



Impact Damage Detection on Thick Reinforced Thermoplastic Pipe Utilizing X-Ray Computed Tomography and Phased Array Ultrasonic Testing Techniques

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Abstract

This study investigated impact damage characterization of reinforced thermoplastic pipes (RTP) using X-ray computed tomography (CT) scan and phased array ultrasonic testing (PAUT) techniques. Two types of RTP samples, namely the standard (ST) and gas-tight (GT) types, were impacted using a drop-weight tower. The X-ray CT scan revealed detailed cross-sectional views of damages, including fiber breakage, matrix degradation, and aluminum layer damage. With the implementation of time-corrected gain method in a zero-degree configuration, PAUT demonstrated damage detection capabilities comparable to the CT scan technique by employing various frequencies and focusing techniques. However, it was challenging to accurately assess the extent of damage in the GT type due to the presence of the aluminum layer. While higher-frequency PAUT transducers improved sizing accuracy for the ST type, sizing damages in the GT type remained challenging. Implementing a focusing technique revealed ultrasonic B-scan cross-sectional images of damage closely resembling those from CT scans, offering insights into through-thickness damage morphology. This research showed that the results from the ultrasonic wave-based technique were in good agreement with those from the X-ray imaging-based technique.

Keywords Reinforced thermoplastic pipe · Thick composite · Phased array ultrasonic · Computed tomography · Non-destructive testing · Impact damage

Abbreviations

2D	Two dimensional
3D	Three dimensional
BVID	Barely visible impact damage
CT	Computed tomography
FCP	Flexible composite pipe
FOV	Field of view

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FSH	Full-screen height
GT	Gas-tight
NDT	Non-destructive testing
PAUT	Phased array ultrasonic testing
RTP	Reinforced thermoplastic pipe
SNR	Signal-to-noise ratio
ST	Standard
TCG	Time-corrected gain
TCP	Thermoplastic composite pipe

1 Introduction

The demand for flexible composite pipes (FCP) in the oil and gas market is rising for good reasons. FCP effectively tackles the significant challenges associated with traditional metal pipes, particularly corrosion in harsh environments, which can lead to leakage. FCP has a high strength-to-weight ratio, is spoolable, and is corrosion-resistant. A typical FCP system comprises three main layers: a thermoplastic inner liner, a fiber reinforcement system, and a thermoplastic outer layer. The reinforcement is either fully bonded to a thermoplastic matrix or unbonded in a continuous string. The former is known as thermoplastic composite pipe (TCP), while the latter is referred to as reinforced thermoplastic pipe (RTP) [1]. RTP is primarily used for lower-pressure and less demanding temperature applications, typically ranging from 30 to 450 bar internal pressure at up to 105°C operating temperature [2]. Due to the unbonded fiber reinforcement, their resistance to hydrostatic external pressure is relatively low. In contrast, TCP can typically handle higher internal and external pressures and temperatures due to its fully bonded structure. Pressure ratings and use temperature depend on the fibers, fiber orientation, reinforcement thickness, and thermoplastic matrix, making them suitable for more demanding applications [3, 4].

Reliable non-destructive testing (NDT) methods are needed to detect damages in RTP resulting from high-force impacts or earthmoving machinery to maintain the integrity of components and to ensure service safety. Studies have indicated that external interference damage causes the most significant risk to RTP serviceability [5–7]. Hence, detecting and precisely measuring damages is crucial for any required repair action to prevent catastrophic events. In burst tests, the short-term burst pressure decreases as the crack dimension of the reinforcement layer damage increases [5] or as the indentation depth from an impact damage is deeper [6]. Various types of RTP exhibit a similar trend of reduced burst pressure when the reinforcement layer is compromised. The damage measurements are subsequently used in a finite element analysis simulation to record the stress intensity factor, which is critical for assessing whether the RTP is fit for continued service or requires immediate repair [7]. In the event of severe impact damage to an RTP that reaches the reinforcement layer, it can compromise structural integrity, reduce mechanical strength, create pathways for fluid ingress, and significantly increase the risk of catastrophic failure.

Many previous studies have employed the existing phased array ultrasonic testing (PAUT) technology to address the urgent need for NDT techniques to detect and measure impact damages in composite structures [8–12]. However, these studies primarily focused on thin composites (generally less than 5 mm thick) commonly used in aerospace and auto-

motive applications. In these thin materials, the effect of ultrasound wave attenuation is less significant due to the shorter travel distance, which results in reduced interaction with interfaces and potential scattering, thereby minimizing cumulative attenuation effects. The C-scan results indicated that the total damage area increased with higher impact energy. However, the detailed impact damage morphology initiated by matrix cracking and delamination propagating radially from the impact location, resembling a pine tree damage pattern, could be more effectively visualized using the volumetric reconstruction method by post-processing the raw ultrasonic data [13, 14].

Conversely, thick composite structures (generally more than 10 mm thick) like FCP experience severe ultrasonic wave attenuation due to the high attenuation coefficient of polymers and polymer composites, approximately four times that of metals [15]. Nevertheless, few studies have addressed the UT capabilities in detecting defects within thick composite structures, primarily for oil and gas applications [16–18]. Implementing the classical time-corrected gain (TCG) method effectively tackles the severe attenuation problems. It demonstrates reliable detection of fabricated defects with good signal-to-noise ