIC are frequency-dependent and the scattering energy mainly travels along the fiber directions in this unidirectional CFRP composite plate at various frequencies.

4.2.3 WDIC of multilayer delaminations in quasi-isotropic CFRP

In this section, the harmonic analysis of small-size FE models was used to extract WDIC of multilayer delaminations in the 3-mm quasi-isotropic composite plate used in chapter 7. A pair of harmonic analyses, a pristine case and a damaged case, was conducted for both one delamination and two delaminations. Figure 111 shows the schematic of the 3-mm-thick quasi-isotropic CFRP composite plate with one delamination and two delaminations. For the case of one delamination in the FEM simulation, a 25-mm delamination is created between plies 20 and 21 by specifying the delamination as two planes, which are defined by the same coordinates but are not tied together. For the case of two delaminations, a 25-mm delamination between plies 20 and 21, and a 20-mm delamination between plies 16 and 17 are generated.

The dimension of the FE models is 100 mm × 100 mm × 3 mm. 3D solid elements (SOLID185) were employed to mesh the composite plate. COMBIN14 spring-damper elements were used to construct the NRB. Similarly, we imposed wave mode excitation through nodal forces by evaluating integrals of stress modeshape components on the loading nodes. The stress modeshapes were obtained for each calculation frequency using the semi-analytical finite element (SAFE) method.

4.2.3.1 WDIC of Multilayer Delaminations in the Quasi-isotropic Composite Plate

Figure 112 (a) shows a WDIC example of A0 wave interaction with one delamination at 120 kHz in the 3-mm quasi-isotropic CFRP composite plate. It can be observed that the interaction between the incident A0 wave and the 25-mm delamination not only involves scattered A0 wave but also involves converted S0 wave. However, the WDIC amplitude of mode converted S0 wave is much smaller than that of scattered A0 wave. The amplitudes are different for each scattering direction.

As a point of interest, the scattering pattern is not symmetric with respect to the 0° direction. This non-symmetric behavior is due to the non-symmetric layup for sub-laminates at the delamination regions.

Figure 112 (b) shows a WDIC example of A0 wave interaction with two delaminations at 120 kHz. It can be observed that the interaction between the incident A0 wave and two delaminations also involves scattered A0 wave and mode converted S0 wave. It should be noted that the WDIC amplitude of scattered A0 wave increases significantly when an additional delamination appears. This is due to trapped waves within the delamination regions. It has been demonstrated that the more delaminations in the composites, the stronger wave energy is trapped. Therefore, the delamination severity can be identified through the WDIC analysis, which is very encouraging. In the case of a pitch-catch damage detection approach, it is likely that the delamination severity can be detected if the sensor is located in the forward direction of the incident wave.

Figure 113 (a) and (b) show the WDIC example of S0 wave interaction with one delamination and two delaminations, respectively. Similar scattering, mode conversion, and direction-dependency phenomena can also be noticed in the WDIC coefficient patterns. It was found that WDIC amplitude of A0 wave is much larger than that of S0 wave even for the case of incident S0 wave.

Figure 114 and Figure 115 show the WDIC amplitude of A0 wave interaction with one and two delaminations at various frequencies. For the case of one delamination, it can be found that the WDIC of scattered A0 wave and mode converted S0 wave is direction and frequency dependent. At low frequency (below 300 kHz), scattered A0 wave is dominant compared to mode converted S0 wave for incident A0 wave. For the case of two delaminations, a similar WDIC pattern was observed. The WDIC amplitude of scattered A0 wave of one delamination is smaller than that of two delaminations at low frequency.

4.3 PREDICTIVE SIMULATION OF SENSOR RESPONSE IN DAMAGED COMPOSITES

4.3.1 GUI development: WFR-COMPOSITES-2D

The predictive tool is a general description of wave generation, propagation, damage interaction, and detection. Parameter exploration is made possible for PWAS size, structure material and thickness, sensor-damage locations, and arbitrary excitations, etc. This framework was coded with MATLAB, and a graphical user interface (GUI) called WFR-2D-Composites was developed. Figure 116 shows the interfaces of WFR-2D-Composites.

Figure 116 (a) shows the WFR-2D-Composites main interface which calculates real-time sensing signals as well as phase-velocity dispersion curves. The parameter control panel allows users to choose the material and layup and modify transmitter-damage-sensing locations. The excitation control panel provides excitation waveform and frequency. Figure 116 (b) shows the scatter information platform for inputting wave-damage interaction coefficients (WDIC). Figure 116 (c) and Figure 116 (d) show the sub-interfaces for loading the WDIC of S0 and A0 incidences. The PWAS properties module allows users to define PWAS geometric and material properties, as shown in Figure 116 (e). The spatial propagation solver, shown in Figure 116 (f), is like a C-scan, which calculates the transient time-space domain wavefield. Thus, the transient spatial wavefield can be obtained at any instance during wave propagation.

Users can visualize wave propagation and interaction with damage easily with the animation functions. Additionally, all the calculation data is available for user analysis with the data saving functions. With this predictive tool, an increase in computation efficiency for large parameter space exploration can be achieved. It may take tens of hours for commercial finite element software to run a full-scale simulation for an accurate solution of a high frequency, short wavelength, and long-distance wave propagation problem, but it may take only several minutes to obtain the same solution with the WFR-2D-Composites coupling along with two- or three-hours local FEM calculation.

4.3.2 Signal prediction in composites with delaminations

To further verify the WDIC of multilayer delaminations extracted from harmonic analysis, full-scale transient FEM simulation of guided wave propagation and interaction with multilayer delaminations in the 3-mm quasi-isotropic composite plate was conducted.

By extracting simulation signals along a circular line on the composite plate with and without delaminations, the scattered waves generated from the guided wave interaction with the multilayer delaminations can be determined and separated from the incident waves by

$$v_z^S(r, \theta, t) = v_z^D(r, \theta, t) - v_z^P(r, \theta, t) \quad (59)$$

where $v_z^D(r, \theta, t)$ and $v_z^P(r, \theta, t)$ are the FEM out-of-plane velocity of guided waves at location (r, θ) for the composite plate with and without delamination, respectively. $v_z^S(r, \theta, t)$ is the out-of-plane velocity of the scattered waves from the multilayer delaminations. r and θ are the radial and azimuthal coordinates of the cylindrical coordinate system shown in Figure 117.

In the FEM simulation, a finite-footprint pressure excitation which matches the wavelength of the desired wave was used to excited pure A0 mode in the 3-mm quasi-isotropic composite plate to verify the WDIC of incident A0 wave. The excitation signal is a three-count tone burst at the central frequency of 120 kHz. The transient WDIC was obtained by extracting the amplitude at 120 kHz from the frequency spectrum of the scattered signals, which are the differences between pristine signals and damaged signals along a circular line as shown in Figure 118.

For the pristine case in Figure 118 (a), it can be found that a straight crested wavefront was generated because of the line force excitation used in the transient FEM simulation for this CFRP composite plate. At 70 μ s, the boundary reflections were successfully absorbed by NRB and no reflections occurred. Figure 118 (b) and (c) show the guided wave propagation and interaction with one and two delaminations on top and bottom surfaces. For the results on top surface, weak interactions with one and two delaminations were noted after A0 waves interact with the delaminations. This is because the top surface is far away from the delaminations as shown in Figure 118, guided wave interactions with delaminations are very weak. However, a stronger interaction was observed when an additional delamination appeared. For the guided wavefield at the bottom surface, which is close to the delaminations, strong trapped waves in the delamination regions can be clearly observed after A0 waves interact with the delaminations. Previous studies have confirmed the multiple reflections within the delamination region.

Figure 119 presents the waveform and FFT comparison of the scattered waves between one and two delaminations in the forward direction ($\theta = 0^\circ$). It can be found that the scattered wave amplitude increases significantly both in the waveform and frequency spectrum when an additional

delamination appears.

For determining the transient WDIC of multilayer delaminations, the out-of-plane velocities of 180 points at $r = 25\text{ mm}$ and $0^\circ \leq \theta \leq 360^\circ$ with 2° step increments were collected for both the pristine plate and the damaged plate with one and two delaminations. Figure 120 (a) shows the transient WDIC of one and two delaminations obtained from FFT results at 120 kHz, respectively. It can be found that the backward scattering amplitude is generally smaller than the forward scattering amplitude for both one and two delaminations. As a point of interest, a larger forward scattering amplitude was noted when the number of delamination increased from one to two. Therefore, the delamination severity could be separated by comparing the forward scattering amplitude. Figure 120 (b) presents the WDIC obtained from harmonic analysis of small-size local FEM. A good match between transient WDIC and harmonic analysis was achieved, which demonstrated the validity of the WDIC extraction from the harmonic analysis of small-size local FE models.

4.3.2.1 Signal Prediction of Multilayer Delaminations in Composites

In this section, the prediction of scattered signals due to the multilayer delaminations was conducted using HGL approach in the 3-mm quasi-isotropic composite plate.

Figure 121 shows the comparison of scattered signal prediction between one and two delaminations in the 5° direction, which has the maximum WDIC amplitude. It was found that large-size scattered signals were received for both delaminations. The scattered signal amplitude increases when the number of delamination increases from one to two. This is consistent with the predicted WDIC pattern. Therefore, it is likely that the delaminations can be detected and identified if the sensor is located in the forward direction of the incident wave in the case of a pitch-catch damage detection approach.

Figure 122 shows the comparison of scattered signal prediction between one delamination and two delaminations in the 90° direction, which is perpendicular to the incident wave. It can be found that weak scattered signals were received for both one and two delaminations. This is because the WDIC amplitudes in the direction perpendicular to the incident wave have relatively small amplitudes. It is unlikely that the delamination can be detected if the sensor is located along these directions in a pitch-catch method.

4.4 ABT PURE-MODE EXCITATION THEORY

Angle beam transducers (ABT) and wedges are generally used to generate and receive single-mode guided waves with specified mode-frequency combinations. In a practical application, the selection of a single-mode guided wave can be realized by using angle beam transducers and wedges for a selected frequency. Let c_w be the velocity of the pressure waves in the wedge, c is the phase velocity of the desired wave mode at a selected frequency in a thin-wall composite structure. θ is the ABT tuning angle, which is the incident angle of the pressure waves impinging on the structure, as shown in Figure 123. To change the ABT tuning angle θ , an angle-adjustable wedge (ABWX-2001) manufactured by Olympus was typically used, as shown in Figure 124. It allows the user to adjust the tuning angle from 0° to 70° to generate various wave modes.

Angle-beam transducers (ABT) are used in ultrasonic NDE practice to induce guided waves by matching the projected wavelength with the wavelength of the guided-wave mode desired for excitation. The ABT consists of a pressure transducer of central frequency f that can rotate on a

cylindrical surface such that various impingement angles θ can be set as desired (Figure 123a). The ABT is coupled to the structure through a thin layer of water or ultrasonic gel. Thus, the only interaction between the ABT and the structure is through normal pressure applied to the structural surface

The selection of the guided-wave mode desired for excitation is done by modifying the impingement angle θ . Figure 123 c presents the angle-beam excitation principles: the impinging wave is a pressure (P) wave traveling in the wedge with wavespeed c_w . The wavelength λ_w of the wedge P-wave is given by

$$\lambda_w = \frac{c_w}{f} \quad (\text{wavelength of P-wave in the wedge}) \quad (60)$$

By geometric projection arguments (Figure 123c), the wavelength λ of the matching wave in the plate is related to the wavelength λ_w of the P-wave in the wedge by the formula

$$\lambda_w = \lambda \cos(90^\circ - \theta) = \lambda \sin \theta \quad (61)$$

The wavelength λ is expressed in terms of guided-wave wavespeed c and frequency f as

$$\lambda = \frac{c}{f} \quad (\text{wavelength of guided-wave in the plate}) \quad (62)$$

Combining Eqs. (60), (61), (62), one writes

$$c_w = c \sin \theta \quad (63)$$

Solution of Eq. (63) yields the ABT angle θ needed to achieve a desired wavespeed c in the plate as

$$\theta = \sin^{-1}(c_w/c) \quad , \quad c > c_w \quad (64)$$

Recall that the guided-wave wavespeed depends on frequency and mode number m . Thus, the general expression of Eq. (64) would be

$$\theta_m(f) = \sin^{-1} \frac{c_w}{c_m(f)} \quad , \quad m=1, \dots, M_{\max} \quad , \quad c_m(f) > c_w \quad (\text{ABT angle}) \quad (65)$$

Equation (64) shows that the angle θ is the inverse sine of the ratio c_w/c . It is apparent that for θ to exist, the guided-wave wavespeed $c_m(f)$ must be greater than the P-wave wavespeed c_w in the wedge. A typical c_w value for common ABTs is $c_w=2720$ m/s, which may be above the wavespeed of the A0 mode in composites. Thus, ABT may not be able to excite A0 guided waves in composite structures, though they may be able to excite them in some metallic structures.

4.5 ANGLE BEAM DAMAGE DETECTION EXPERIMENTS

4.5.1 SH0 mode and S0 mode for delamination and impact damage detection in 2-mm quasi-isotropic CFRP

A 2-mm thick in-house quasi-isotropic CFRP composite plate with a stacking sequence of [-

45/90/45/0]_{2s} was investigated. The specimen dimension was 500 mm × 500 mm × 2 mm. The simulated delamination was introduced by inserting a Teflon film in the composite plate before curing in a compression-molding 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 1-inch diameter. Figure 125 shows the schematic of the 2-mm quasi-isotropic composite plate with purpose-built delamination.

Ultrasonic nondestructive testing (NDT) was conducted on the composite plate to verify and image the simulated delamination. An ultrasonic immersion tank was used to inspect the specimen. In the experiment, a 10 MHz, 1-inch focused transducer was used to detect the delamination. The scan area is 50 mm × 50 mm. Figure 126 shows the B-scan and C-scan images of NDT results on the top surface. The C-scan image shows the presence of simulated delamination in the composite plate. The depth of the delamination can be observed from the B-scan image, which is 0.5 mm from the bottom surface. From the C-scan image, the size and shape of the delamination can be clearly observed. Therefore, the simulated delamination can be detected and quantified from the NDT detection, which is consistent with the design.

A small coupon was cut from the 2-mm quasi-isotropic composite plate and was used to conduct the impact testing. A drop-weight impact tower was utilized to induce an impact on a fixed composite coupon. In this study, the coupon dimensions were changed from 6" x 4" (ASTM D7136 standard dimension) to 12" x 6". Note that the in-plane dimensions of the coupon were three times the size of ASTM D7136 standard in order to make the panel size more realistic for guided wave propagation. In order to accommodate the larger plate, two rectangular frames were designed and manufactured. They were clamped to the ASTM D7136 fixture to conduct impact tests on the same drop-weight impact tower. The controlled impact event is recorded by a piezoelectric load cell, which can accurately record data of the applied impact force, energy absorbed by the specimen during the impact event.

The details of the impact test are given in Table 10. This table 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 1-inch impact damage size in the 2-mm thick quasi-isotropic composite coupon.

The force-time history and absorbed energy of the impact event are given in Figure 127. The load curve shows peaks at a certain maximum load and is parabolic in shape. When there are irregularities in the parabolic shape of the load curve, this indicates that the specimen has undergone extensive internal damage. The maximum-recorded contact force of this impact event was 3.57 kN. The energy-time plot given in Figure 127 is taken from the force-time curve through the integration of the data. The energy-time plot had better describe the peak energy experienced and energy absorbed by the specimen. Here, the energy absorbed is the difference between the value at the end of the plot and the initial value. The difference between the peak energy observed and the energy absorbed can be used to determine the efficiency of energy absorption by the material. Furthermore, the energy-time history can demonstrate the percentage of impact energy that is absorbed by the specimen to create the irreversible process of damage. It can be found that over 65% of the impact energy is absorbed by the specimen where 1-inch impact damage is formed.

After the impact testing, the ultrasonic NDT inspection was conducted using a 10 MHz, 1-inch

focused transducer. The NDT inspection results are shown in Figure 128. Multiple impact-induced delaminations across the thickness were observed from B-scan results. It can be found that the size of the impact damage obtained is around 1 inch from the C-scan result.

4.5.1.1 Pure Mode Generation Using ABT-ABT

The tuning angle of the 2 mm quasi-isotropic CFRP composite plate was calculated for the pure-mode guided wave generation. The material properties were measured experimentally using the ultrasonic immersion technique, given in Table 7.

Dispersion curves of the 2-mm quasi-isotropic CFRP composite plate were obtained using the SAFE method. For the SAFE approach, 32 one-dimensional (1D) quadratic elements across the thickness direction were used to ensure the convergence of the solution. Phase-velocity dispersion curves of the 2-mm quasi-isotropic CFRP composite plate in the 0° direction are shown in Figure 129 (a).

In this study, the wedge velocity of the adjustable wedge is 2720 m/s and the ABT central frequency is 500 kHz. The theoretical tuning angle was calculated based on Eq. (1), as shown in Figure 129 (b). It can be found that the wave modes cannot be excited when the phase velocities are below c_w . At 500 kHz, S0 mode and SH0 mode can be excited and the ABT tuning angles are around 26° and 49° , respectively. Therefore, the incident angles should be set to 26° and 49° to excite pure S0 mode and SH0 mode in the 2-mm quasi-isotropic CFRP composite plate. In addition, the group-velocity dispersion curves are given in Figure 129 (c), and the group velocities of S0 mode and SH0 mode at 500 kHz are 5.49 mm/ μ s and 3.39 mm/ μ s, respectively. These group velocities will be used to validate the generated guided waves in the composite plate.

First, the adjustable ABT pair was used to generate pure S0 mode in the 2-mm quasi-isotropic CFRP composite plate. For the excitation of pure S0 mode at 500 kHz, the incident angle of the wedge was set to 26° 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. The response signals from the receiver ABT were collected by a digital oscilloscope, which used 100 averages to improve the signal-to-noise ratio.

To validate the excited guided wave, the response signals at five different locations were measured by moving the receiver ABT with a constant interval of 10 mm. The waveforms at various locations are shown in Figure 130 (a). It can be found that strong and nondispersive wave packets were obtained. The time of flight (TOF) of the direct wave packet was determined for each location and plotted as a function of distance from the excitation, as shown in Figure 130 (b). Linear regression was used to estimate the group velocity, yielding a value of 5.43 mm/ μ s, which agrees with the theoretical S0-mode group velocity of 5.49 mm/ μ s at 500 kHz, as shown in Figure 129 (c). Therefore, the excited guided wave in the 2-mm quasi-isotropic CFRP composite plate is pure S0 mode as expected.

Second, the ABT-ABT was used to excite the pure shear horizontal (SH0) wave in the 2-mm quasi-isotropic CFRP composite plate. The incident angles of the wedges were adjusted to the theoretical tuning angle of SH0 mode. For the excitation of pure SH0 mode at 500 kHz, the incident angle of 49° was used 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 pure-mode guided wave, the response signals at five different locations

were measured as shown in Figure 131 (a). It can be found that strong single wave packets were received at all the locations. The TOF of the direct wave packet was determined for each location and plotted as a function of distance, as shown in Figure 131 (b). Similarly, linear regression was used to estimate the group velocity, yielding a value of 3.41 mm/ μ s, which compared favorably with the theoretical SH0-mode group velocity of 3.39 mm/ μ s at 500 kHz. Therefore, the excited guided wave in the 2-mm quasi-isotropic CFRP composite plate is pure SH0 mode as expected. The experimental results demonstrate that although the ABT excitation consists of pressure waves, the SH0 was successfully generated due to the anisotropy of the quasi-isotropic composite layup.

4.5.1.2 Damage Detection Using Multiple Pure-mode Guided Waves

In this section, the pure S0 and SH0 modes generated by the ABT-ABT were utilized to detect the simulated delamination and actual impact damage in the 2-mm quasi-isotropic composite plate. The experimental setup of damage detection was shown in Figure 132. A 100-mm distance was ensured between the transmitter ABT and the receiver ABT using a rigid frame. For the inspection of pure S0 mode at 500 kHz, the incident angle of the wedge was set to 26°, while the incident angle of 49° was used for the excitation of pure SH0 mode. In the experiment, the measurements were conducted by placing the ABT-ABT on the pristine area, delamination, and impact damage, respectively.

The pure S0 mode was used to detect the delamination simulated by Teflon insert and actual impact damage. Signal comparison among pristine, delamination simulated by Teflon insert, and actual impact damage was shown in Figure 133. Strong and non-dispersive wave packets of S0 mode were observed for all the cases, as depicted in Figure 133 (a). A high signal to noise ratio was obtained even in the presence of damage. It can be found that no obvious amplitude change was observed for the case of Teflon insert, whereas a significant amplitude drop was clearly noted due to the presence of impact damage. Similarly, the same phenomena were noted in the frequency spectrum, as shown in Figure 133 (b). Therefore, pure S0 mode is sensitive to the actual impact damage but not sensitive to the delamination simulated by Teflon insert.

Similarly, the pure SH0 mode generated by the adjustable ABT pair was used to detect the delamination simulated by Teflon insert and actual impact damage. Figure 134 shows the signal comparison among pristine, delamination simulated by Teflon insert, and impact damage using pure SH0 mode. Strong wave packets of pure SH0 mode were observed for all three cases. It can be found that large amplitude drops were clearly observed for both Teflon insert and impact damage. Similarly, the amplitude drops were noted in the frequency spectrums. Therefore, the SH0 mode is sensitive to both delamination simulated by Teflon insert and actual impact damage. However, SH0 mode cannot separate the delamination and impact damage since the same amplitude drop was observed for both cases.

To distinguish the damage types, pure S0 mode and SH0 mode have to be used together. Because the pure S0 and SH0 modes are both sensitive to actual impact damage, whereas only pure SH0 mode is sensitive to the delamination simulated by Teflon insert. This is related to the motion characteristics of the respective mode shapes and corresponding wavelengths. Thus, the use of pure S0 and SH0 modes allowed damage separation that was not possible otherwise.

4.5.2 SH0 mode and S0 mode for delamination and impact damage detection in 3-mm quasi-isotropic CFRP

The adjustable ABT pair was used as the transmitter and receiver to generate the pure SH0-mode

guided wave and detect delaminations. A spacing of 100 mm was ensured between transmitter and receiver using a rigid frame, as presented in Figure 135. For the inspection using SH0 mode at 500 kHz, the incident angle of the wedge was set to 48°. A narrow-band three-count tone burst at the central frequency of 500 kHz was used as the excitation signal.

Signal comparison among the pristine and delaminations is shown in Figure 135. It can be found that strong and non-dispersive wave packets were observed in the response signals, as shown in Figure 136 (a). The peak-to-peak amplitude of the SH0 mode response signals are around 220 mV, 150 mV, and 90 mV for the pristine case, one delamination, and two delaminations, respectively. The amplitude drop can be observed due to the presence of delaminations. In addition, the amplitude further decreased when the delamination number increases from one to two. Similarly, amplitude drop can be noted in the frequency spectrum, as shown in Figure 136 (b). Therefore, delaminations simulated by Teflon inserts can be successfully detected using the pure SH0 mode. One and two delaminations were distinguished based on the amplitude information.

To estimate the sizes of the delaminations, a line scanning method was developed by moving the adjustable ABT pair with a step of 3 mm to cover the delaminations, as shown in Figure 137. Error bars were obtained from the data of three repeated experiments to ensure the consistency and accuracy of the experiment. It can be found that a good consistency was achieved, and a significant amplitude drop was observed from the maximum amplitude at various locations. For the comparison between one and two delaminations, a 25% signal loss was observed for the case of one delamination, whereas a 50% signal loss can be noted for the case of two delaminations. Thus, a further amplitude drop was observed when the number of delamination increases. The sizes of both one and two delaminations can be roughly estimated from the maximum amplitude information at various locations, which agrees with the ultrasonic C-scan results.

4.5.3 Quasi-isotropic Composite Plate with Impact Damage

A coupon was cut from the 3-mm quasi-isotropic CFRP composite plate and was used to conduct the impact testing. Then, the pure SH0 mode generated by adjustable ABT was used to detect the impact damage and estimate its size.

4.5.3.1 Impact Testing and Ultrasonic Nondestructive Inspection

A drop-weight tower with low friction guide rails was used to induce collision between a mass of known weight and a fixed composite specimen. In order to conduct the impact testing on a larger specimen, the specimen dimensions were changed from 6" x 4" (standard ASTM dimension) to 12" x 6" (the maximum in-plane dimension of the ASTM D7136 fixture). Two rectangular frames were constructed that can hold the specimen and be clamped to the D7136 fixture to conduct impact tests on the same drop-weight tower. The modified experimental setup is shown in Figure 138. The controlled impact event is recorded by a piezoelectric load cell, which can accurately record data of the applied impact force, energy absorbed by the specimen, and the displacement of the specimen during the impact event.

A 12" x 6" coupon was cut from the 3-mm quasi-isotropic CFRP composite plate and was used to conduct the impact testing. The details of the impact testing are given in Table 11. This table indicates that the coupon was impacted by an impactor mass of 3.06 kg with the potential energy of 17.56 J. This energy was chosen from engineering judgment to try to obtain a 1-inch impact damage size in the 3-mm thick composite coupon.

The force-time history of the impact event is given in Figure 139. The load curve shows peaks at a certain maximum load and is parabolic in shape. The maximum-recorded contact force for this impact event was 5.18 kN. When the load curve is symmetric, its shape indicates that the impact energy is primarily deflected and little or no damage has occurred in the specimen. When there are irregularities in the parabolic shape of the load curve, this indicates that the specimen has undergone extensive internal damage (Sun and Hallett 2017).

After the impact testing, an ultrasonic NDE inspection was conducted using a 10 MHz, 1-inch focused transducer. The NDE inspection results are shown in Figure 140. From the C-scan results, it can be found that the size of the impact damage obtained is around 1 inch. Multiple impact-induced delaminations across the thickness were observed from the B-scan result, as shown in Figure 140 (a).

4.5.3.2 Impact Damage Detection Using Pure SH0 Mode Guided Wave

The adjustable ABT pair was used to generate pure SH0 mode guided wave and detect the impact damage in the 3-mm quasi-isotropic CFRP coupon after impact testing. A spacing of 100 mm was ensured between the transmitter ABT and receiver ABT using a rigid frame, as shown in Figure 141. The incident angle of the wedge was set to 48° for pure SH0 mode excitation at 500 kHz. A three-count tone-burst excitation at the central frequency of 500 kHz was used as the excitation signal.

Signal comparison between the pristine and impact damage is shown in Figure 142. Strong response signals with a high signal-to-noise ratio were observed for both cases showing non-dispersive wave packets, as presented in Figure 142 (a). The peak-to-peak amplitude of the SH0-mode response signals for the pristine and the impact damage are around 220 mV and 160 mV, respectively. The amplitude drop was clearly observed due to the presence of impact damage. Therefore, the impact damage can be successfully detected using the pure SH0 mode generated by the angle beam transducers. Similarly, amplitude drop and a large peak shift were noted from the frequency spectrum, as shown in Figure 142 (b). This is because the impact damage, in the form of matrix cracking, fiber breakage, and interlaminar delamination, will cause a significant reduction in the local stiffness and increase in the local damping. This local stiffness reduction will cause the frequency shift as observed in the experiment. In addition, the large frequency shift is also due to the local damping effect. Because the wave undergoes a frequency-dependent attenuation as it travels, which preferentially absorbs the high-frequency components.

To estimate the size of the impact damage, the line scanning method was used by moving the ABT pair with a step of 3 mm to cover the impact damage, as shown in Figure 143. In the experiment, error bars were obtained from the data of three repeated experiments. It can be noted that a very good consistency result was achieved. Moreover, it can be found that a notable amplitude drop was observed from the maximum amplitude at various locations, as presented in Figure 143. The size of impact damage can be roughly estimated as 25 mm from the amplitude information at various locations, which matches the ultrasonic C-scan results. Therefore, the pure SH0 mode generated by angle beam transducers was successfully used to detect and quantify the impact damage.

4.5.4 SH0 mode for impact damage detection in 4-mm quasi-isotropic CFRP

To effectively transmit and receive the pure SH0 mode at 500 kHz, we first need to use the semi-analytical finite element (SAFE) method to determine the theoretical tuning angles for the ABT

and the PAT for the 4-mm quasi-isotropic CFRP composite coupon. Figure 144 (a) displays the theoretical tuning angle vs. frequency plot for the ABT in which we can clearly see that at a frequency of 500 kHz, the variable angle wedge needs to be set at an angle of approximately 48 degrees to generate the pure SH0 mode in the 4-mm quasi-isotropic coupon using the ABT. From Figure 144 (b), we can observe the incident angle vs. frequency plot for the PAT. We can clearly see that at a frequency of 500 kHz, the PAT can capture the pure SH0 mode at an angle of 39.43 degrees. This information can be used to for experimental validation to see if indeed SH0 mode is being transmitted and received.

Now, keeping the angle of the variable angle wedge at approximately 48 degrees, we can generate the pure SH0 mode in the pristine 4-mm composite coupon. Using the PAT we can receive the signal at various angles ranging from 0 degrees to 70 degrees as can be observed in Figure 145 (a). From this figure, we can see that the maximum amplitude of the signal is at a receiving angle of 39.25 degrees which matches very well with the theoretical value of the receiving angle of the PAT which was 39.43 degrees as displayed in Figure 145 (b). This clearly demonstrates that the pure SH0 mode was generated by the ABT and received by the PAT for the 4-mm quasi-isotropic CFRP composite coupon. The waveform of the receiving signal at 39.25 degrees is displayed in Figure 145 (b) which clearly looks like a pure SH0 mode.

Furthermore, pitch-catch experiments were conducted using the experimental setup displayed in Figure 146 to generate the pure SH0 mode and the signals at different distances were measured using the PAT as displayed in Figure 146 (a). Using the signal envelope and the time-of-flight information, we can plot the time of flight vs. distance plot as displayed in Figure 146 (b). Taking the slope of the time of flight vs. distance plot, we can calculate the experimental group velocity as 3.81 mm/ μ s which matches very well with the theoretical group velocity (3.52 mm/ μ s) of the SH0 mode. In this way we can confirm that we can generate and receive the pure SH0 mode using the ABT-PAT pair in the 4-mm quasi-isotropic CFRP composite coupon.

Once we confirmed that the ABT-PAT transducer pair can be used to generate and receive pure SH0 mode, we conducted the modified ASTM D7136 drop weight impact testing on the 4-mm quasi-isotropic coupon having in-plane dimensions of 12" x 6" as described by the experimental setup shown in Figure 147. A mass, height, and energy combination estimated before from engineering judgment similar to the case of the 3-mm coupon, was used to conduct the drop weight impact testing experiment to produce approximately 1" impact damage in the 4-mm composite coupon.

The immersion tank inspection method as shown in Figure 148 (b) was used to obtain the B-scan and C-scan images from the top surface scan as can be observed in Figure 148. From the B-scan image, the distribution of the impact damage across the thickness of the 4-mm composite coupon can be observed. It can also be observed that the very center of the impact location is undamaged as a clear back wall reflection from the center of the impact location is visible in the B-scan image. From the C-scan image it can be clearly estimated that the impact damage diameter is approximately 1" with the maximum damage occurring in the -45° direction.

Prior to conducting the impact damage experiment, the pitch-catch experiment using the pure SH0 mode was conducted on a pristine area and the signals received by the PAT were recorded. After conducting the impact testing experiment that produces an impact damage size of approximately 1", the same pitch-catch experiment was again conducted – now on the impacted area, for the detection of the impact damage. Figure 149 (a) displays the pure SH0 time-domain signals received

by the PAT for the pristine scenario and the impact damage scenario and Figure 149 (b) displays the frequency spectrum of the waveforms. Upon comparing the measured signals by the PAT and their FFT results, for the pristine scenario and the impact damage scenario, we can clearly see an amplitude drop and slight frequency shift in the signal due to the presence of the 1" impact damage.

Next, if we plot the receiving angle of the PAT vs the amplitude for the pristine scenario and the impact damage scenario as displayed in Figure 150, we can clearly see from the comparison of the signals that there is an amplitude drop in the signal due to the presence of the 1" impact damage. We can also see that due to the presence of the 1" impact damage a new peak at 19.5 degrees has also appeared. This new peak has appeared due to mode conversion.

Now, if we take a closer look at the plot of receiving angle vs. amplitude for the impact damage scenario as displayed in Figure 150 (a), we can see that there is a new peak at 19.5 degrees which is close to the tuning angle of the A1 mode. The theoretical tuning angle of the A1 mode can be observed in Figure 150 (b) as 21.5 degrees. If we look at the time-domain waveform at the 19.5-degree peak, it will look like the signal displayed in Figure 151 (b) which represents a dispersive, mode converted A1 mode. Figure 151 (a) displays the time-domain waveform at 19.5 degrees and Figure 151 (b) displays the FFT of the time-domain waveform.

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5.3 INVENTION DISCLOSURE

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6 SUMMARY AND CONCLUSIONS

The project involved a judicious combination of advance theoretical developments and carefully conducted experiments. The project developed new knowledge in the area of predictive sensing of aerospace composites. The results of this project will enable the development of a methodology and associated instrumentation for the in-situ on-demand evaluation of damage evolution in a critical composite component during the structural health monitoring (SHM) process.

The specimens for damage detection experiments in aerospace composites were fabricated and tested. Controlled impact events in CFRP composite coupons of increasing thicknesses were conducted to produce a specific size of impact damage i.e., 1". The results demonstrate that controlled damage is much easier to be obtained in thin laminates (2–4 mm) compared to thicker laminates (5–6 mm). Simulated delaminations by Teflon inserts were employed in laminated composites as compared to actual impact damage for effective and accurate SHM and NDE validation.

A newly introduced ultrasonic immersion technique was used to estimate the stiffness properties of a composite material without destructive testing. The results demonstrated that the proposed approach yielded a more accurate estimation of CFRP material properties for guided wave prediction. Then, fast and efficient algorithms were developed for predicting with verified accuracy the dispersion curves of phase and group velocities as well as the associated skew angle in multilayered composites. The research results have also been transitioned into practical tools that are being used by other researchers worldwide. A graphical user interface (GUI) predictive code named *LAMSS-COMPOSITES*, has been downloaded by numerous researchers from the US and other countries. For details of this code, see the website <http://www.me.sc.edu/research/lamss/html/software.html>.

To model guided wave excitation in composites, an accurate, efficient, and versatile model based on a semi-analytical finite element (SAFE) approach was developed for excitation of 1D and 2D guided waves in composites. Directionality and damping effect were considered in 2D guided wave propagation in composites. It was found that computational time savings of several orders of magnitude are obtained by using the SAFE approach instead of full-scale multi-physics FEM simulations. For the first time, how material damping affects the tuning between surface-mounted transducers and guided waves in composite structures was clarified and experimentally validated. In this research, intrinsic upper limits exist on the frequency of guided wave excitability in polymeric composites. To perform the scattering analysis, a hybrid global-local (HGL) approach based on global SAFE and local FEM was developed to obtain the predictive simulation of 2D guided wave interaction with damage in composites. A novel method was developed for fast and efficiently predicting the damage scatter polar plots from multiple delaminations in a thick composite structure in which numerous guided wave modes are simultaneously residing. A user-friendly software WFR 2D Composites was developed for wave generation, propagation, damage interaction, which can be used to conduct fast predictive simulation and parametric studies. It was found that the HGL approach achieved remarkable performance in terms of computational accuracy, efficiency, and versatility. Finally, a novel angle beam NDE technique was developed for the rapid detection of different types of manufacturing flaws and operational damage in composite structures over large areas using pure shear horizontal waves. This is the first time when a pressure-wave angle beam transducer was used to excite pure SH0 waves in quasi-isotropic composites, a fact which is not possible in isotropic metals. This method is much more efficient than the point-by-point through-thickness scan used in the conventional C-scan technique because

guided waves can propagate a long distance with less energy loss. Considerable time saving can be achieved while maintaining the ability to evaluate the various composite damage types.

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8 TABLES

Table 1. Impact tests conducted on 2-mm quasi-isotropic coupons

Coupon	Avg. thickness (mm)	Mass (kg)	Height (cm)	Energy (J)	Impact velocity (m/s)	Momentum (Ns)	Damage size (in)	Ei (J)	% of Ei absorbed
B	2.15	3.059	19.512	5.855	1.791	5.478	0.6	4.906	64
C	2.13	3.059	19.512	5.855	1.772	5.420	0.63	4.802	52
D	2.11	3.059	32.194	9.661	2.204	6.740	0.77	7.427	67
E	2.19	3.059	32.194	9.661	2.209	6.757	0.8	7.463	69
F	2.14	3.059	46.828	14.052	2.626	8.034	0.95	10.550	61
G	2.02	3.059	46.828	14.052	2.679	8.193	0.93	10.972	60
H	2.19	3.059	53.462	16.042	2.858	8.743	1.015	12.495	54
I	2.17	3.059	53.462	16.042	2.899	8.866	1.04	12.850	65

Table 2. Impact tests conducted on 4-mm quasi-isotropic coupons

Coupon	Avg. thickness (mm)	Mass (kg)	Height (cm)	Energy (J)	Impact velocity (m/s)	Momentum (Ns)	Damage size (in)	Ei (J)	% of Ei absorbed
A	4.18	3.059	53.462	16.042	2.884	8.822	1.317	12.724	77
B	4.19	3.059	53.462	16.042	2.881	8.811	1.271	12.692	75
C	4.07	3.059	35.121	10.539	2.283	6.984	0	7.9721	58
D	4.14	3.059	35.121	10.539	2.332	7.134	0	8.3188	64
E	4.21	3.059	44.877	13.466	2.575	7.877	0.32	10.142	55
F	4.17	3.059	44.877	13.466	2.739	8.378	0.33	11.474	58
G	4.05	3.059	49.169	14.754	2.815	8.612	0.42	12.122	55
H	4.08	3.059	49.169	14.754	2.787	8.526	1.33	11.882	77
I	4.25	3.059	39.023	11.710	2.423	7.411	0	8.9792	53
J	4.09	3.059	46.828	14.052	2.657	8.126	0.28	10.795	59
K	4.16	3.059	53.462	16.042	2.895	8.855	1.37	12.817	75
L	4.21	3.059	53.462	16.042	2.839	8.683	1.34	12.323	77

Table 3. Impact tests conducted on 6-mm quasi-isotropic coupons

Coupon	Avg. thickness (mm)	Mass (kg)	Height (cm)	Energy (J)	Impact velocity (m/s)	Momentum (Ns)	Damage size (in)	Ei (J)	% of Ei absorbed
Q-6-A	6.29	3.059	53.462	16.042	2.980	9.12	0	13.619	65
Q-6-A	6.29	3.059	78.047	23.419	3.630	11.10	0.25	20.122	61
Q-6-A	6.29	5.406	20.556	10.901	2.060	11.14	0.29	11.530	62
Q-6-A	6.29	5.406	41.112	21.801	2.850	15.41	0.44	21.970	59
Q-6-A	6.29	7.628	14.196	10.622	1.770	13.50	0.48	11.998	61
Q-6-A	6.29	7.628	28.391	21.244	2.470	18.84	1.91	23.323	76
Q-6-B	6.32	3.059	58.535	17.565	3.060	9.36	0	14.350	67
Q-6-B	6.32	7.628	28.391	21.244	2.530	19.30	1.9	24.394	82
Q-6-C	6.28	6.566	24.988	16.095	2.340	15.36	0.3	18.040	57
Q-6-C	6.28	6.566	33.318	21.460	2.660	17.46	1.8	23.191	78
Q-6-D	6.27	5.406	61.668	32.702	3.540	19.14	2.2	33.848	76
Q-6-E	6.18	5.406	51.390	27.251	3.320	17.95	1.88	29.802	82
Q-6-F	6.25	5.406	41.112	21.801	2.870	15.51	1.79	22.356	79

Table 4. Impact tests conducted on 12" x 6", 6-mm quasi-isotropic coupons

Coupon	Avg. thickness (mm)	Mass (kg)	Height (cm)	Energy (J)	Impact velocity (m/s)	Momentum (Ns)	Damage size (in)	Ei (J)	% of Ei absorbed
QL6A	6.23	5.406	41.110	21.802	2.911	15.74	0.095	22.91	52%
QL6A	6.23	5.406	61.666	32.703	3.600	19.46	2.2	35.03	74%
QL6B	6.25	5.406	51.388	27.253	3.322	17.96	0.4	29.82	49%
QL6B	6.25	5.406	56.527	29.978	3.429	18.54	2	31.78	73%
QL6C	6.26	5.406	53.957	28.615	3.402	18.39	0.45	31.28	51%
QL6C	6.26	5.406	55.242	29.297	3.365	18.19	2	30.60	68%
QL6D	6.23	5.406	56.527	29.978	3.430	18.54	0.37	31.79	49%

Table 5 Engineering constants of the prepreg for thick unidirectional CFRP plate.

E_{11}	E_{22}	E_{33}	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}	ρ
171.14 GPa	13.36 GPa	13.36 GPa	0.19	0.19	0.34	6.17 GPa	6.17 GPa	5.0 GPa	1570 kg/m ³

Table 6 Engineering constants of the prepreg for the unidirectional CFRP plate.

E_{11}	E_{22}	E_{33}	ν_{12}	ν_{13}	ν_{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

Table 7 Engineering constants of the unidirectional prepreg.

E_{11}	E_{22}	E_{33}	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}	ρ
153 GPa	8.7 GPa	8.7 GPa	0.37	0.37	0.5	6.9 GPa	6.9 GPa	2.9 GPa	1625 kg/m ³

Table 8 Material properties of 2024-T3 aluminum.

Young's modulus (E)	Poisson's ratio (ν)	Density (ρ)
73.1 GPa	0.33	2780 kg/m ³

Table 9 Engineering elastic properties of the woven CFRP composite plate (Gresil and Giurgiutiu 2015).

E_{11}	E_{22}	E_{33}	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}	ρ
65 GPa	67 GPa	8.6 GPa	0.09	0.09	0.3	5 GPa	5 GPa	5 GPa	1605 kg/m ³

Table 10 Impact testing conducted on a 2-mm quasi-isotropic CFRP coupon.

Mass (kg)	Drop height (cm)	Velocity (m/s)	Energy (J)	% of absorbed Energy
3.06	55.61	3.3	16.69	65

Table 11 Impact testing conducted on the 3-mm thick quasi-isotropic composite coupon.

Mass (kg)	Drop Height (cm)	Velocity (m/s)	Energy (J)
3.06	58.54	3.07	17.56

9 FIGURES

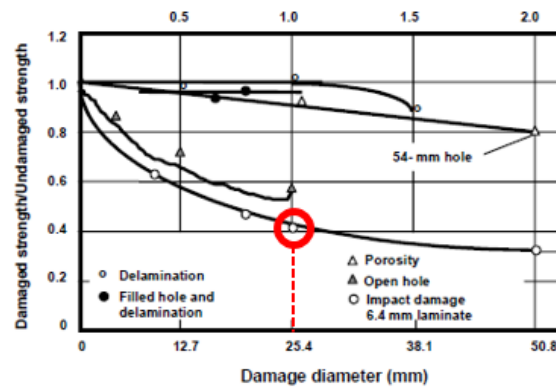


Figure 1. Effect of impact damage diameter on compressive strength of composite [25]

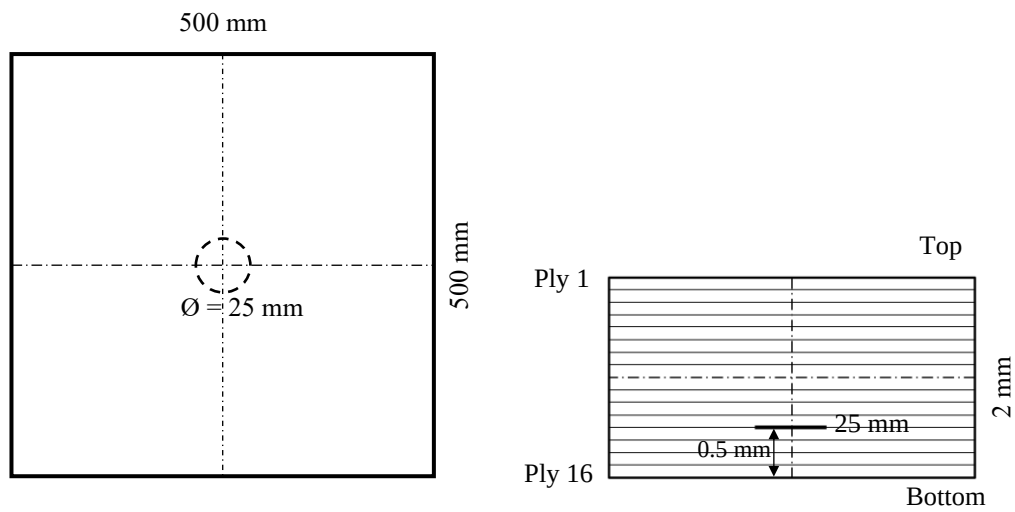


Figure 2. Schematic of 2-mm quasi-isotropic $[-45/90/45/0]_{2s}$ carbon fiber-reinforced polymer (CFRP) composite plate with delamination simulated by Teflon insert.

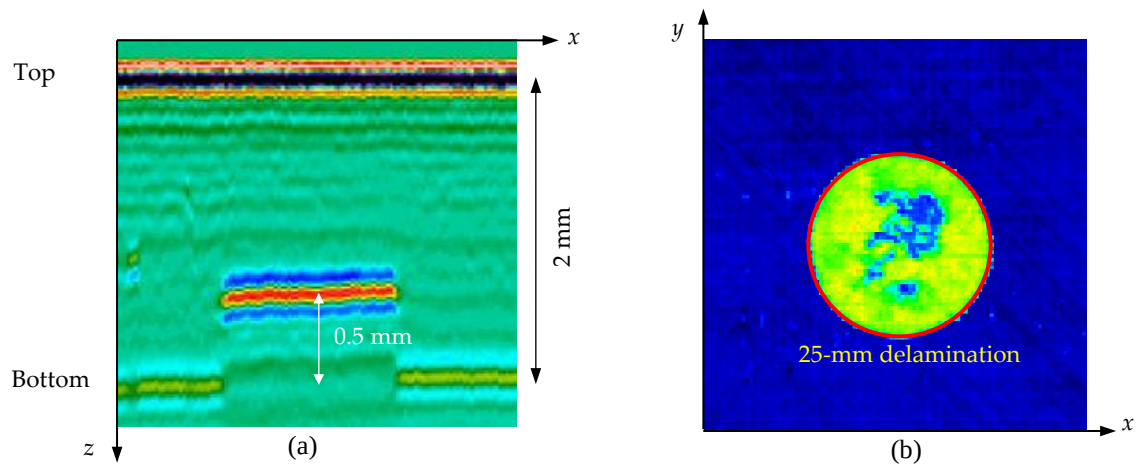


Figure 3. Ultrasonic NDT inspection results showing the delamination simulated by Teflon insert: (a) B-scan image; (b) C-scan image.

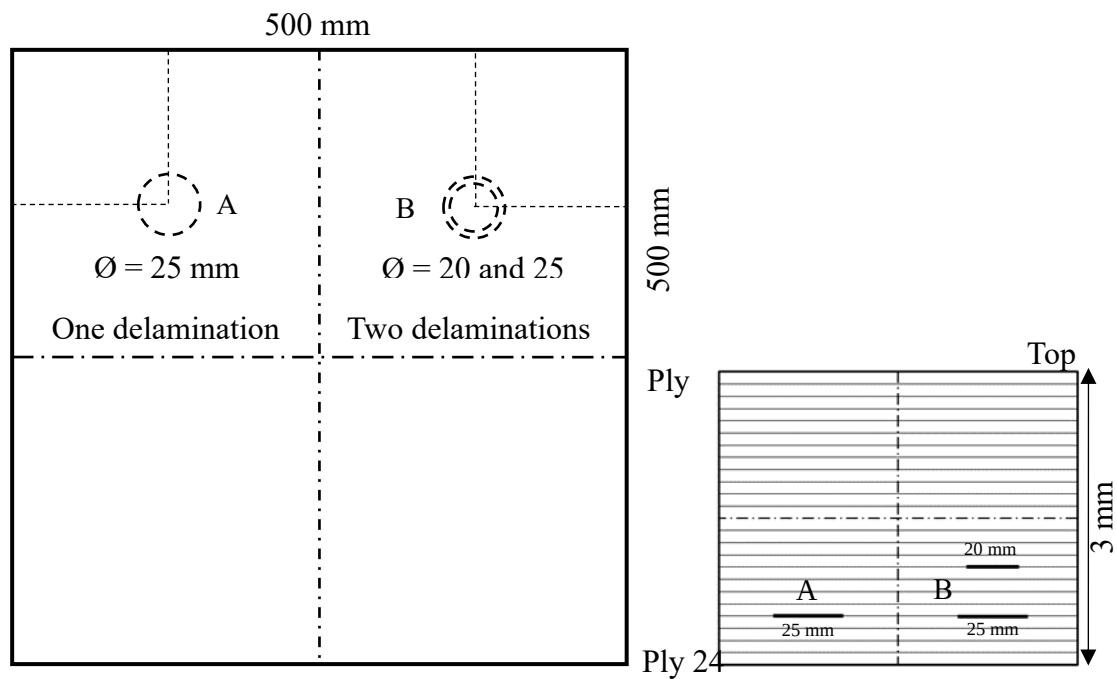


Figure 4. Schematic of 3 mm thick quasi-isotropic $[-45/90/45/0]_{3s}$ carbon fiber-reinforced polymer (CFRP) composite plate with one delamination and two delaminations.

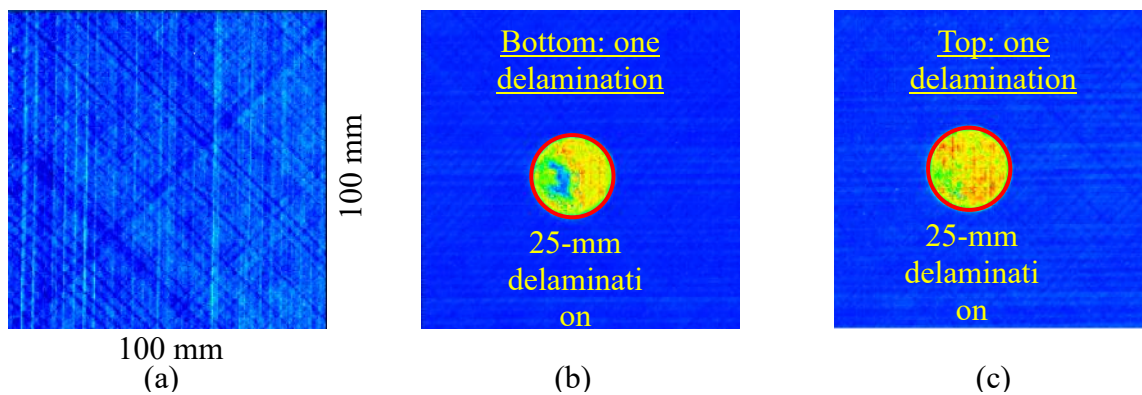


Figure 5. NDT ultrasonic C-scan results: (a) pristine area; (b) bottom scan of one delamination; (c) top scan of one delamination.

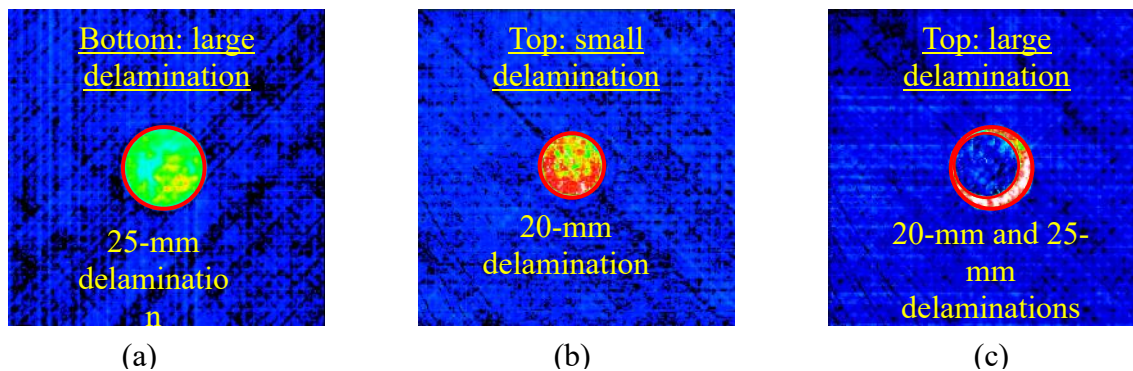
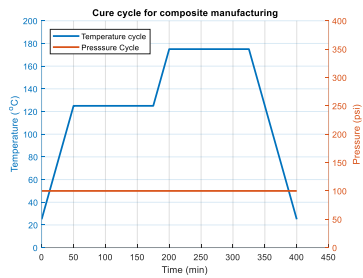


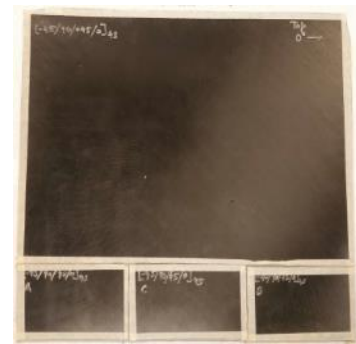
Figure 6 Ultrasonic NDT inspection results of two delaminations: (a) bottom scan showing 25-mm delamination; (b) top scan showing 20-mm delamination; (c) top scan showing 20-mm and 25-mm delaminations.



(a)



(b)



(c)

Figure 7. Manufacturing of quasi-isotropic composite plates: (a) Cure cycle; (b) compression molding machine; (c) Final composite plate with 6" x 4" cut-outs

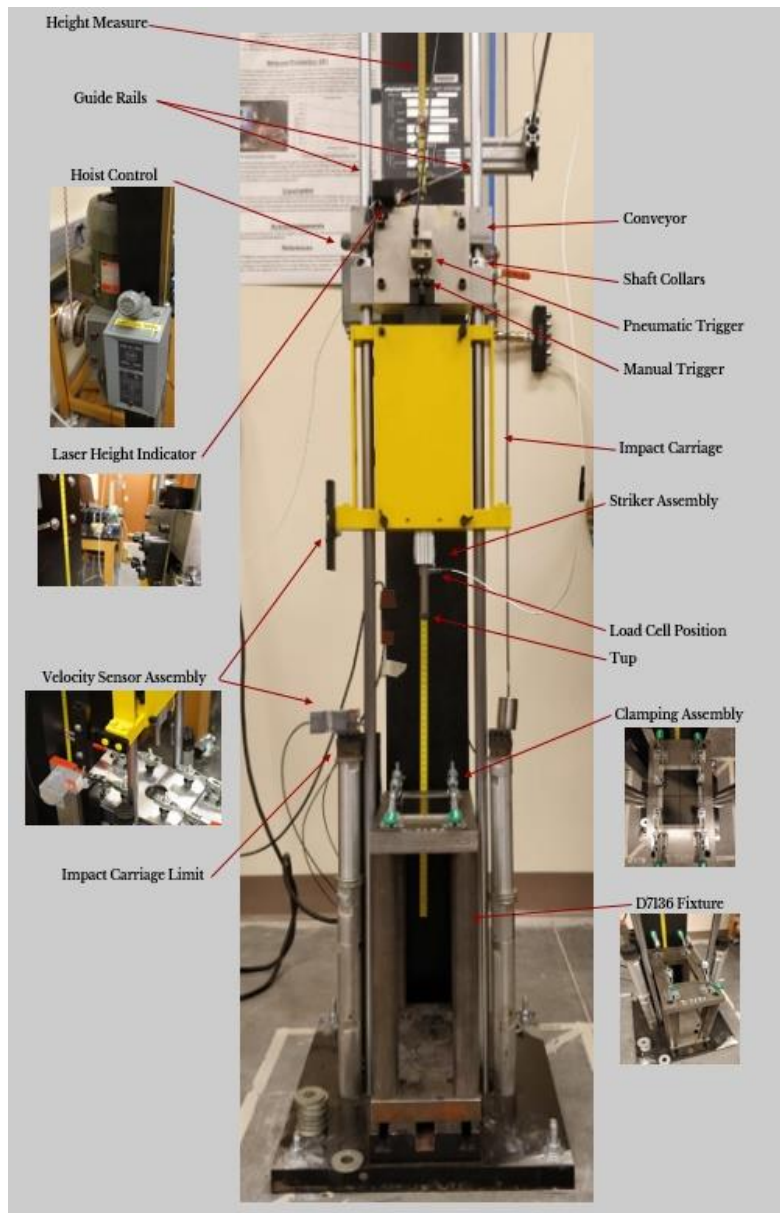
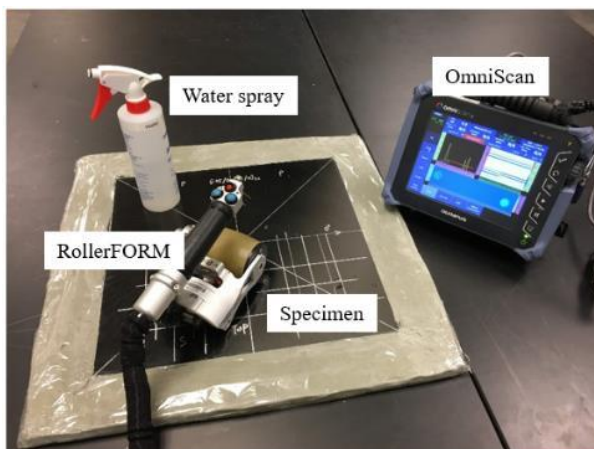
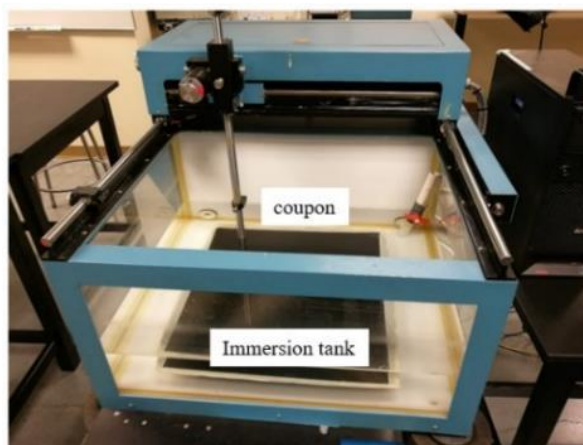


Figure 8. Dynatup 8200 drop weight impact testing machine



(a)



(b)

Figure 9. UT scans were performed using (a) RollerFORM inspection (b) Immersion tank inspection

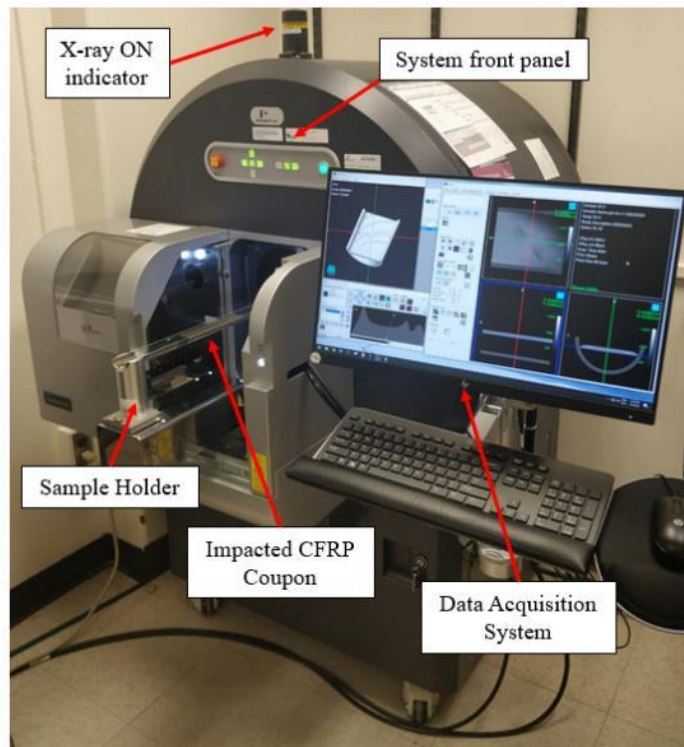


Figure 10. PerkinElmer Quantum GX microCT Imaging System

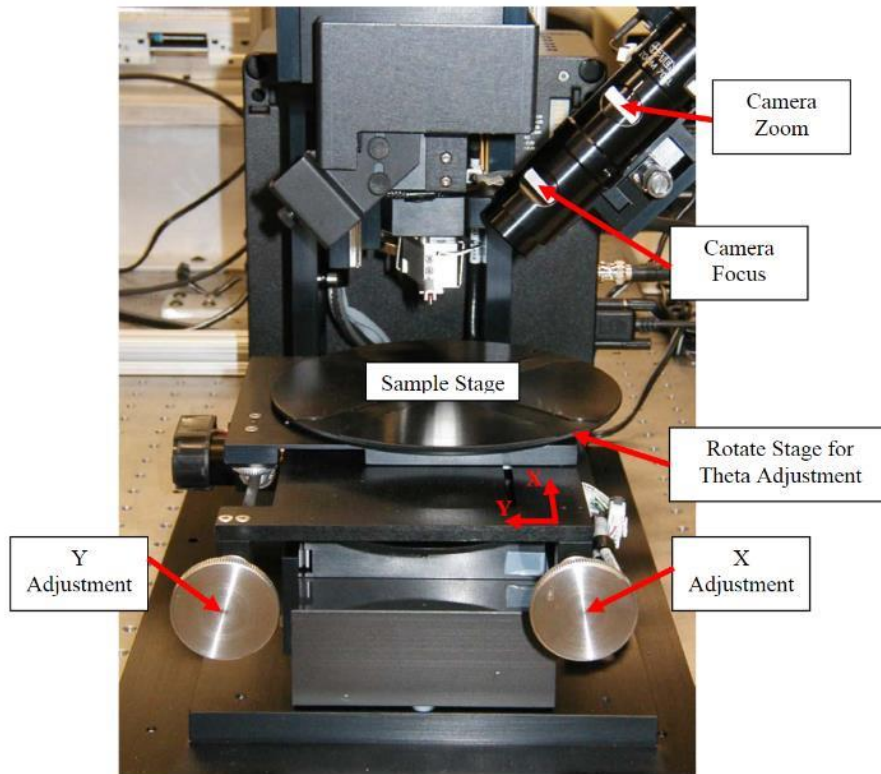


Figure 11. Veeco Dektak 3ST surface profiler

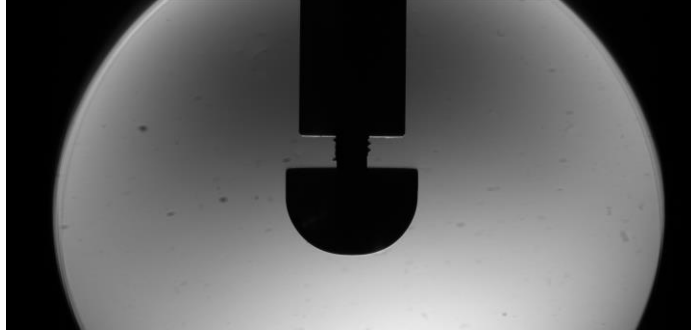


Figure 12. Shadowgraph of the impactor tip

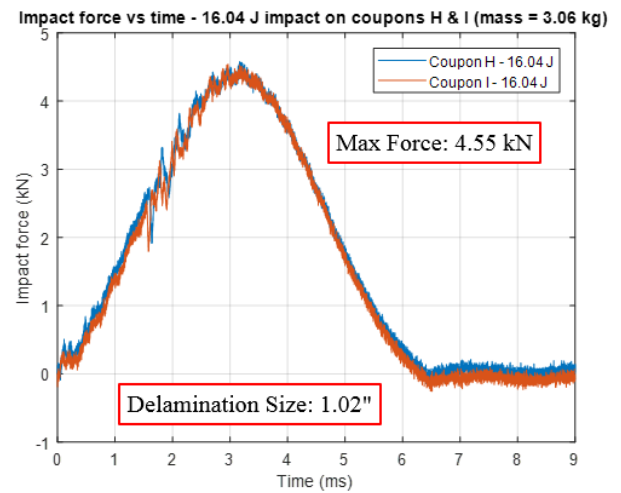
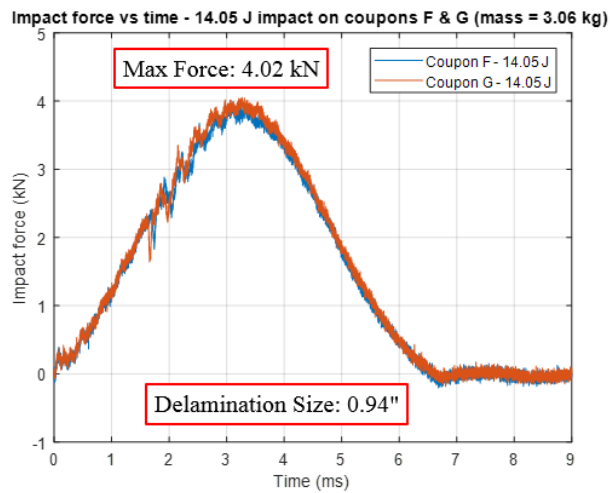
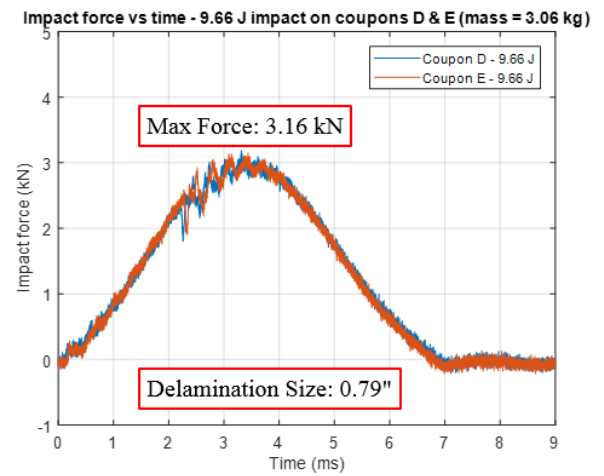
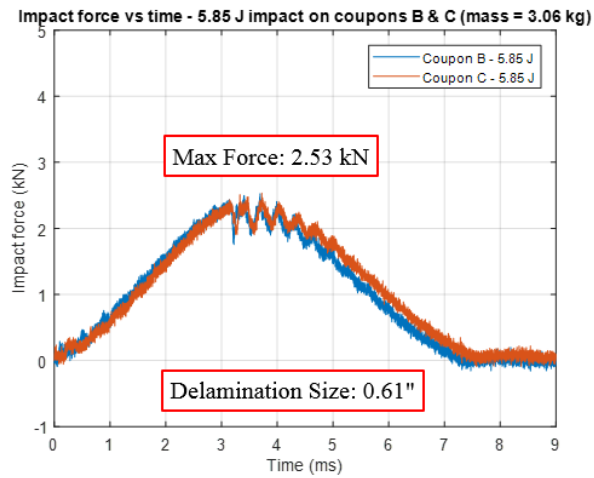


Figure 13. Force-time history of $[-45/90/+45/0]_{2s}$ coupons

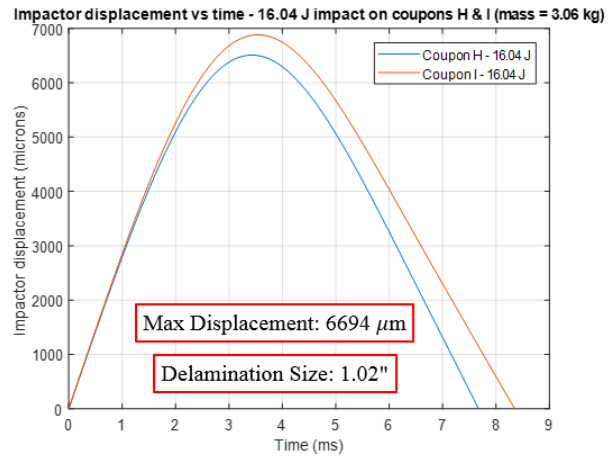
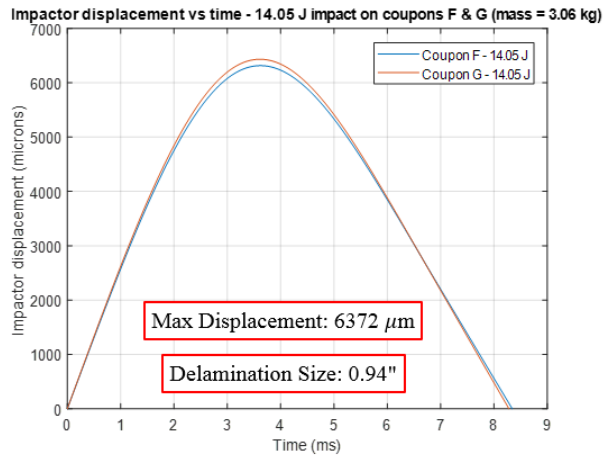
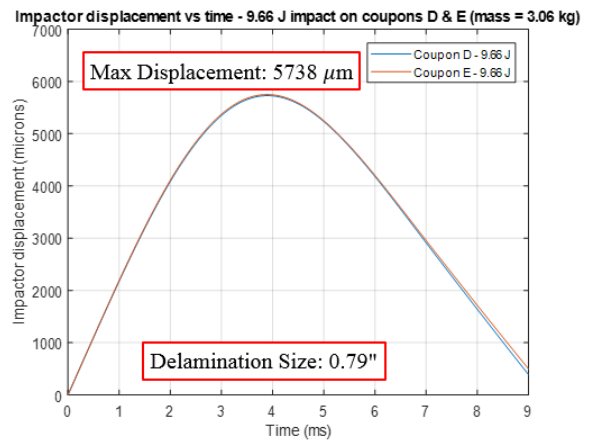
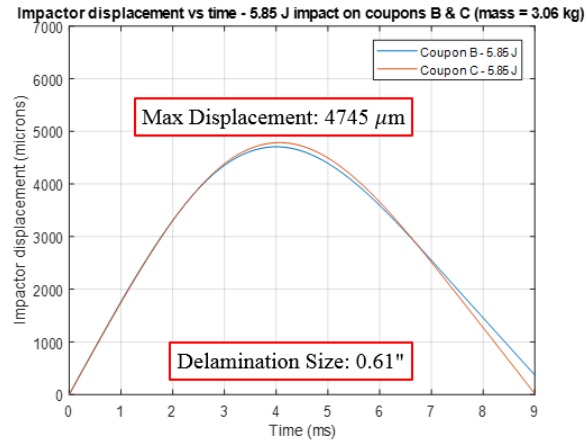


Figure 14. Displacement-time history of $[-45/90/+45/0]_{2s}$ coupons

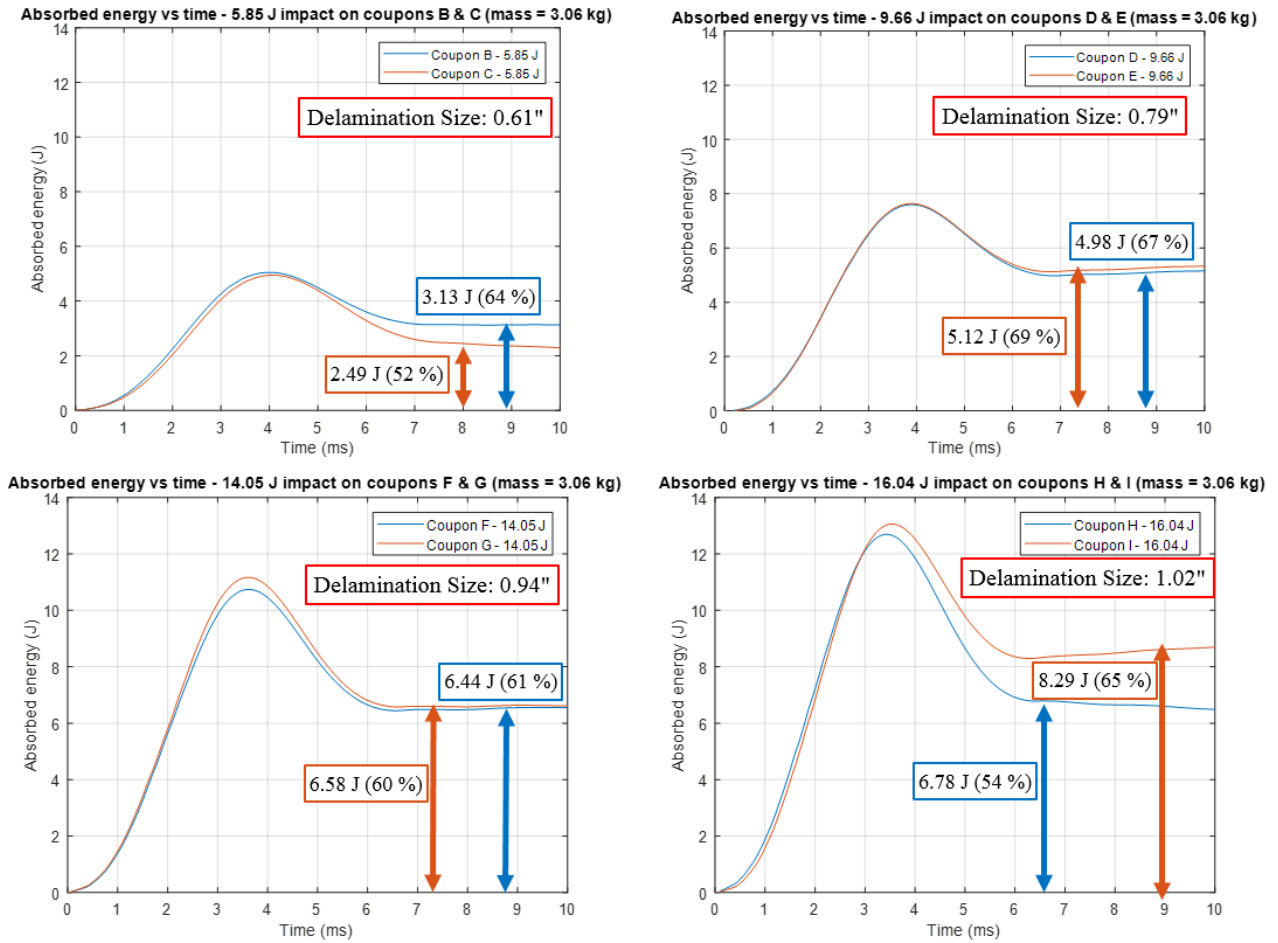
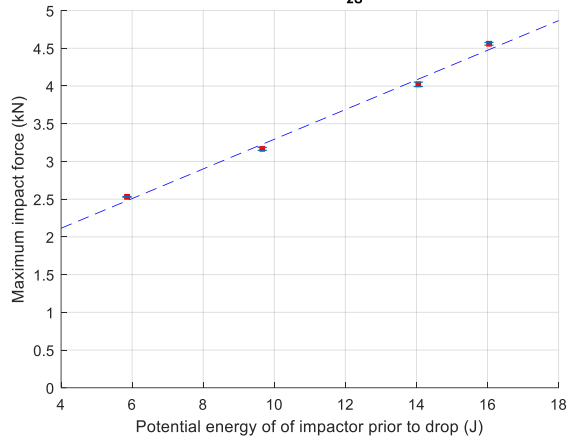
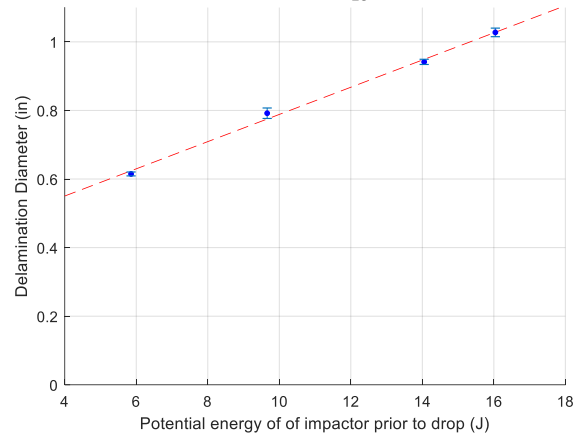


Figure 15. Energy-time history of $[-45/90/+45/0]_{2S}$ coupons

Maximum impact force vs potential energy of impactor (mass = 3.06 kg
for a 2 mm thick [-45/90/45/0]_{2S} CFRP composite



Delamination diameter vs potential energy of impactor (mass = 3.06 kg
for a 2 mm thick [-45/90/45/0]_{2S} CFRP composite



Final absorbed energy vs potential energy of impactor (mass = 3.06 kg)
for a 2 mm thick [-45/90/45/0]_{2S} CFRP composite

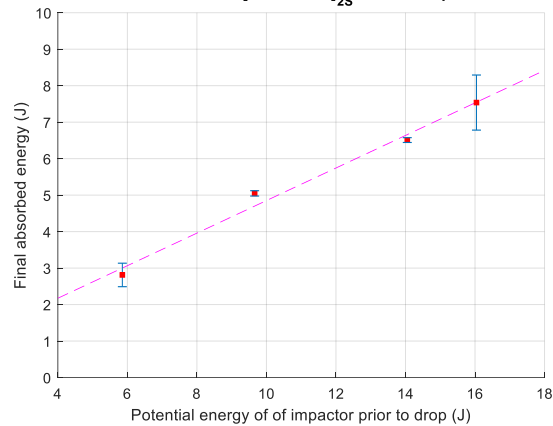


Figure 16. Maximum impact force, delamination size and absorbed energy of [-45/90/+45/0]_{2S} coupons

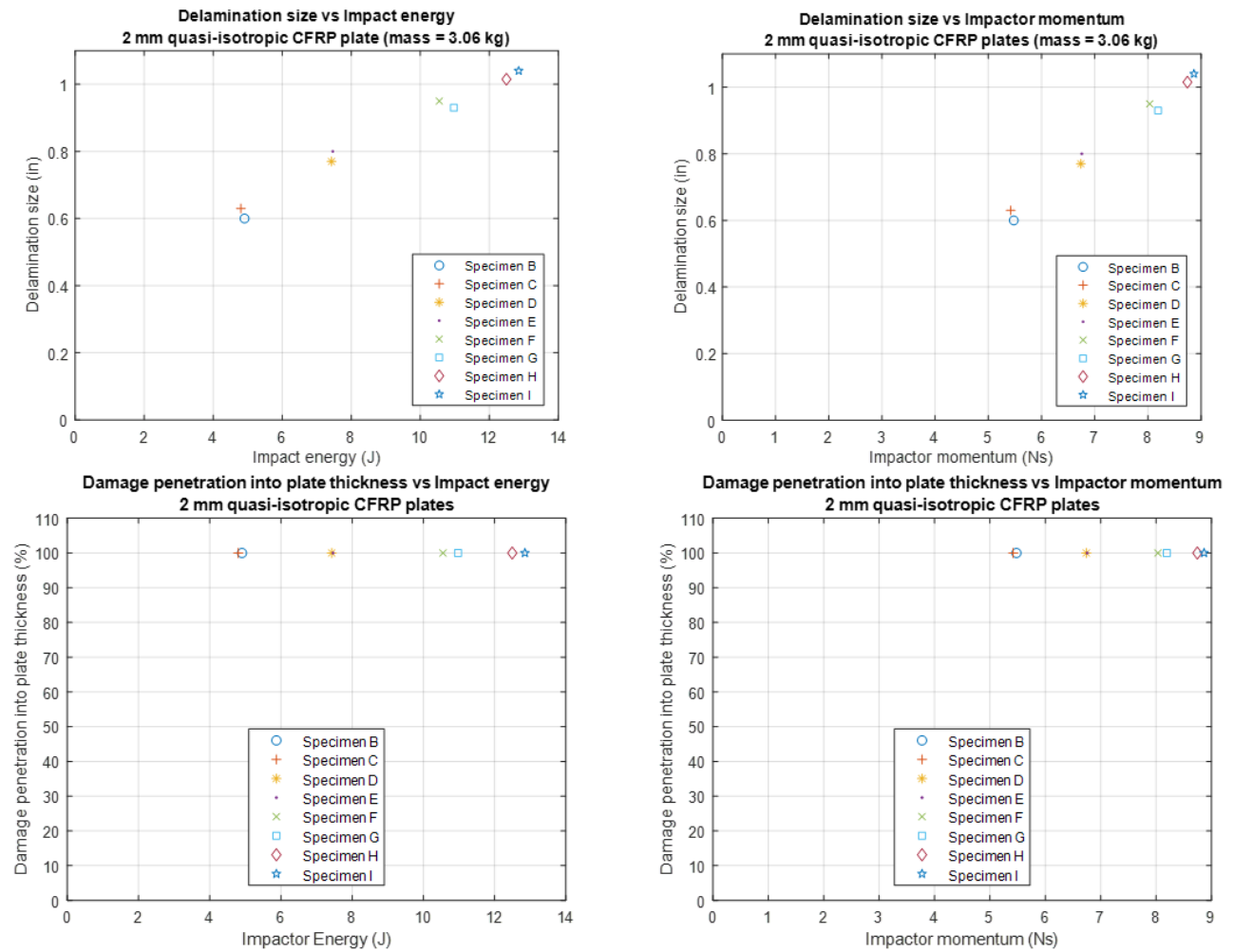


Figure 17. Effect of impact energy and momentum on delamination size in $[-45/90/+45/0]_{2S}$ coupons

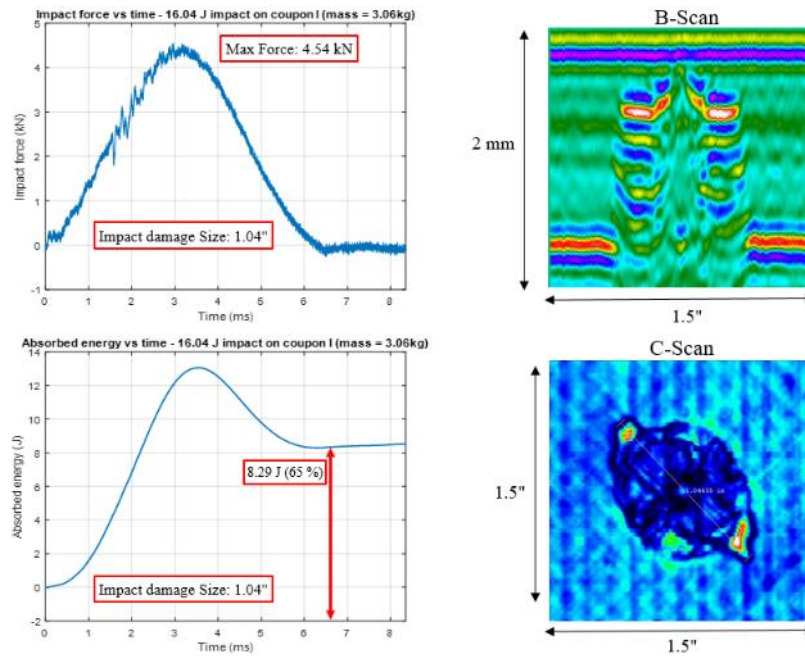
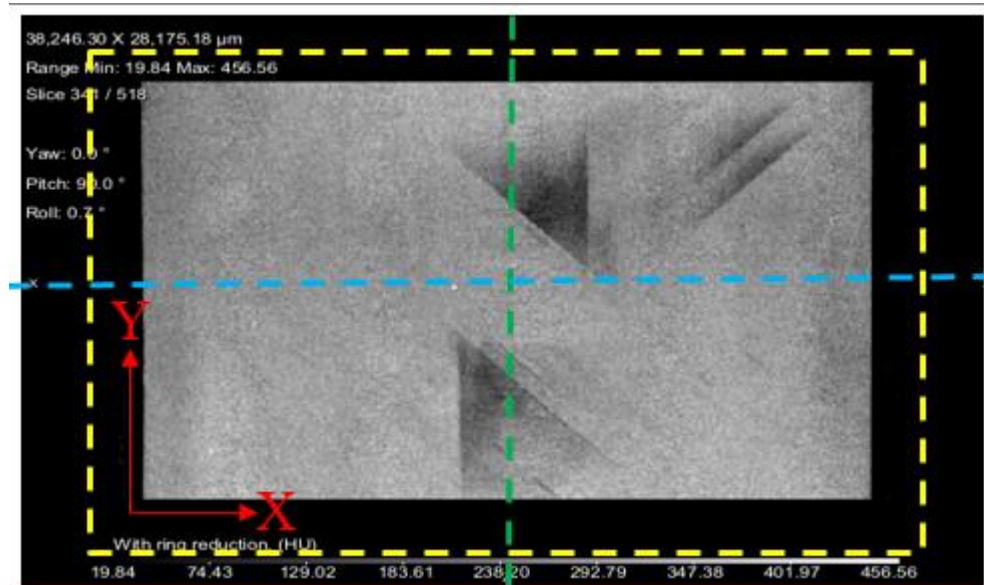
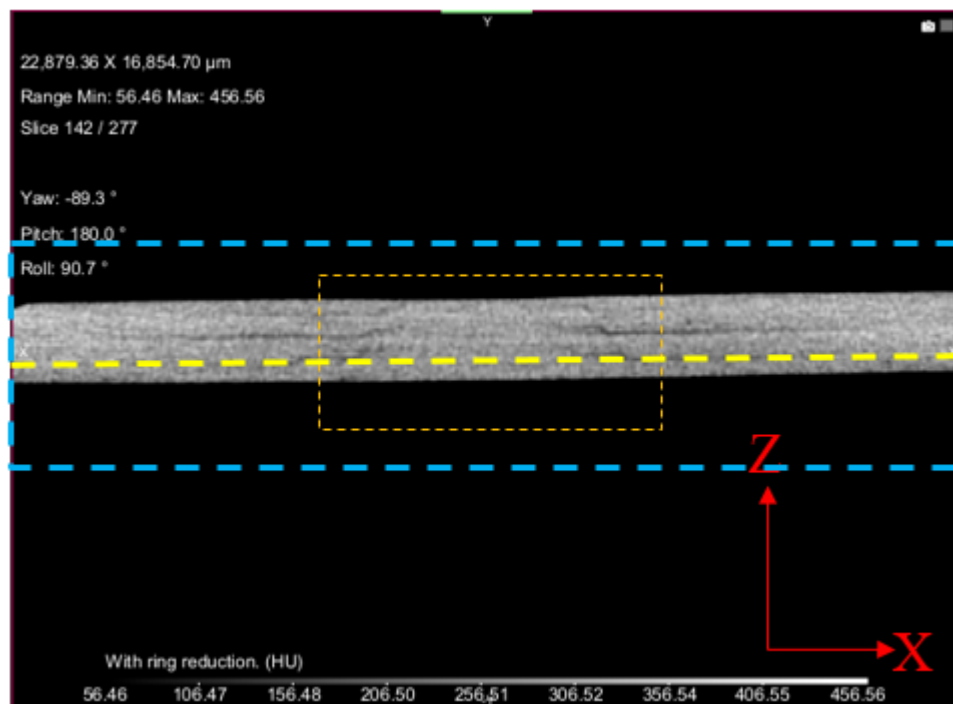


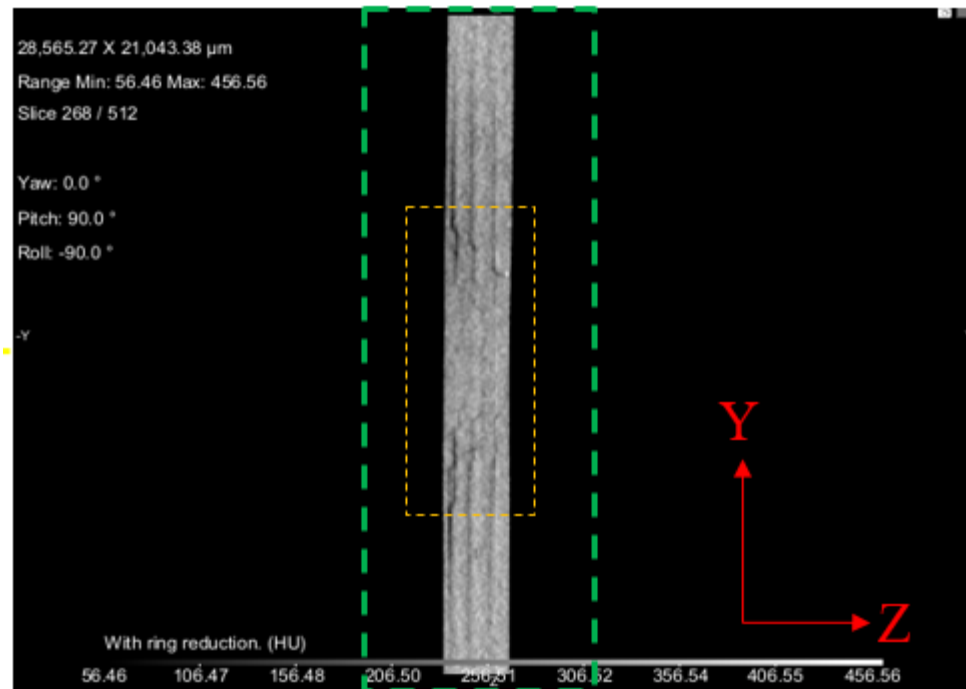
Figure 18. Quad plot of 2-mm coupon with force-history, energy-history, B-scan and C-scan



(a)



(b)



(c)

Figure 19. X-ray micro-CT of 2mm coupon with 1" impact damage

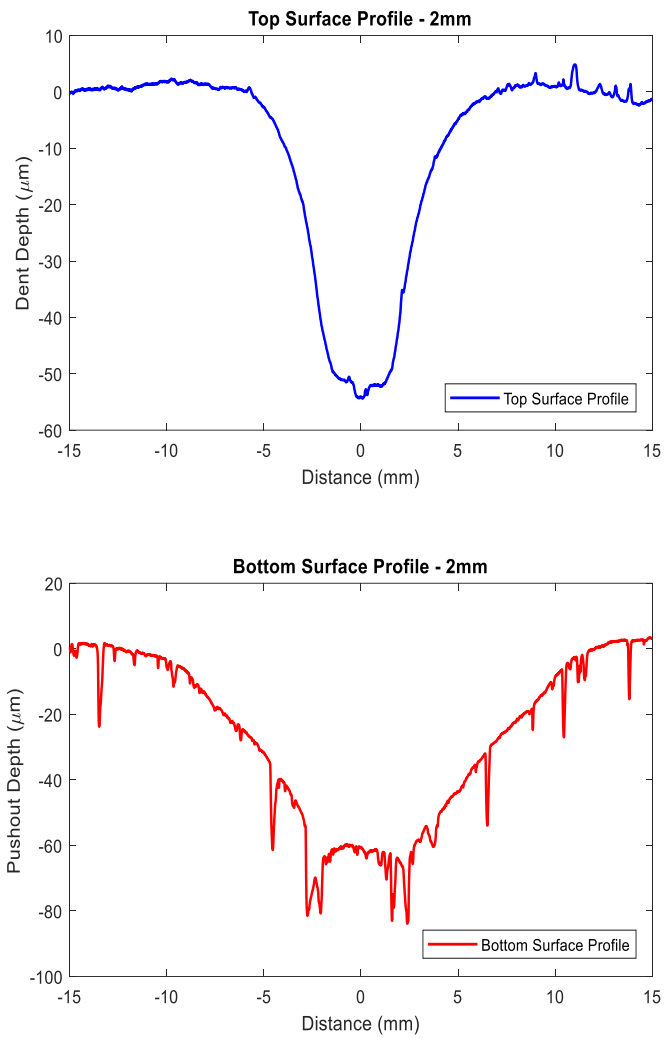


Figure 20. Profilometry scans of 2-mm coupon: (a) Top surface; (b) Bottom surface

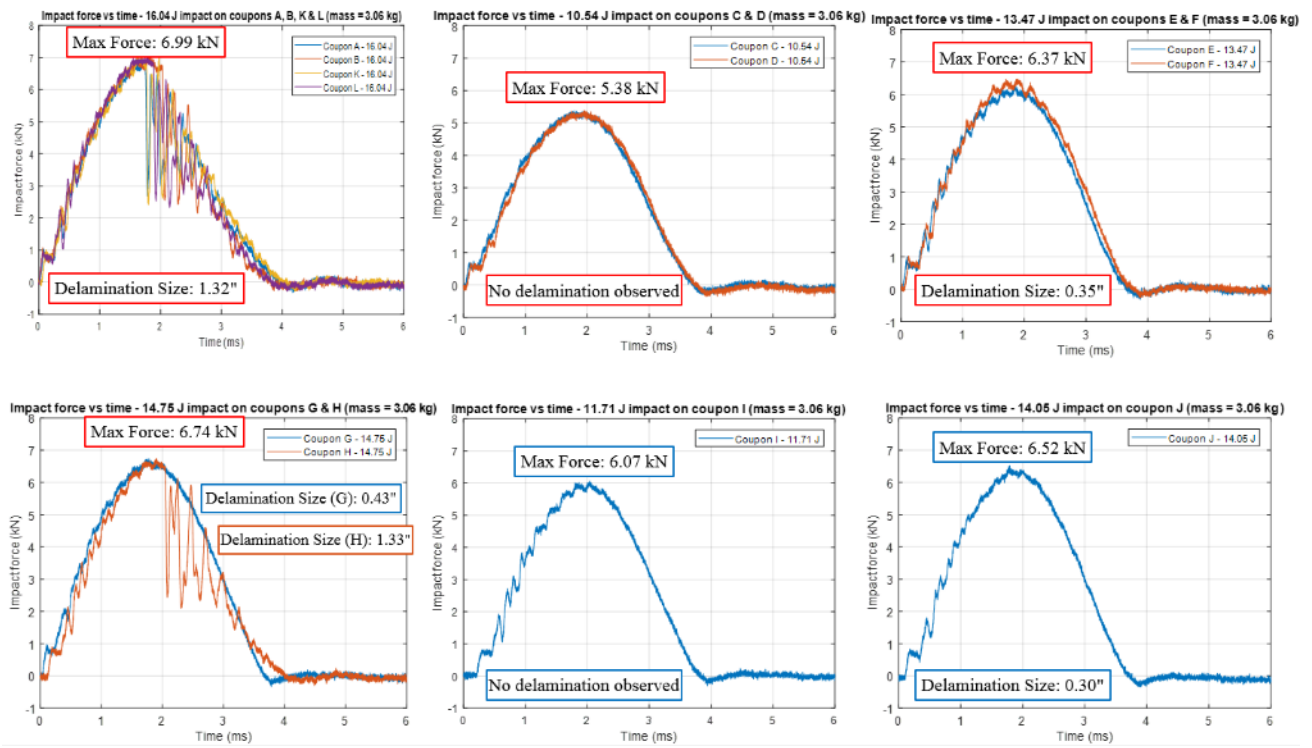


Figure 21. Force-time history of $[-45/90/+45/0]_{4s}$ coupons

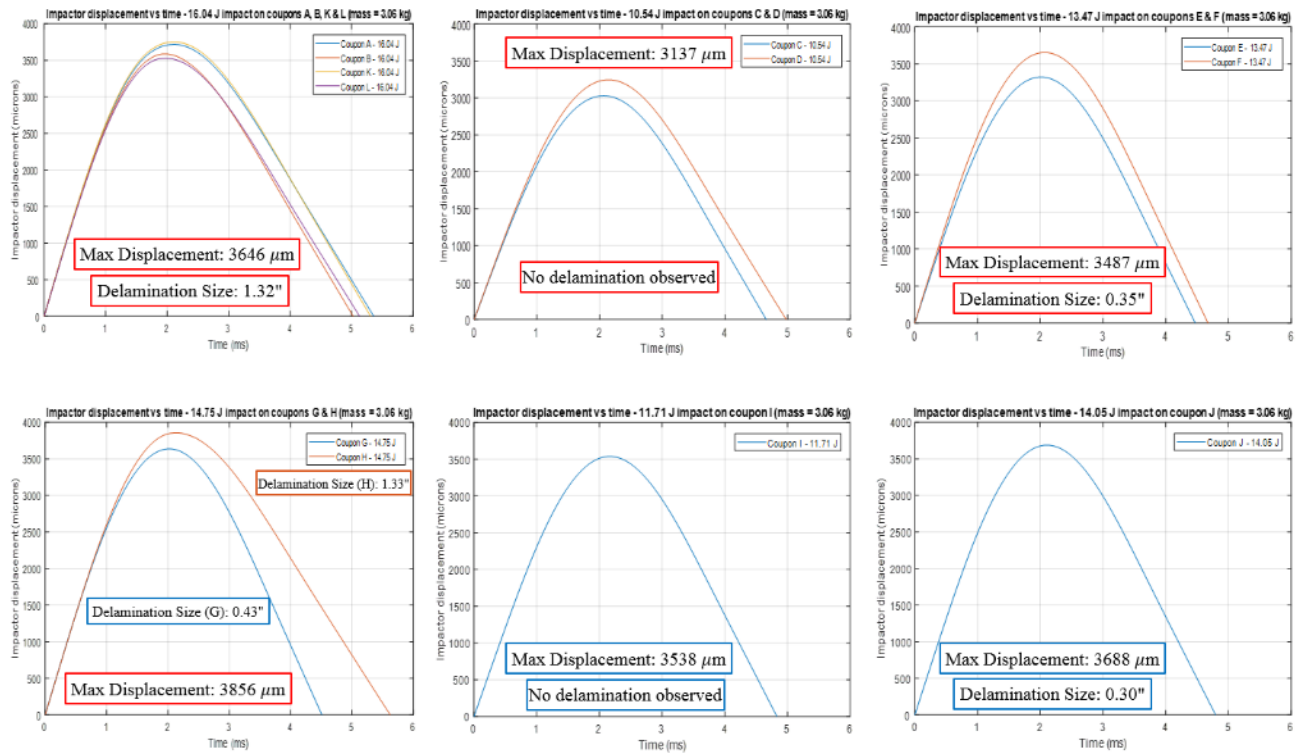


Figure 22. Displacement-time history of $[-45/90/+45/0]_{4S}$ coupons

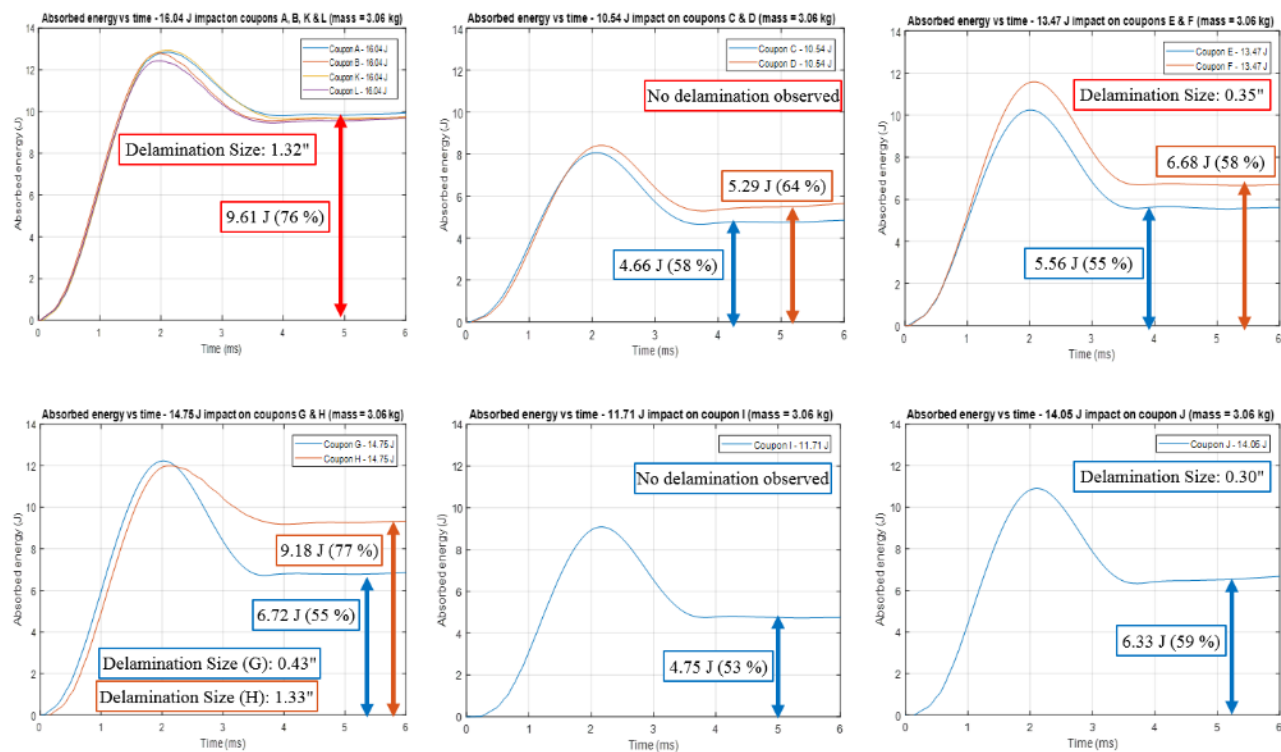
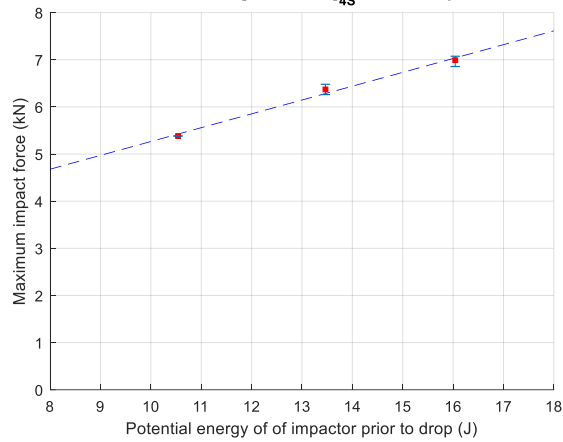
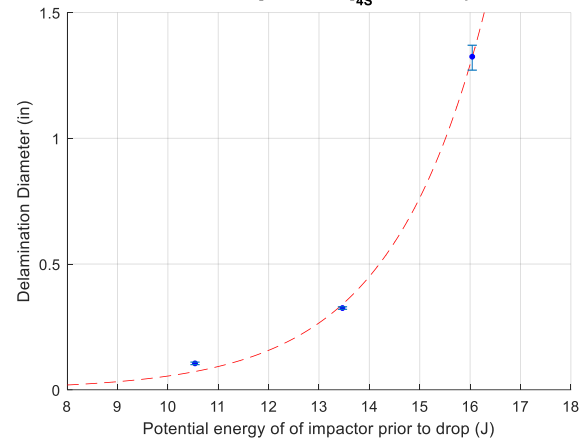


Figure 23. Energy-time history of $[-45/90/+45/0]_{4S}$ coupons

Maximum impact force vs potential energy of impactor (mass = 3.06 kg for a 4 mm thick [-45/90/45/0]_{4S} CFRP composite



Delamination diameter vs potential energy of impactor (mass = 3.06 kg for a 4 mm thick [-45/90/45/0]_{4S} CFRP composite



Final absorbed energy vs potential energy of impactor (mass = 3.06 kg for a 4 mm thick [-45/90/45/0]_{4S} CFRP composite

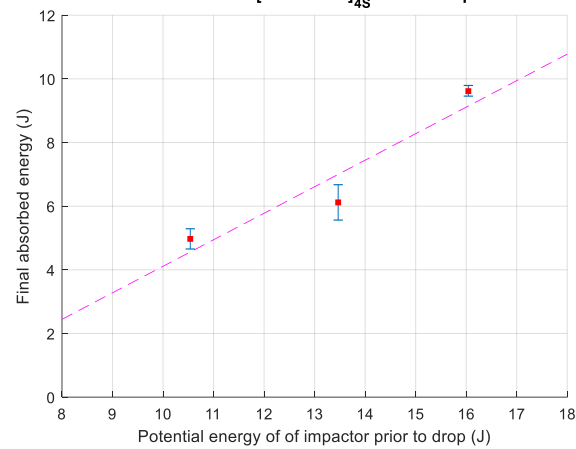


Figure 24. Maximum impact force, delamination size and absorbed energy of [-45/90/+45/0]_{4S} coupons

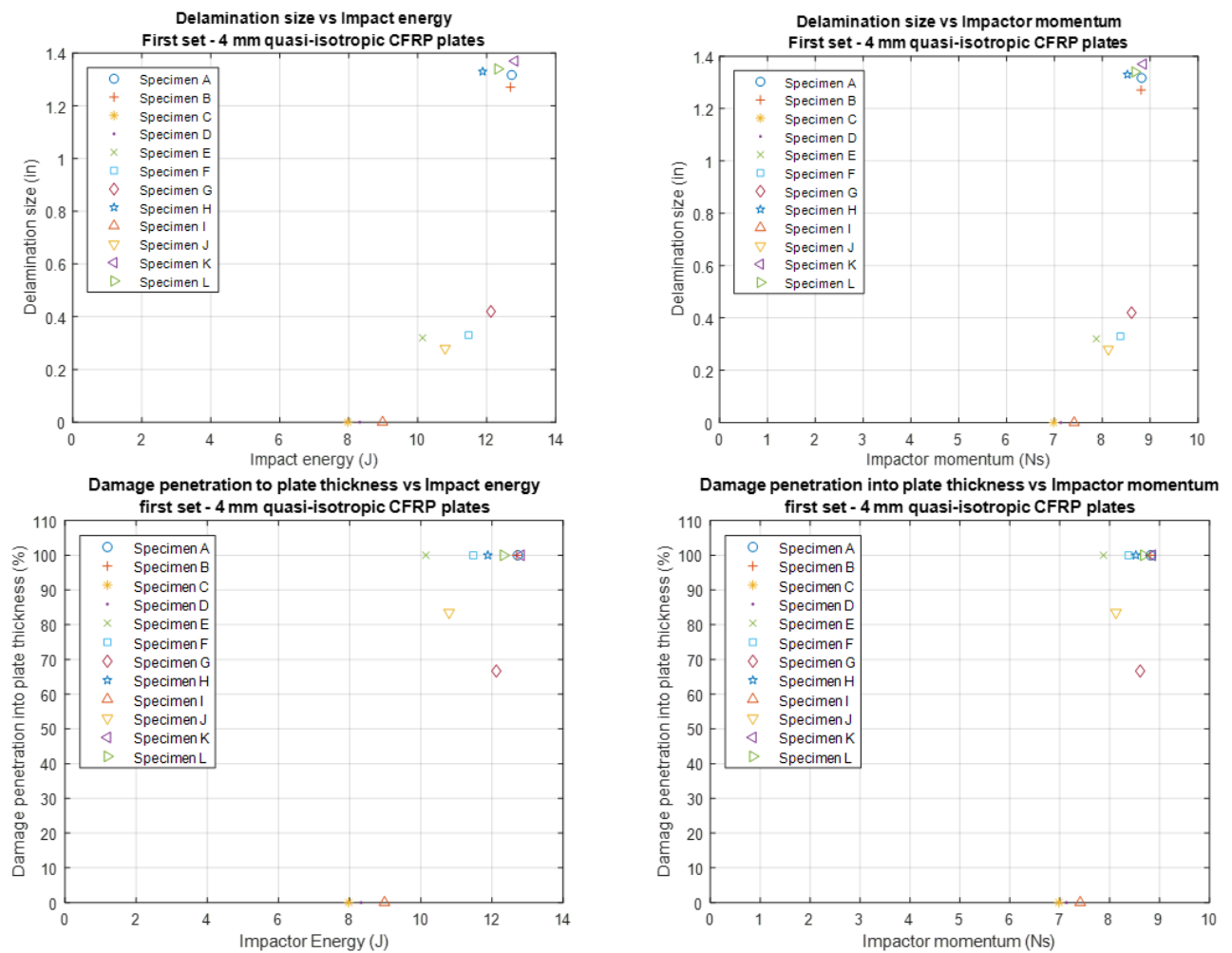


Figure 25. Effect of impact energy and momentum on delamination size in $[-45/90/+45/0]_{4s}$ coupons

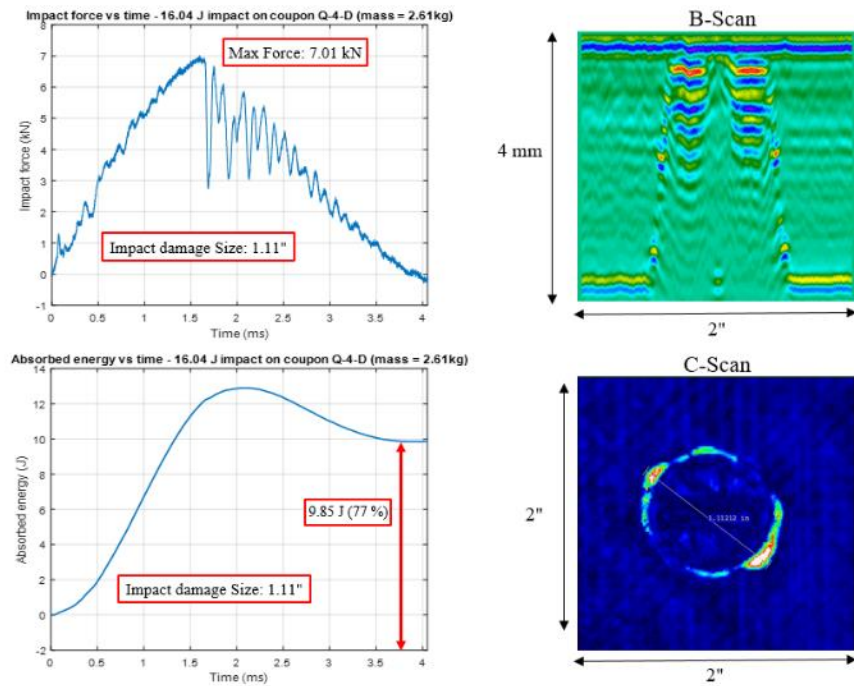
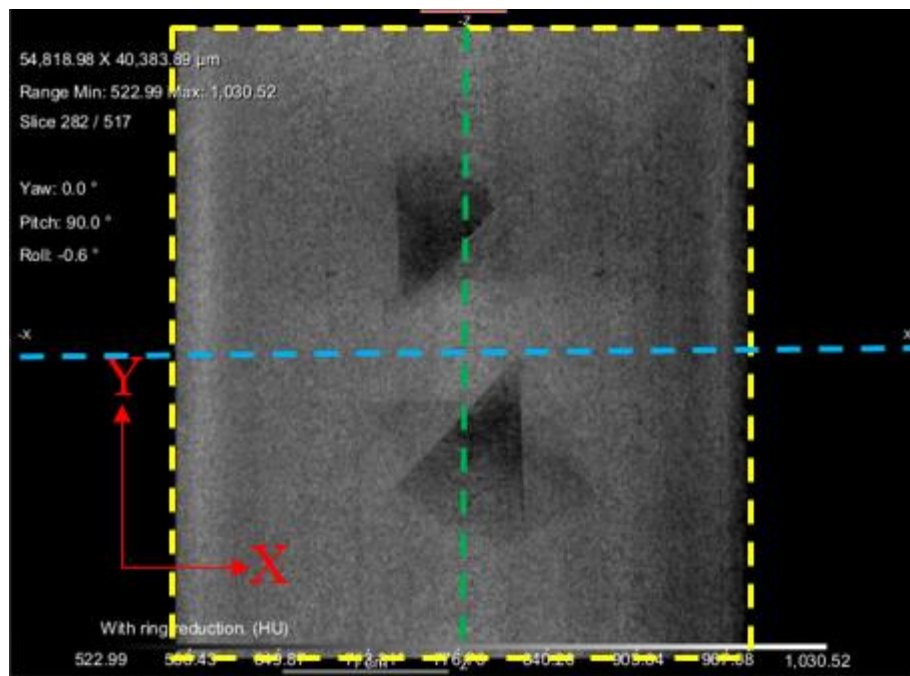
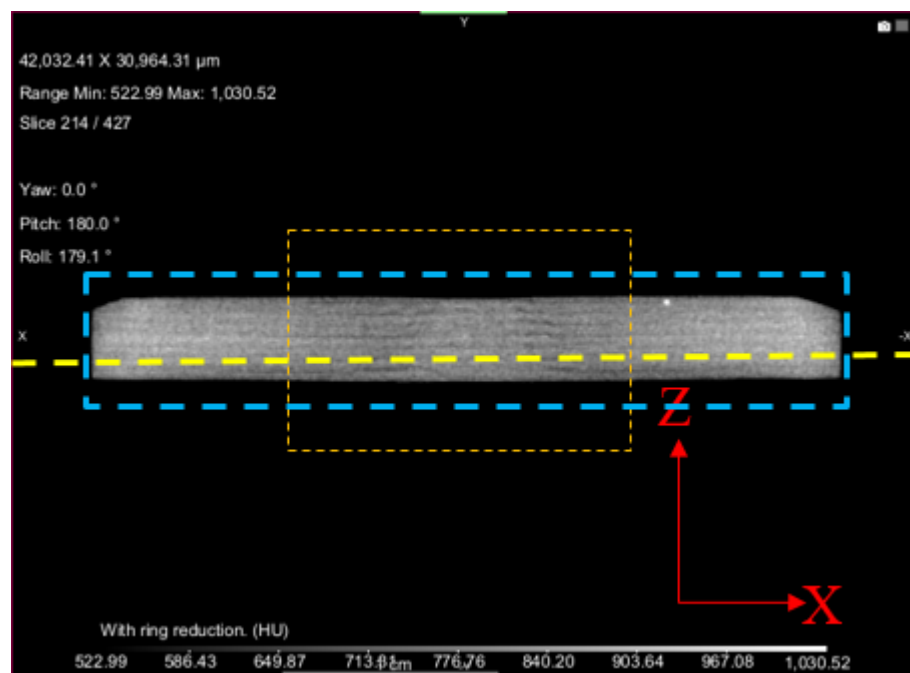


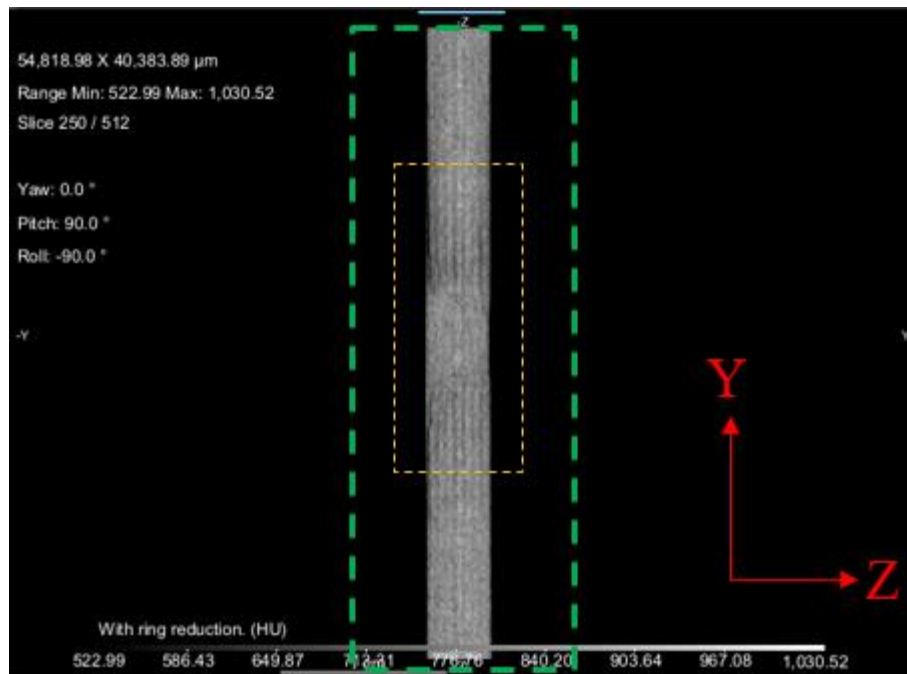
Figure 26. Quad plot of 4-mm coupon with force-history, energy-history, B-scan and C-scan



(a)



(b)



(c)

Figure 27. X-ray micro-CT of 4mm coupon with 1" impact damage

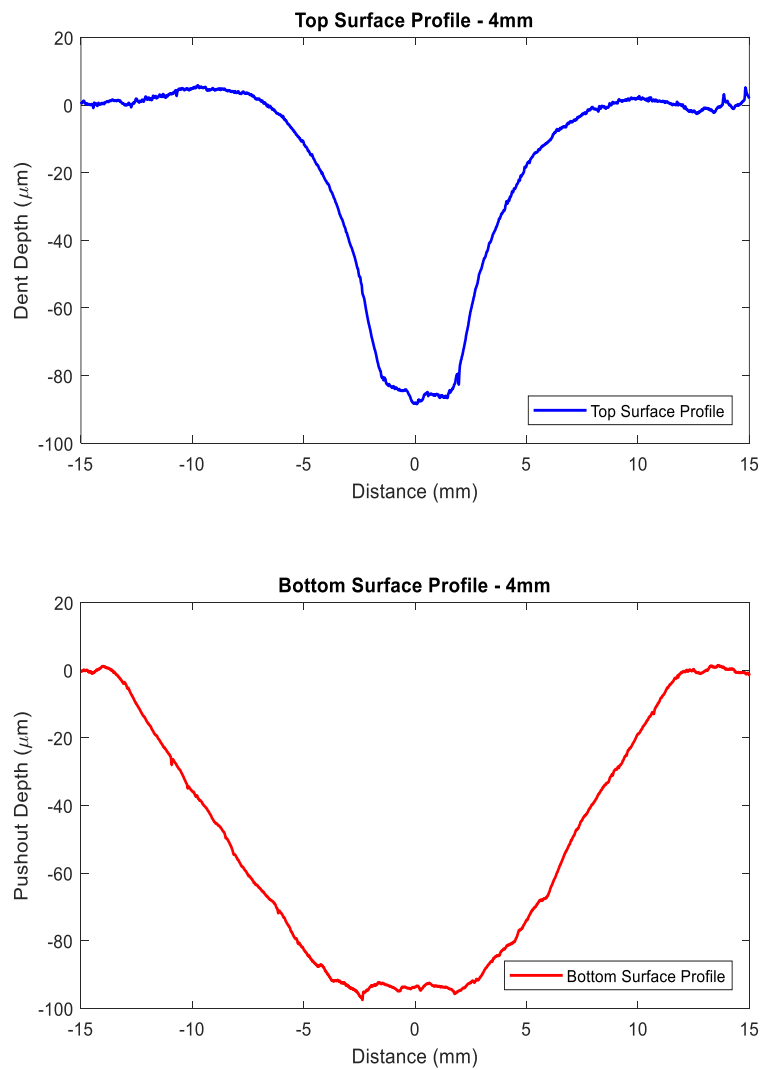


Figure 28. Profilometry scans of 4-mm coupon: (a) Top surface; (b) Bottom surface

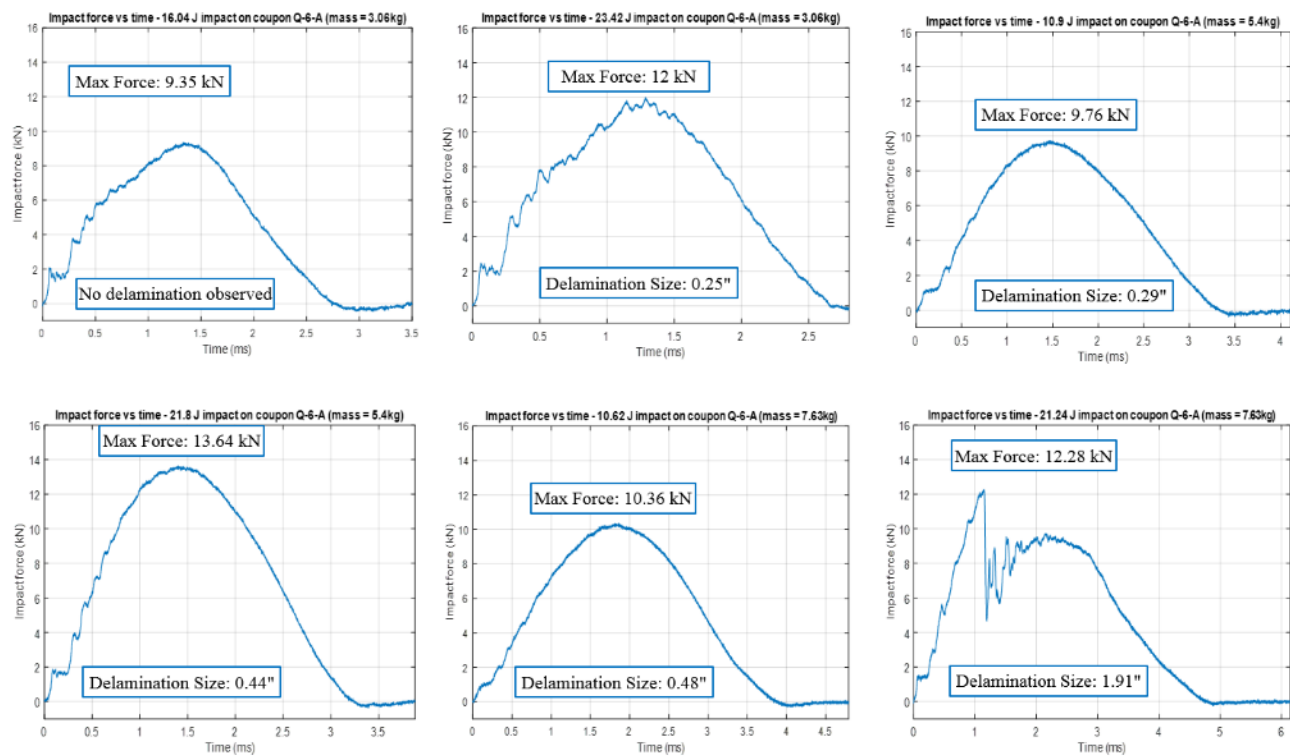


Figure 29. Force-time history of $[-45/90/+45/0]_s$ coupon Q-6-A for multiple impacts

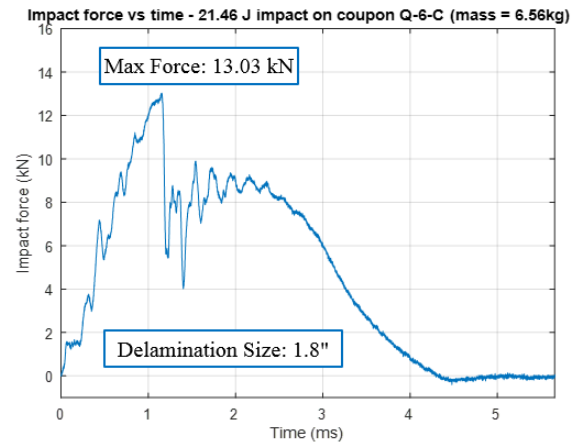
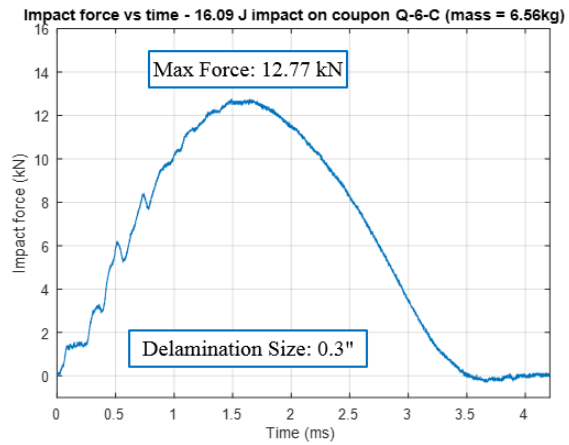
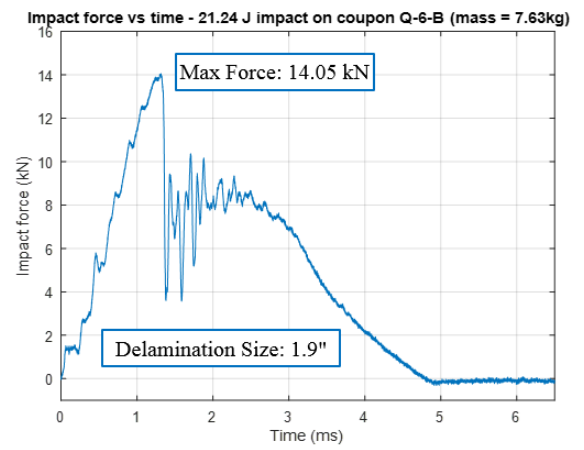
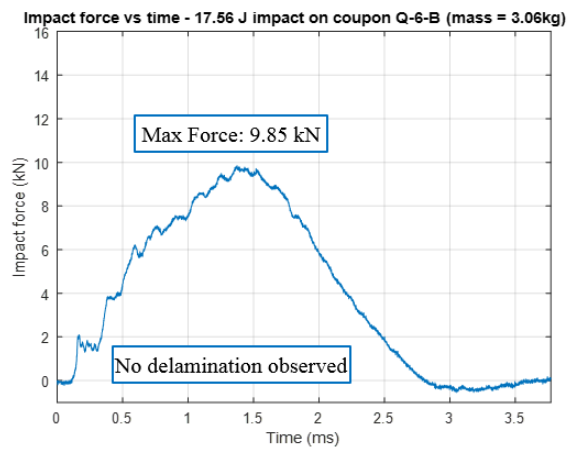


Figure 30. Force-time history of $[-45/90/+45/0]_{6S}$ coupons Q-6-B and Q-6-C for multiple impacts

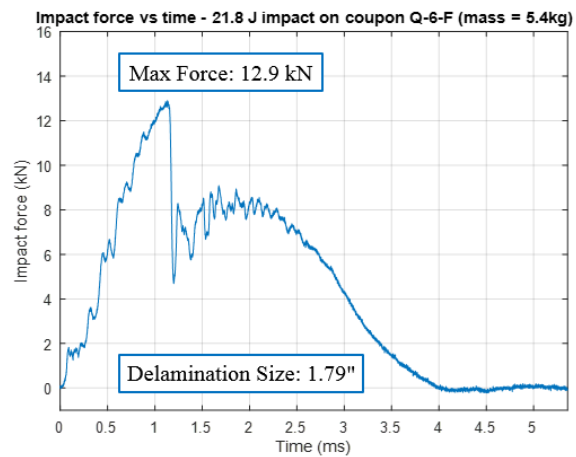
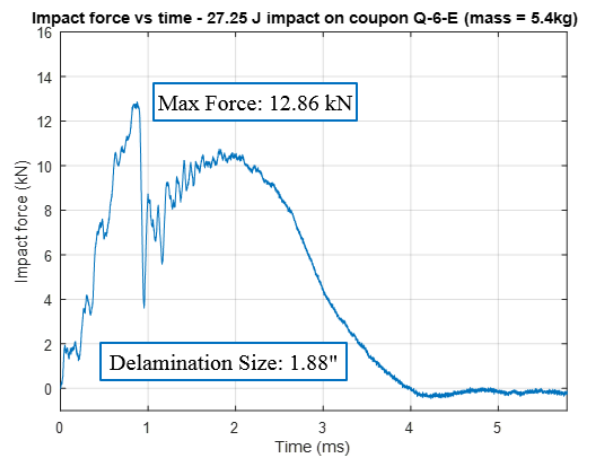
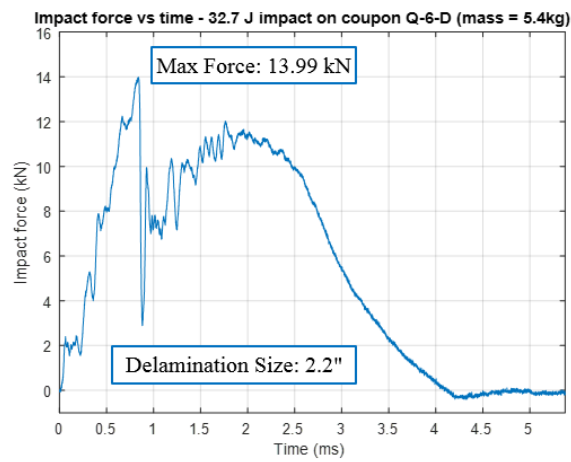


Figure 31. Force-time history of $[-45/90/+45/0]_{6S}$ coupons Q-6-D, Q-6-E and Q-6-F

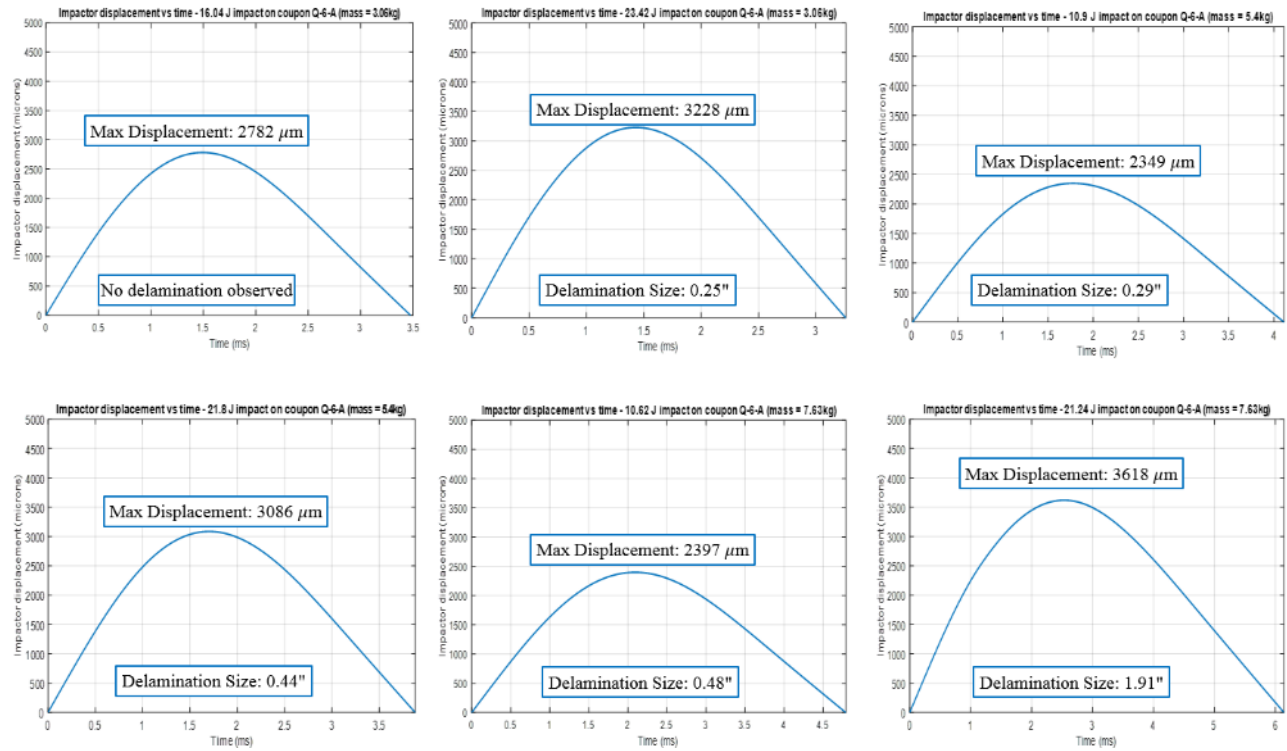
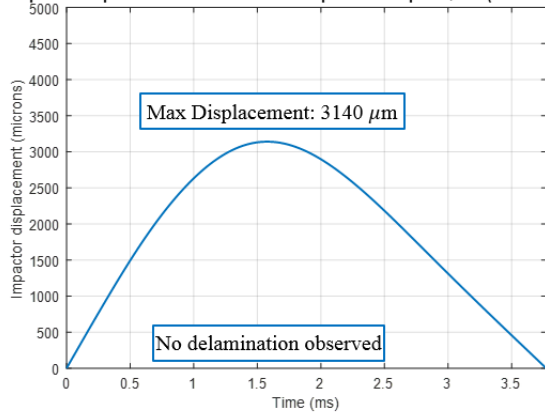
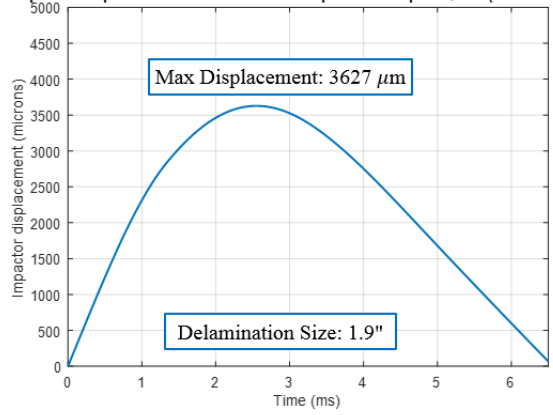


Figure 32. Displacement-time history of $[-45/90/+45/0]_{6s}$ coupon Q-6-A for multiple impacts

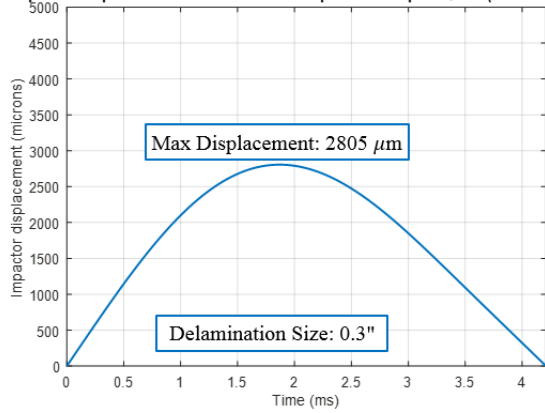
Impactor displacement vs time - 17.56 J impact on coupon Q-6-B (mass = 3.06kg)



Impactor displacement vs time - 21.24 J impact on coupon Q-6-B (mass = 7.63kg)



Impactor displacement vs time - 16.09 J impact on coupon Q-6-C (mass = 6.56kg)



Impactor displacement vs time - 21.46 J impact on coupon Q-6-C (mass = 6.56kg)

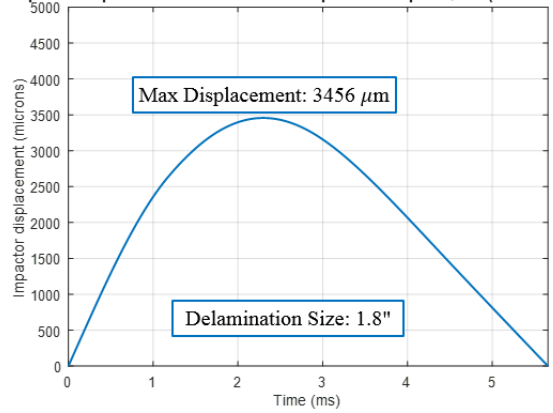


Figure 33. Displacement-time history of $[-45/90/+45/0]_{6S}$ coupons Q-6-B and Q-6-C for multiple impacts

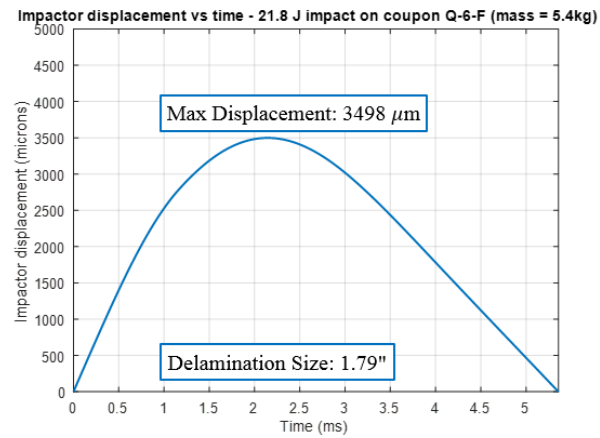
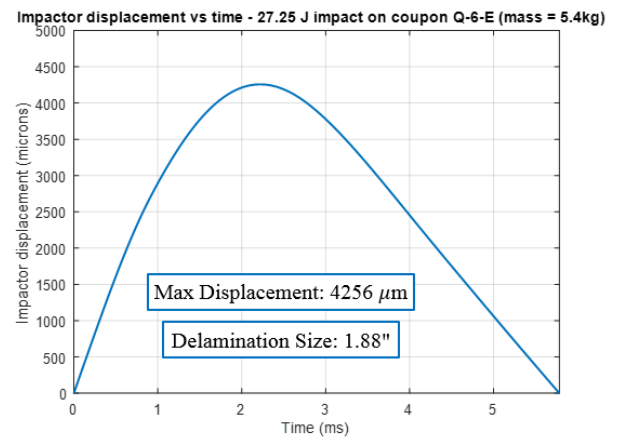
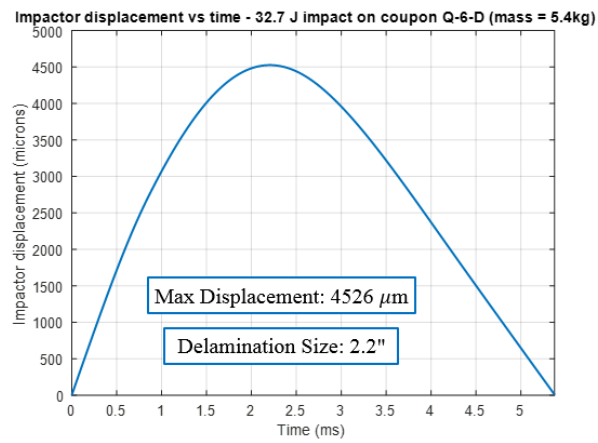


Figure 34. Displacement-time history of [-45/90/+45/0]_{6S} coupons Q-6-D, Q-6-E and Q-6-F

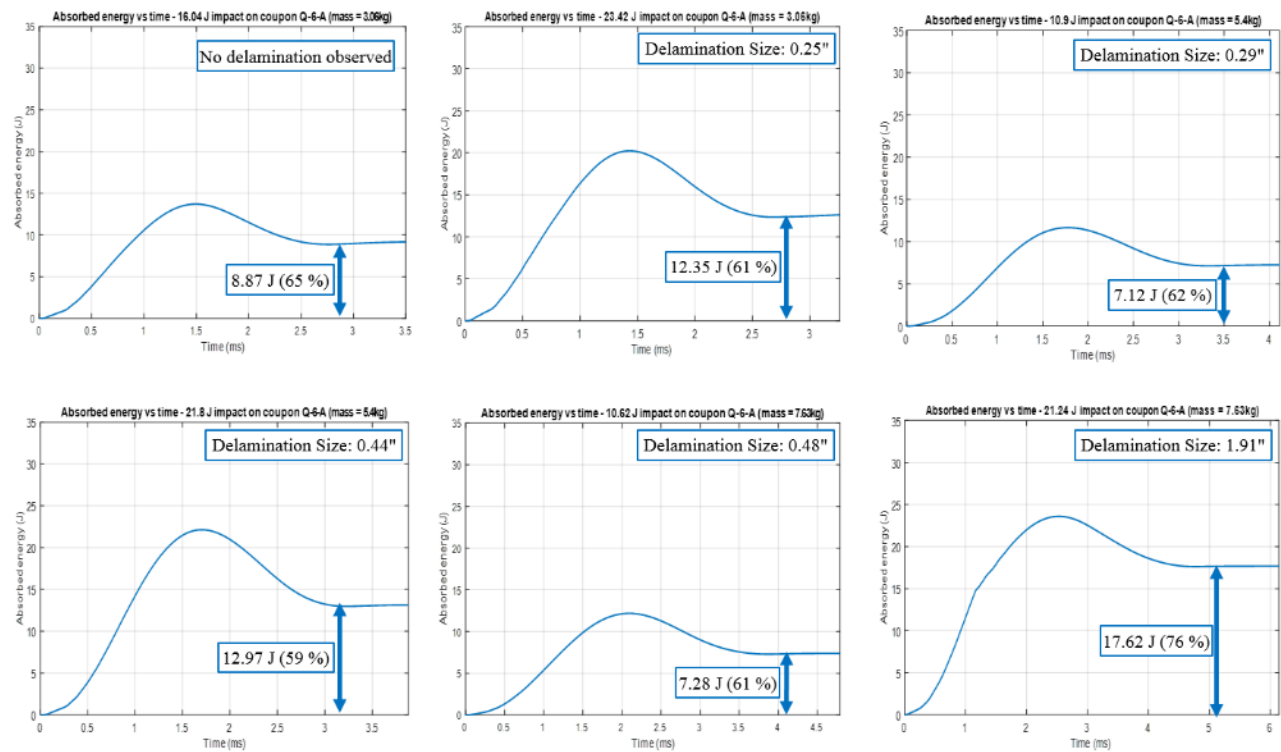
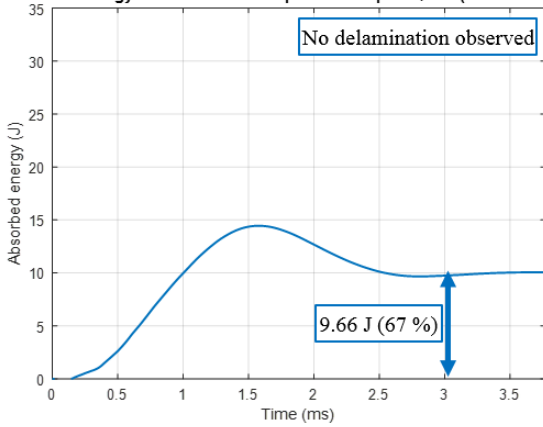
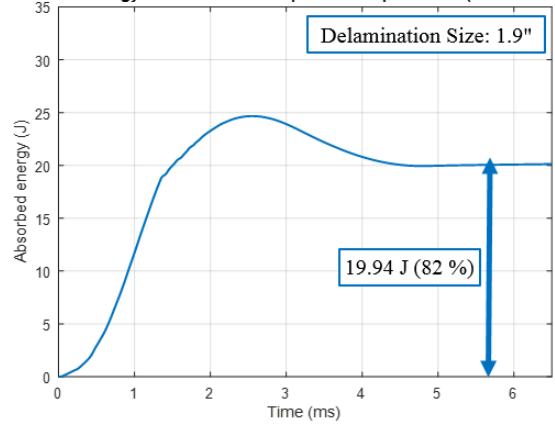


Figure 35. Energy-time history of $[-45/90/+45/0]_{6s}$ coupon Q-6-A for multiple impacts

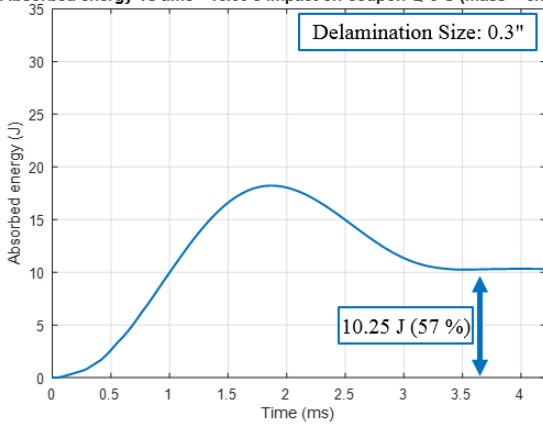
Absorbed energy vs time - 17.56 J impact on coupon Q-6-B (mass = 3.06kg)



Absorbed energy vs time - 21.24 J impact on coupon Q-6-B (mass = 7.63kg)



Absorbed energy vs time - 16.09 J impact on coupon Q-6-C (mass = 6.56kg)



Absorbed energy vs time - 21.46 J impact on coupon Q-6-C (mass = 6.56kg)

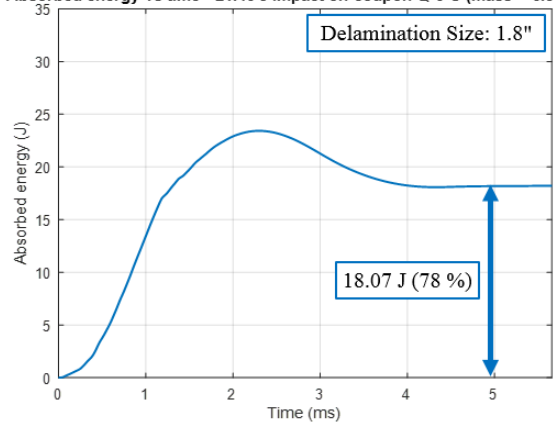


Figure 36. Energy-time history of $[-45/90/+45/0]_{6S}$ coupons Q-6-B and Q-6-C for multiple impacts

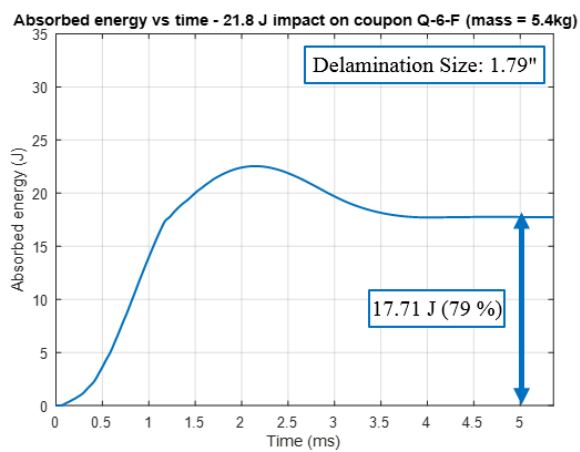
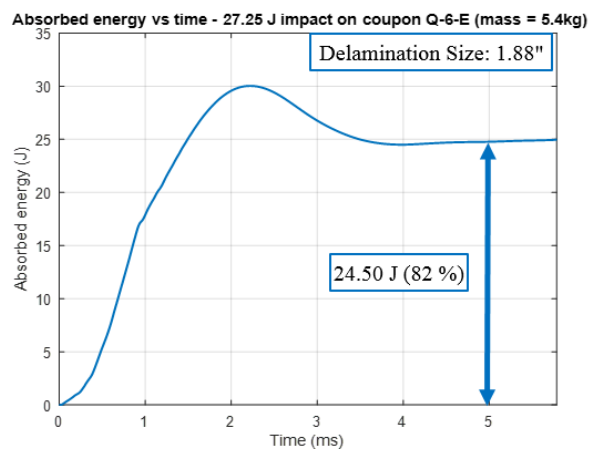
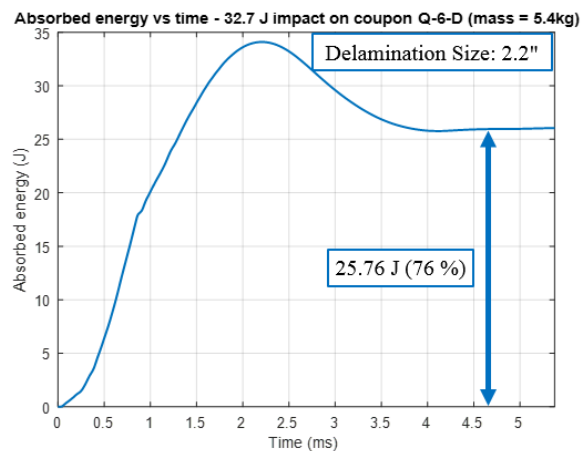


Figure 37. Energy-time history of $[-45/90/+45/0]_{6S}$ coupons Q-6-D, Q-6-E and Q-6-F

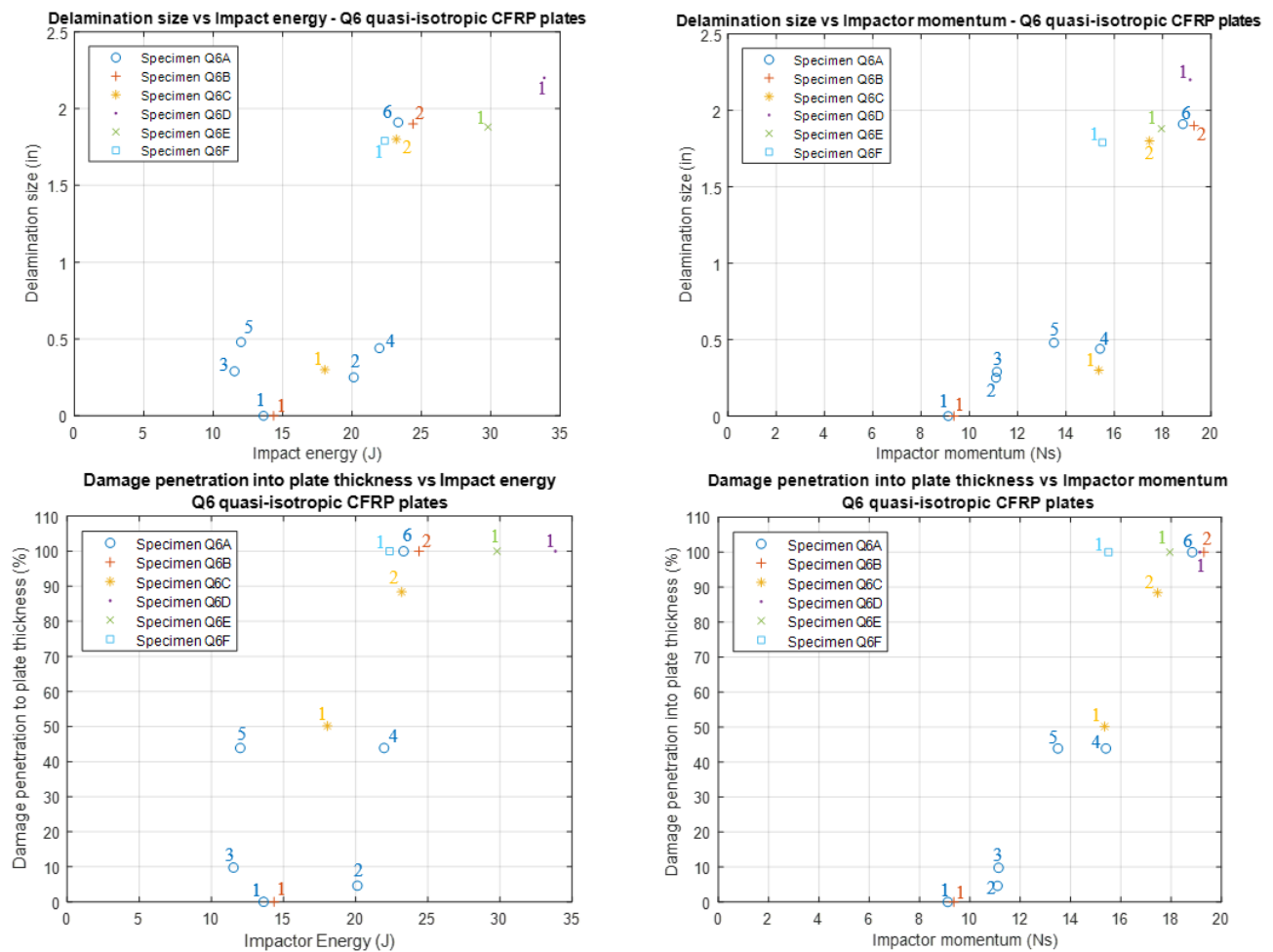


Figure 38. Effect of impact energy and momentum on delamination size in $[-45/90/+45/0]_{6S}$ coupons

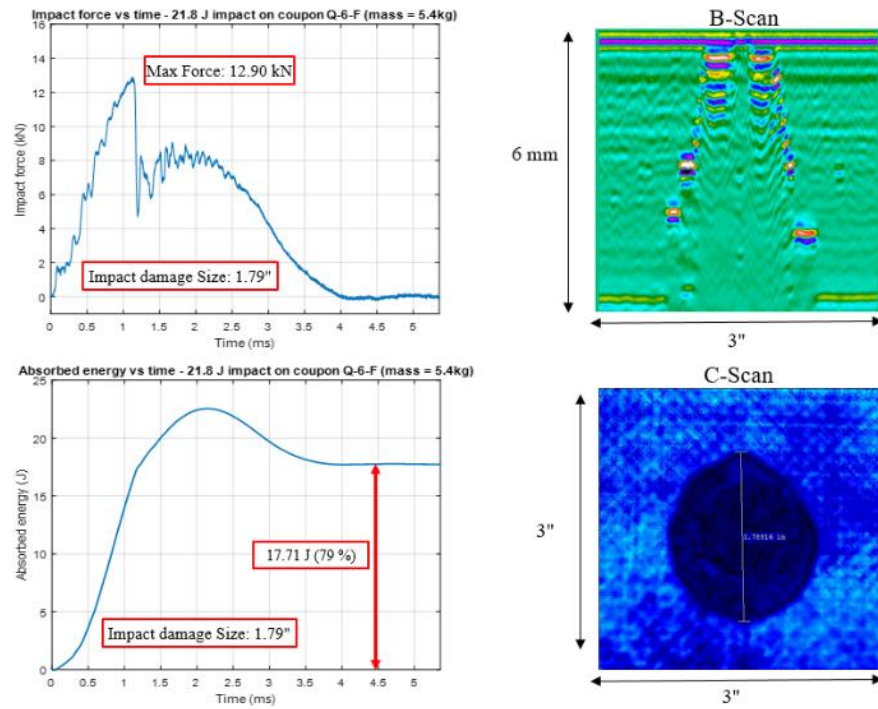
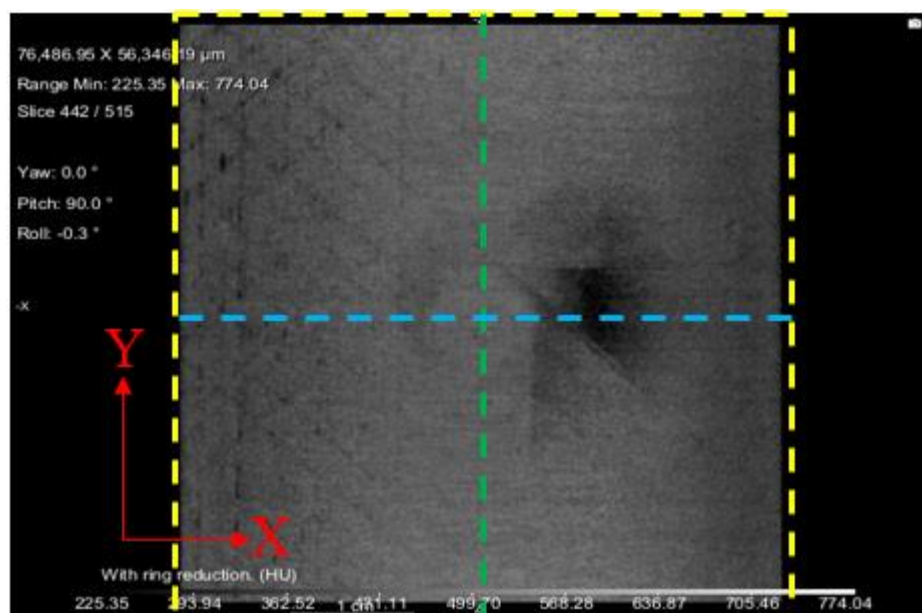
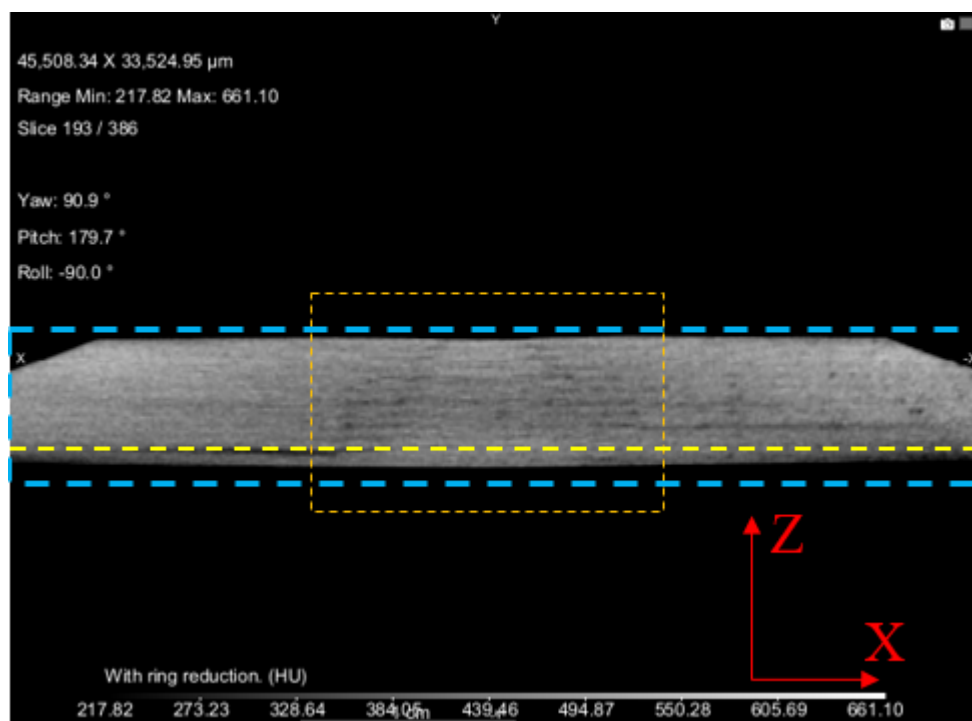


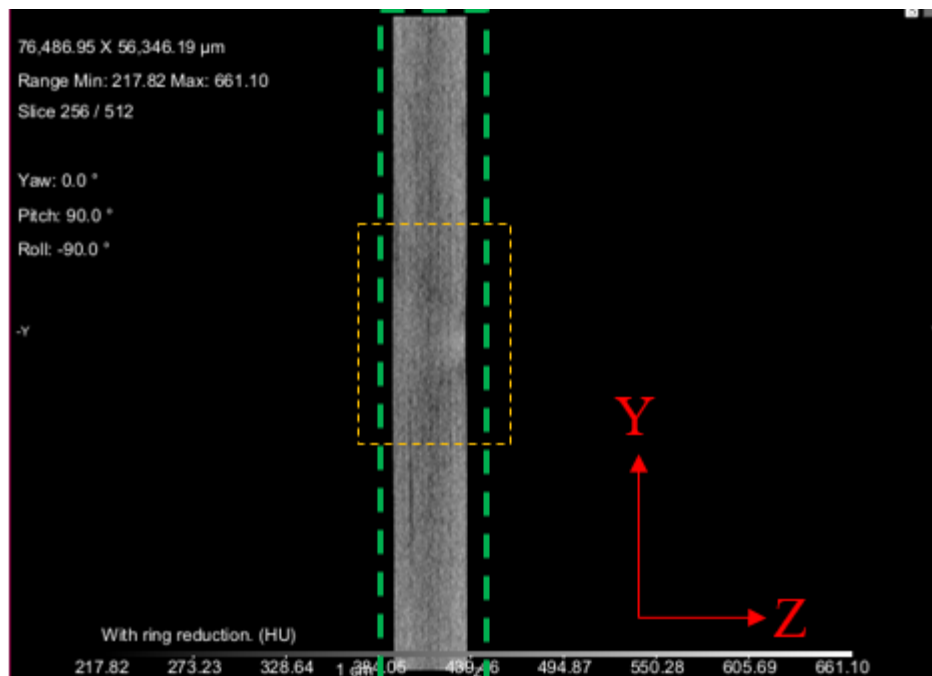
Figure 39. Quad plot of 6-mm coupon with force-history, energy-history, B-scan and C-scan



(a)



(b)



(c)

Figure 40. X-ray micro-CT of 6mm coupon with 1" impact damage

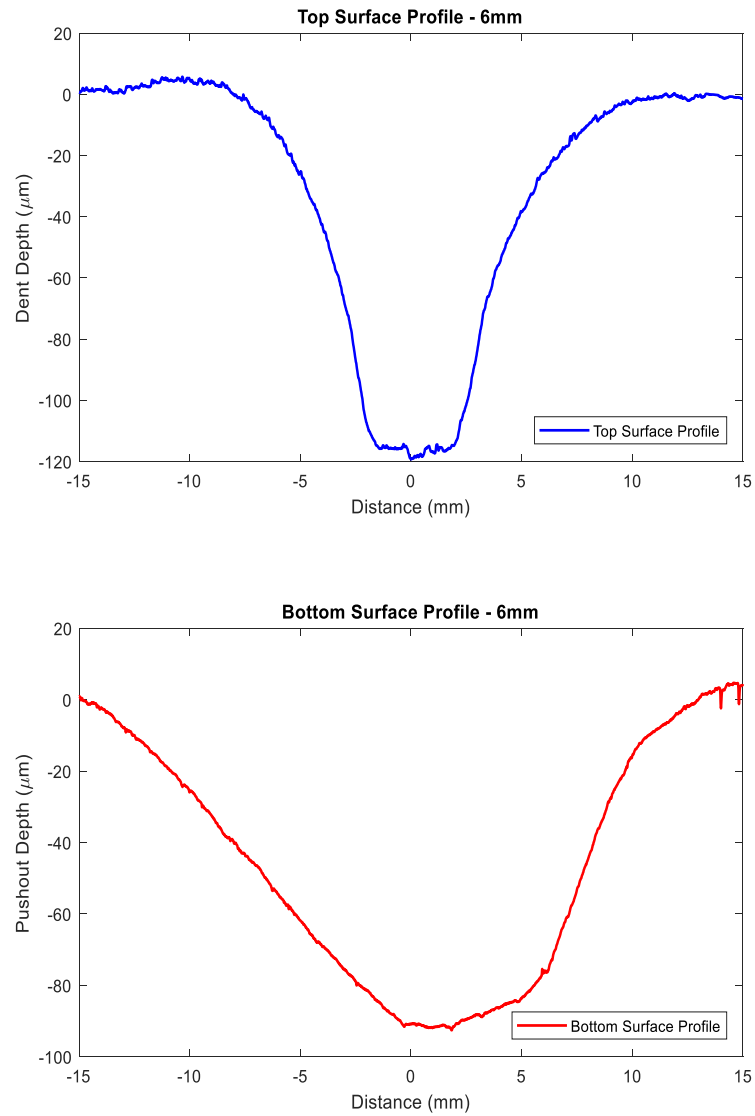


Figure 41. Profilometry scans of 6-mm coupon: (a) top surface; (b) bottom surface

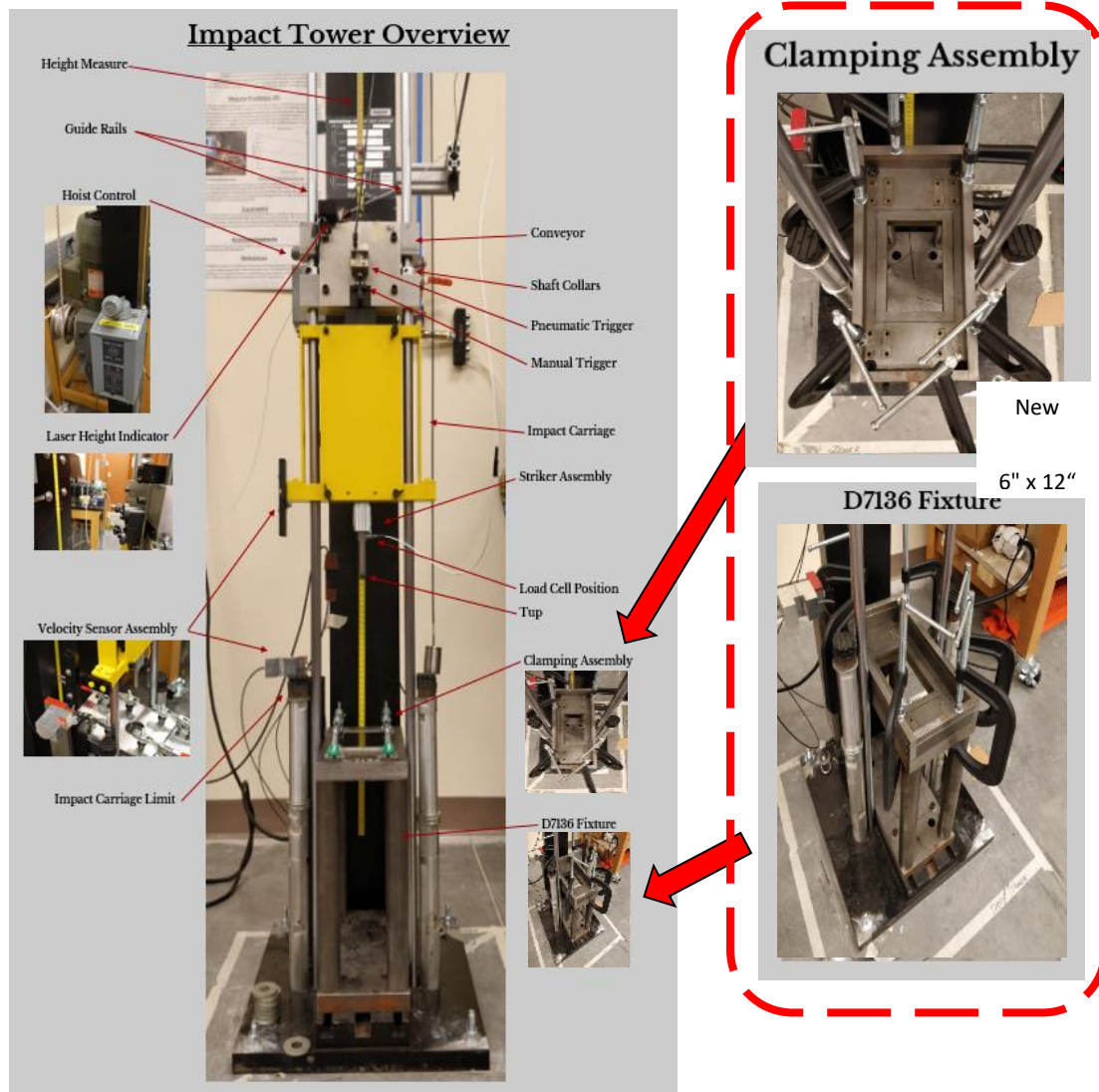


Figure 42. Proposed modification of the coupon holding fixture on the Dynatup 8200 drop weight impact testing machine

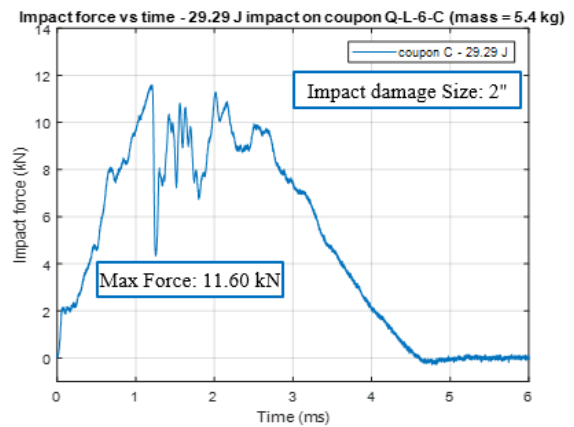
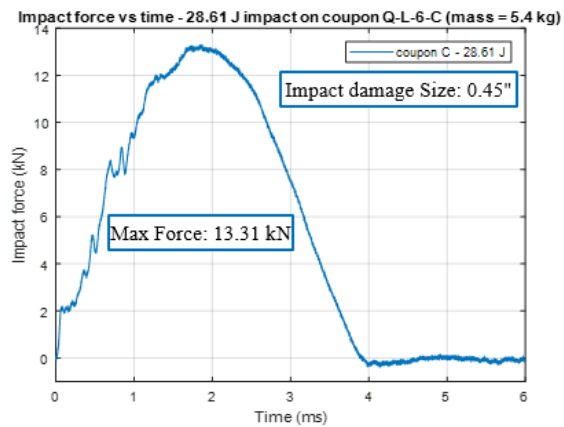
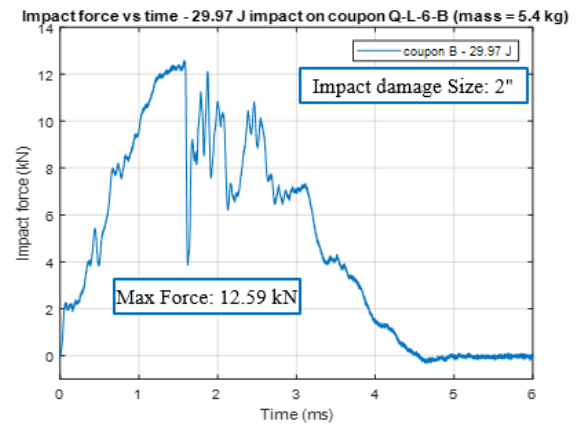
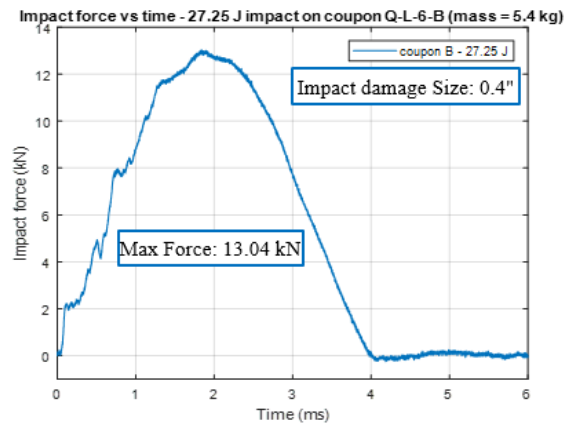
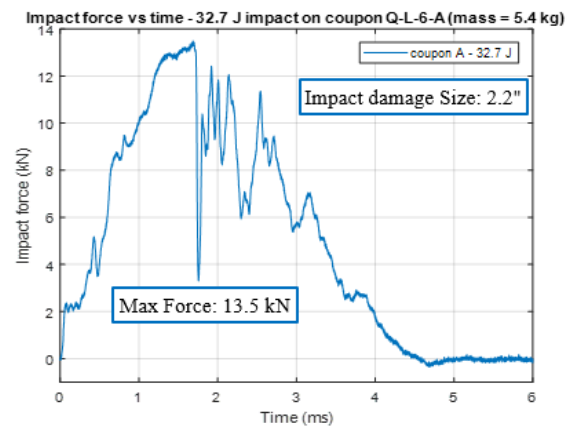
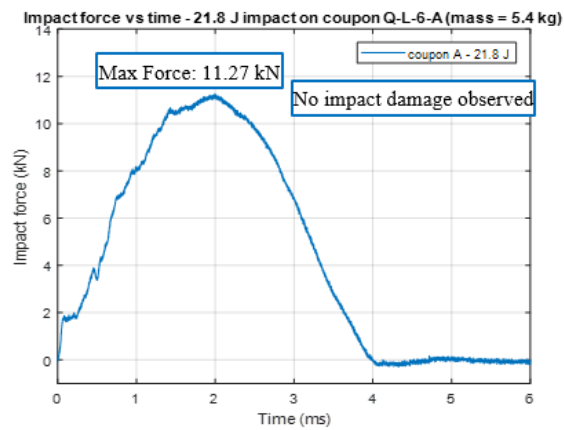


Figure 43. Force-time histories of coupons QL6A, QL6B and QL6C for double impacts

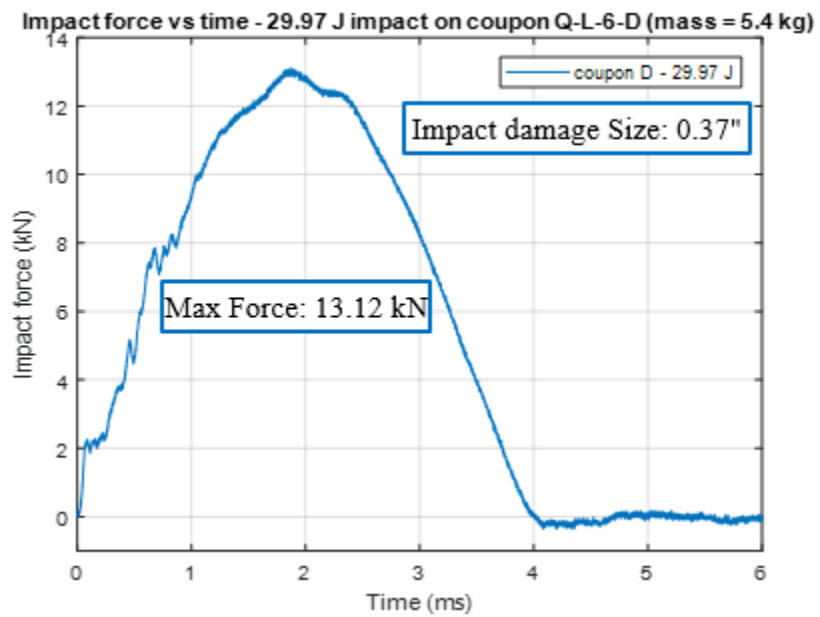


Figure 44. Force-time history of coupons QL6D for single impact

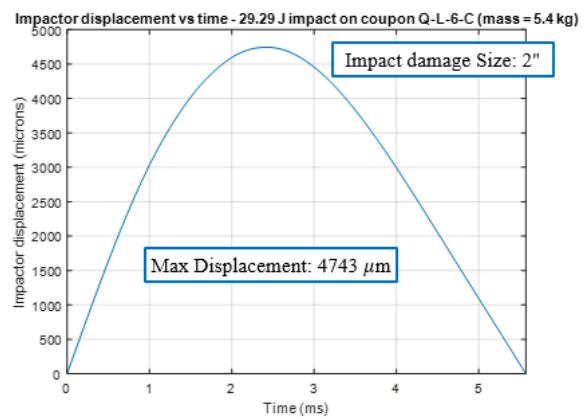
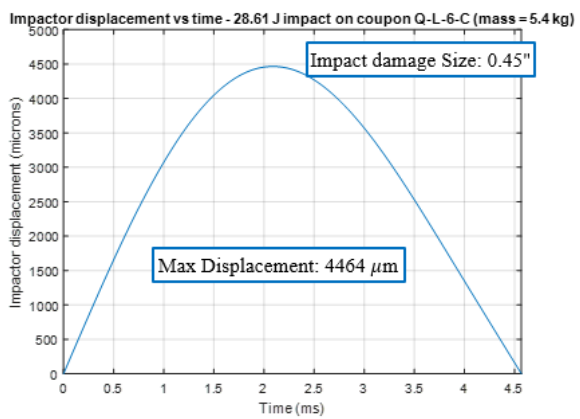
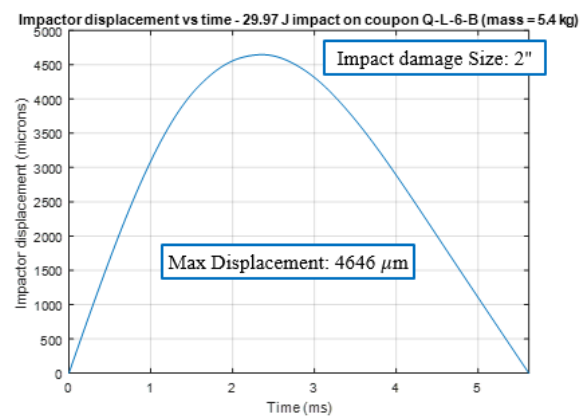
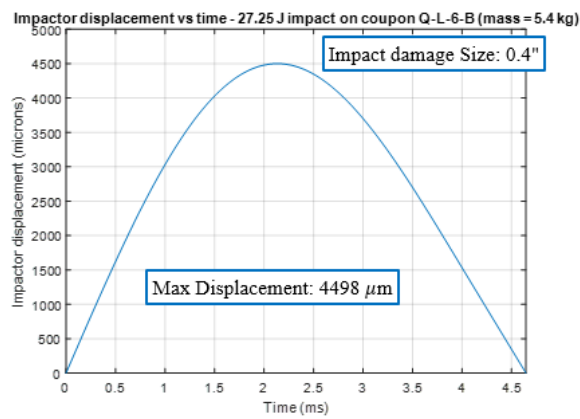
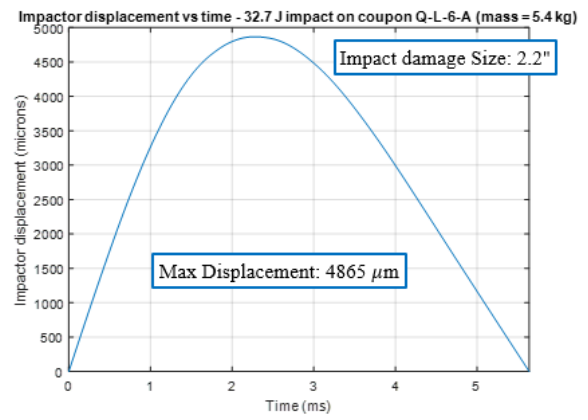
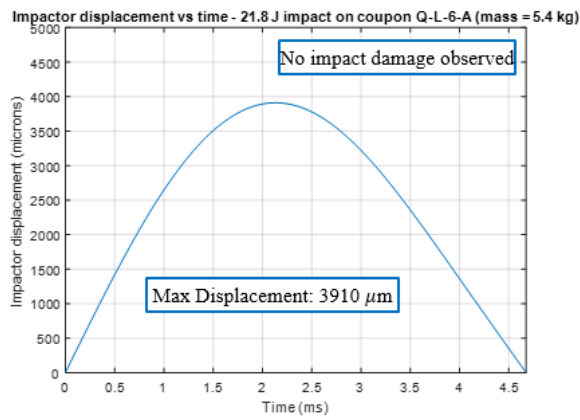


Figure 45. Displacement-time histories of coupons QL6A, QL6B and QL6C

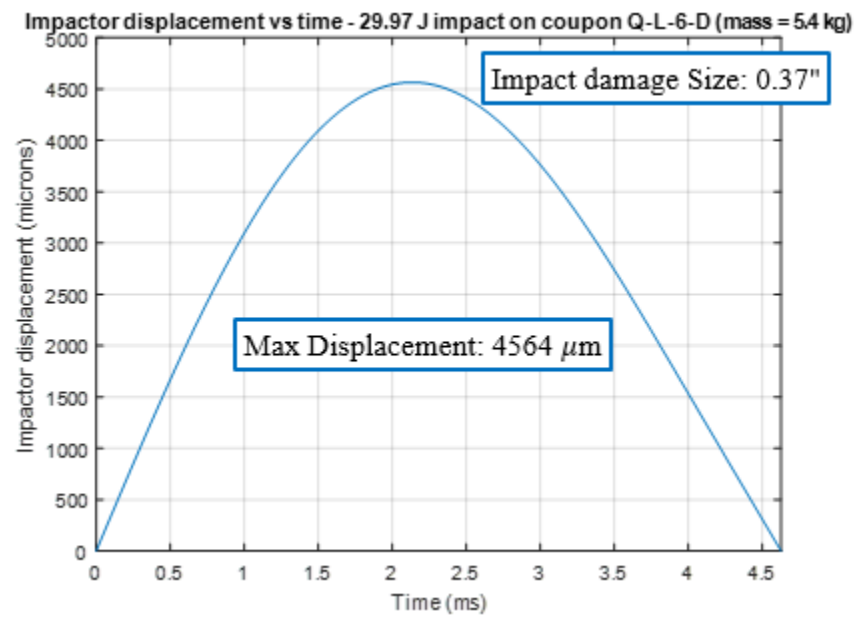
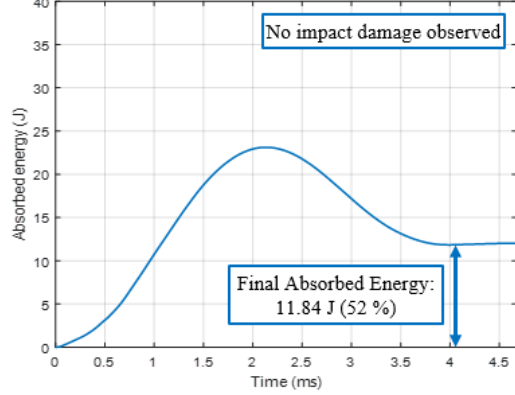
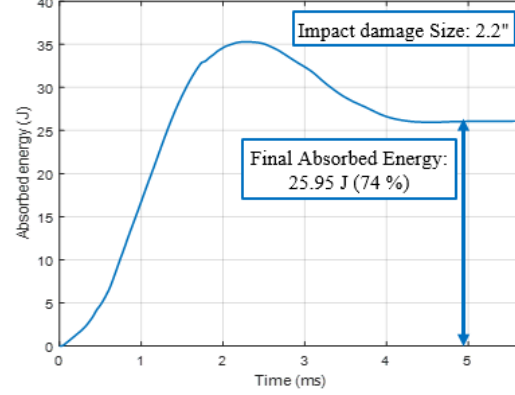


Figure 46. Displacement-time history of coupons QL6D

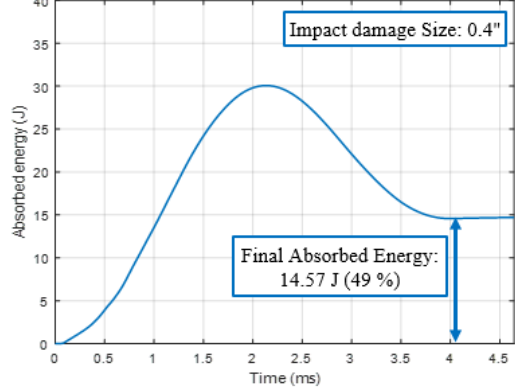
Absorbed energy vs time - 21.8 J impact on coupon Q-L-6-A (mass = 5.4 kg)



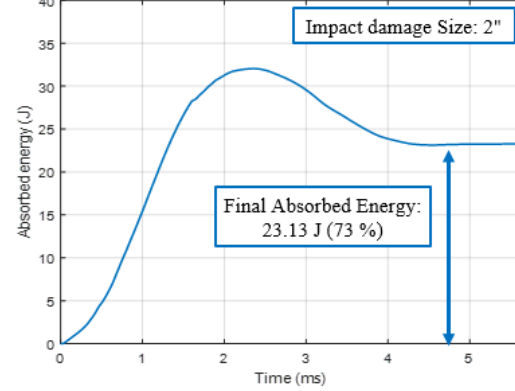
Absorbed energy vs time - 32.7 J impact on coupon Q-L-6-A (mass = 5.4 kg)



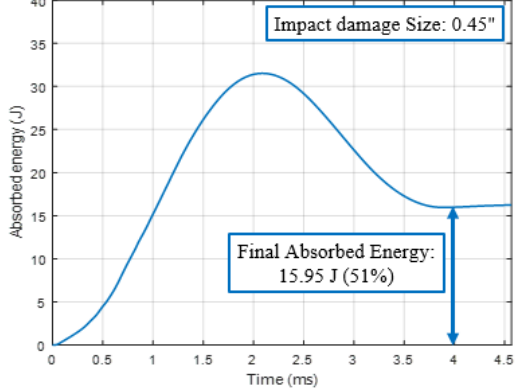
Absorbed energy vs time - 27.25 J impact on coupon Q-L-6-B (mass = 5.4 kg)



Absorbed energy vs time - 29.97 J impact on coupon Q-L-6-B (mass = 5.4 kg)



Absorbed energy vs time - 28.61 J impact on coupon Q-L-6-C (mass = 5.4 kg)



Absorbed energy vs time - 29.29 J impact on coupon Q-L-6-C (mass = 5.4 kg)

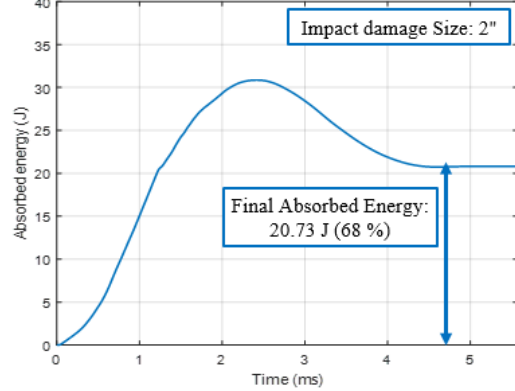


Figure 47. Energy-time histories of coupons QL6A, QL6B and QL6C

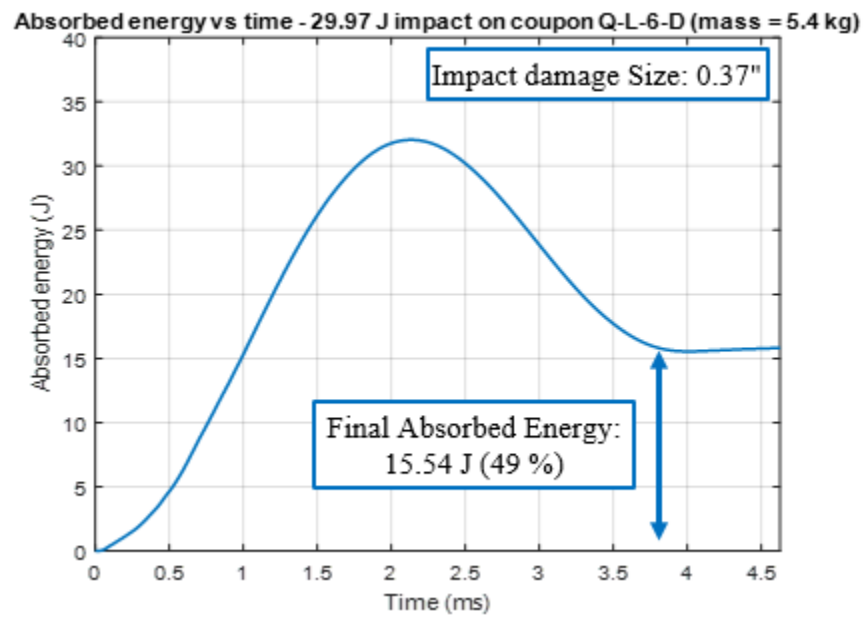


Figure 48. Energy-time history of coupons QL6D

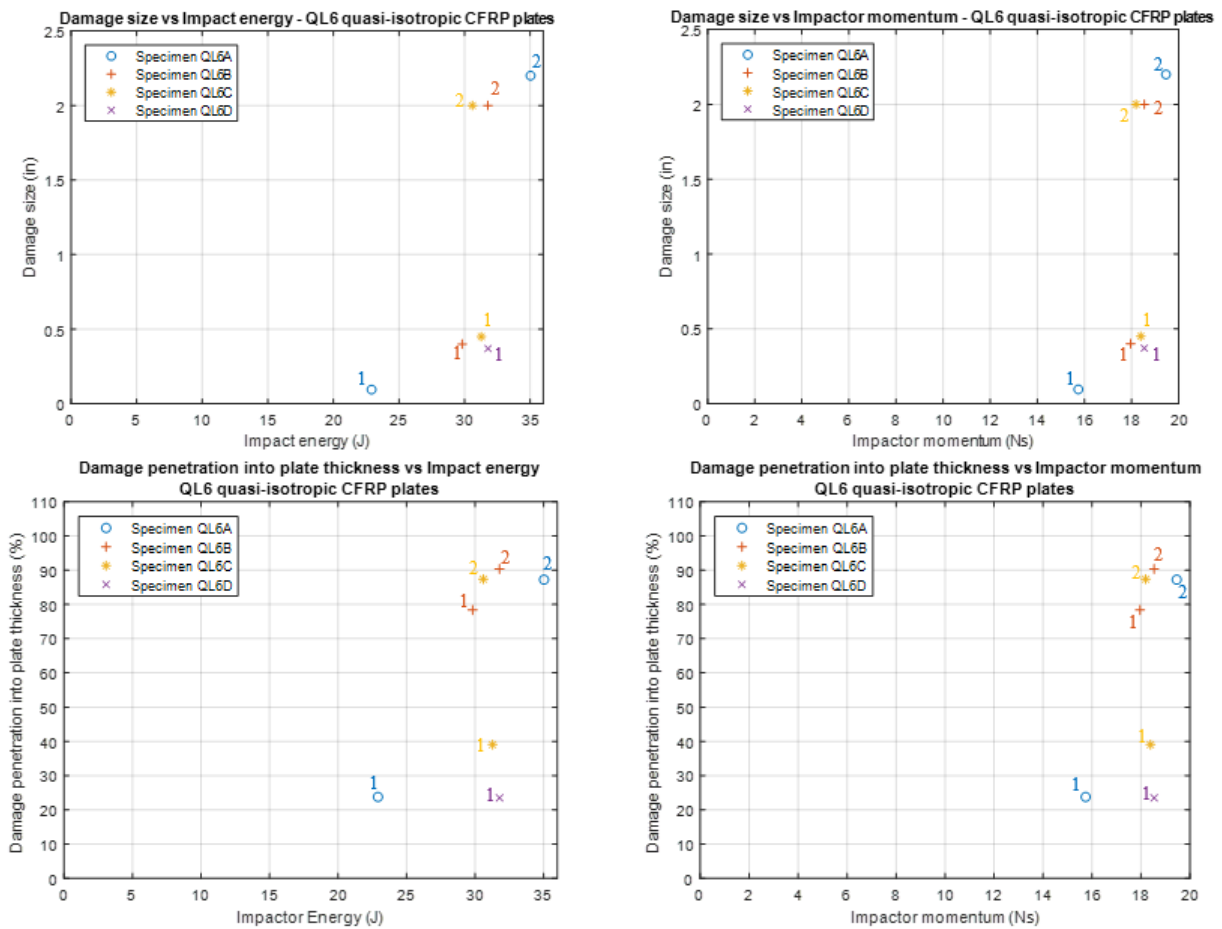


Figure 49. Effect of impact energy and momentum on impact damage size and damage penetration across the thickness for coupons QL6A, QL6B, QL6C and QL6D

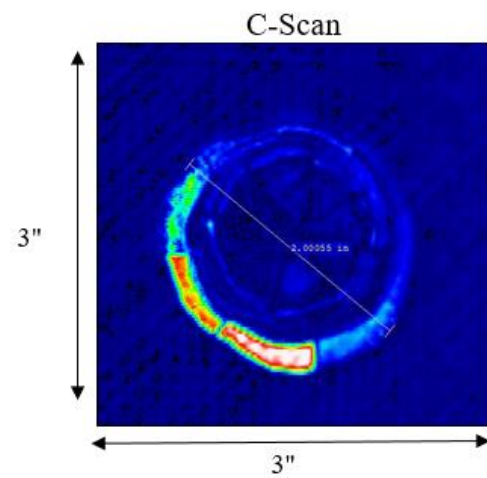
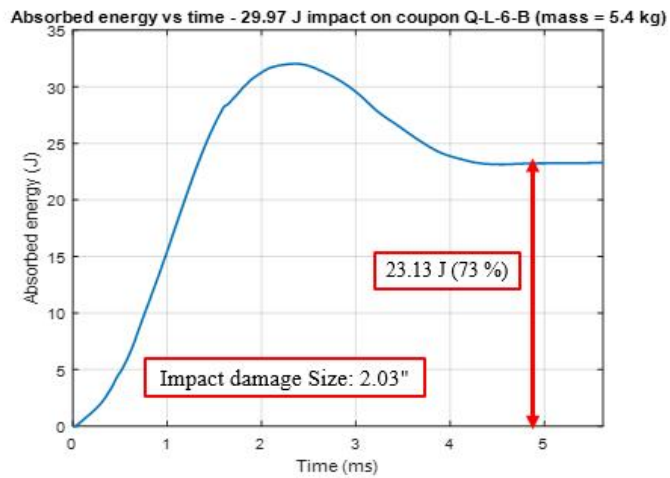
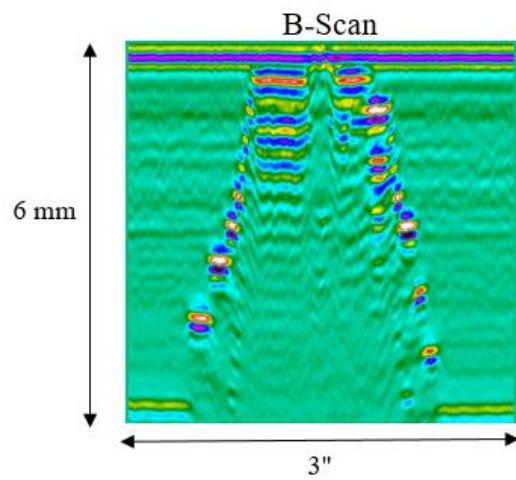
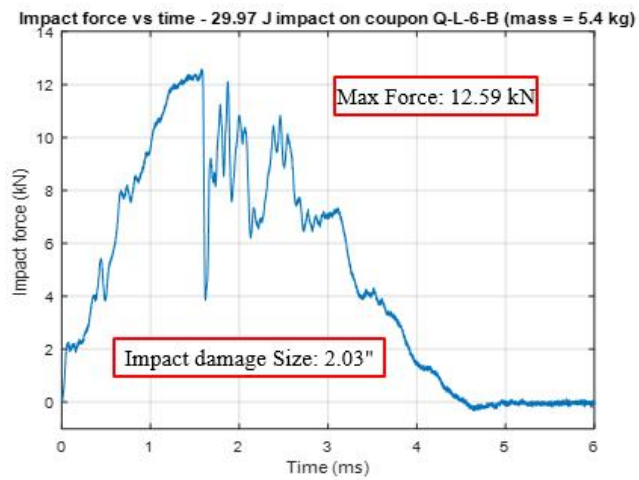


Figure 50. Quad plot of QL6B coupon with force-history, energy-history, B-scan and C-scan

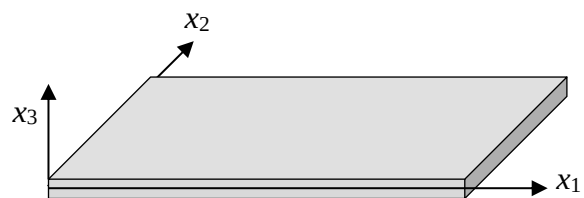
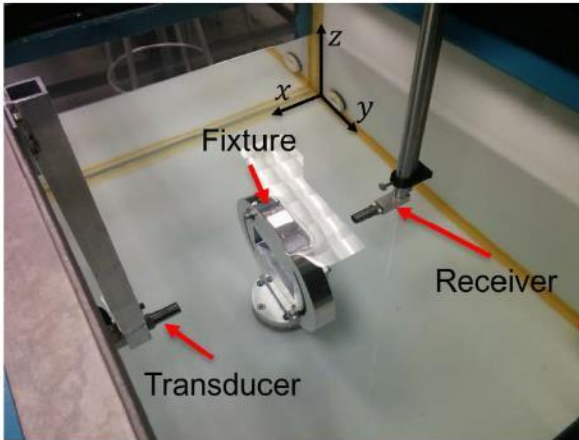
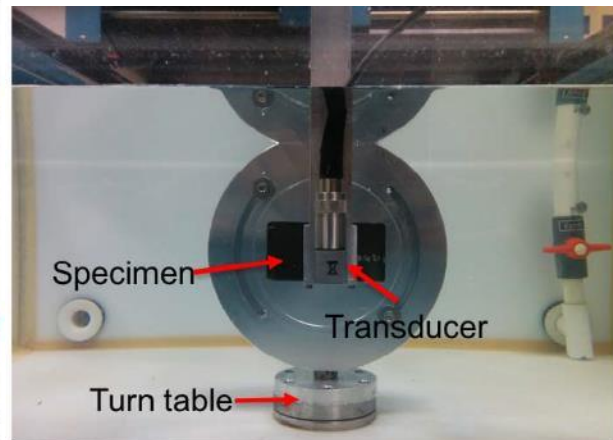


Figure 51 Schematic of the specimen and its corresponding coordinate [62]



(a)



(b)

Figure 52 Water tank setup for ultrasonic determination of composite stiffness matrix components: (a) overall view showing the transducers attached to the linear gantry and the fixture mounted on the turntable; (b) zoom in to the specimen fixture mounted on the turntable [61]

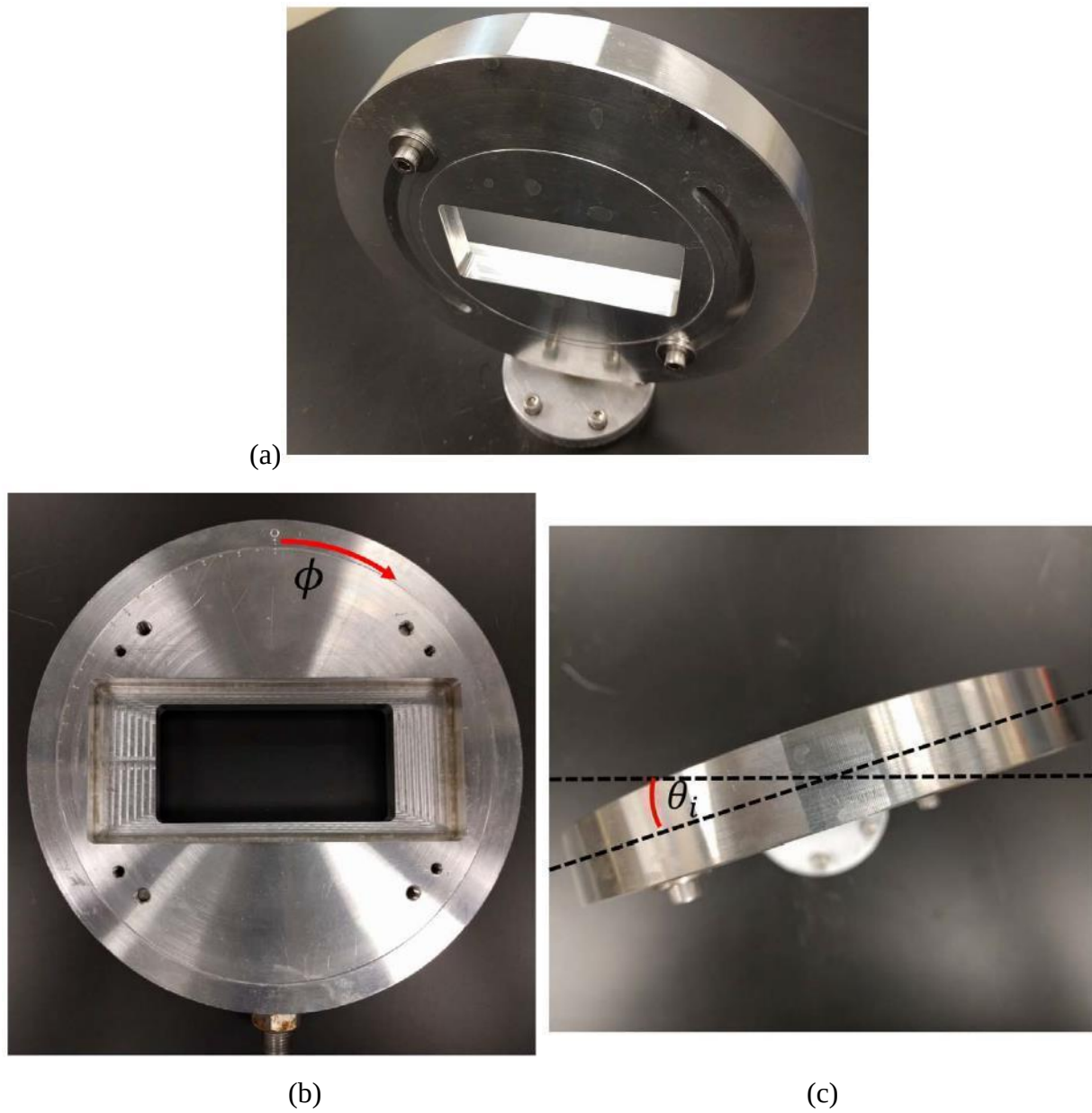


Figure 53 Fixture for holding the composite specimen during ultrasonic scanning: (a) overall view; (b) front view showing the in-plane positioning by polar angle ϕ ; (c) top view showing the spin scanning angle θ [61]

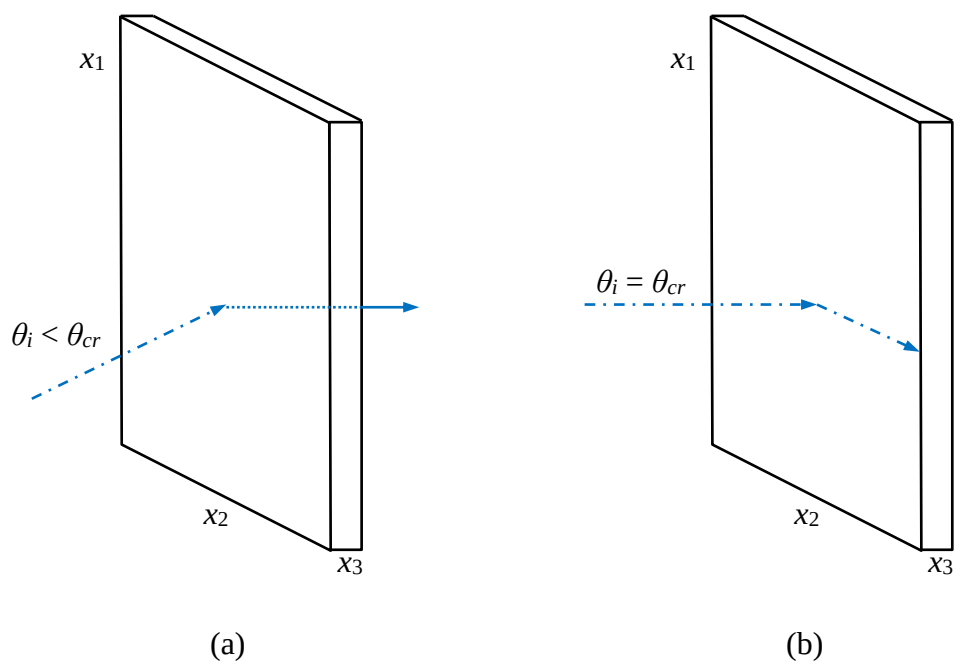


Figure 54 Propagation of the refracted wave created by an ultrasonic beam impinging at angle θ_i onto a composite specimen: (a) below the critical angle, i.e., for $\theta_i < \theta_{cr}$, the refracted wave exists the specimen; (b) at the critical angle i.e., for $\theta_i = \theta_{cr}$ the refracted travels inside the specimen parallel to the specimen surface

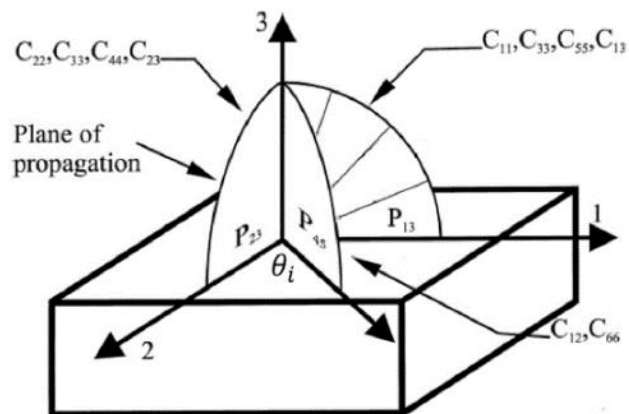


Figure 55 Wave propagation in planes of material symmetry depends only on reduced set of stiffness components [59]

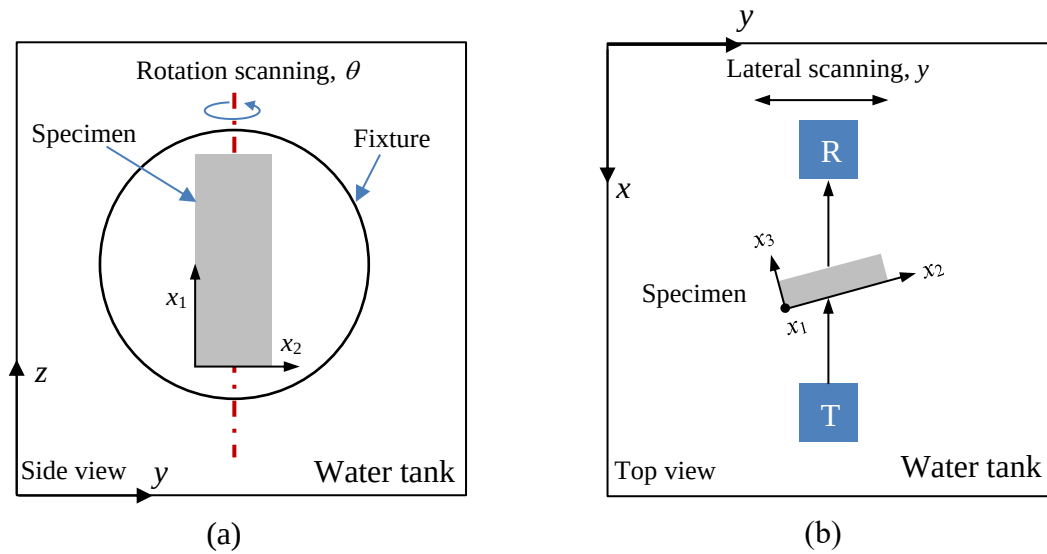


Figure 56 Schematic of through-transmission scan in x_2 - x_3 plane with the specimen x_2 axis being kept horizontal: (a) side view; (b) top view. Note that other axes of rotation can be obtained by setting the fixture at other polar inclination [62]

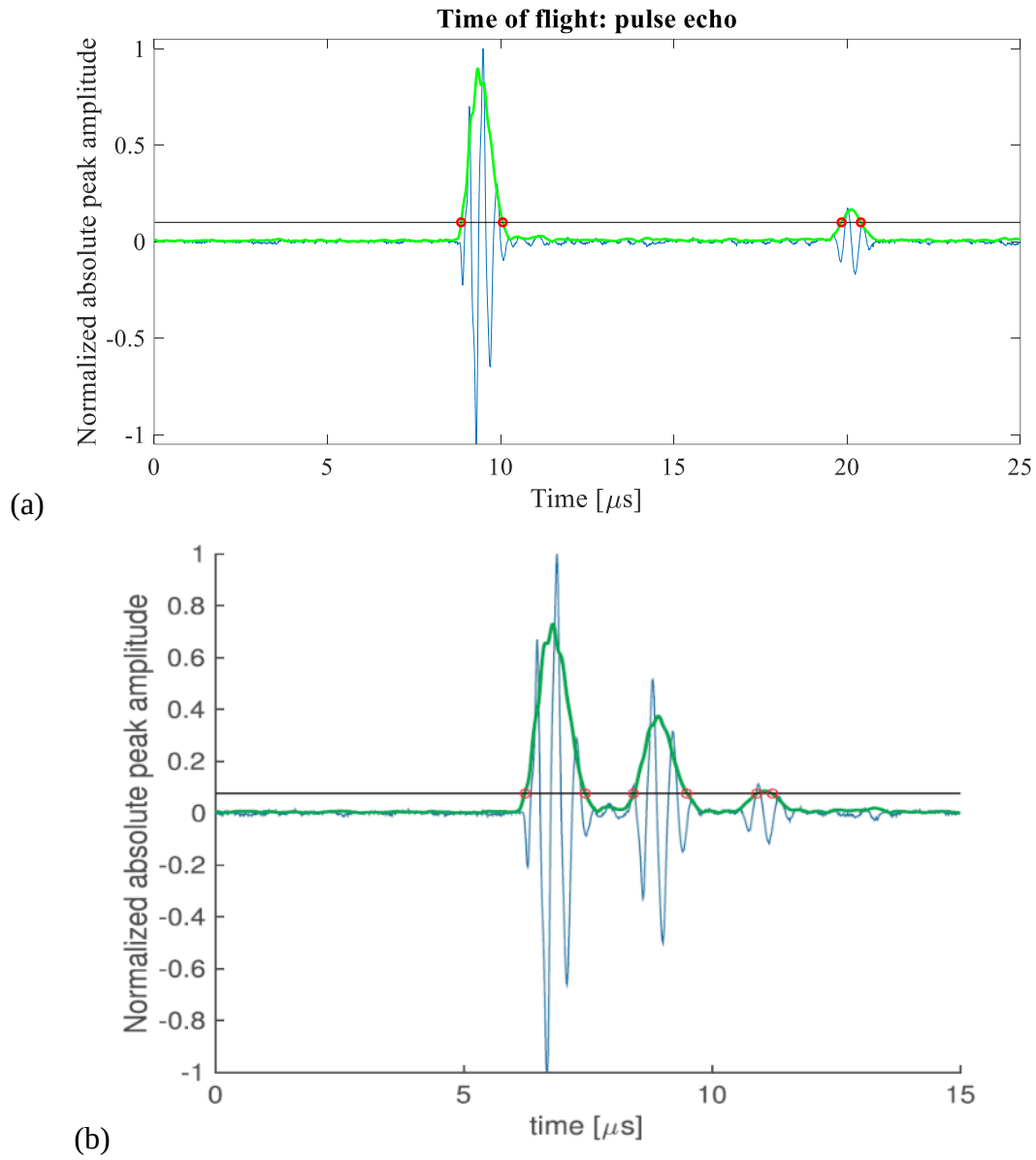


Figure 57 Determination of the thickness-wise pulse-echo time of flight in unidirectional CFRP specimens of various thicknesses: (a) 16.43-mm thickness [62]; 3-mm thickness [61]

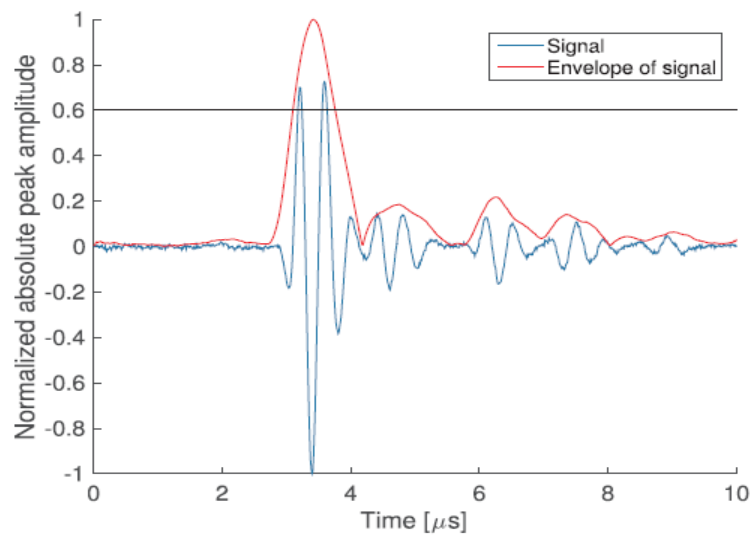


Figure 58 Time of flight determination by the location of the largest peak in the signal envelope [61]

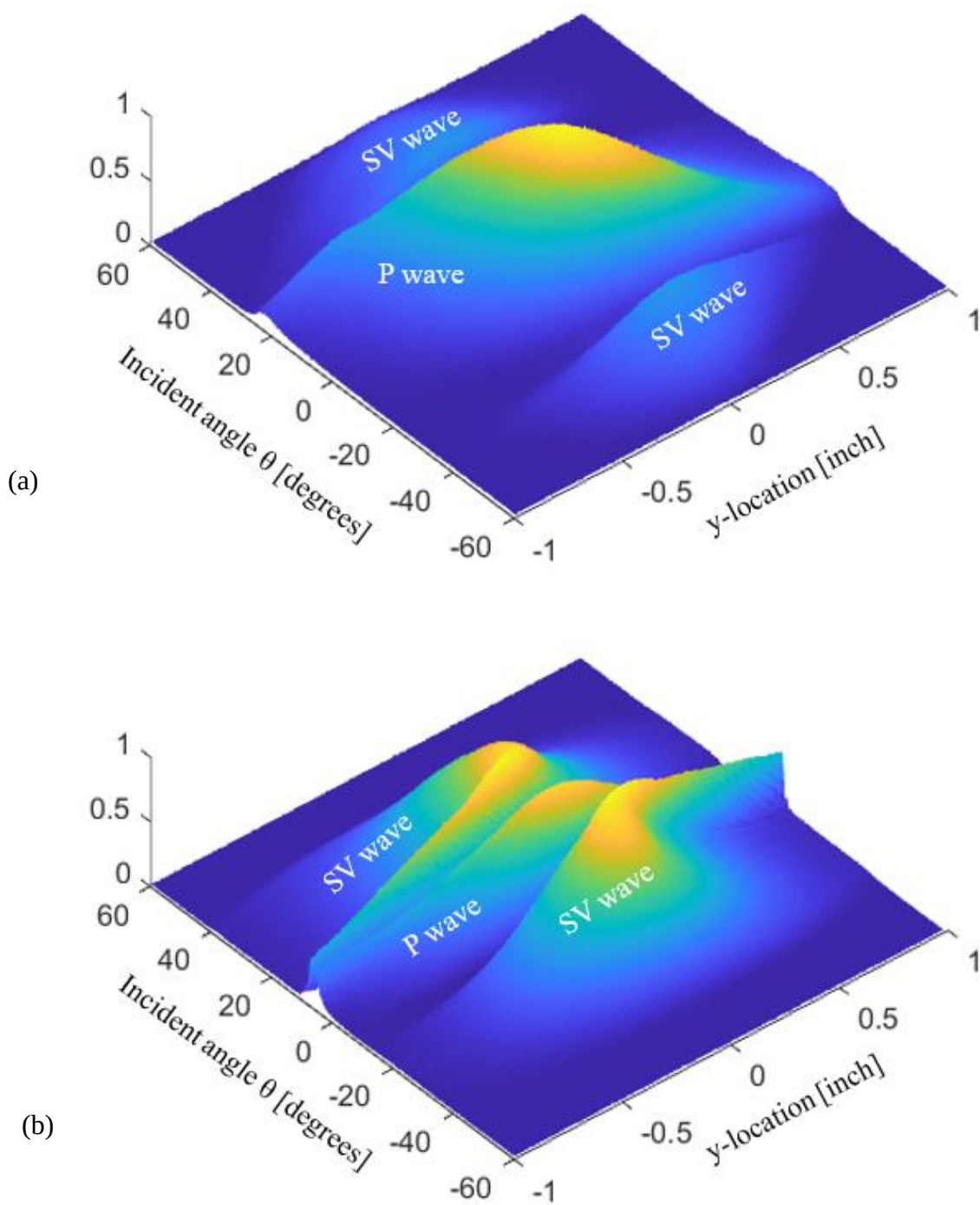


Figure 59 Signal peak amplitude recorded at each incidence angle θ and location y : (a) rotation θ about the x_1 axis (ultrasonic beam in the x_2 - x_3 plane); (b) rotation θ about the x_2 axis (ultrasonic beam in the x_1 - x_3 plane) The valleys in the plot represent critical angle

effects in which the P wave disappear and the SV wave becomes detectable [62]

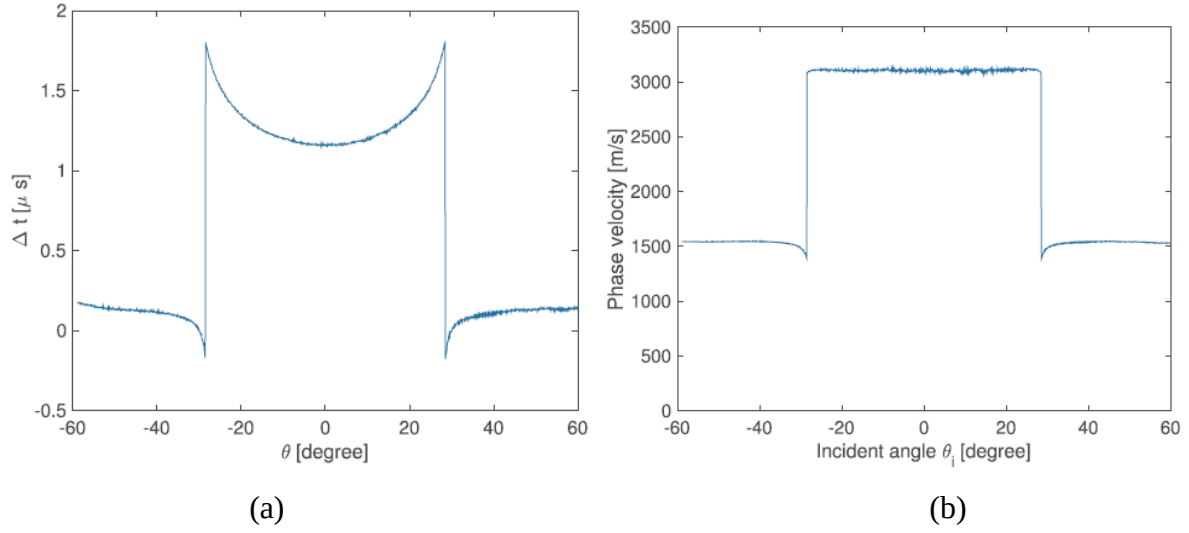


Figure 60 Time shift and phase velocity results for rotation θ about the x_1 axis (ultrasonic beam in the x_2 - x_3 plane) in a 3-mm thick unidirectional CFRP specimen: (a) Δt ; (b) wavespeed (aka phase velocity) [61]

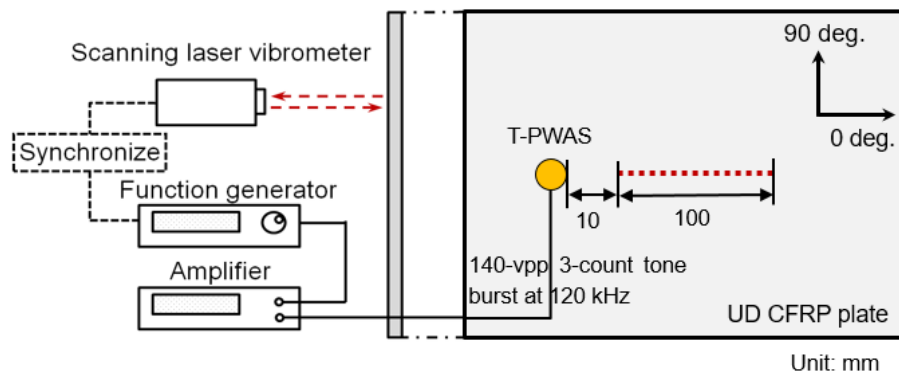


Figure 61 Schematic of the PWAS-SLDV system: line scan in the 0° direction.

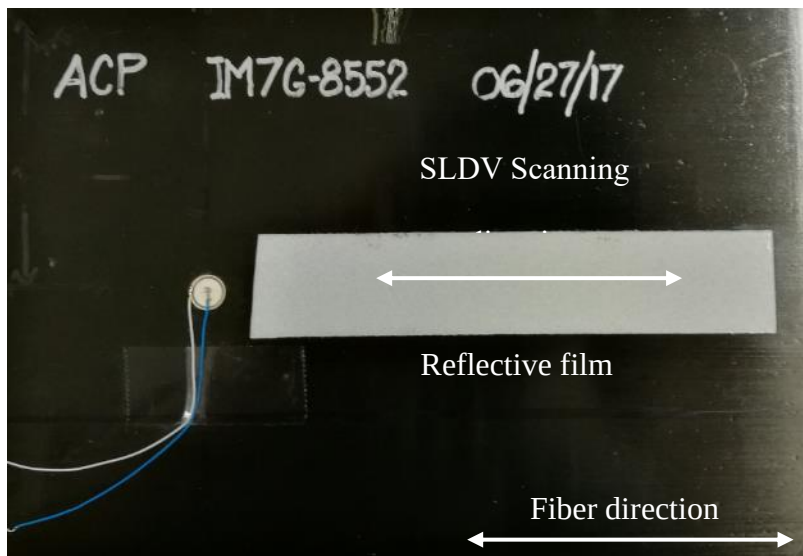


Figure 62 Thick IM7G-8552 CFRP plate used for validation in the 0° direction.

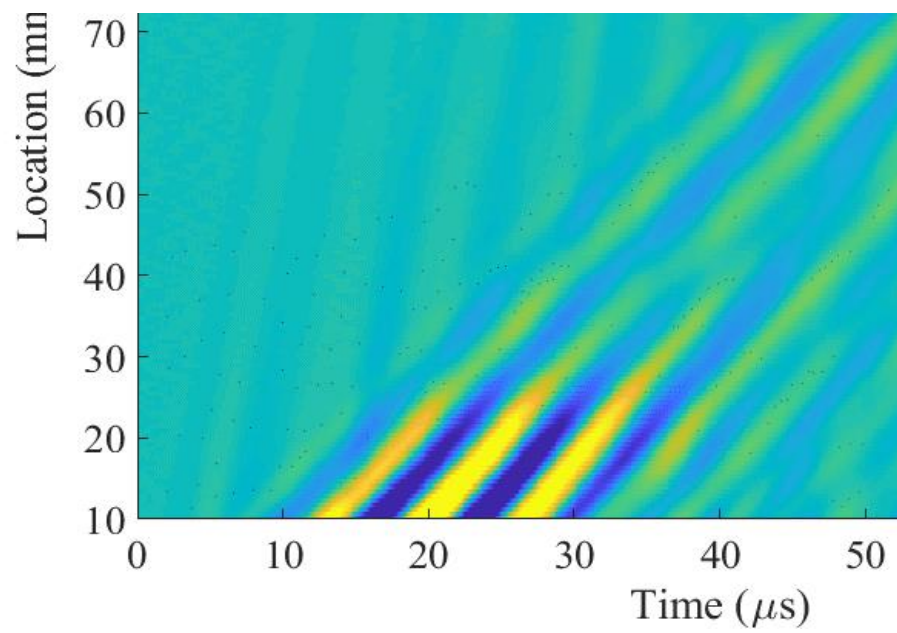


Figure 63 Time-space wavefield for 15.5-mm IM7G-8552 unidirectional CFRP composite plate in the 0° direction.

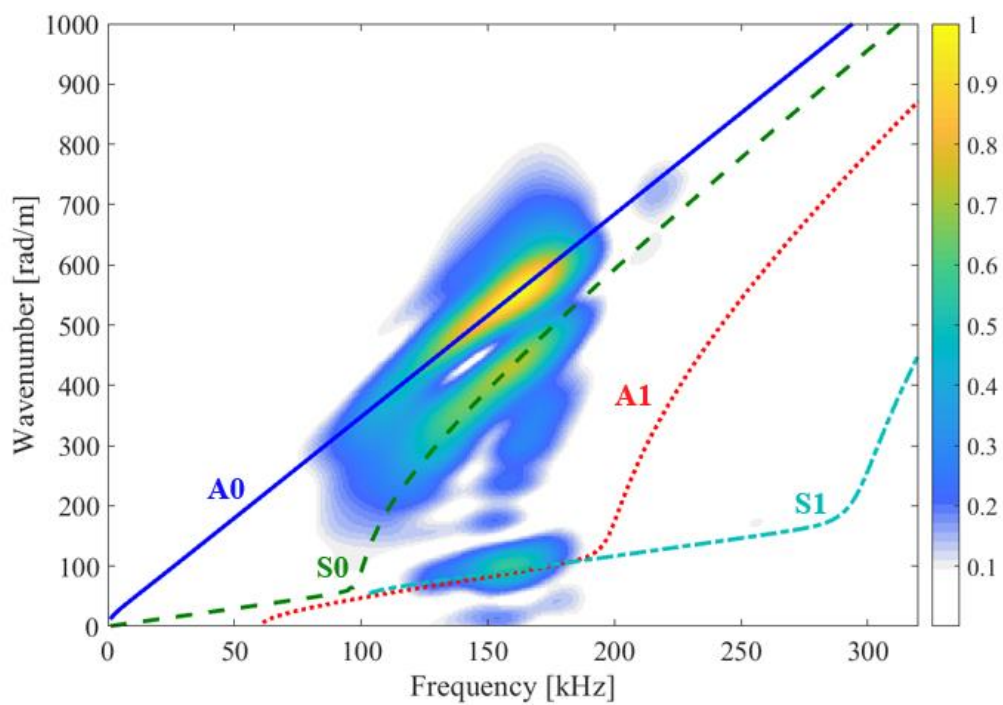


Figure 64 Comparison between measured and predicted frequency-wavenumber dispersion curves in the 0° direction.

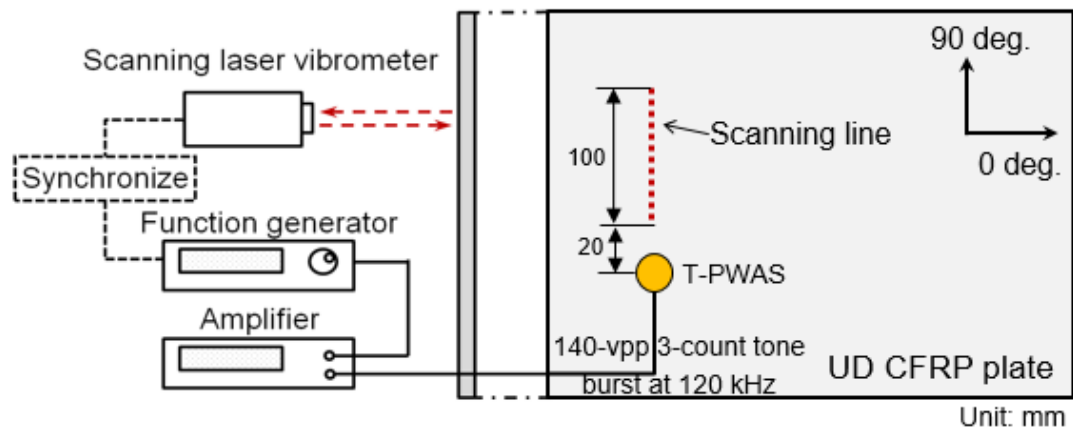


Figure 65 Schematic of the hybrid PWAS-SLDV system: SLDV line scan in the 90° direction at 120 kHz.

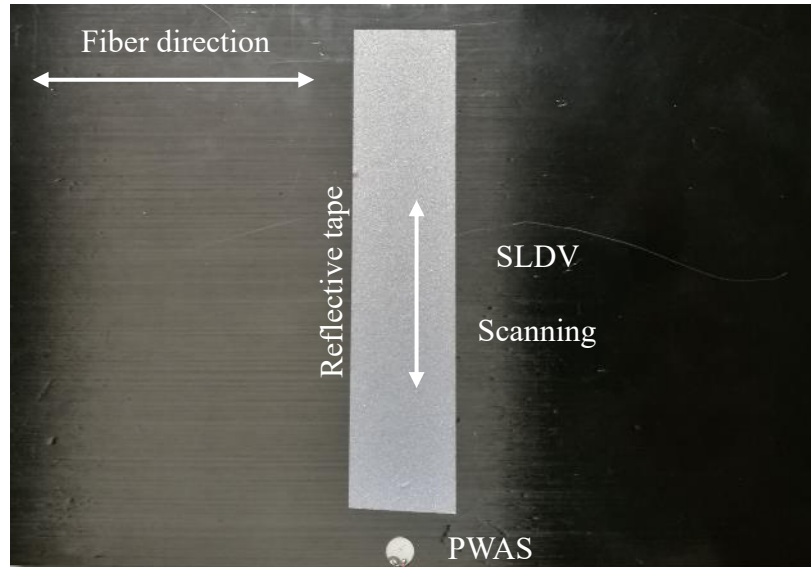


Figure 66 15.5-mm IM7G-8552 unidirectional CFRP composite plate used for the validation in the 90° direction.

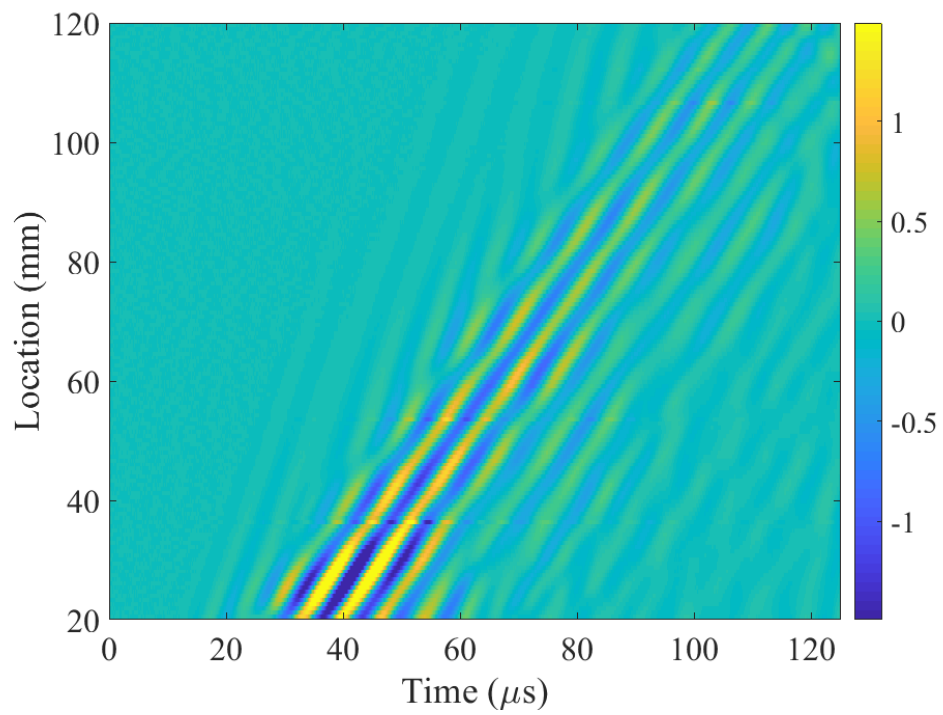


Figure 67 Time-space wavefield for 15.5-mm IM7G-8552 unidirectional CFRP composite plate in the 90° direction.

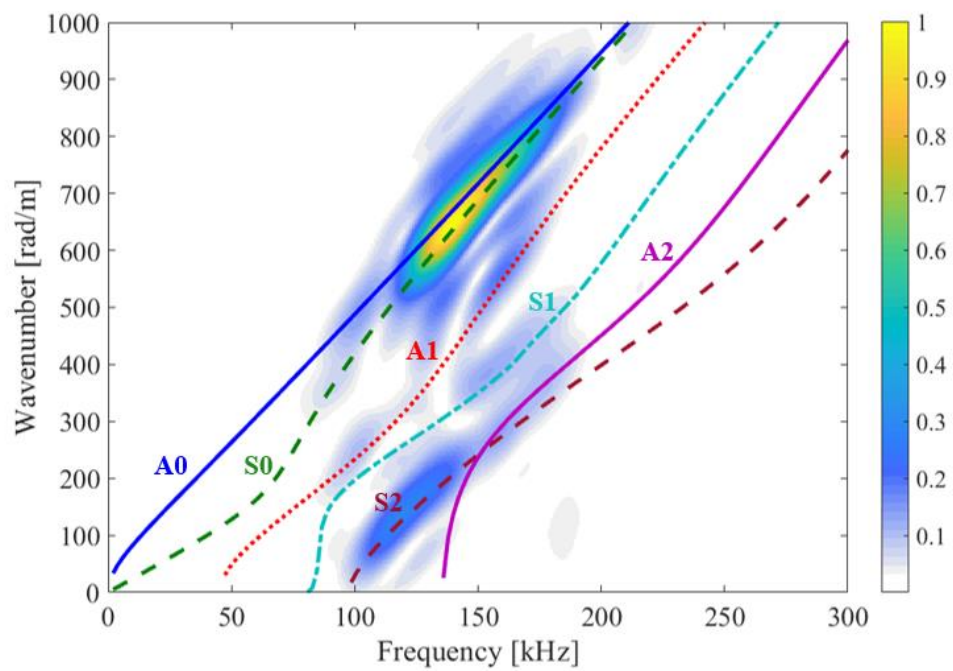


Figure 68 Comparison between experimental and predicted wavenumber-frequency dispersion curves in the 90° direction.

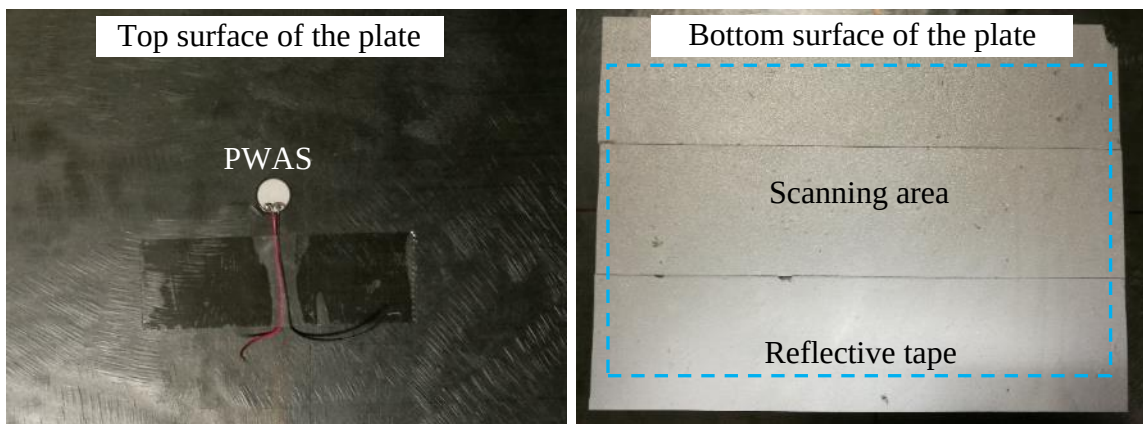


Figure 69 PWAS-SLDV experimental setup on the 1.8-mm thick CFRP composite plate.

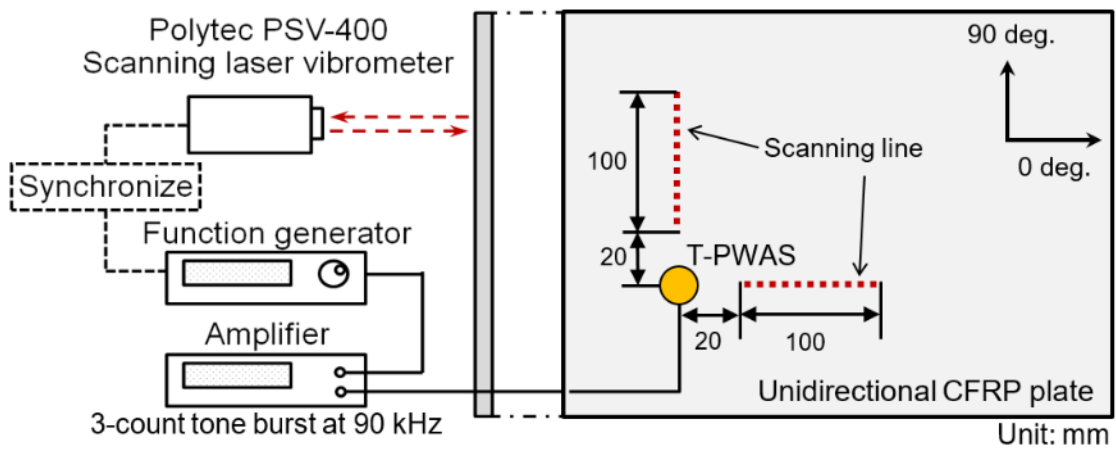


Figure 70 Schematic of the hybrid PWAS-SLDV system: line scan in the 0° and 90° directions.

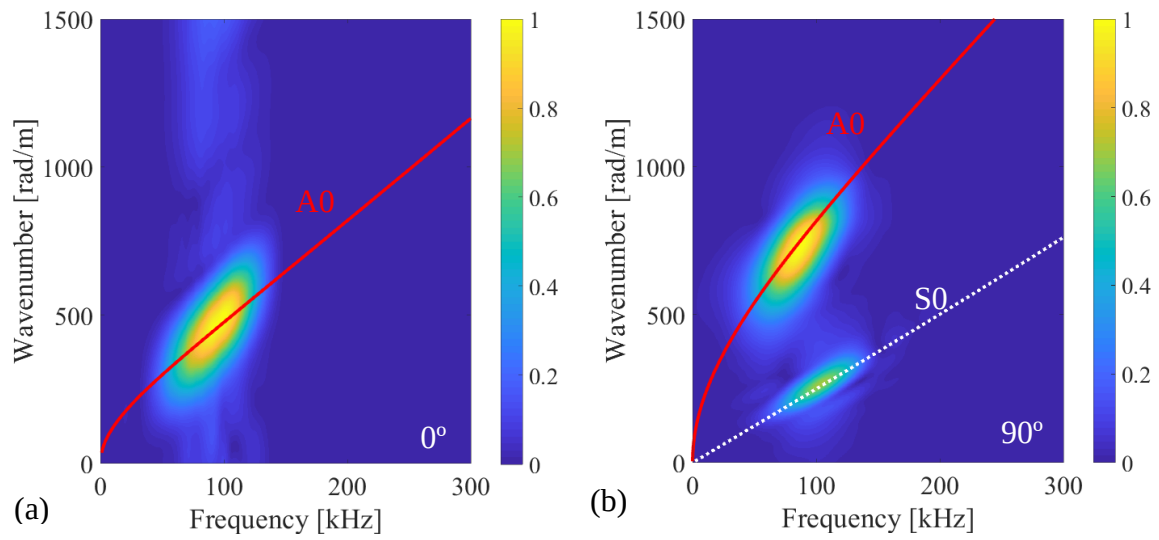


Figure 71 Comparison between experimental and predicted frequency-wavenumber dispersion curves: (a) 0° (fiber direction) (b) 90° (transverse direction).

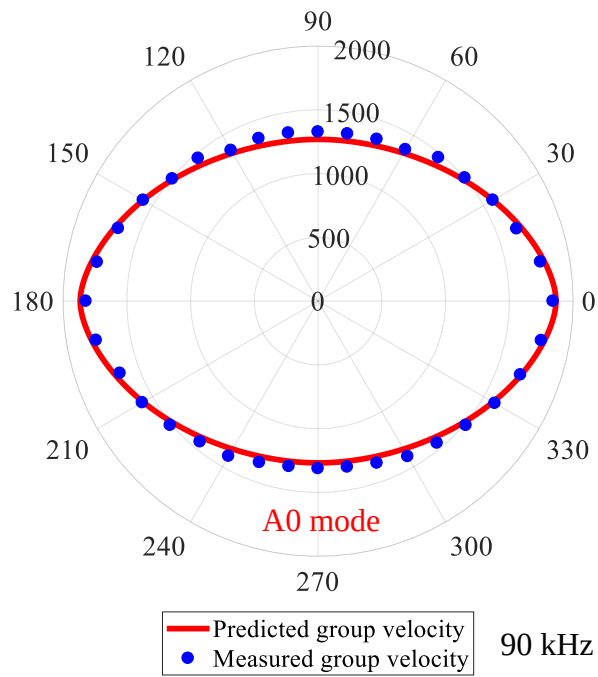


Figure 72 Directivity plot of the measured and predicted group velocities for A0 mode wave in the unidirectional composite plate.

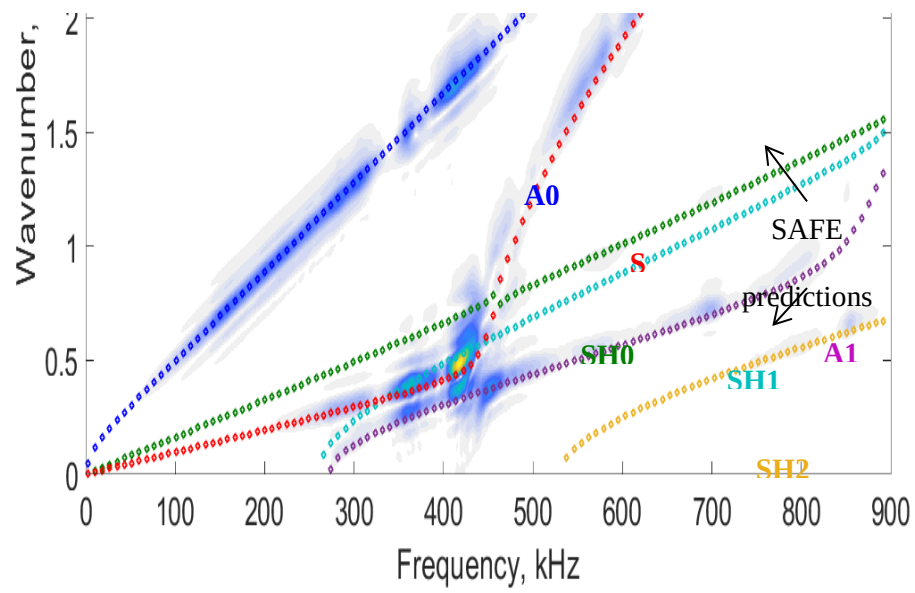


Figure 73 Comparison between experimental and theoretical frequency-wavenumber dispersion curves in the 0° direction.

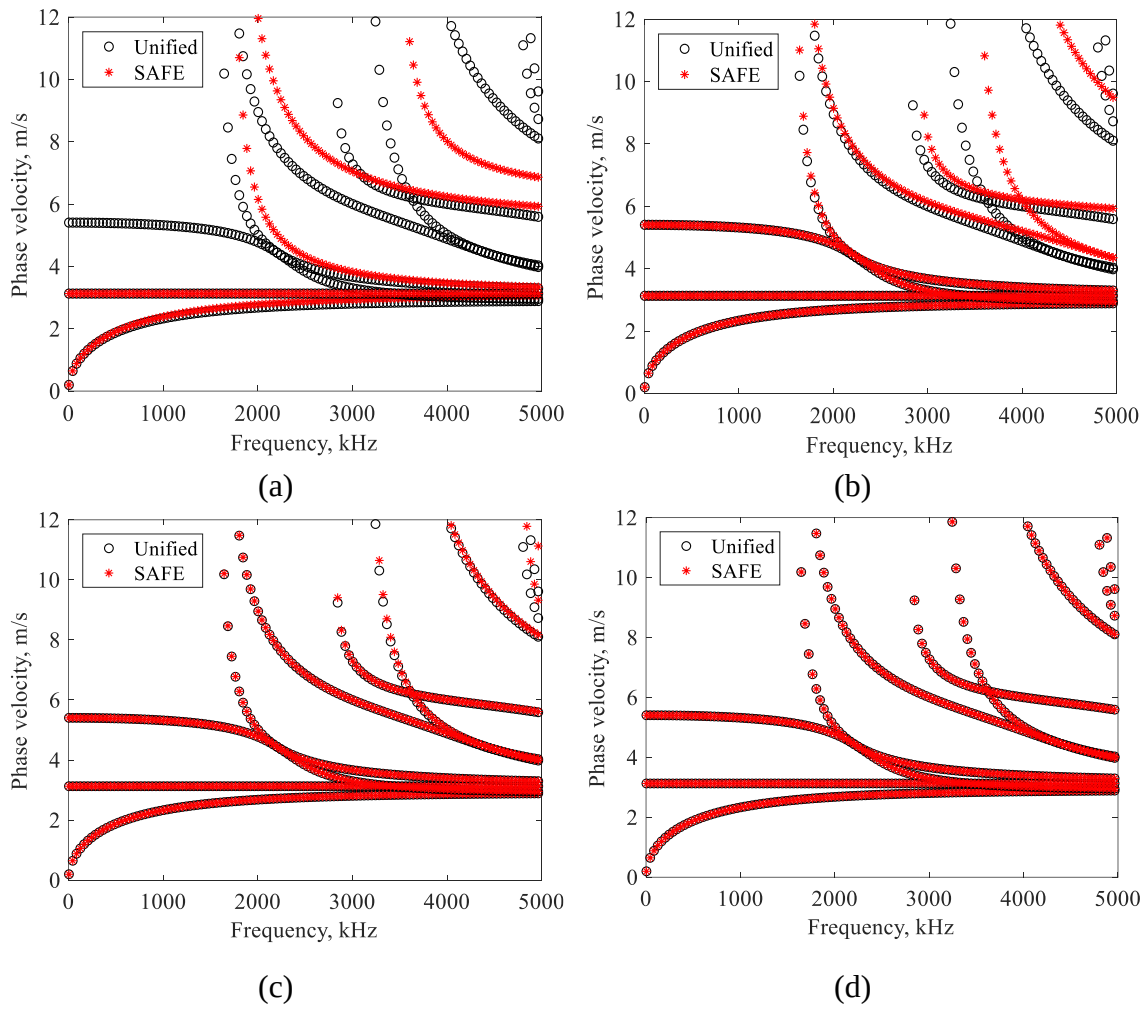


Figure 74 Convergence study of the SAFE approach for a 1-mm aluminum plate: (a) 1 element; (b) 2 elements; (c) 5 elements; (d) 15 elements.

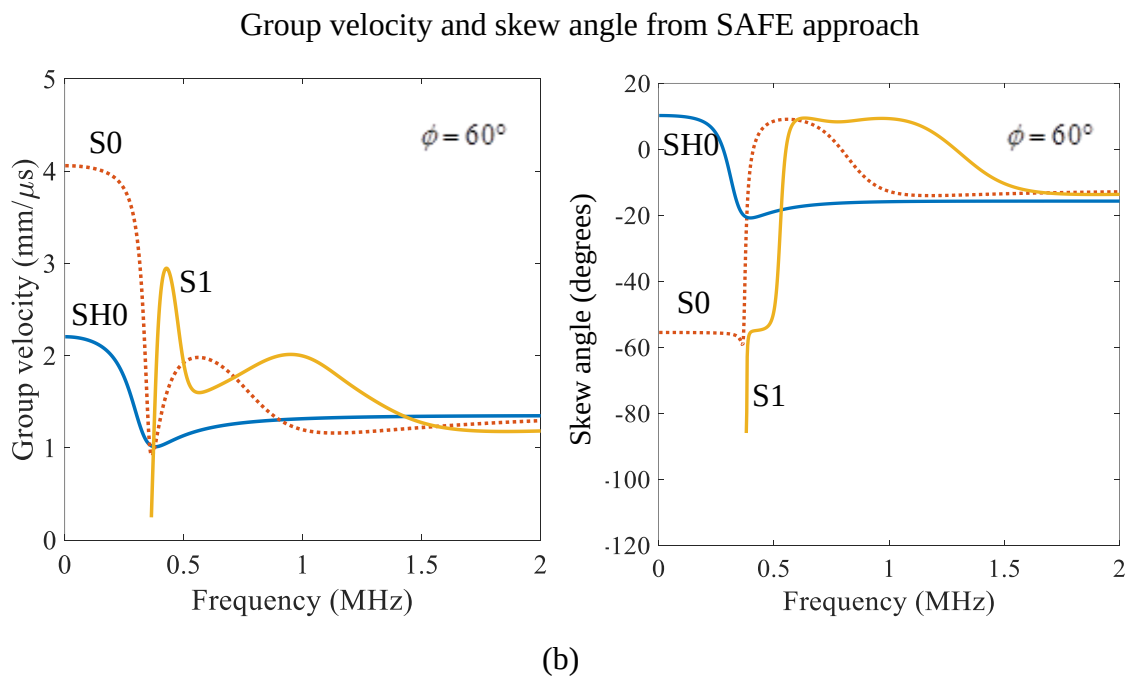
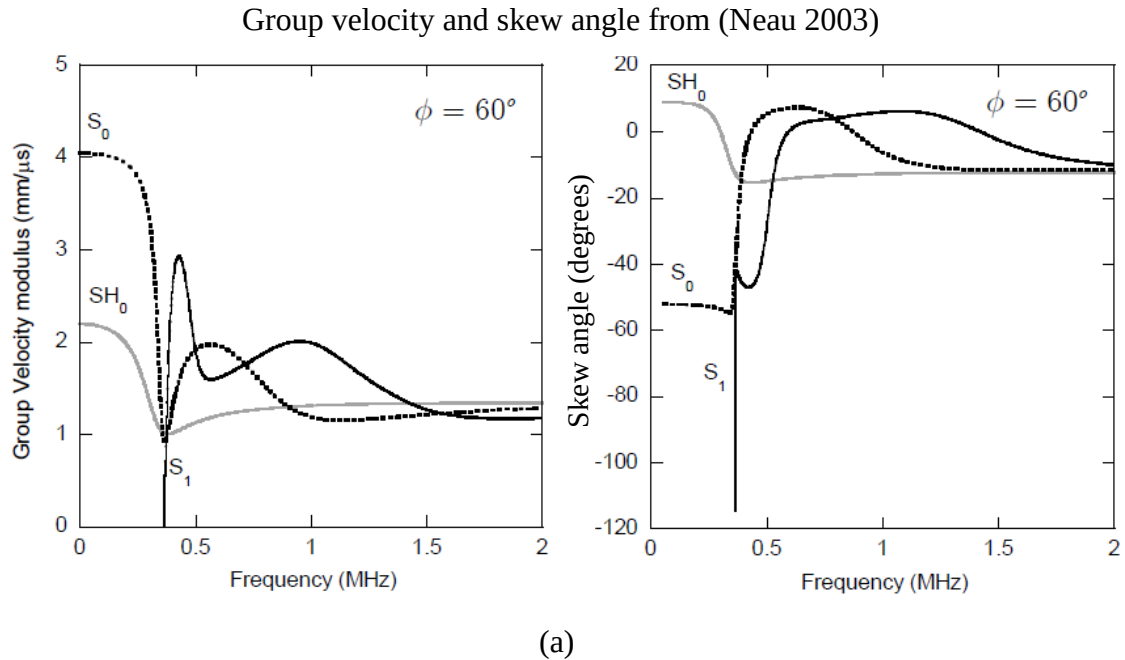


Figure 75 Comparison of the calculation of group velocity and skew angle between analytical method and SAFE approach in the 60° direction for symmetric modes: (a) ref. (Neau 2003); (b) current work.

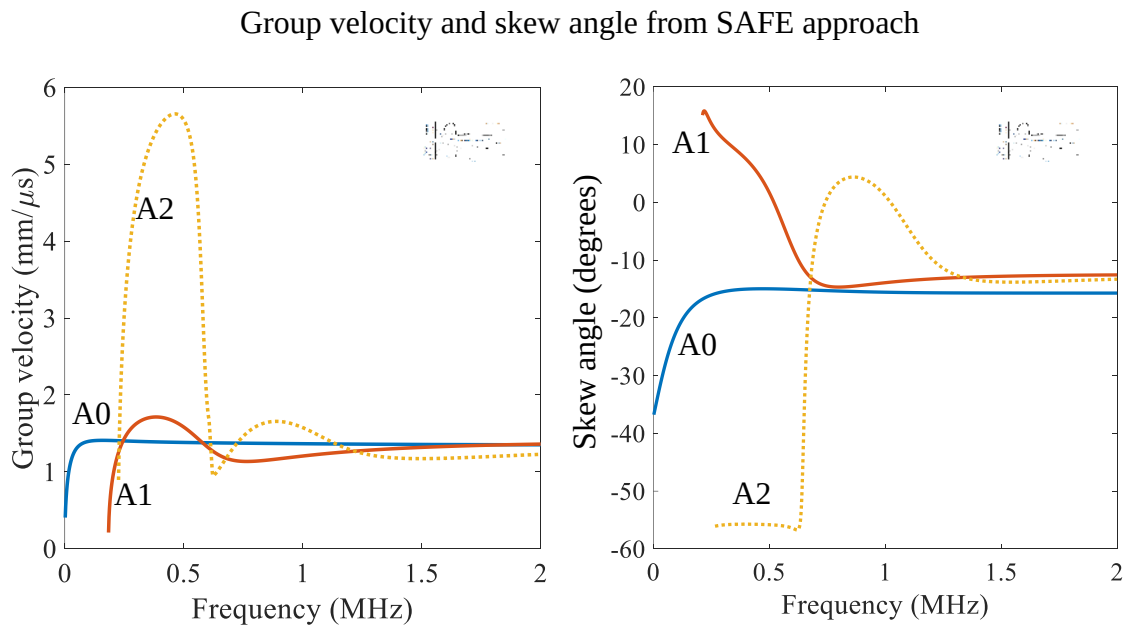
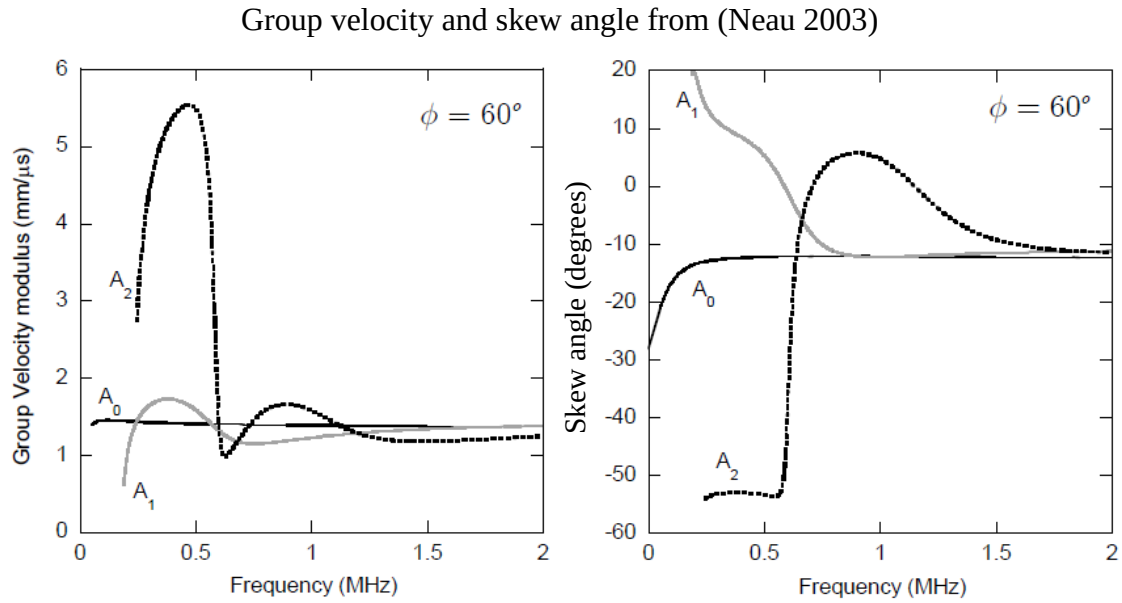


Figure 76 Comparison of the calculation of group velocity and skew angle between analytical method and SAFE approach in the 60° direction for anti-symmetric modes: (a) ref. (Neau 2003); (b) current work.

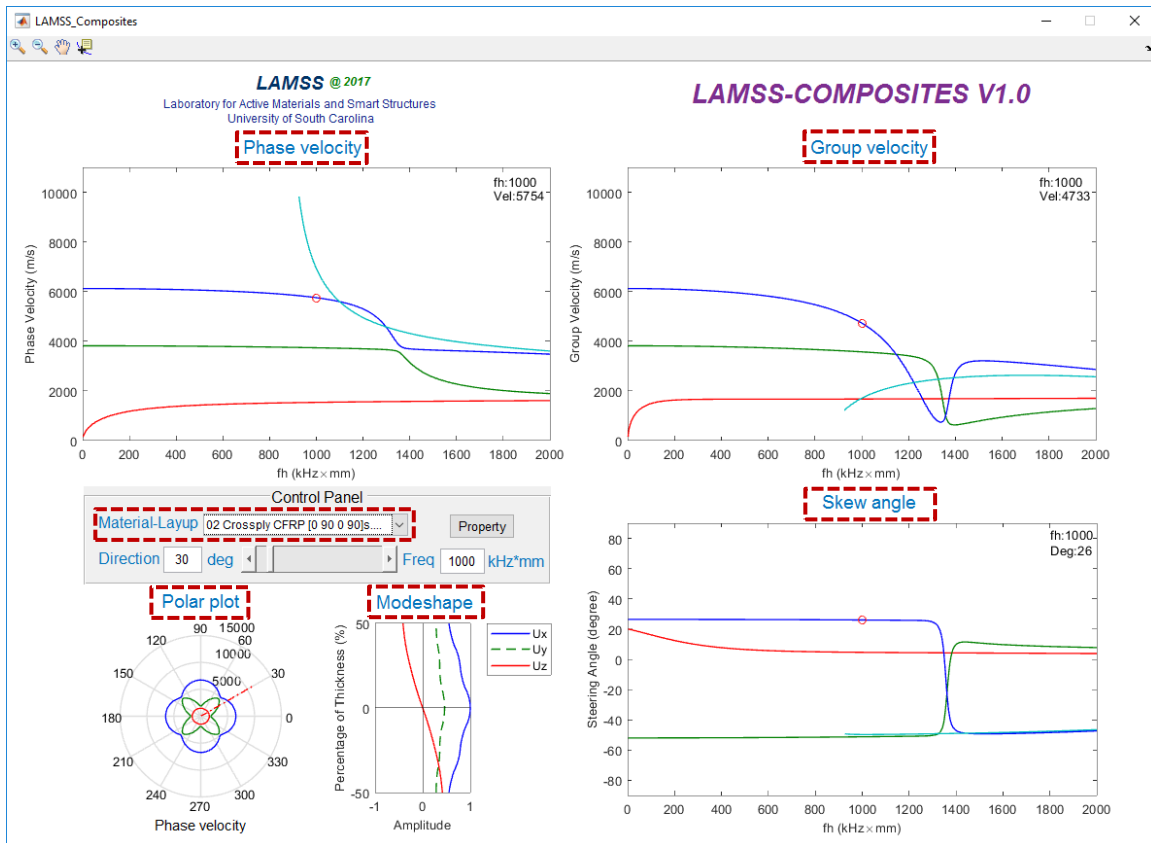


Figure 77 Main interface of LAMSS-COMPOSITES: phase velocity, group velocity, and skew angle for the 30-deg propagation in a $[0/90]_{2s}$ crossply CFRP laminate.



Figure 78 'Material-Layup' pop-up menu for choosing database.

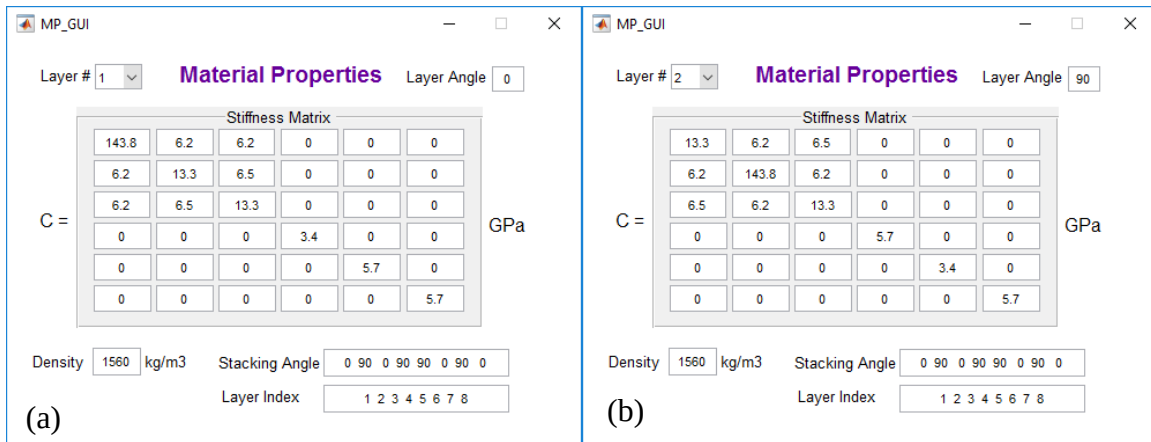


Figure 79 Material properties for the crossply CFRP composite plate $[0/90]_{2s}$: (a) Layer #1; (b) Layer #2.

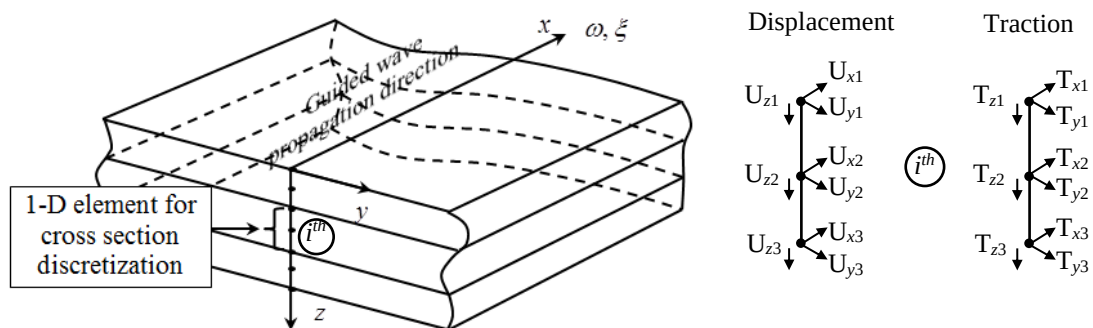


Figure 80 SAFE model of 1D guided wave propagation.

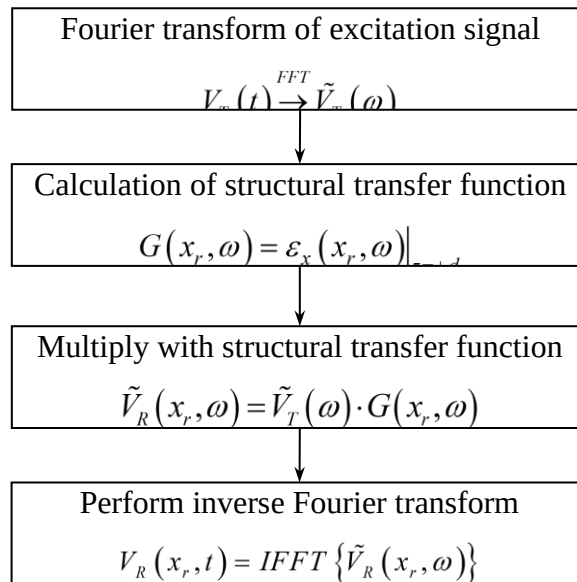


Figure 81 Flow chart of time domain simulation for 1D guided wave propagation.

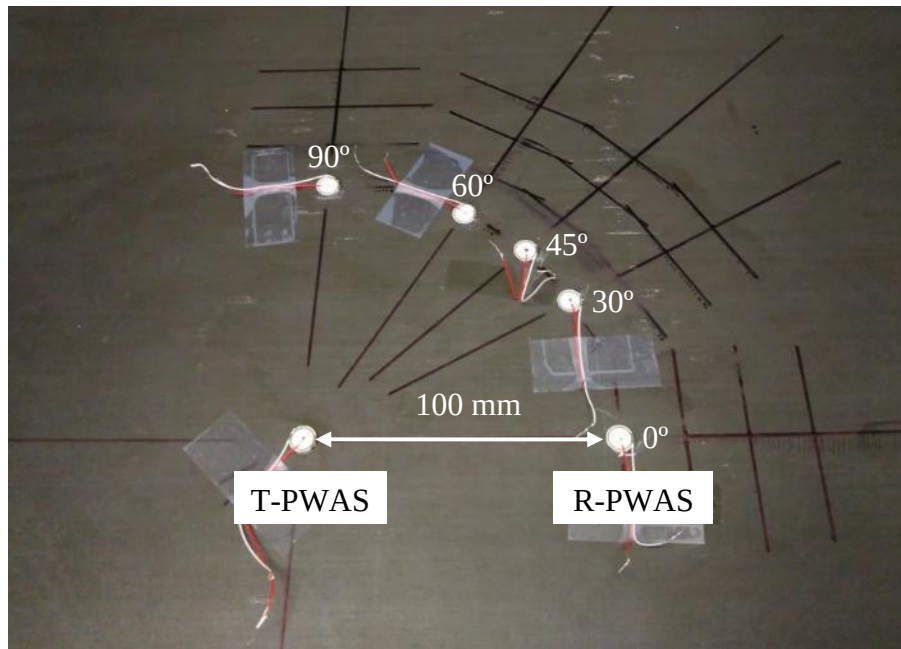


Figure 82 Experimental setup on the 1.8-mm unidirectional CFRP plate.

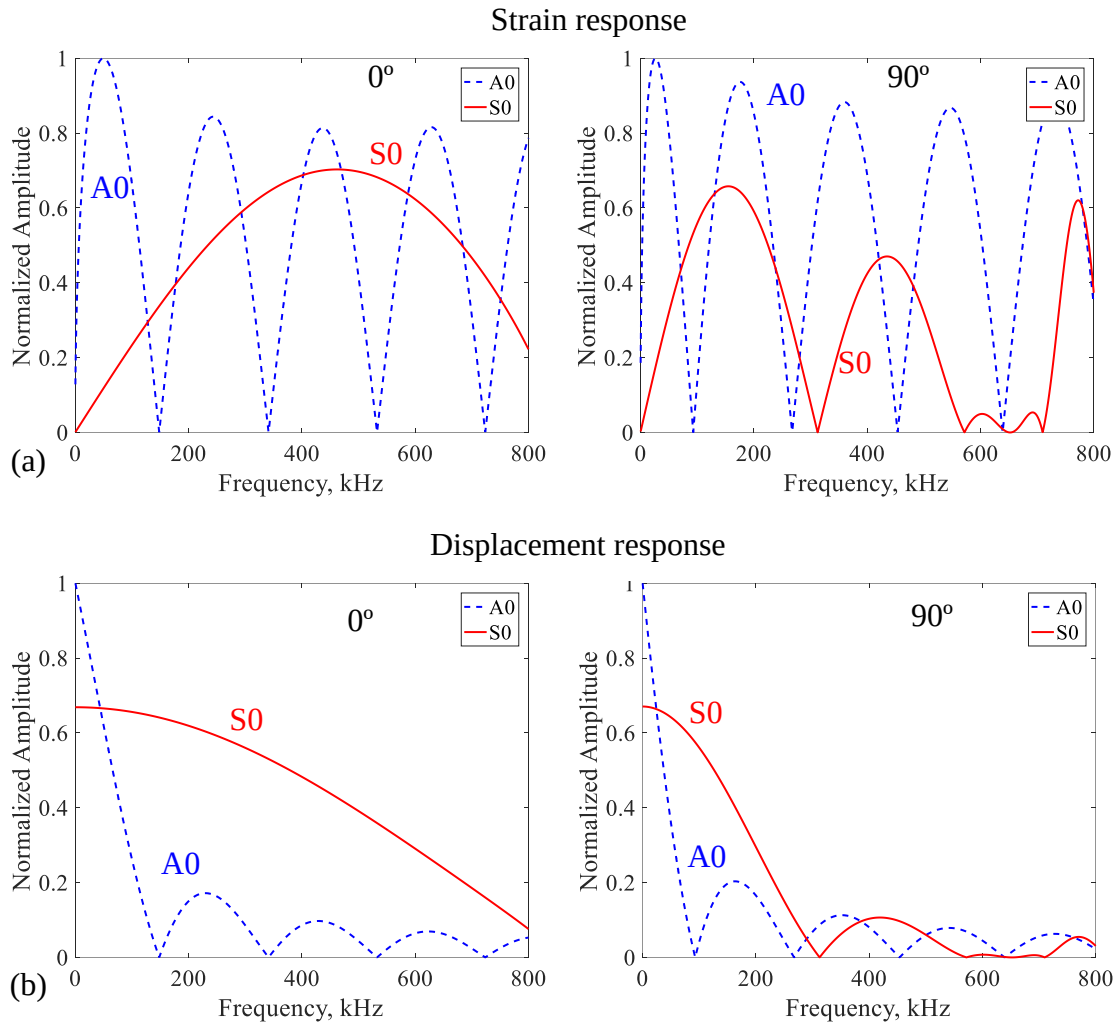
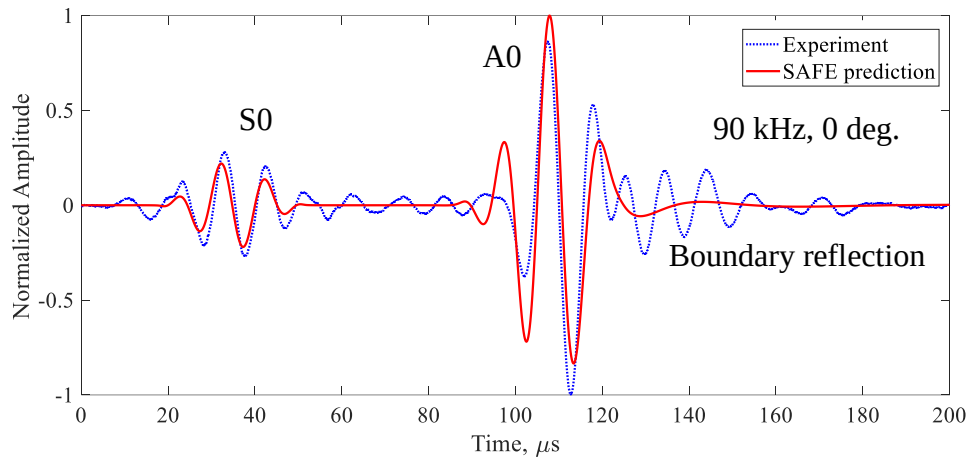
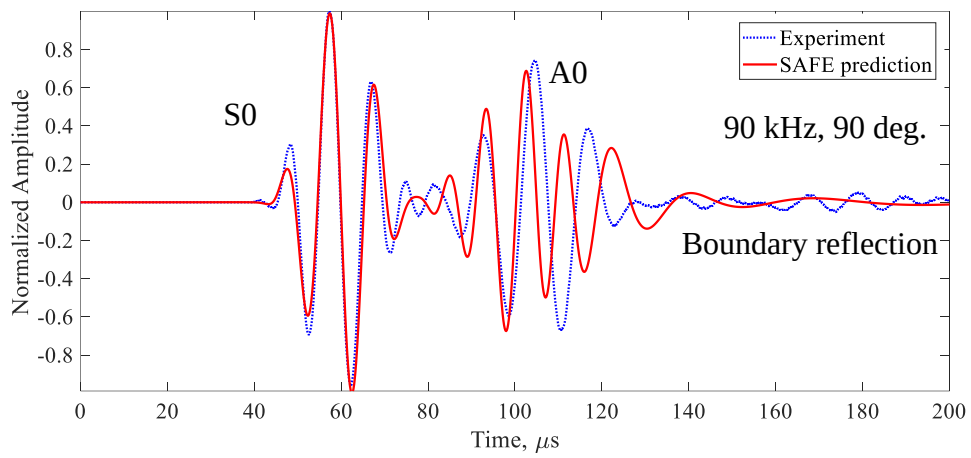


Figure 83 Tuning curves of the unidirectional composite plate in the 0° and 90° predicted by SAFE approach: (a) strain response ε_x ; (b) displacement response u_x .



(a)



(b)

Figure 84 Comparison between the experiment and SAFE prediction at 90 kHz excitation: (a) 0° (fiber direction); (b) 90° (transverse direction).

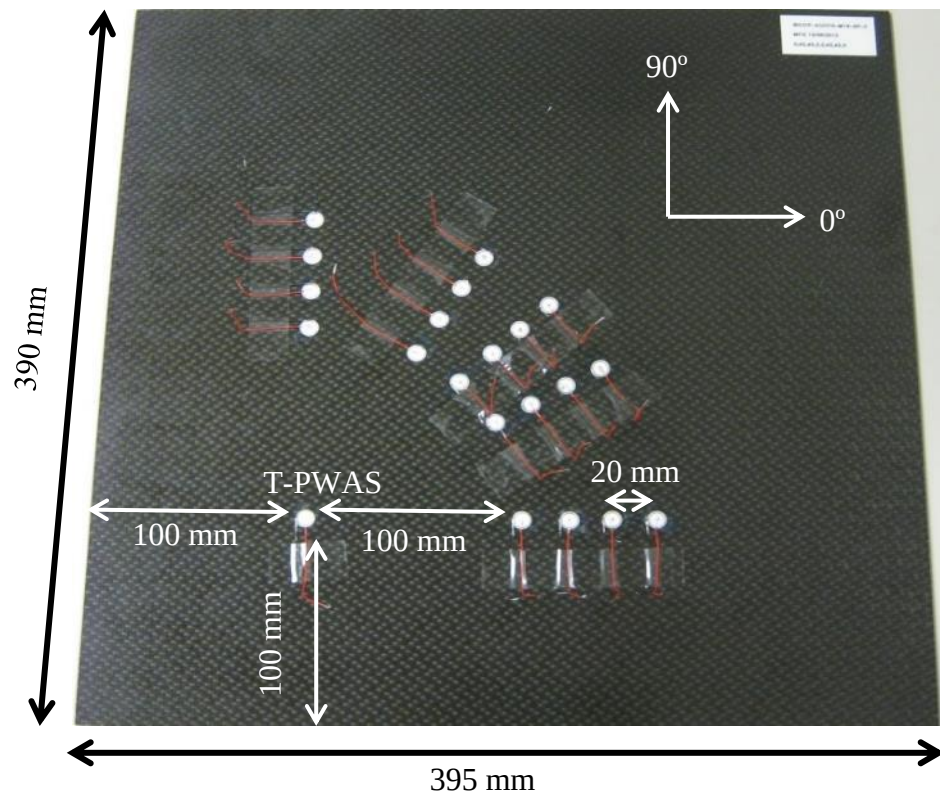


Figure 85 Experimental setup on 2-mm woven CFRP plate (Gresil and Giurgiutiu 2015).

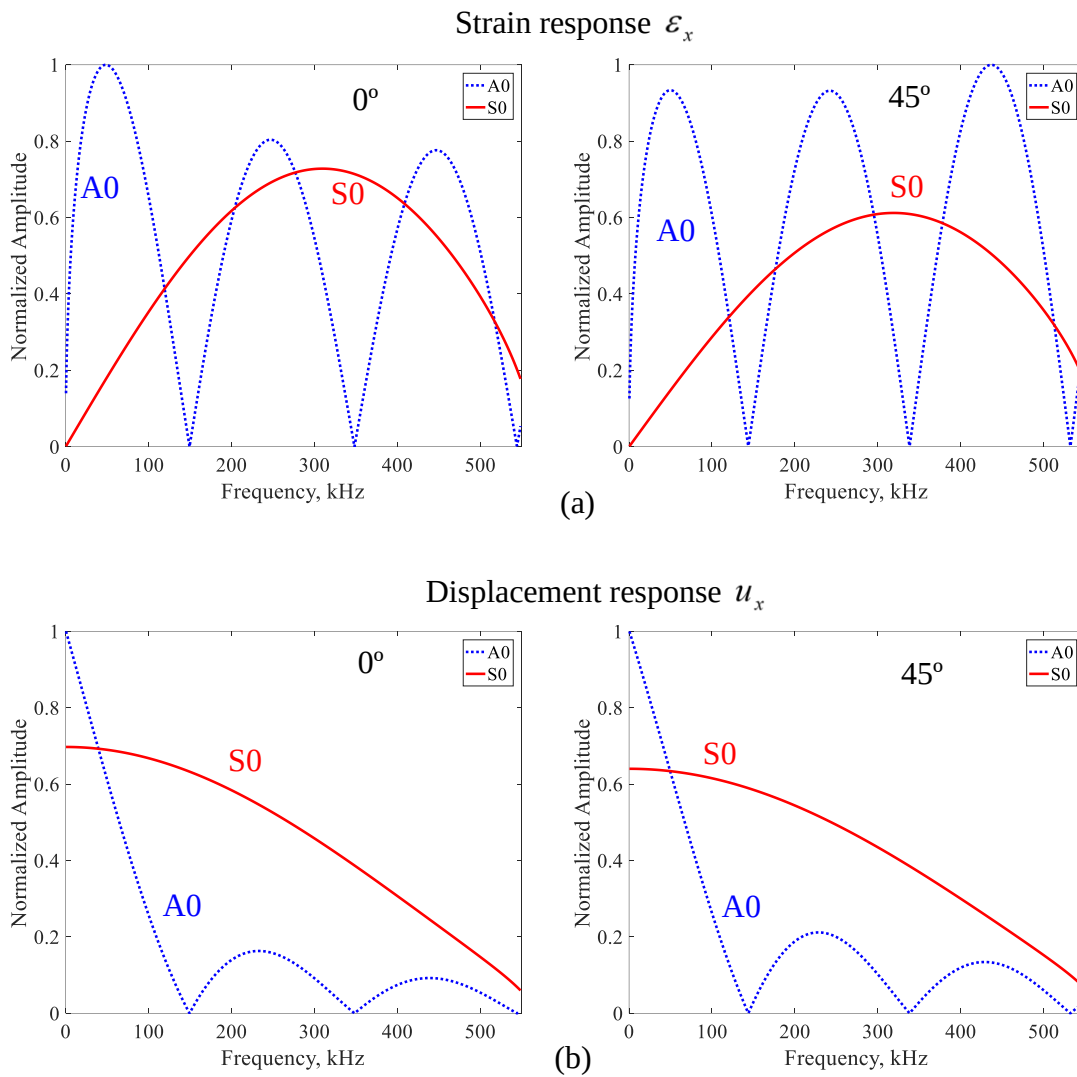
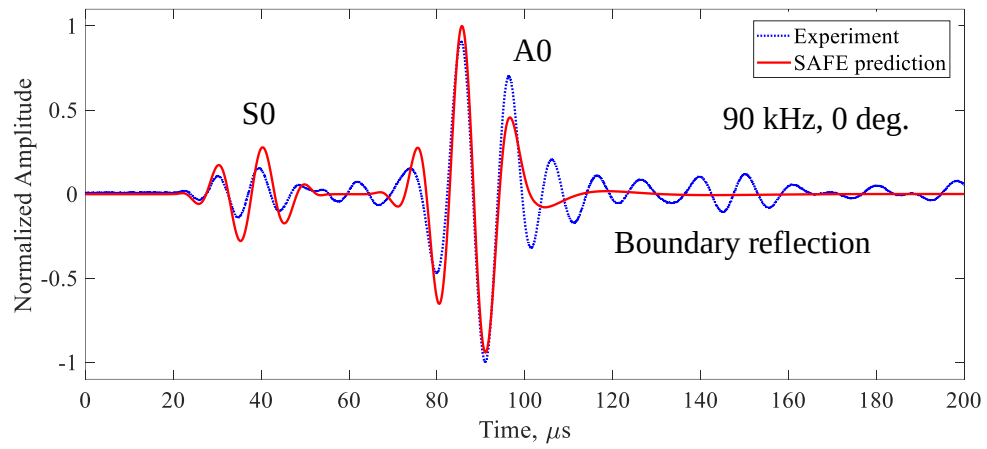
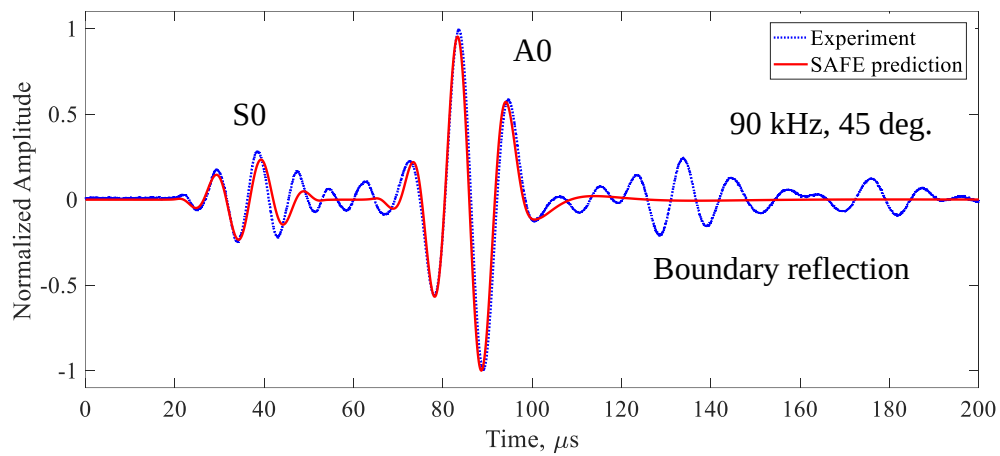


Figure 86 Predicted tuning curves of the woven composite plate in the 0° and 45° directions: (a) strain response ε_x ; (b) displacement response u_x .



(a)



(b)

Figure 87 Waveform comparison between SAFE prediction and experiment at 90 kHz excitation: (a) 0°; (b) 45°.

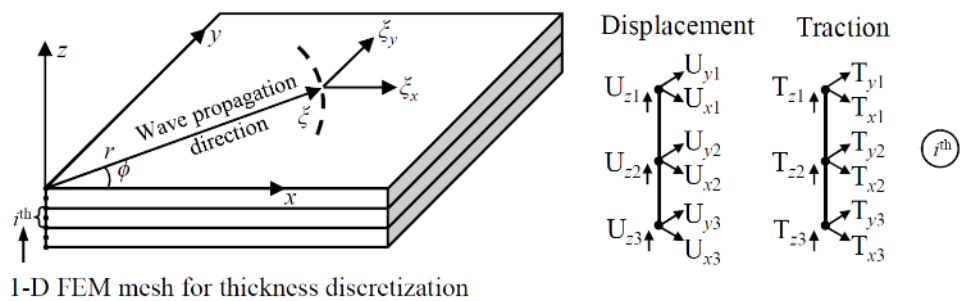


Figure 88 SAFE model of guided wave propagation.

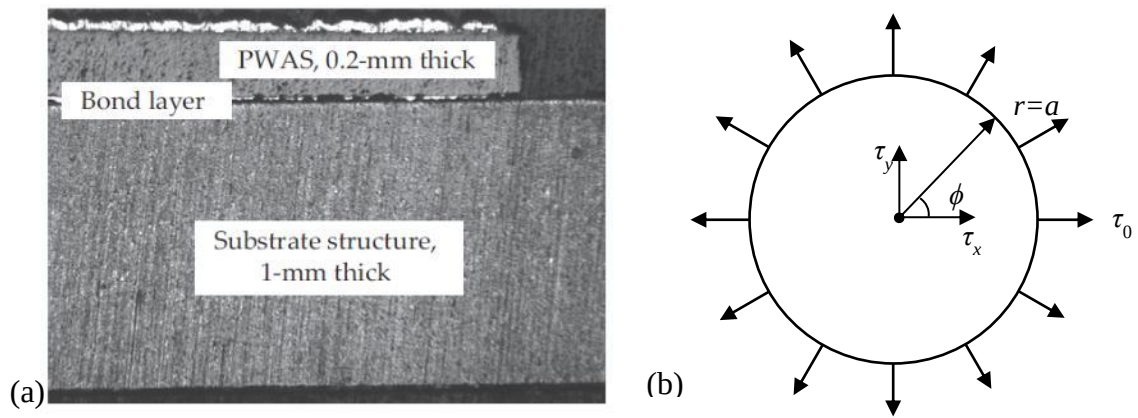


Figure 89 Interaction between the PWAS and the host structure: (a) micrograph picture of an actual PWAS installed on a 1-mm plate (Giurgiutiu 2014); (b) schematic model showing surface shear stress of ideal bonding.

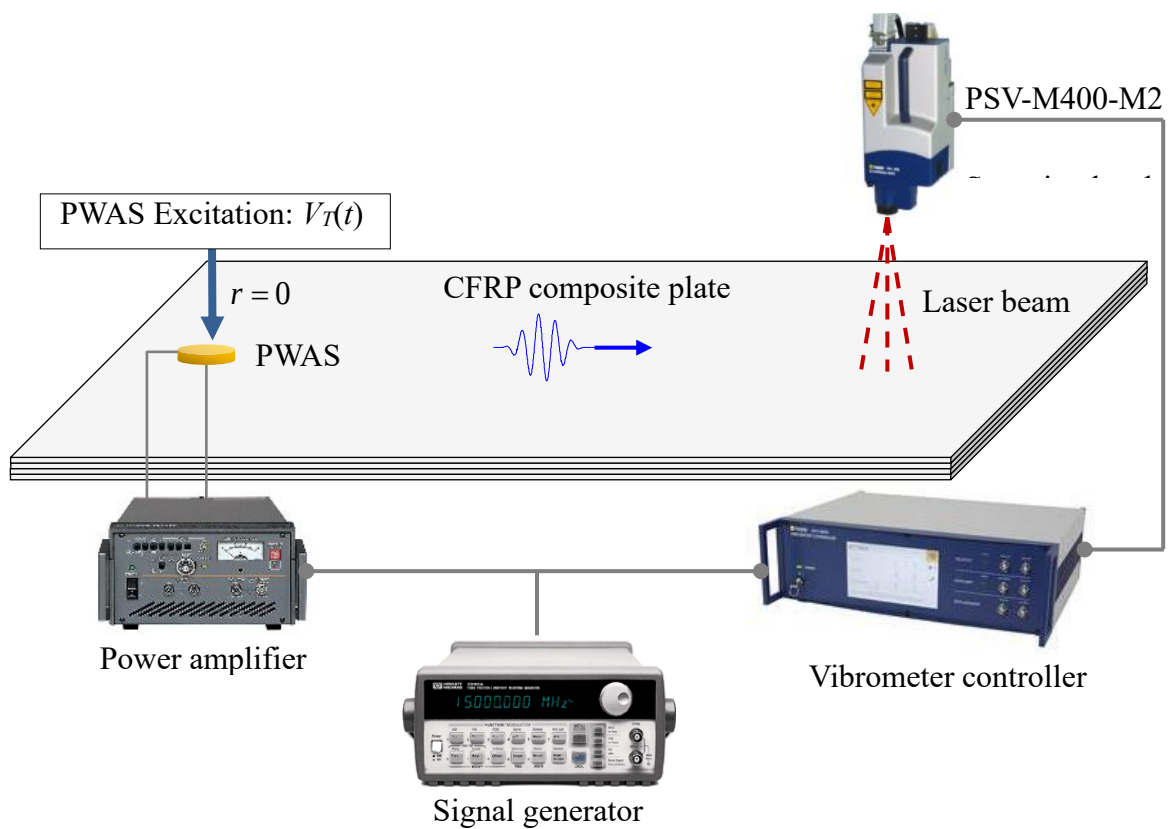


Figure 90 Experimental setup of the hybrid SLDV-PWAS measurements.

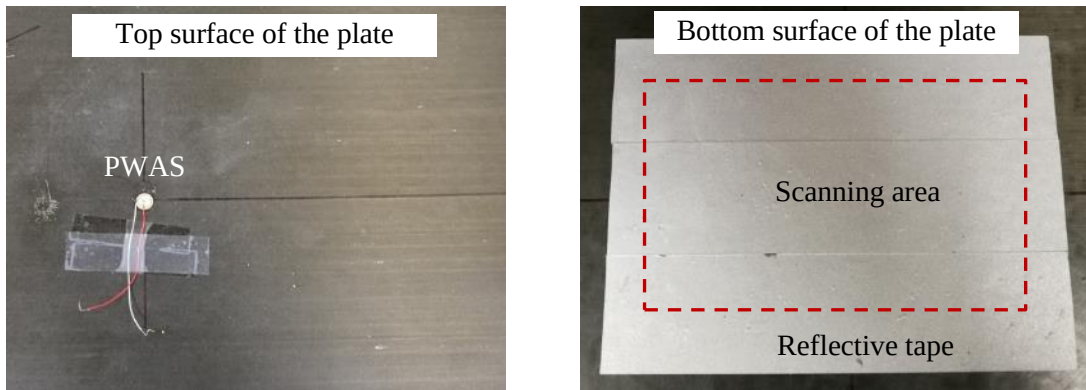


Figure 91 Experimental setup on the 1.8-mm thick unidirectional CFRP composite plate.

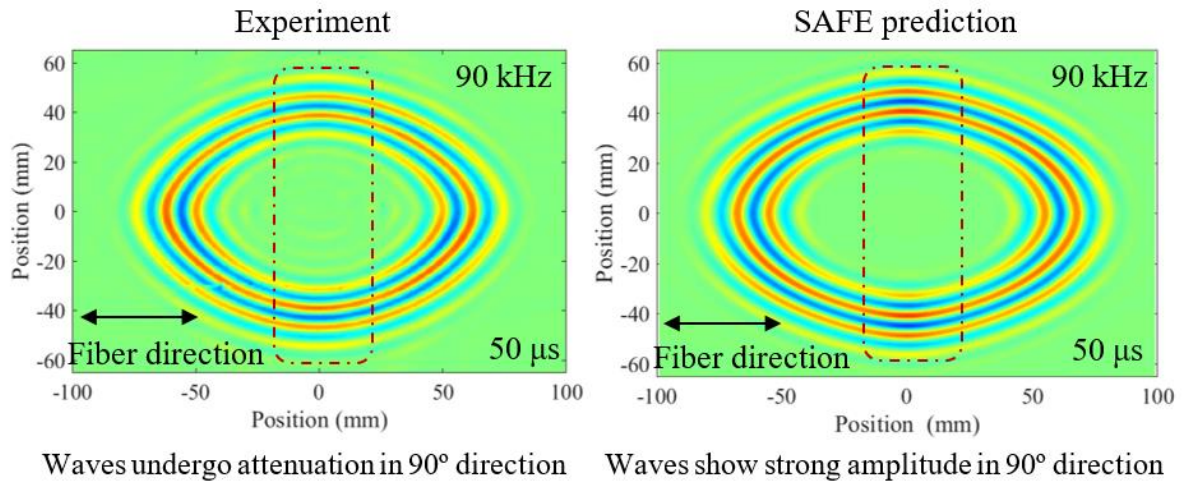


Figure 92 Guided-wave propagation patterns in the unidirectional CFRP composite plate: (a) experiment; (b) SAFE prediction.

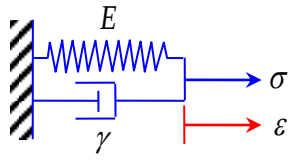


Figure 93 The Kelvin-Voigt damping model.

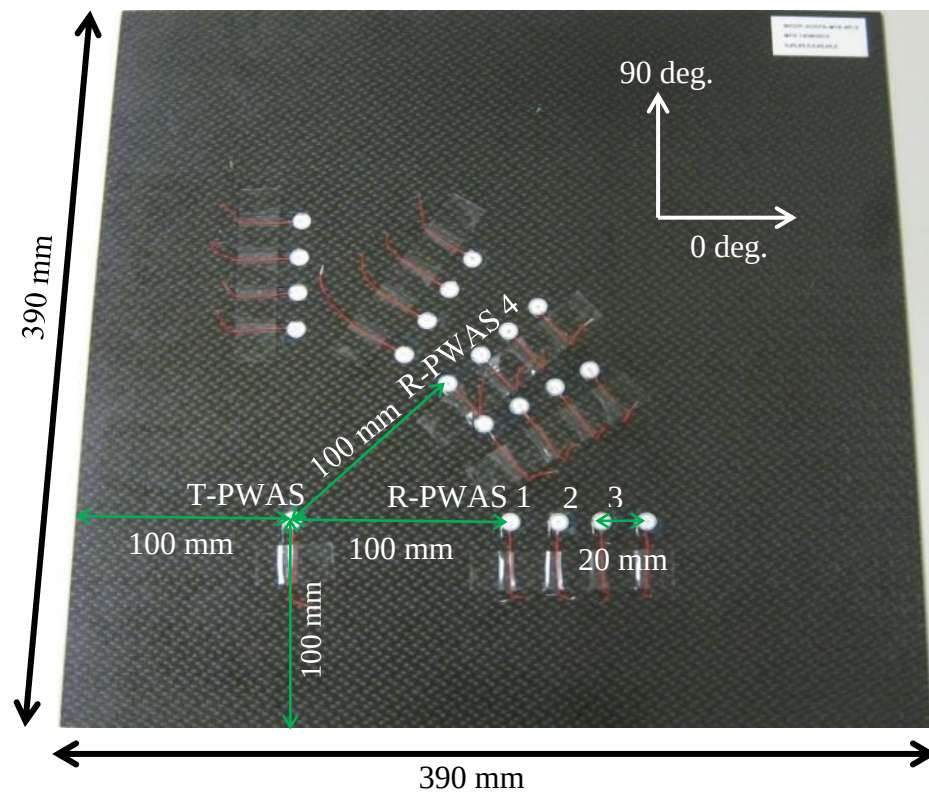


Figure 94 Experimental setup on the composite plate from (Gresil and Giurgiutiu 2015).

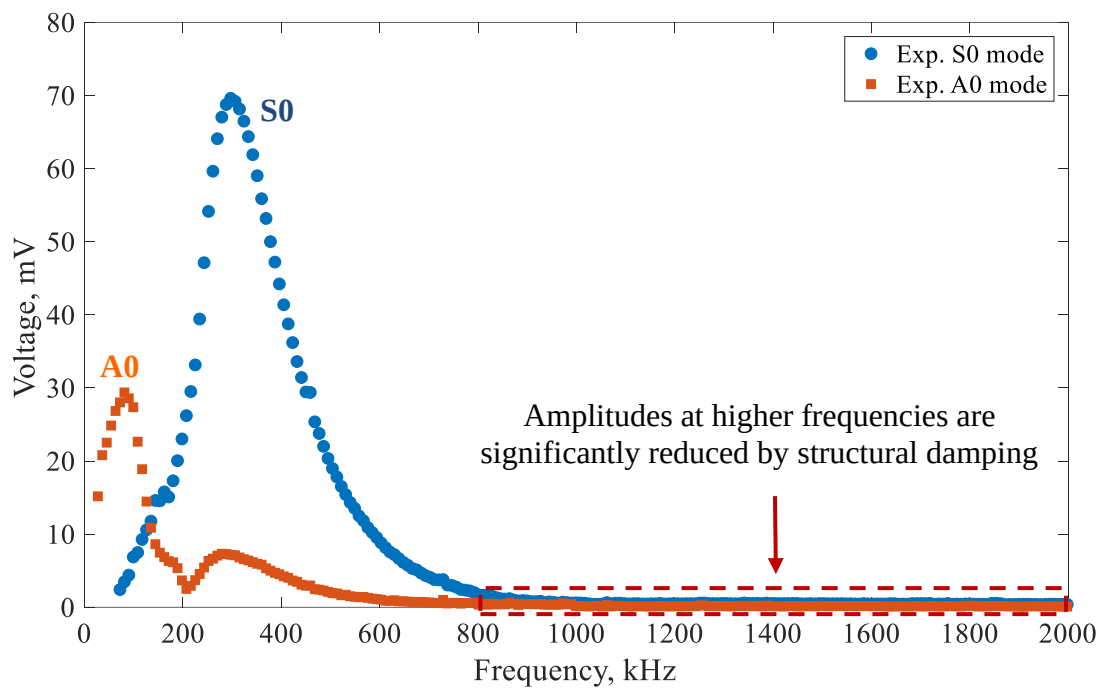


Figure 95 Experimental tuning curves with damping at 100 mm in the 0° direction (9-mm-diameter circular PWAS, 2-mm woven composite plate).

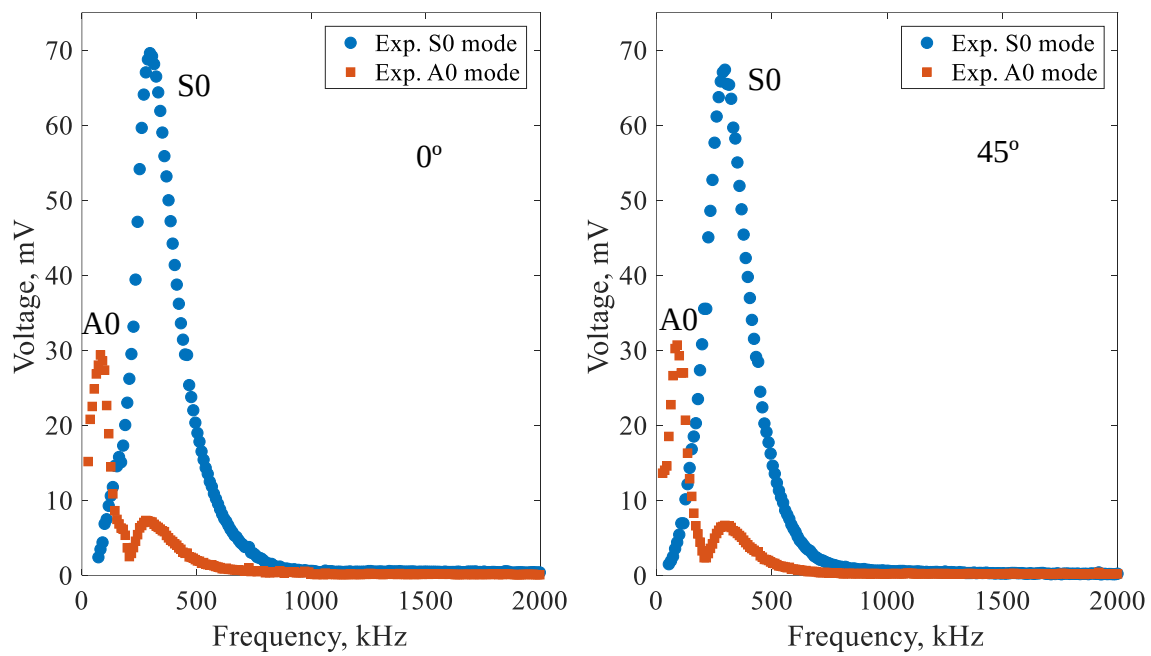


Figure 96 Comparison between tuning curves in the 0° and 45° directions (9-mm-diameter circular PWAS, 2-mm woven composite plate).

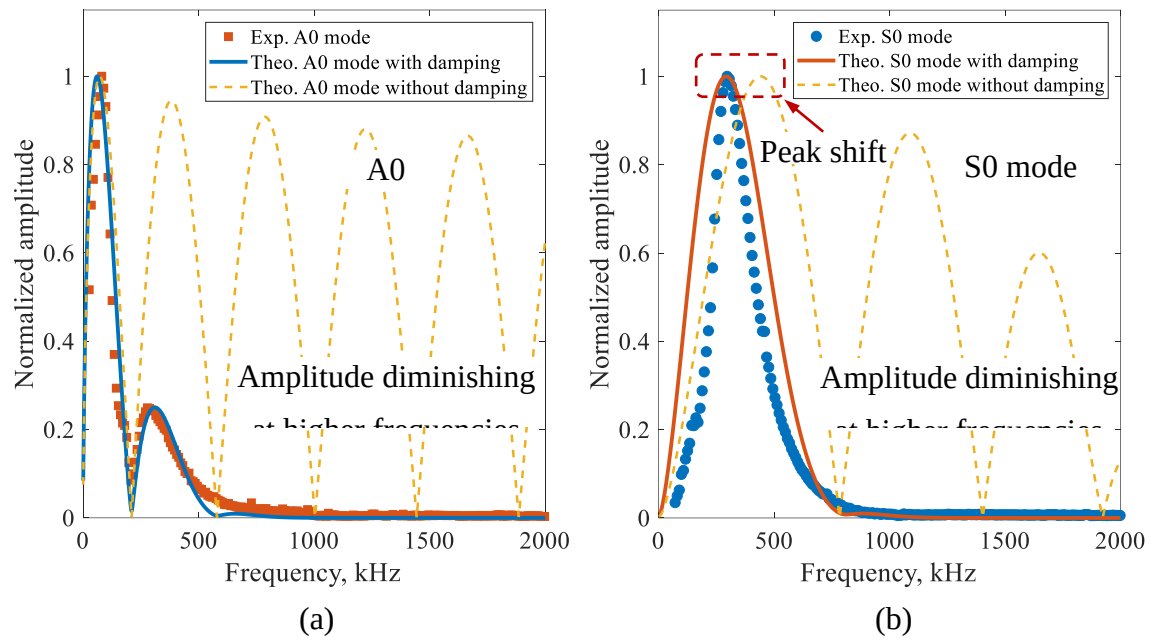


Figure 97 Comparison between experimental and theoretical 2D Lamb-wave tuning curves: (a) A0 mode; (b) S0 mode ($\eta_0 = 12\%$, $f_0 = 1.5$ MHz, 9-mm-diameter circular PWAS, 2-mm woven composite plate, circular crested Lamb waves).

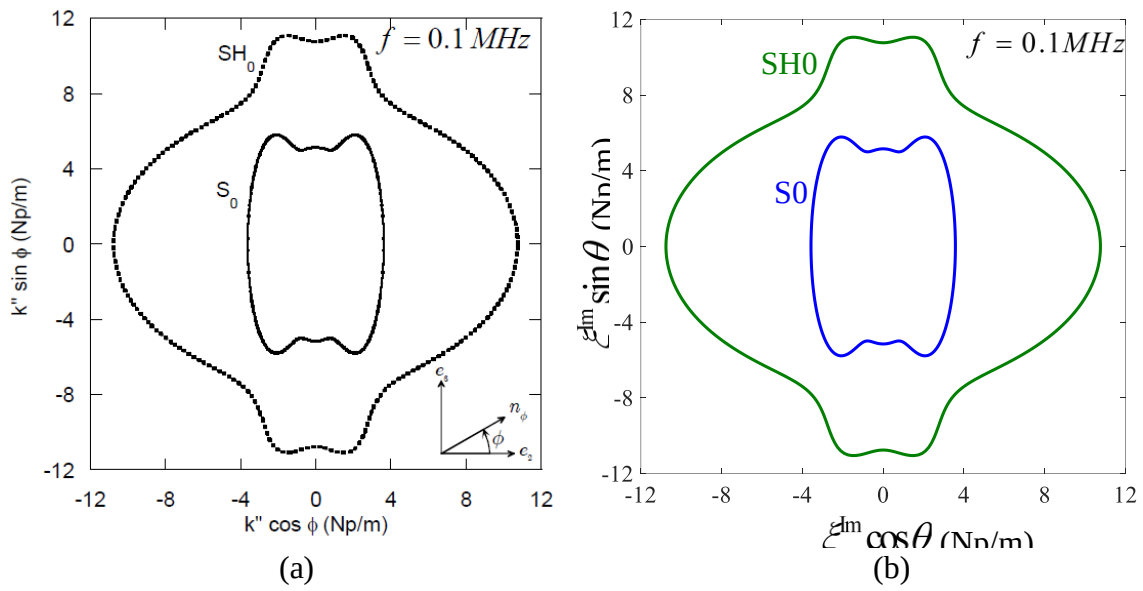


Figure 98 Verification of damping attenuation for symmetric modes (S0 and SH0) in the carbon-epoxy plate: (a) ref. (Neau 2003); (b) SAFE predictions.

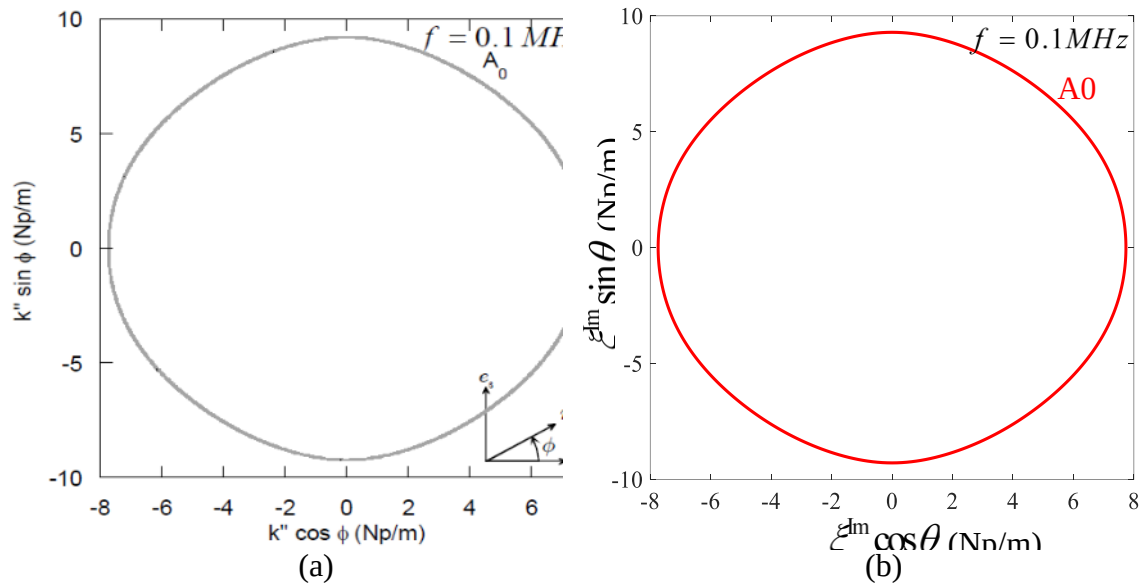


Figure 99 Verification of damping attenuation for anti-symmetric mode (A0) in the carbon-epoxy plate: (a) ref. (Neau 2003); (b) SAFE predictions.

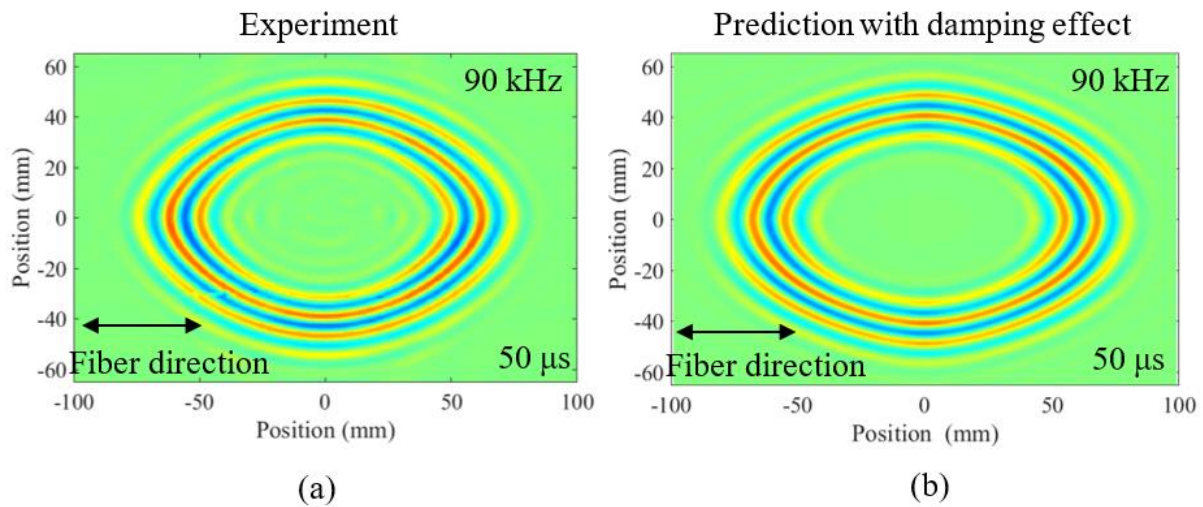


Figure 100 Wave propagation patterns in the CFRP composite plate: (a) experiment; (b) SAFE prediction with damping effect.

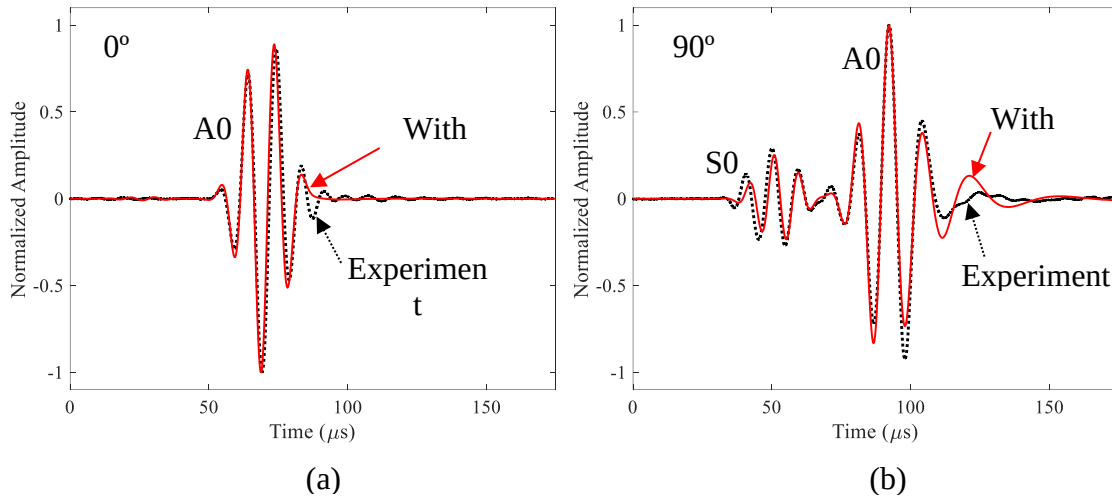


Figure 101 Waveform comparison between experiment and prediction with damping effect in the composite plate: (a) 0° (fiber direction); (b) 90° (transverse direction).

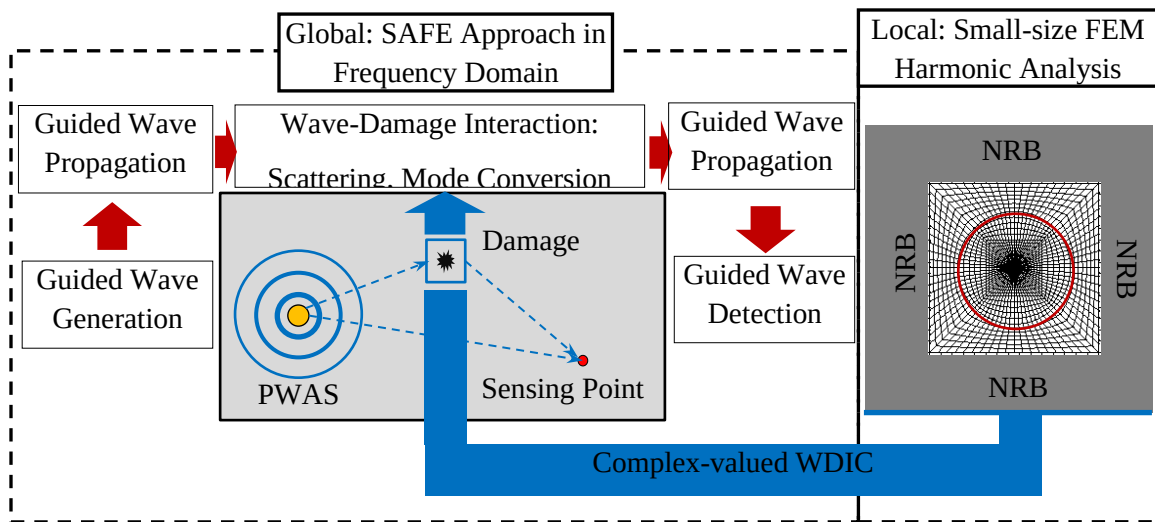
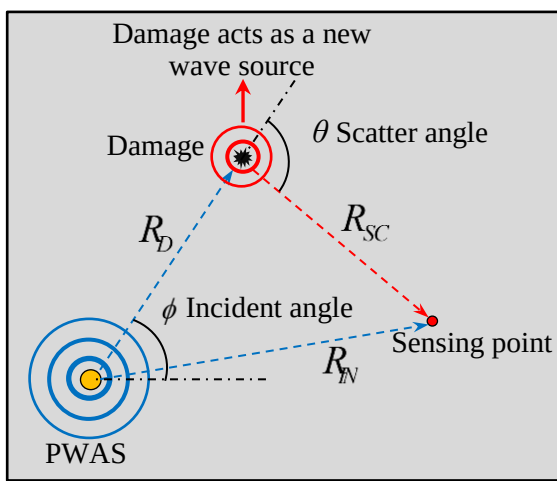


Figure 102 Overview of hybrid global/local (HGL) approach.



Frequency and direction dependent wave-damage interaction coefficients

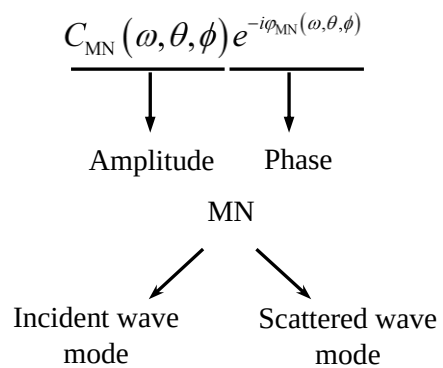


Figure 103 Schematic of guided-wave frequency dependent complex-valued wave damage interaction coefficients (WDIC) (Modified from Shen 2014).

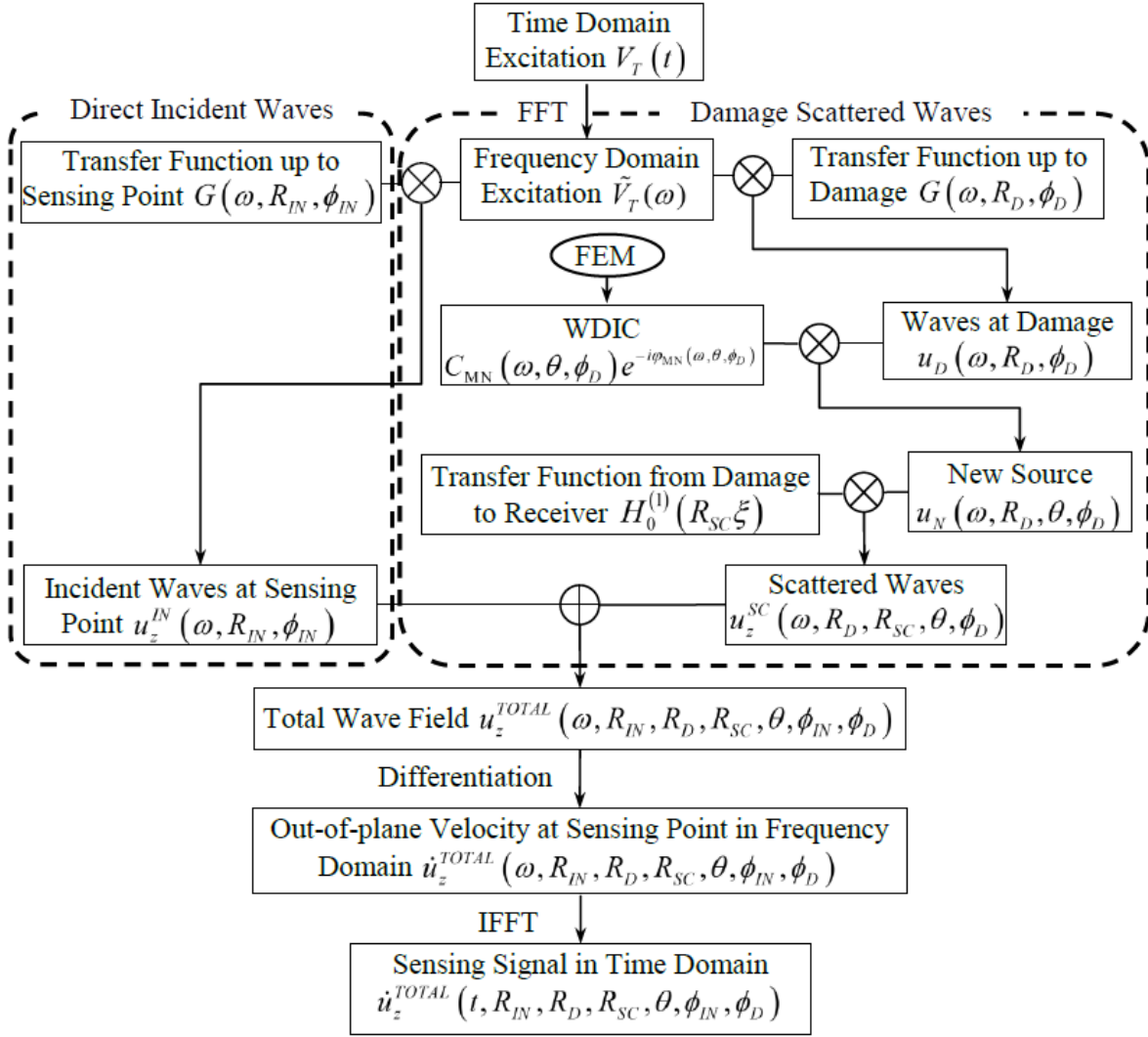


Figure 104HGL framework flowchart.

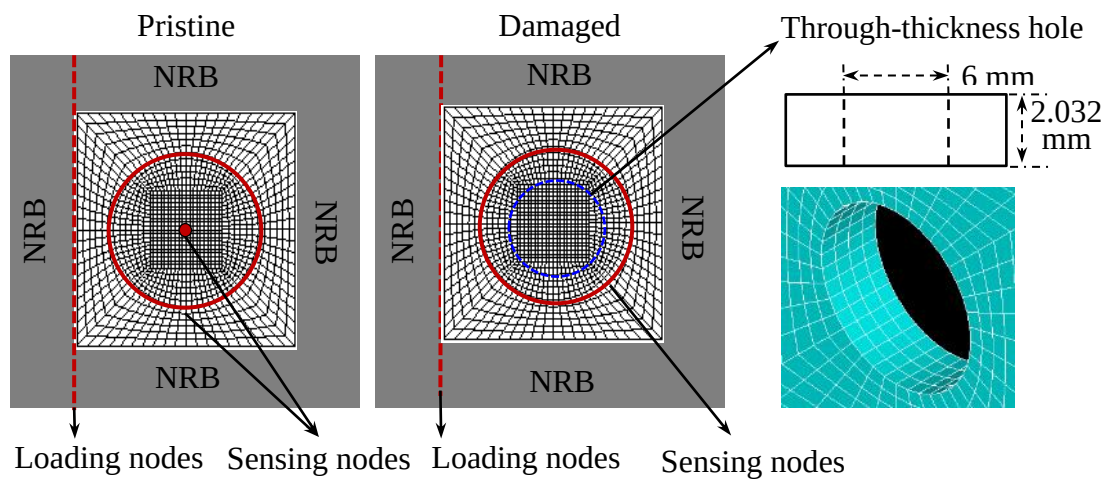


Figure 105 Small-size local FEM pair for WDIC extraction.

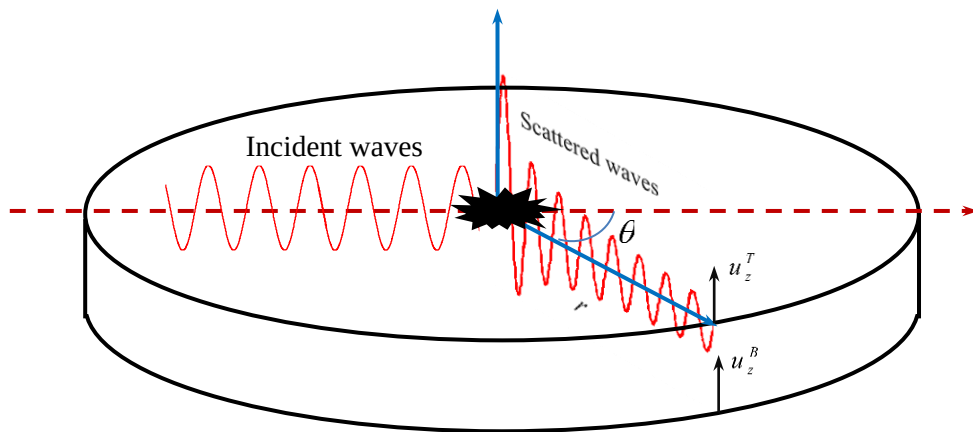


Figure 106 Extraction of WDIC from small-size FEM.

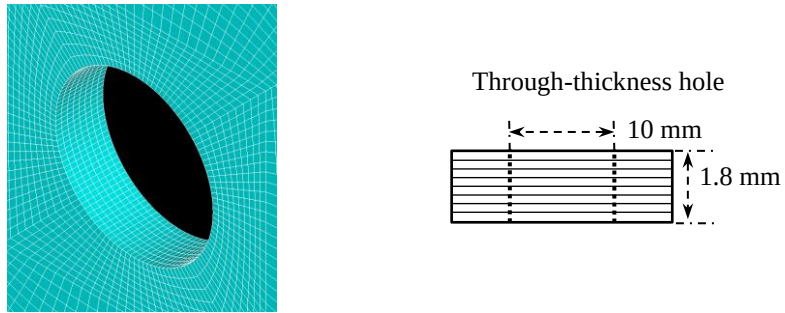


Figure 107 Schematic of the through-thickness hole in a 1.8-mm-thick unidirectional CFRP composite plate.

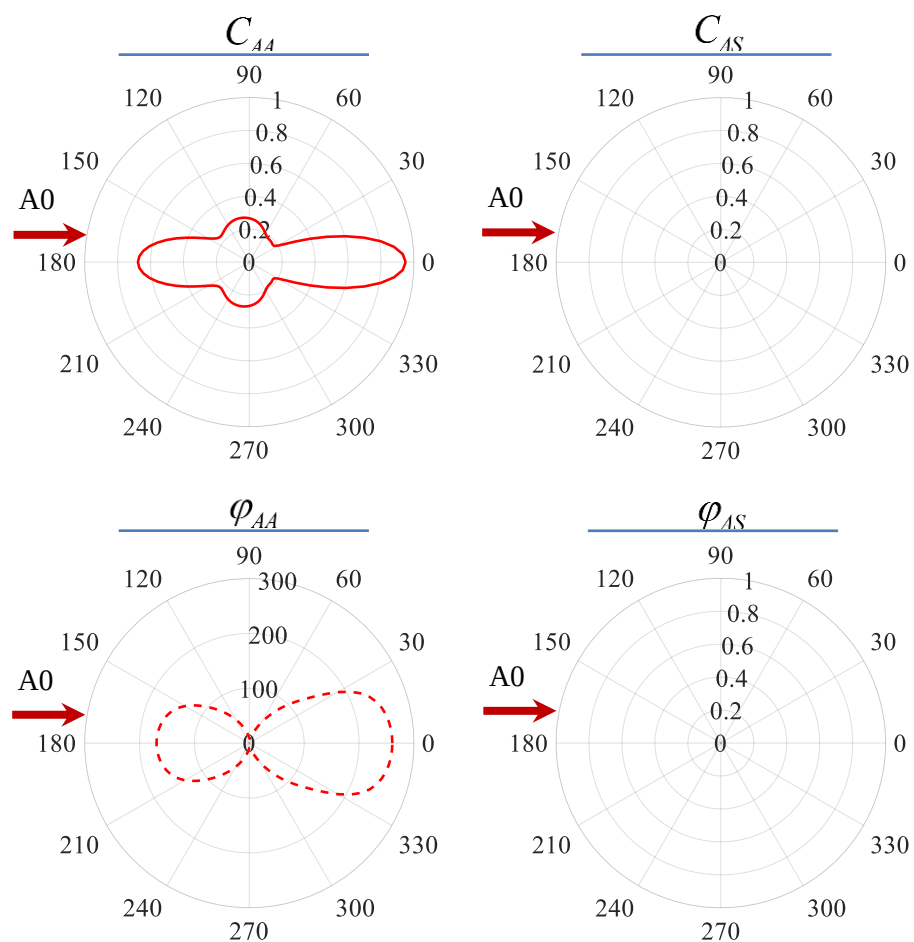


Figure 108WDIC example of A0 wave interaction with a 10-mm-diameter hole at 120 kHz in the unidirectional composite plate.

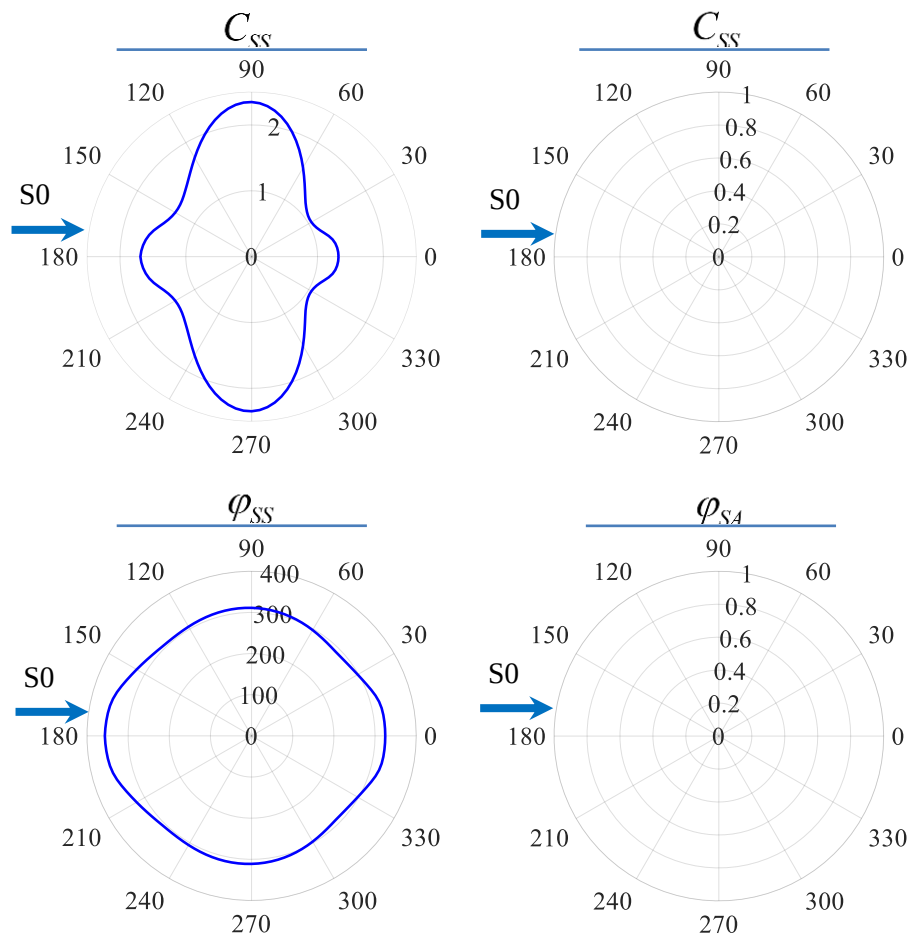


Figure 109WDIC example of S0 wave interaction with a 10-mm-diameter hole at 120 kHz in the unidirectional composite plate.

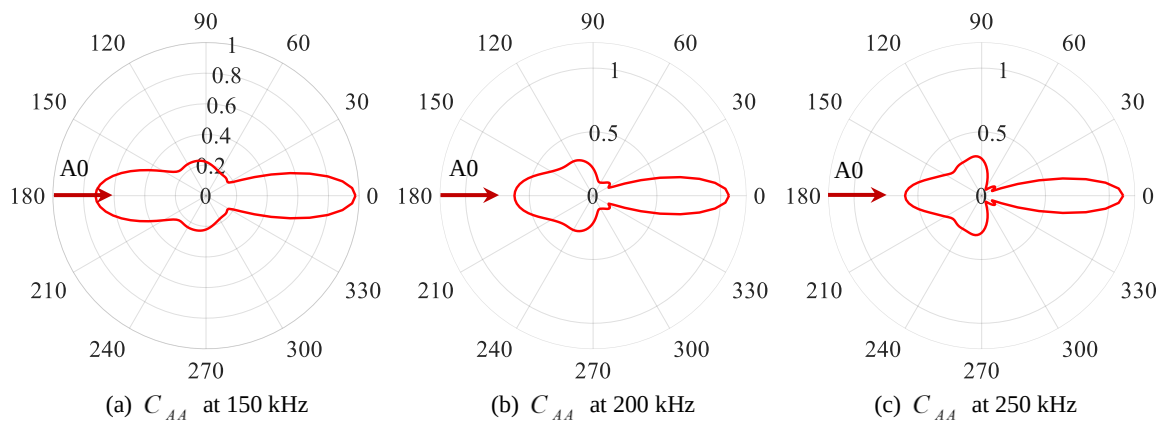


Figure 110WDIC of A0 wave interaction with the through hole in the unidirectional composite plate at different frequencies: (a) 150 kHz, (b) 200 kHz, (c) 250 kHz.

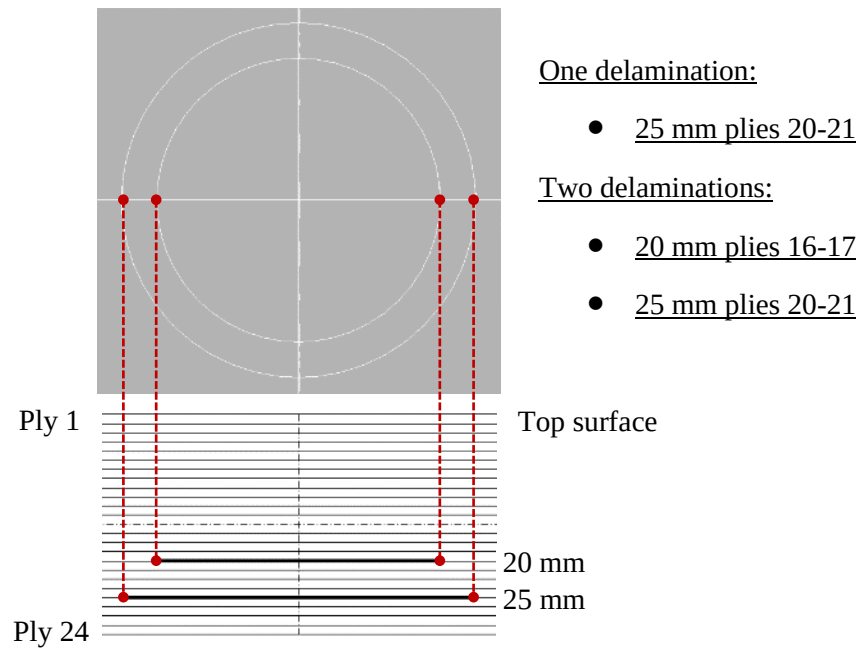


Figure 111 Schematic of the 3-mm quasi-isotropic CFRP composite plate with multilayer delaminations.

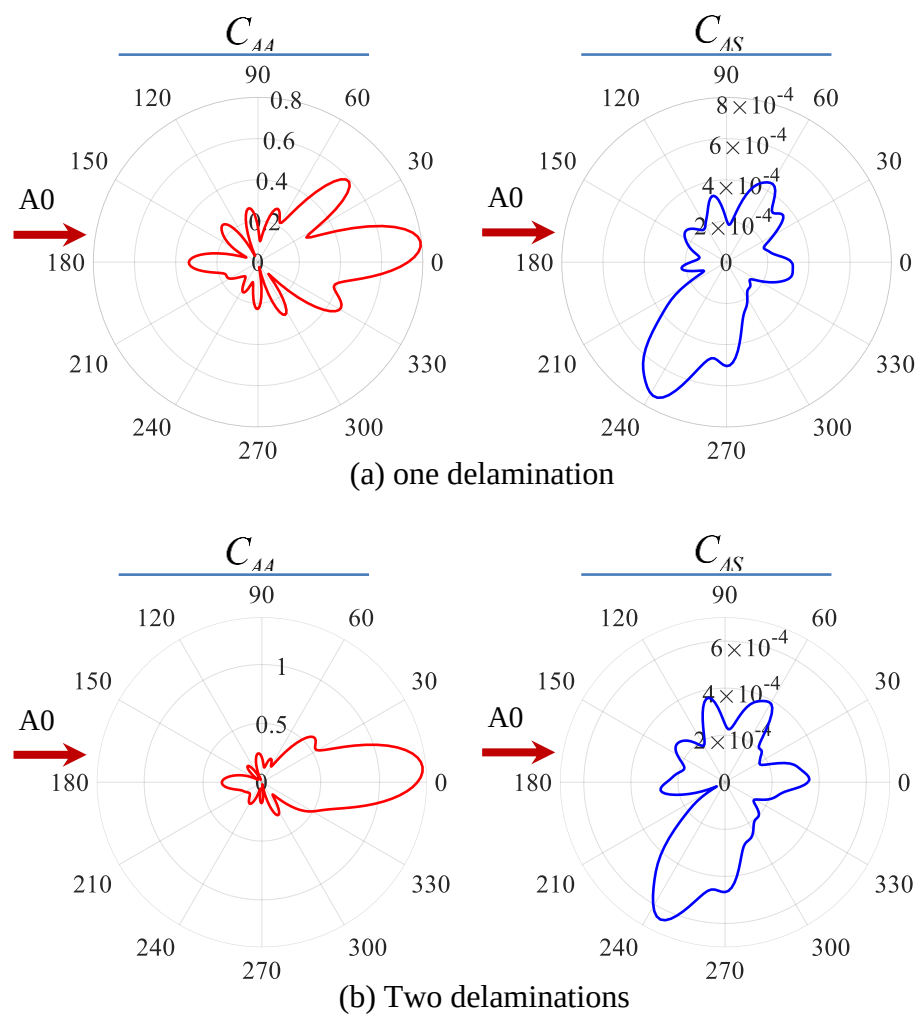


Figure 112WDIC example of A0 wave interaction with multilayer delaminations at 120 kHz in a 3-mm quasi-isotropic composite plate: (a) one delamination; (b) two delaminations.

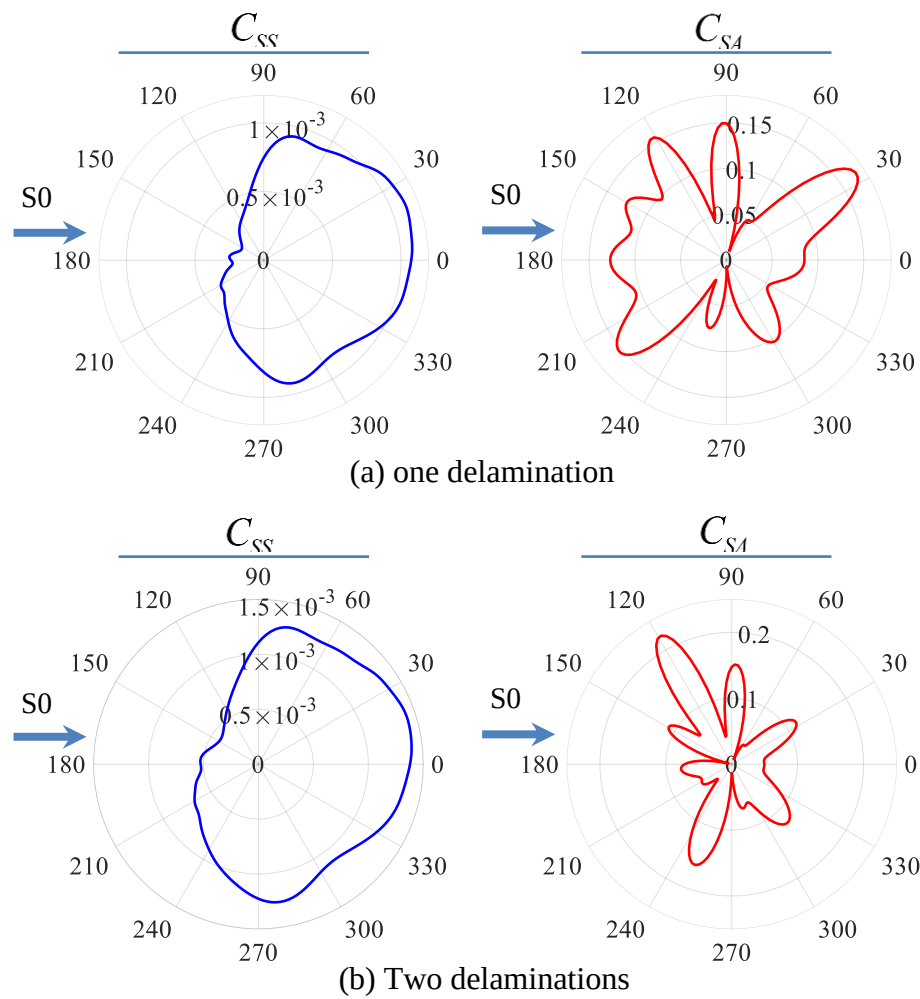


Figure 113 WDIC example of S0 wave interaction with multilayer delaminations at 120 kHz in a 3-mm quasi-isotropic composite plate: (a) one delamination; (b) two delaminations.

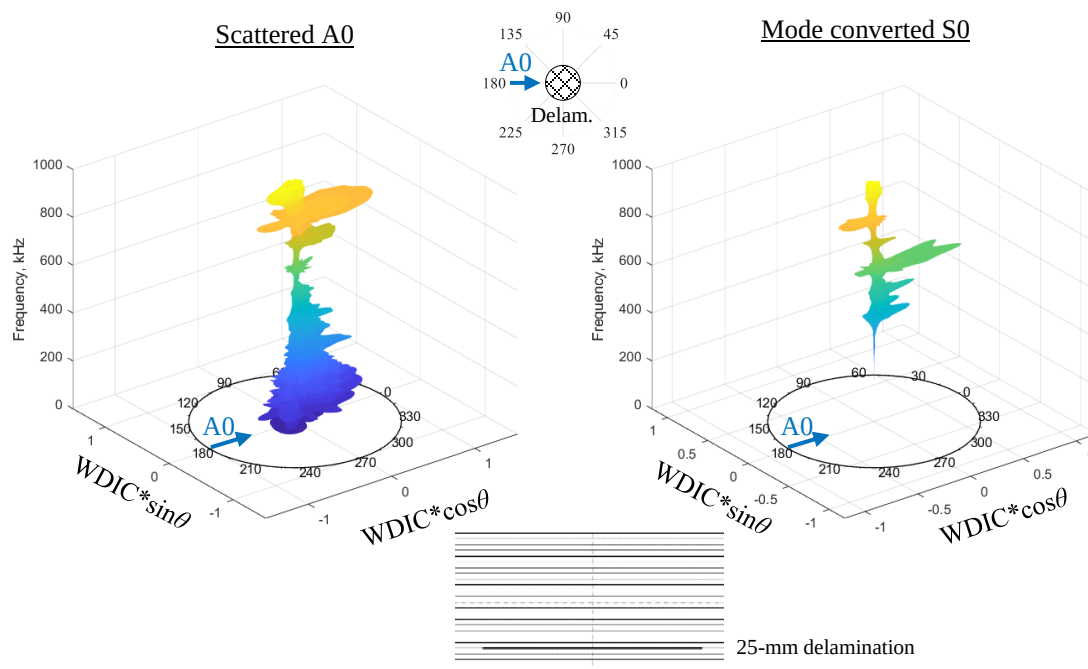


Figure 114 WDIC of A0 wave interaction with the one delamination in the quasi-isotropic composite plate at different frequencies.

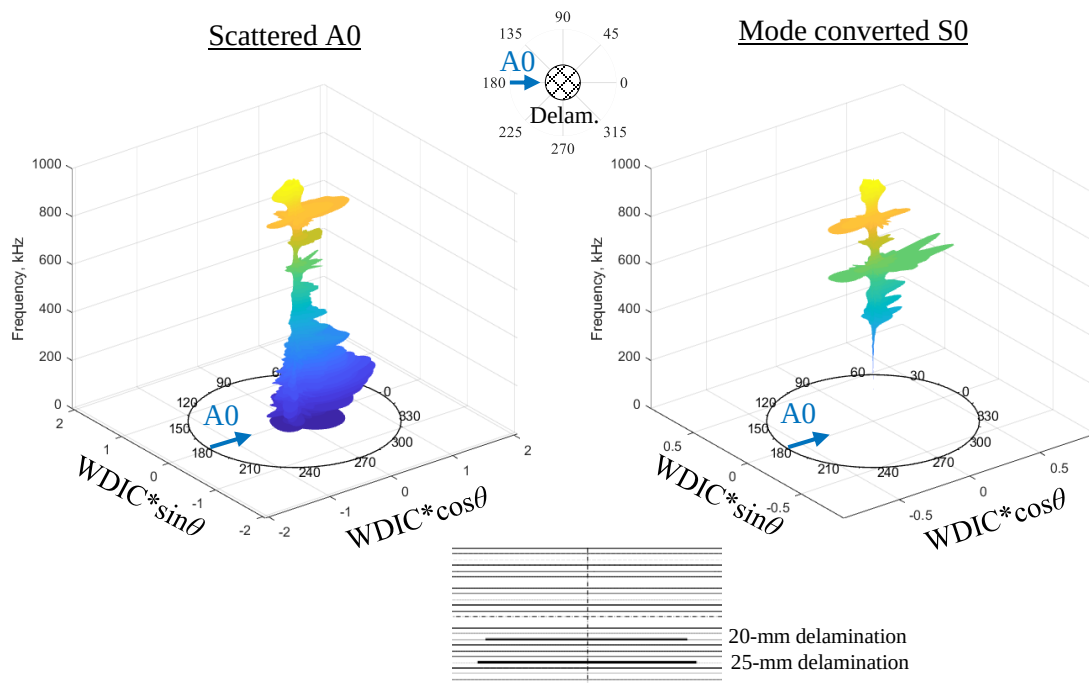


Figure 115 WDIC of A0 wave interaction with the two delaminations in the quasi-isotropic composite plate at different frequencies.

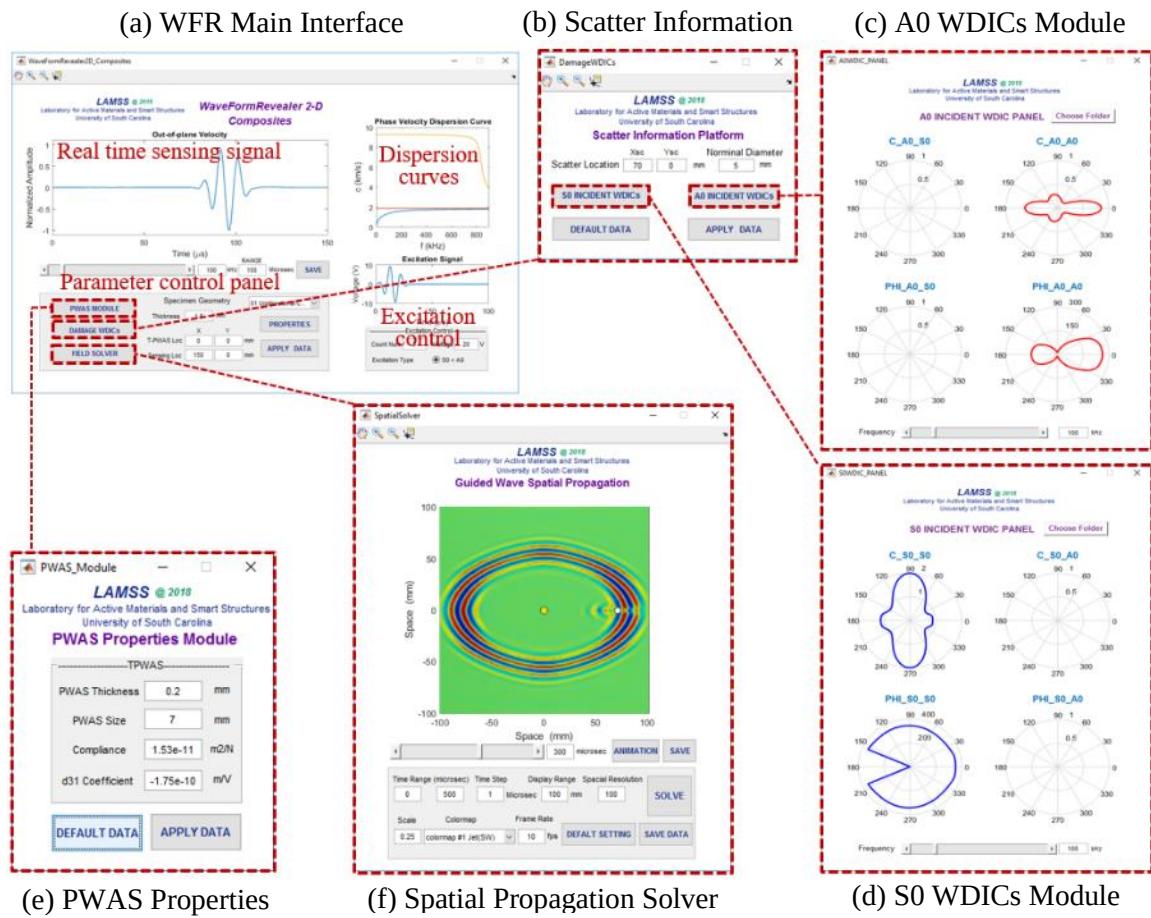


Figure 116 GUI of WFR-2D-Composites: (a) WFR-2D main interface; (b) damage information platform; (c) A0 WDIC module; (d) S0 WDIC module; (e) PWAS properties module; (f) spatial propagation solver.

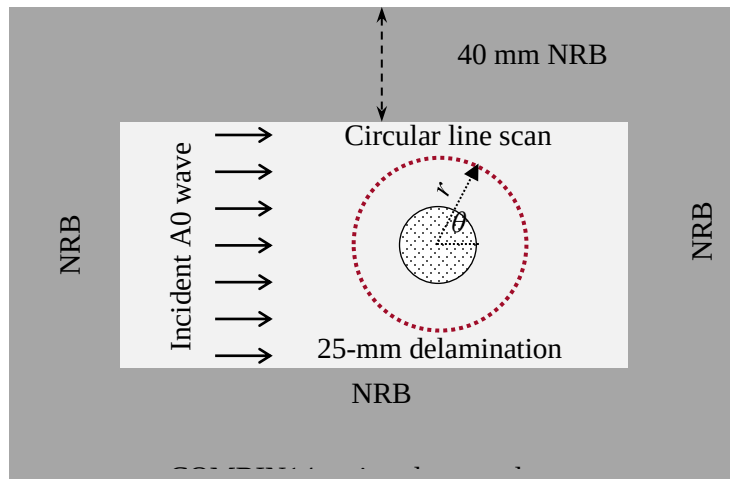


Figure 117 Finite element model for A0 wave interaction with multilayer delaminations in 3-mm quasi-isotropic composite plate.

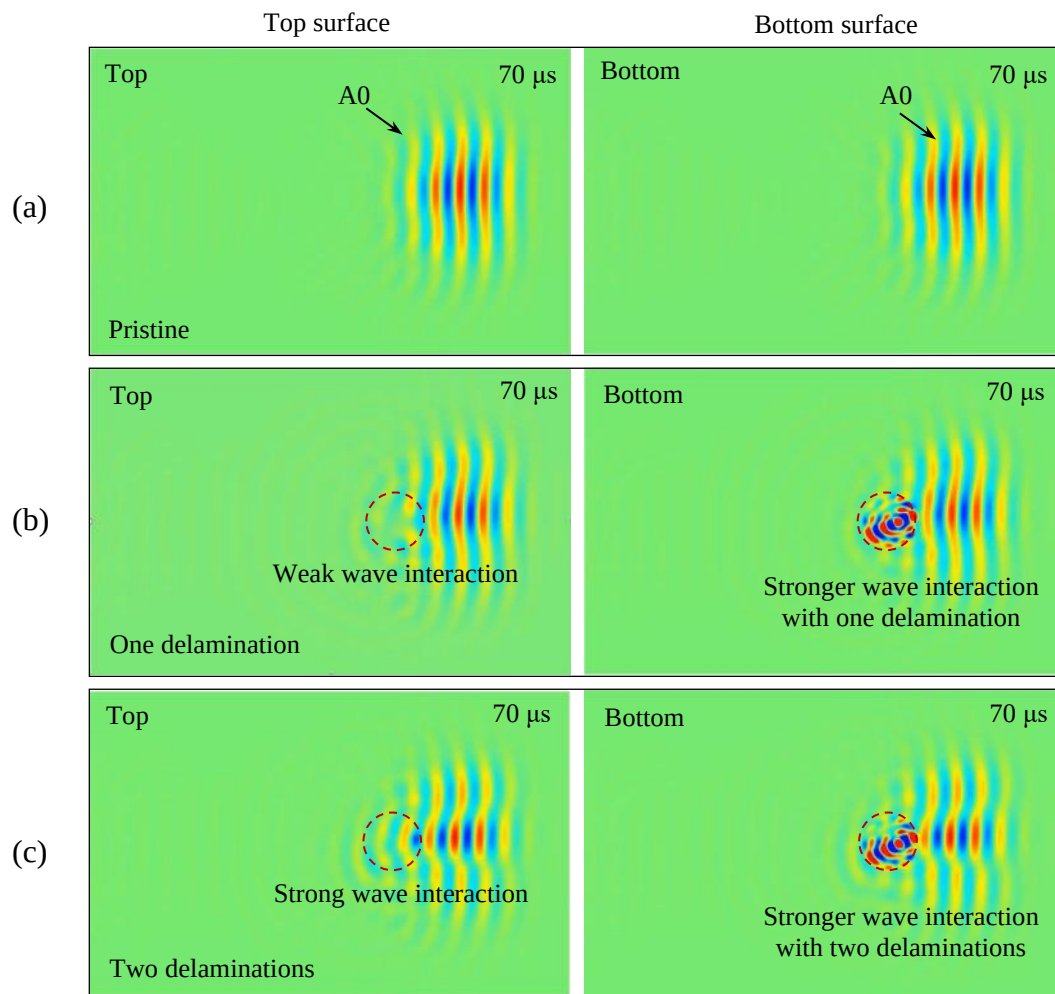


Figure 118 Comparison of transient spatial wavefield in 3-mm quasi-isotropic composite plate showing out-of-plane velocity on top and bottom surfaces: (a) pristine plate; (b) one delamination; (c) two delaminations.

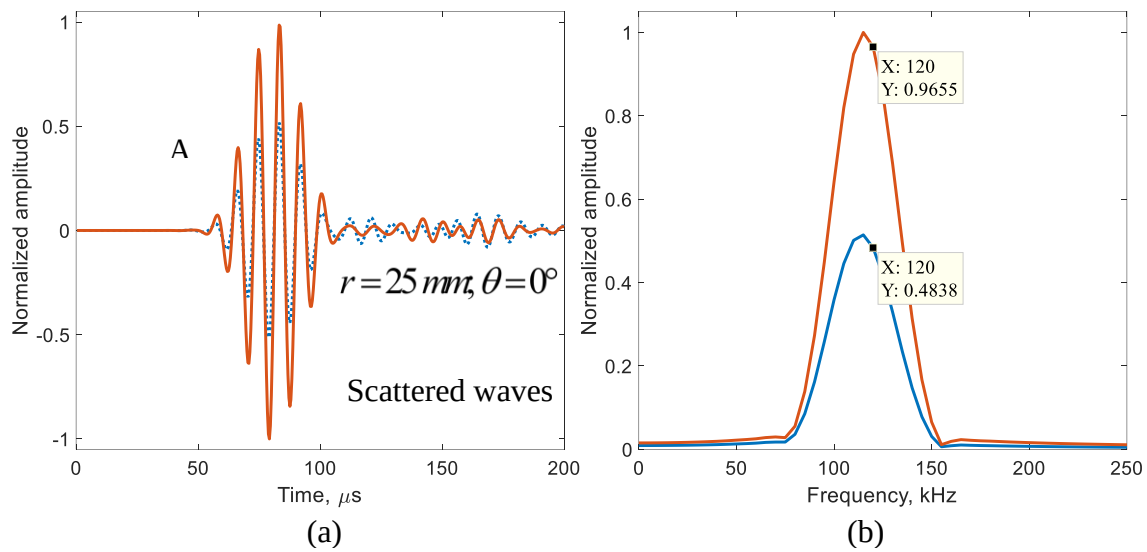


Figure 119 Comparison of the scattered signals between one delamination and two delaminations in the 0° direction: (a) waveform; (b) FFT.

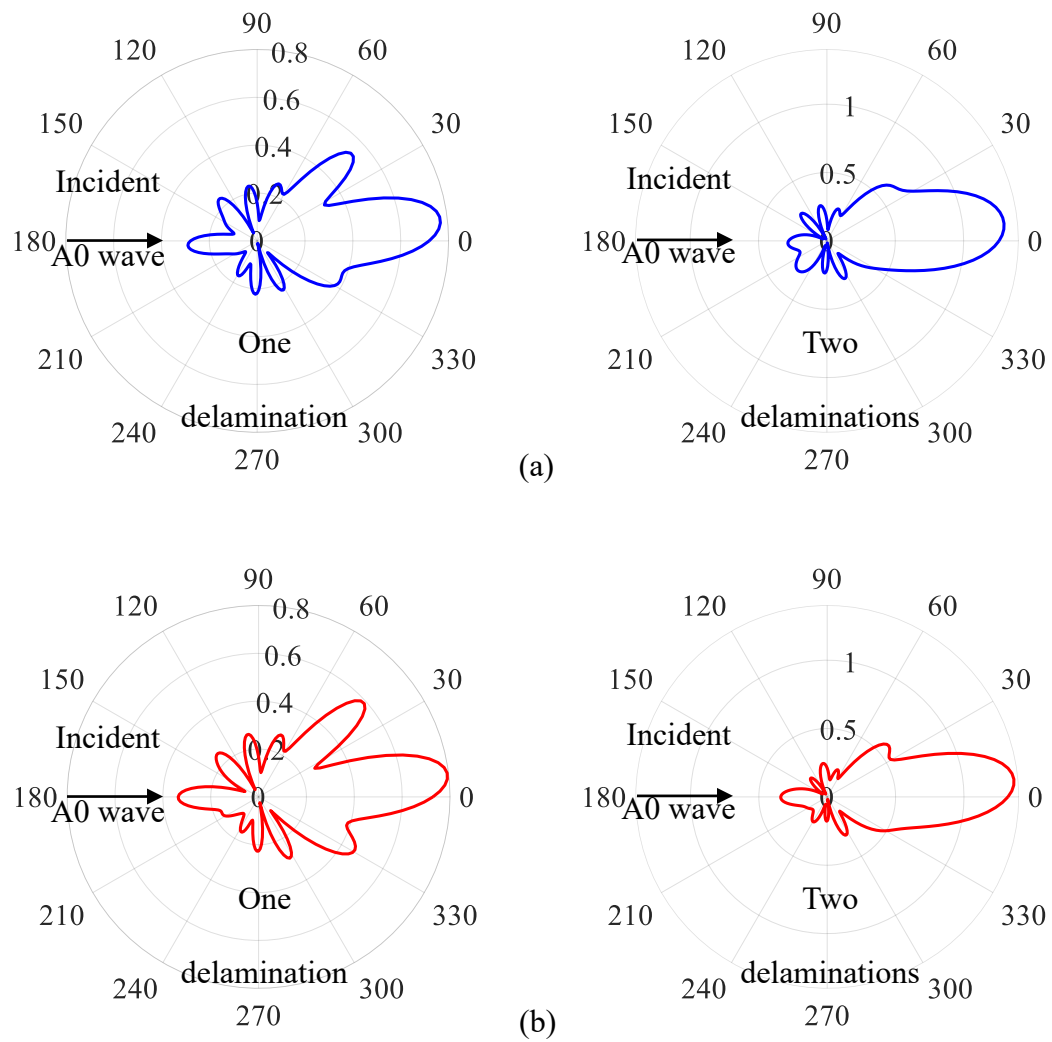


Figure 120 Comparison between transient WDIC and harmonic WDIC at 120 kHz: (a) WDIC extracted from transient FEM simulation for one and two delaminations; (b) harmonic WDIC for one and two delaminations.

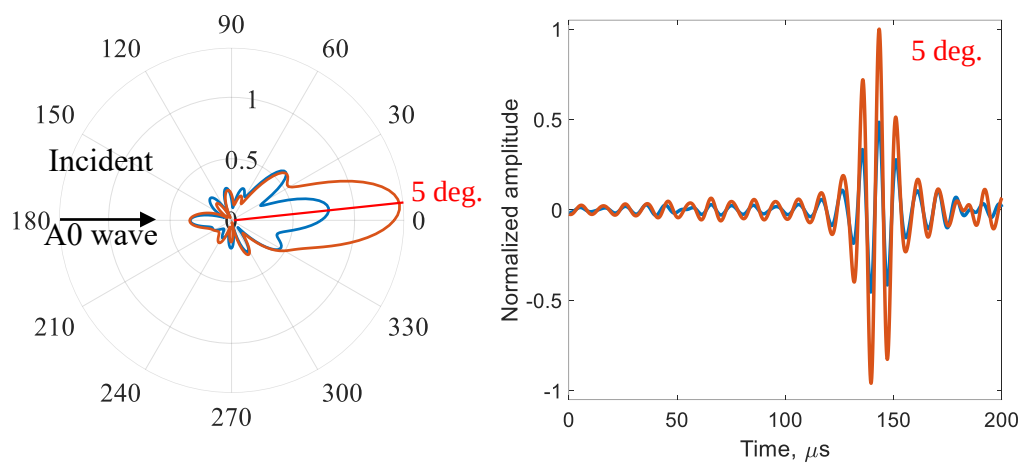


Figure 121 Comparison of scattered signal prediction between one delamination and two delaminations in the 5° direction showing the maximum WDIC amplitude for both delaminations: 120 kHz, 100 mm from the delamination center.

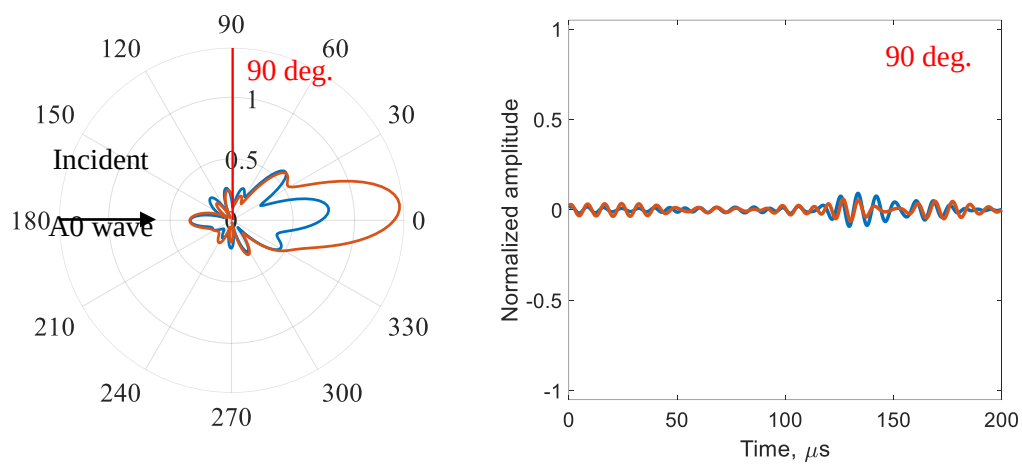


Figure 122 Comparison of scattered signal prediction between one delamination and two delaminations in the 90° direction showing small WDIC amplitude: 120 kHz, 100 mm from the delamination center.

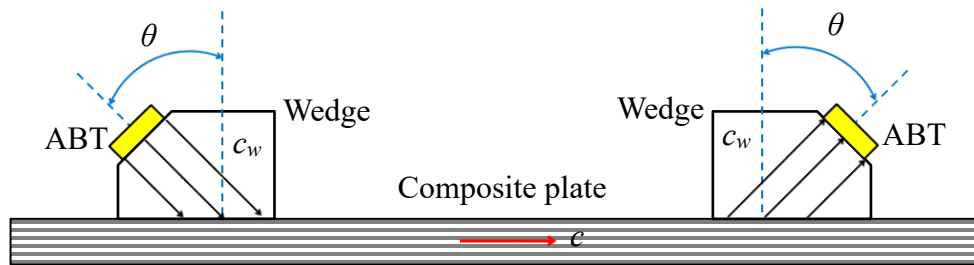


Figure 123 Single-mode guided wave generation and detection using angle beam transducers and wedges in a composite laminate.



Figure 124 Olympus angle-adjustable wedge and angle beam transducer.

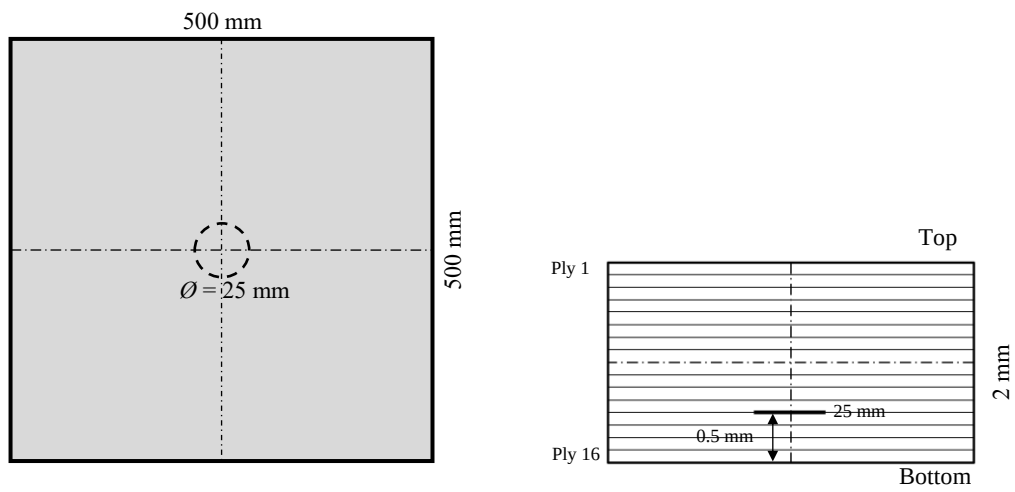


Figure 125 Schematic of 2-mm quasi-isotropic $[-45/90/45/0]_{2s}$ carbon fiber-reinforced polymer (CFRP) composite plate with delamination simulated by Teflon insert.

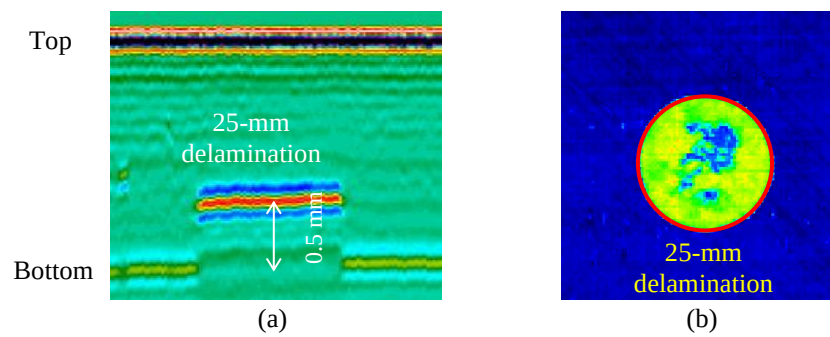


Figure 126 Ultrasonic inspection results of 2-mm quasi-isotropic composite plate with simulated delamination: (a) B-scan image; (b) C-scan image.

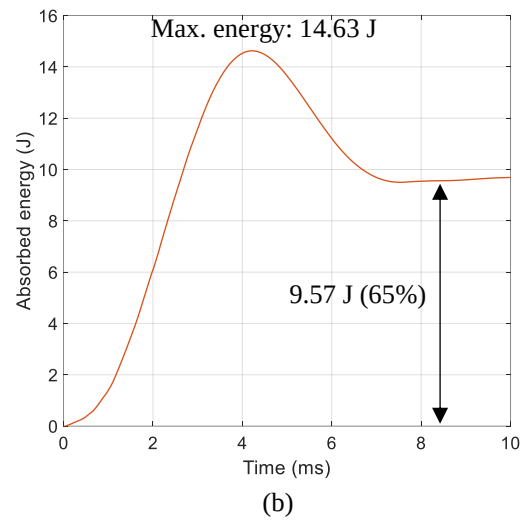
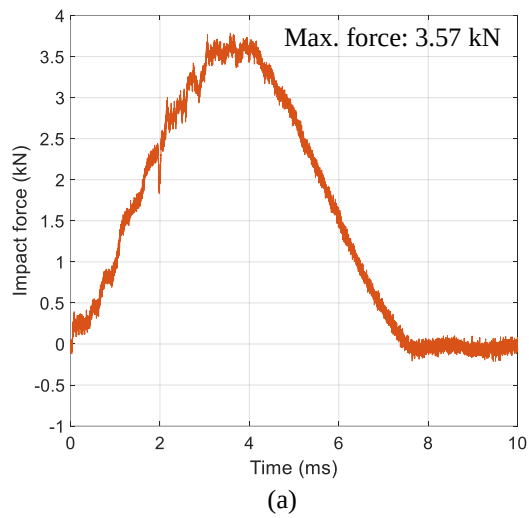


Figure 127 Force-time history and absorbed energy of the 2-mm [-45/90/45/0]_{2S} quasi-isotropic composite coupon: (a) force history; (b) absorbed energy.

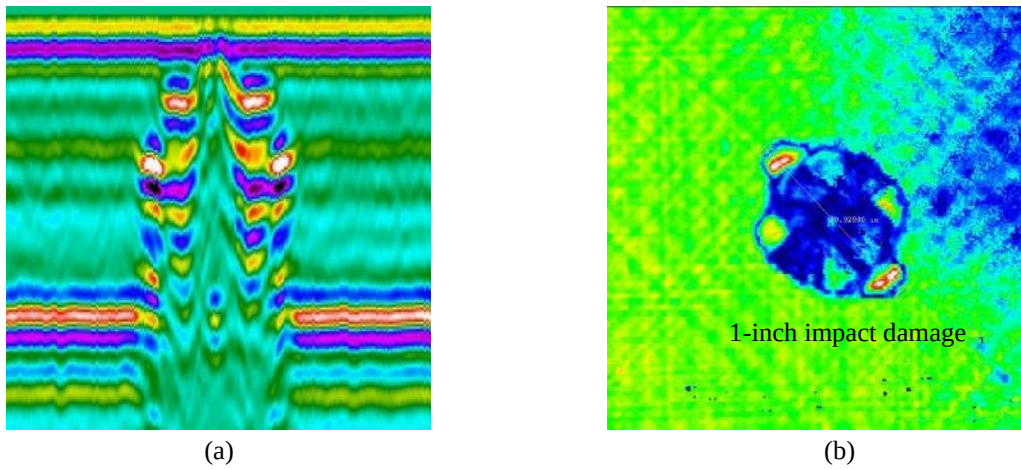


Figure 128 Ultrasonic NDT inspection results of the impact damage in the 2-mm quasi-isotropic composite coupon: (a) B-scan image; (b) C-Scan image.

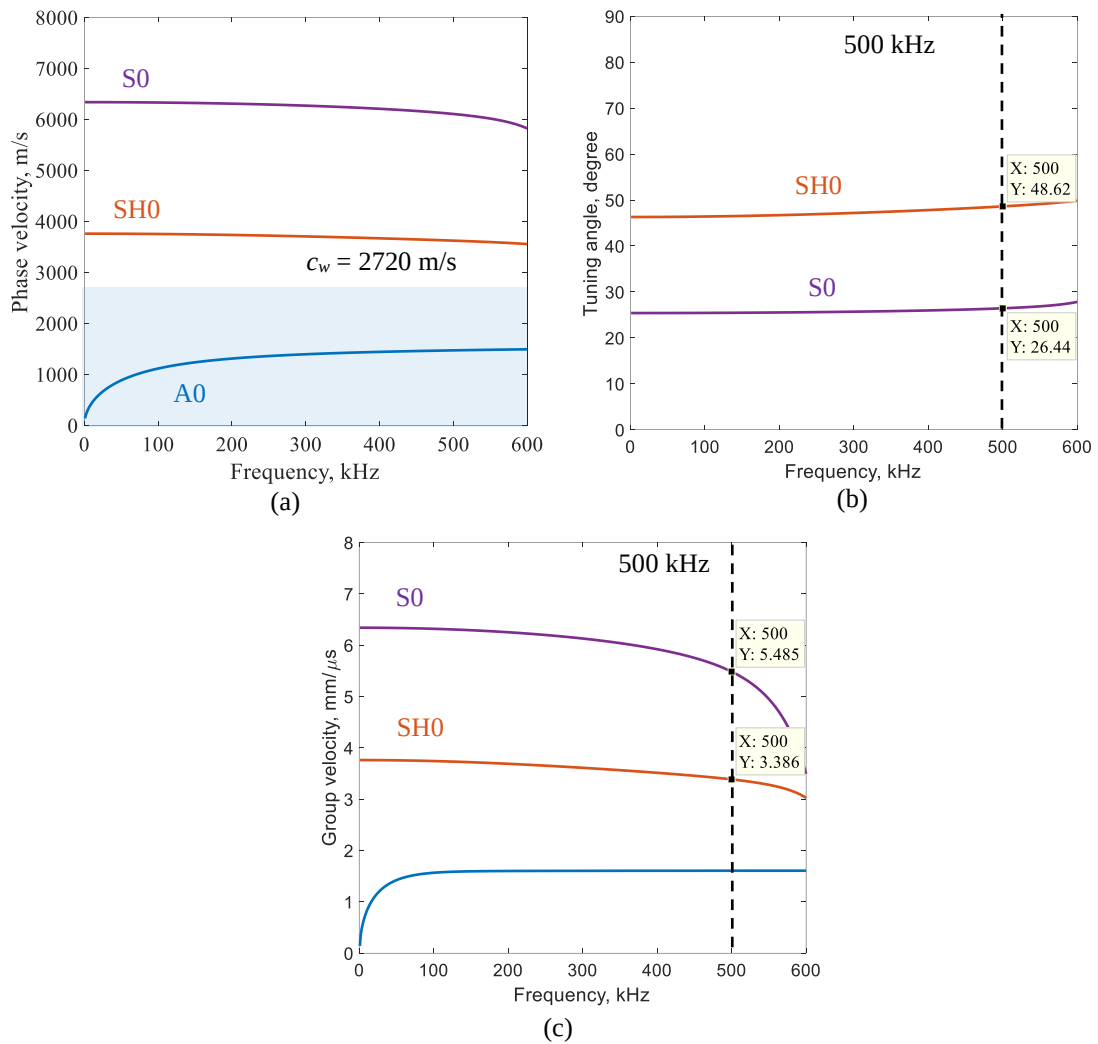


Figure 129 Dispersion curves of the 2-mm $[-45/90/45/0]_{2s}$ quasi-isotropic composite plate: (a) phase velocity; (b) ABT tuning angle; (c) group velocity.

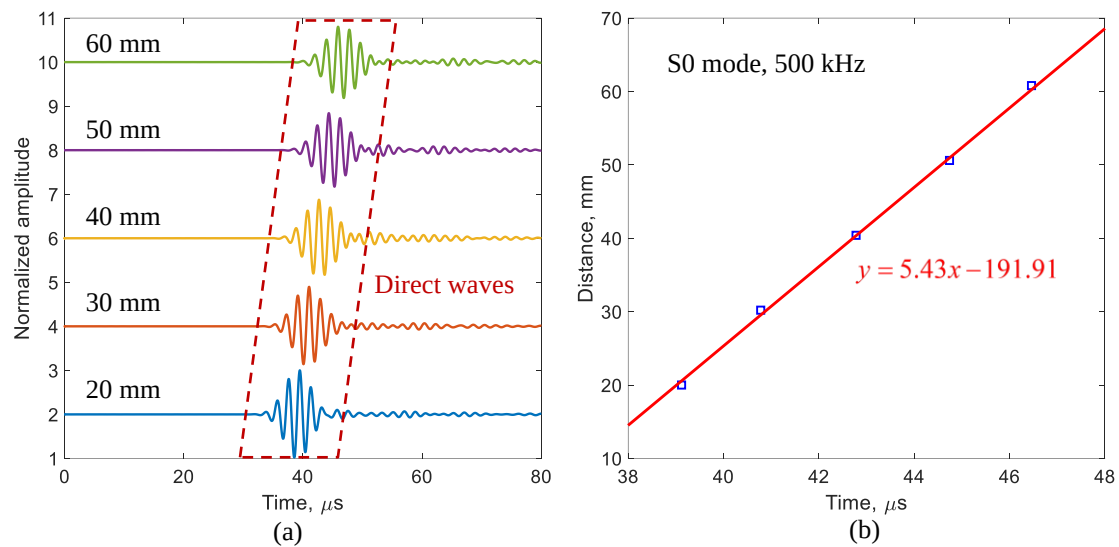


Figure 130 Experimental group-velocity measurement of S0 mode excitation: (a) waveforms at various locations; (b) correlation between distance and time of flight for the group velocity calculation.

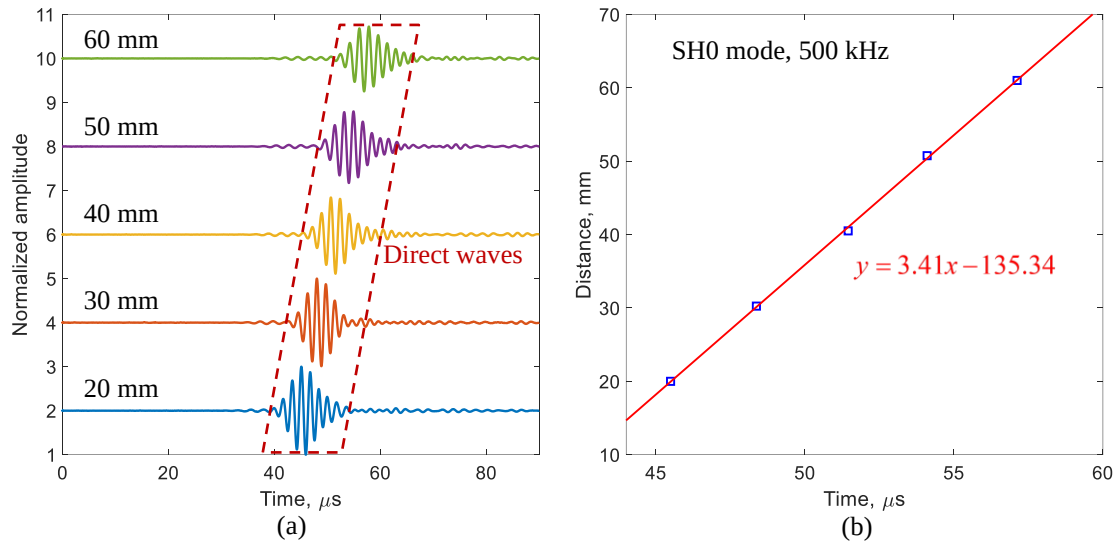


Figure 131 Experimental group-velocity measurement for SH0 mode excitation: (a) waveforms at various locations; (b) correlation between distance and time of flight for the group velocity calculation.

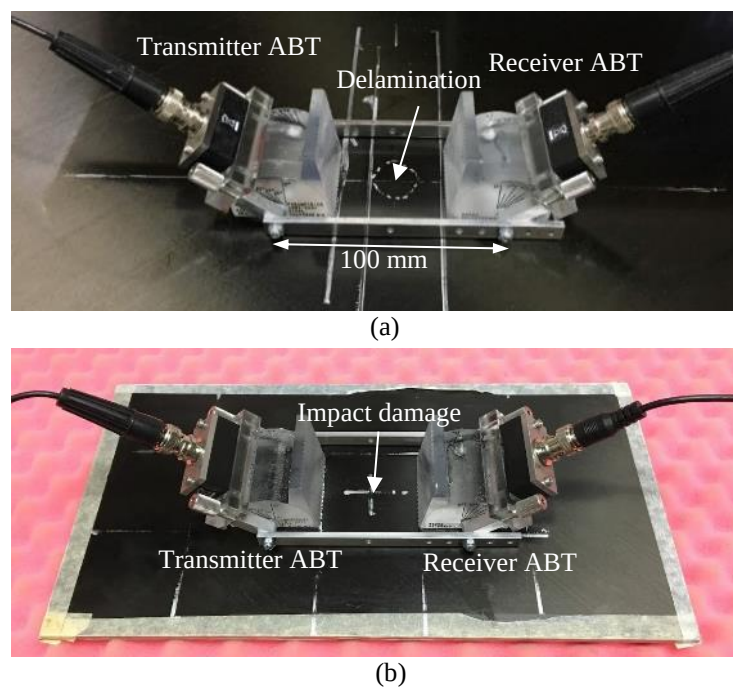


Figure 132 Experimental setup for damage detection using multiple pure-mode guided waves excited by ABT-ABT on a 2-mm quasi-isotropic CFRP composite plate: (a) delamination simulated by Teflon insert; (b) impact damage.

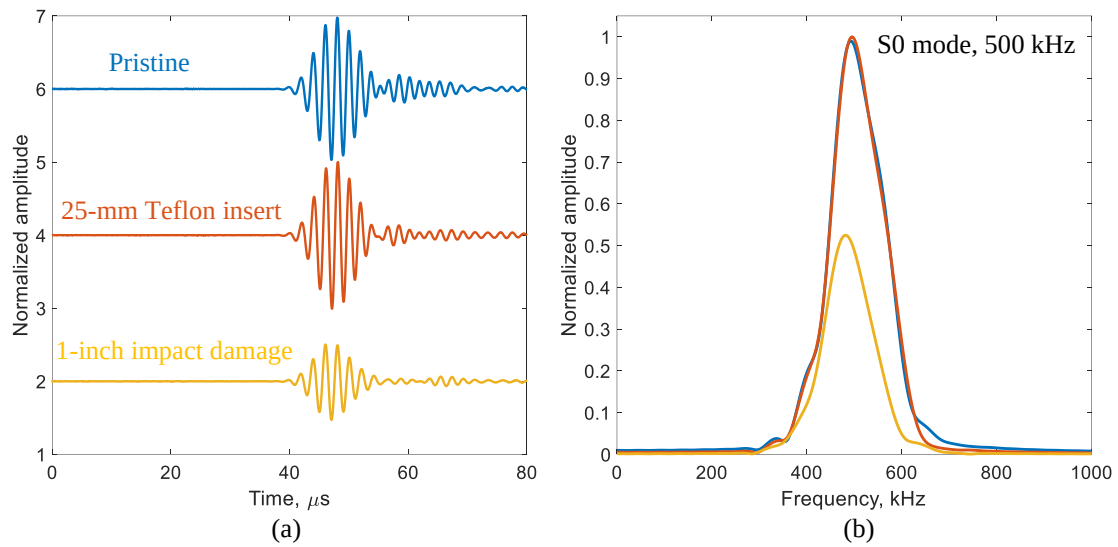


Figure 133 Signal comparison among pristine, Teflon insert, and impact damage using pure S0 mode at 500 kHz in 2-mm quasi-isotropic composite plate: (a) time-domain signals; (b) frequency spectrums.

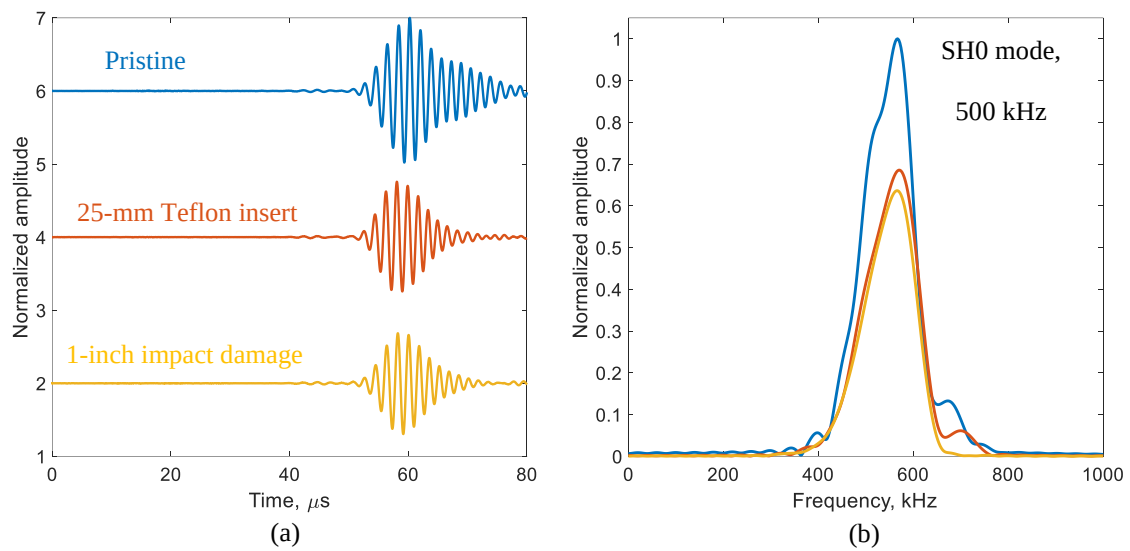


Figure 134 Signal comparison among pristine, Teflon insert, and impact damage using pure SH0 mode at 500 kHz in 2-mm quasi-isotropic composite plate: (a) time-domain signals; (b) frequency spectrums.

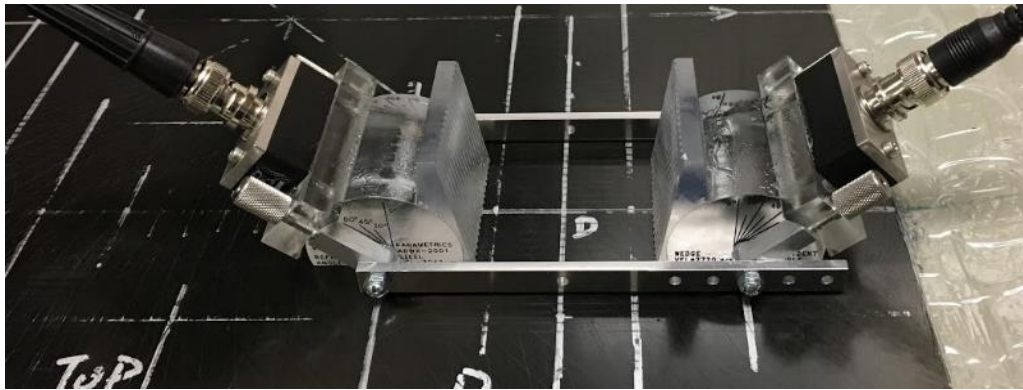


Figure 135: Experimental setup for delamination detection in the quasi-isotropic composite plate.

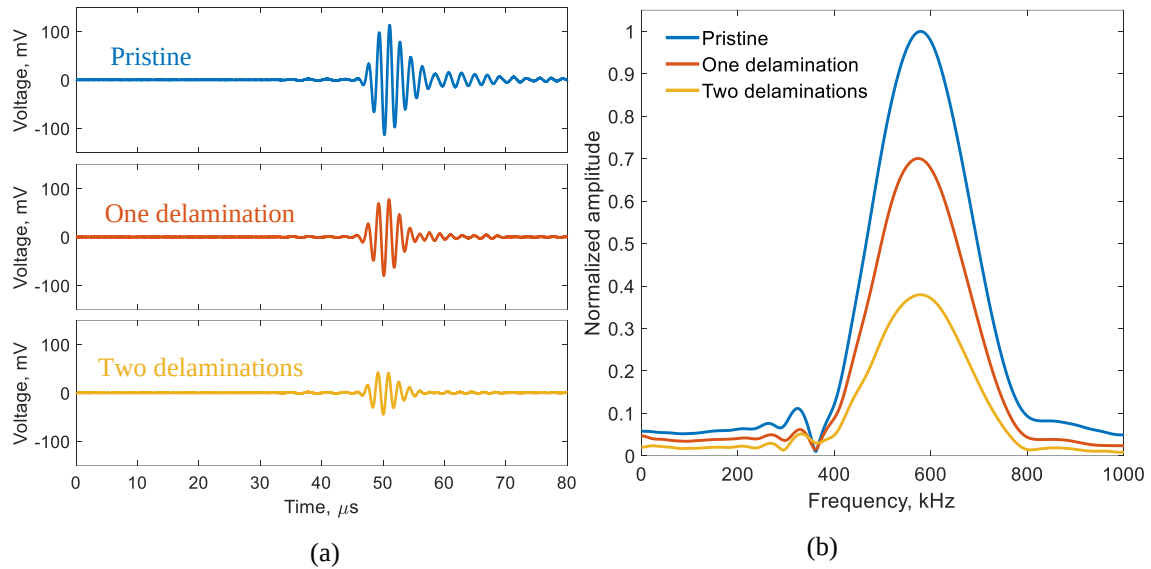


Figure 136 Experimental signal comparison among pristine and delaminations using the pure SH0 mode generated by angle beam transducers: (a) measured signals; (b) FFT results.

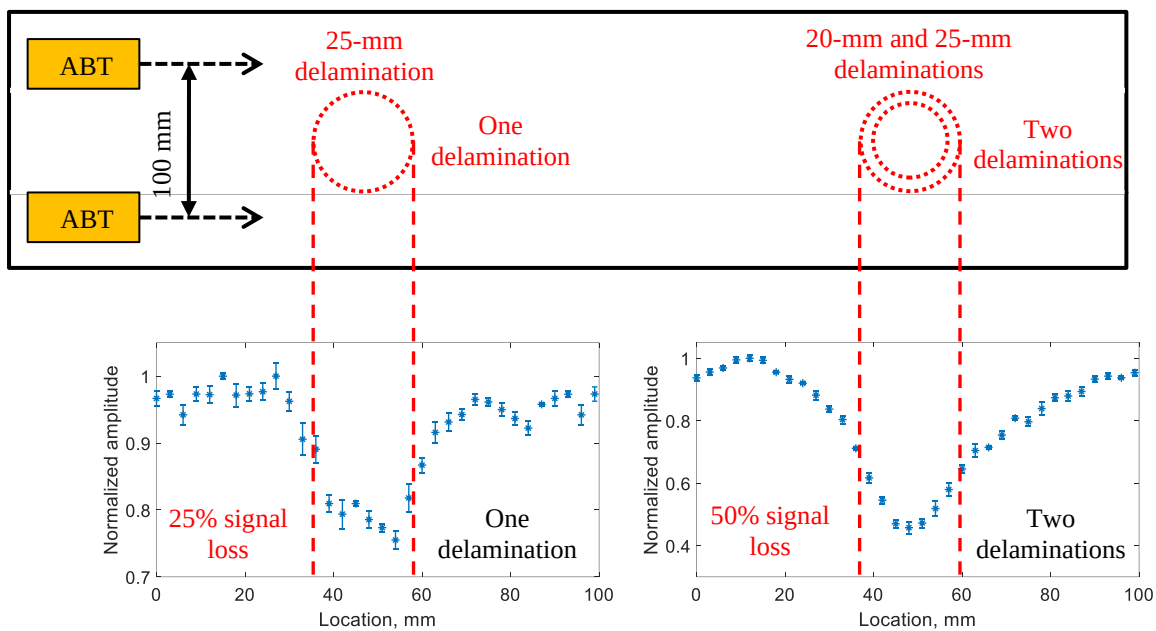


Figure 137 Size estimation of one delamination and two delaminations using pure SH0 mode generated by angle beam transducers.

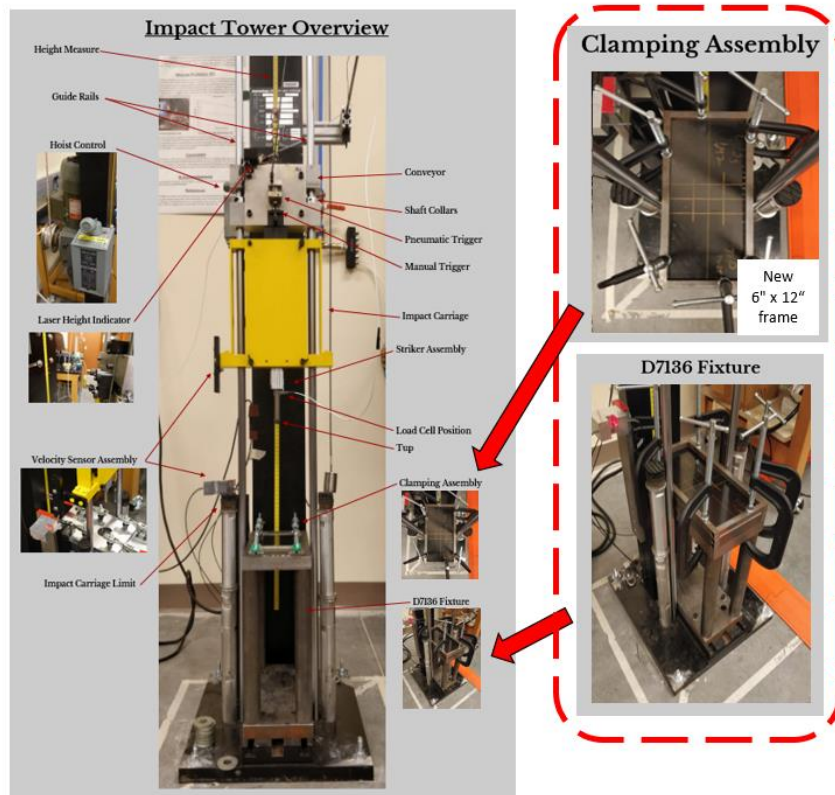


Figure 138 Dynatup 8200 drop-weight impact testing machine with the modified fixture.

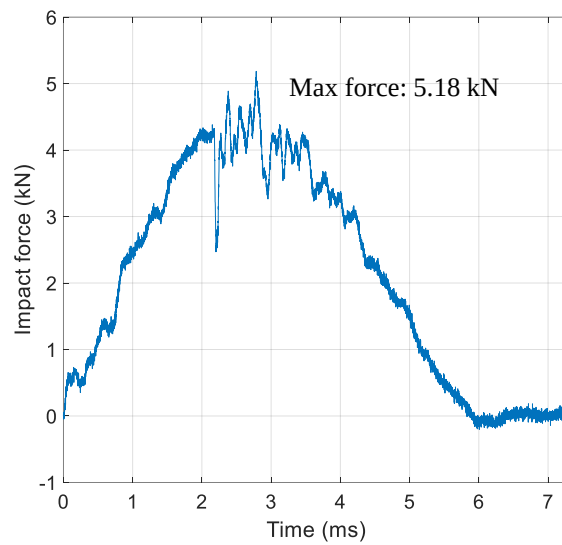
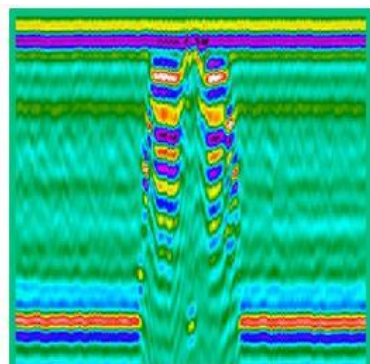
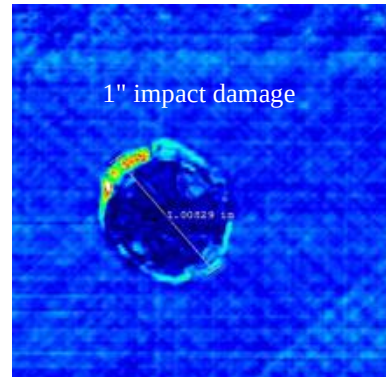


Figure 139 Force-time history of 3-mm quasi-isotropic composite coupon.



(a)



(b)

Figure 140 Ultrasonic inspection results of the coupon after impact testing: (a) B-scan; (b) C-scan.

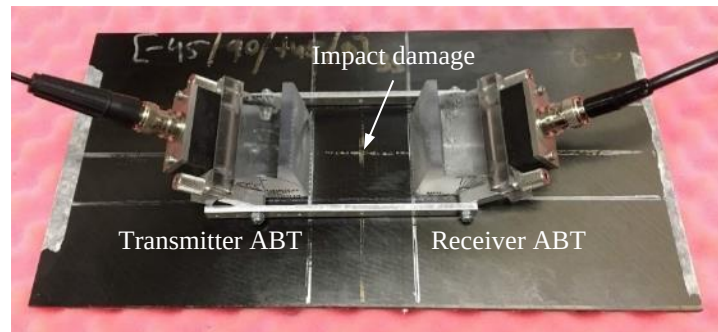


Figure 141 Experimental setup for the impact damage detection using adjustable ABT pair.

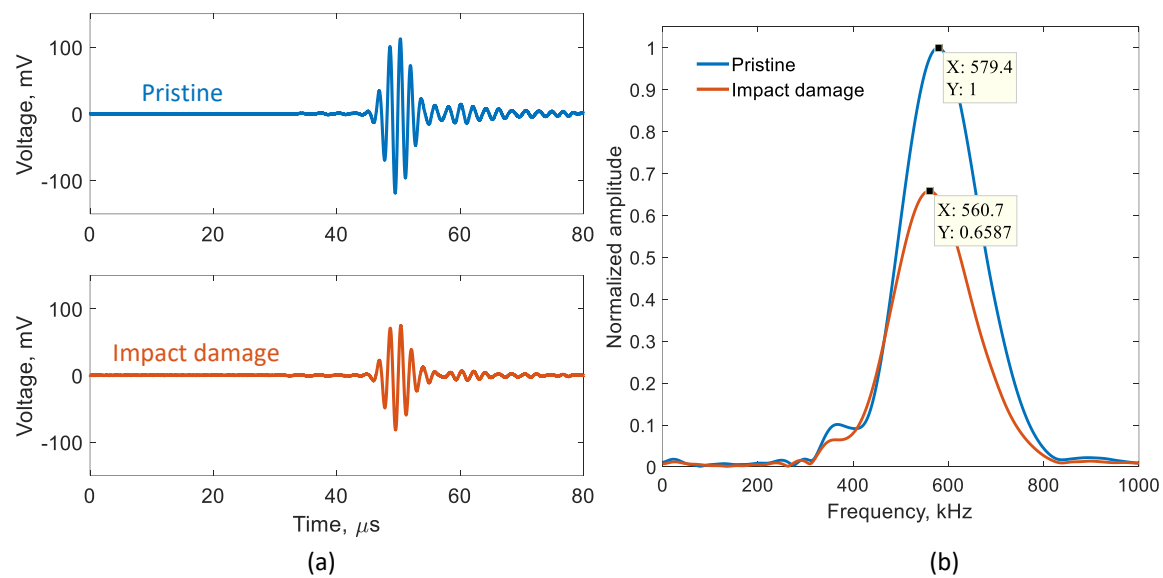


Figure 142 Signal comparison between the pristine and impact damage: (a) signals; (b) FFT results.

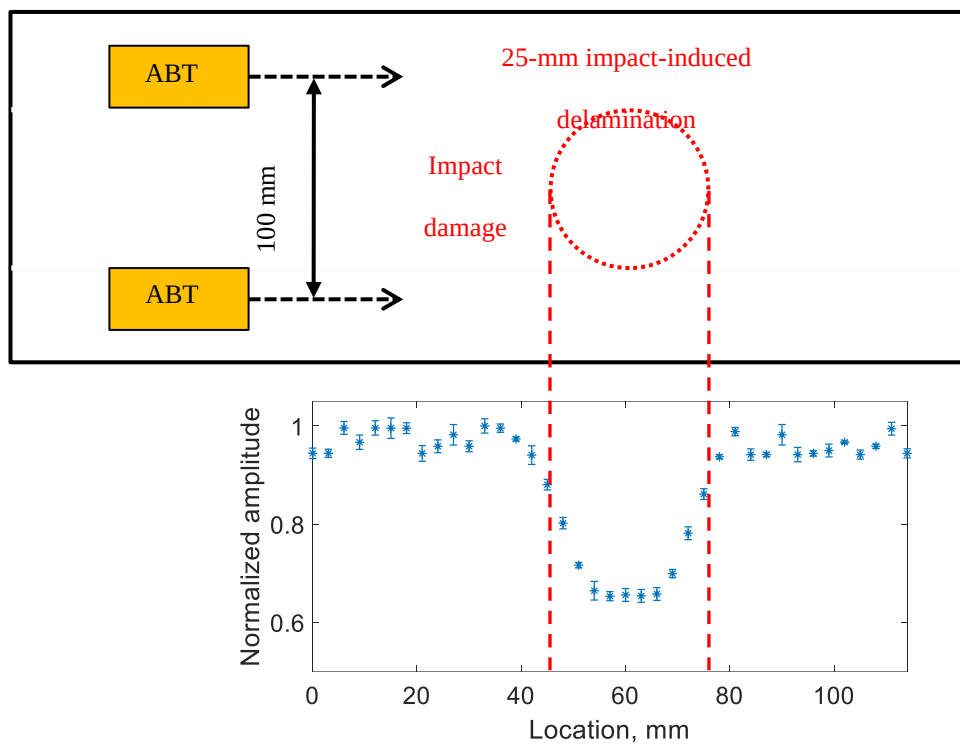


Figure 143 Impact damage size estimation using adjustable ABT pair to generate pure SH0 mode, showing the amplitude drop (marks with error bars) in the impact damage region.

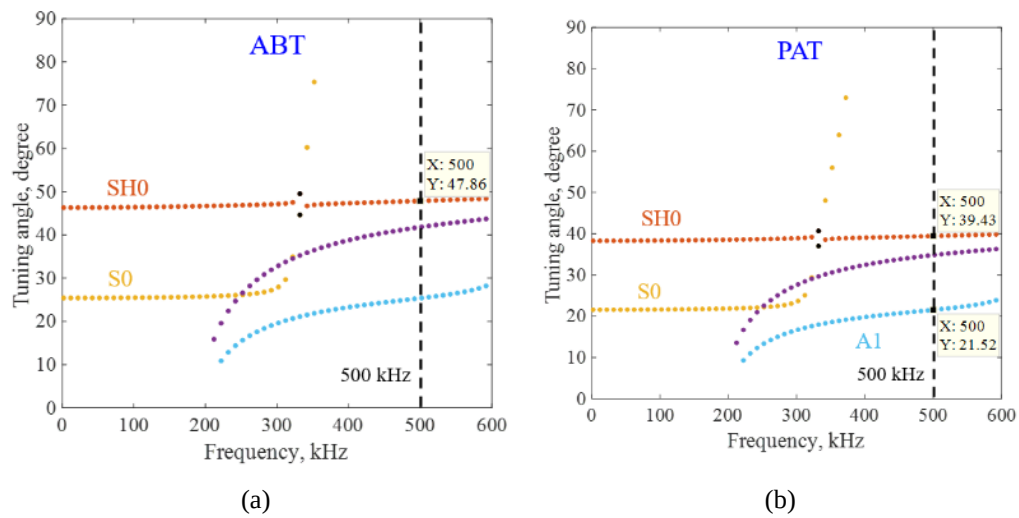
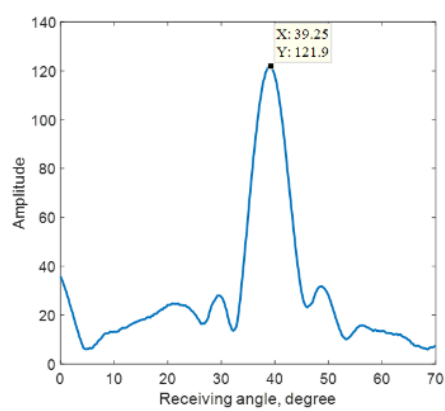
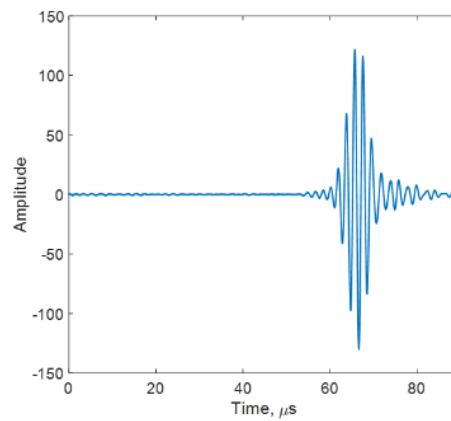


Figure 144 Theoretical tuning angles for (a) transmitting ABT (b) receiving PAT



(a)



(b)

Figure 145 Receiving angle vs amplitude for PAT; (b) Waveform at 39.25 degrees

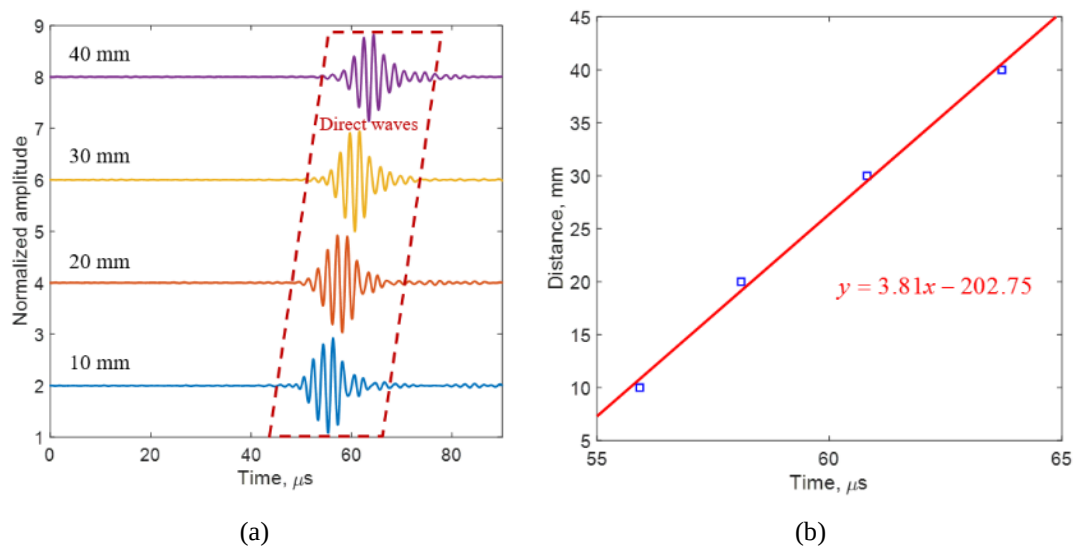


Figure 146 Group velocity calculation - (a) Measured signals at different distances; (b) Time of flight vs. distance plot

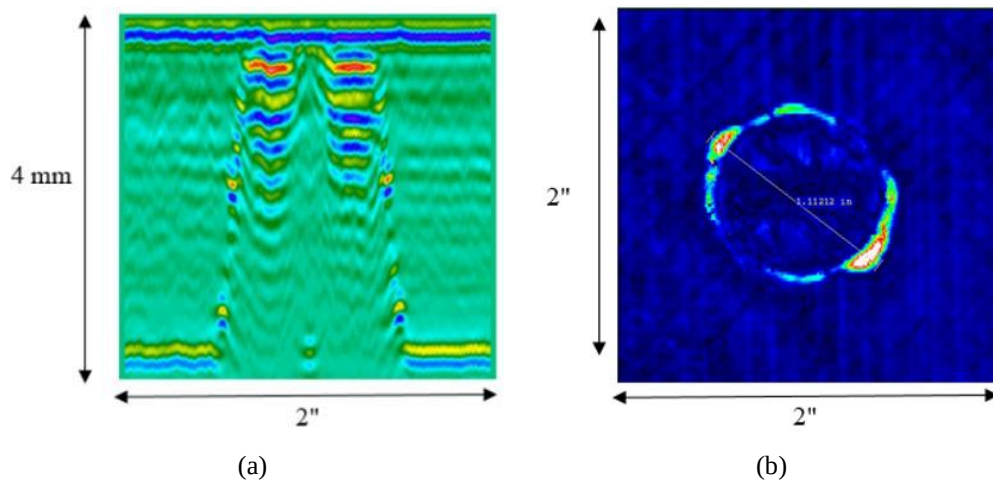


Figure 147 B-scan image; (b) C-scan image of 1" impact damage in 4-mm composite coupon

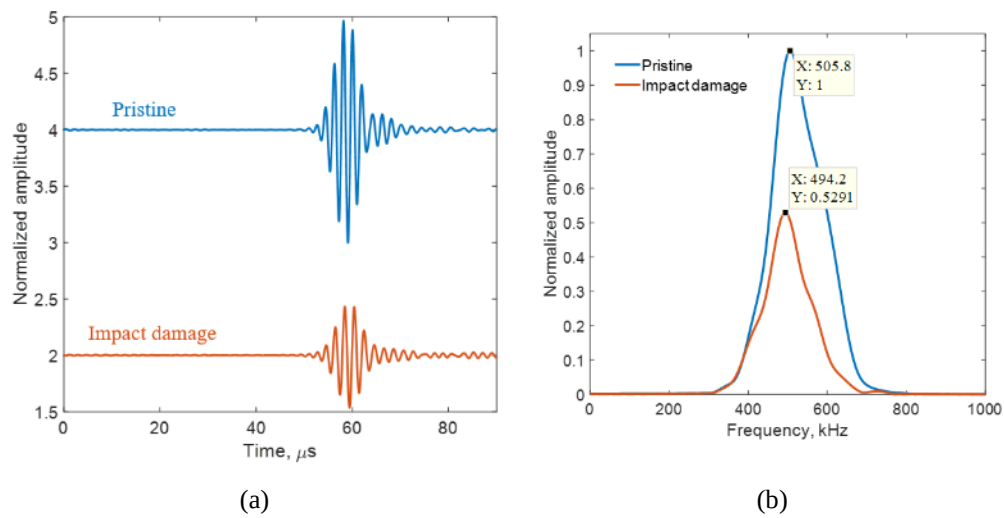


Figure 148 Comparison of pristine vs impact damage – (a) Measured signals; (b) FFT results

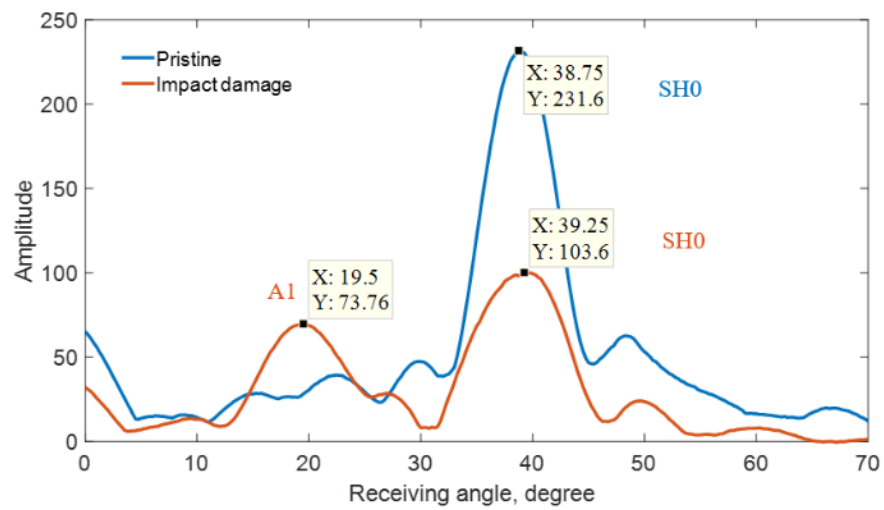
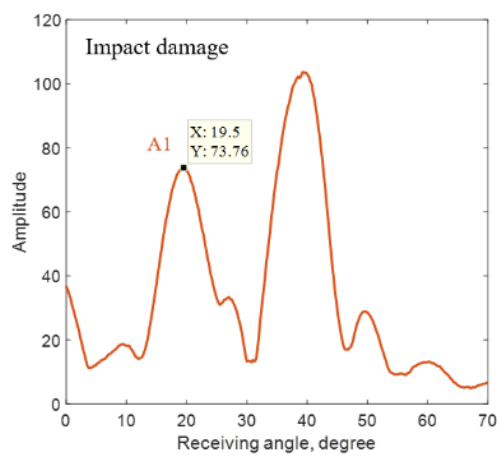
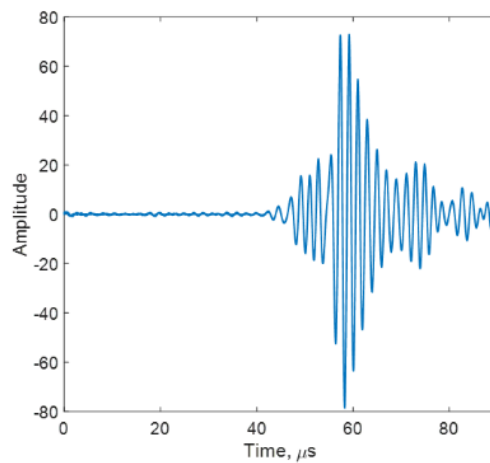


Figure 149 Comparison of pristine vs. impact damage - receiving angle vs. amplitude for PAT



(a)



(b)

Figure 150(a) Receiving angle vs amplitude for PAT; (b) Waveform at 19.5 degrees

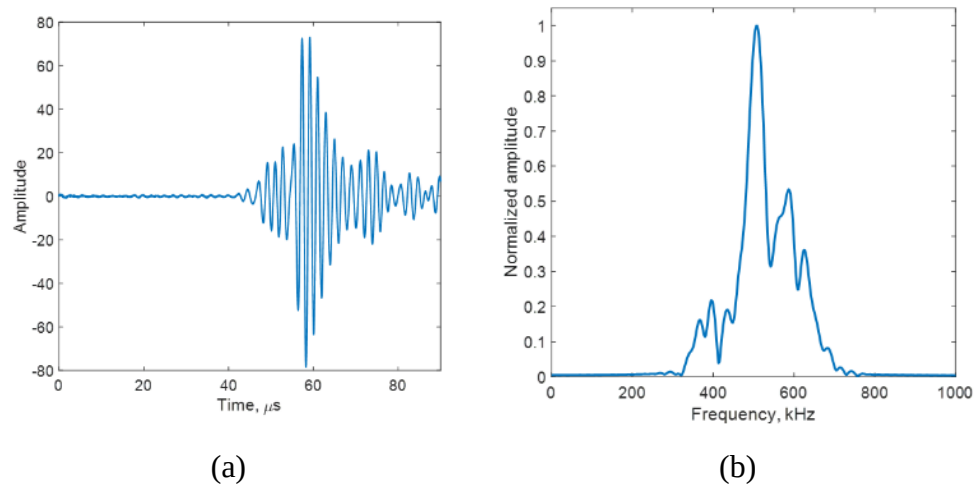


Figure 151 (a) Waveform at 19.5 degrees; (b) FFT of waveform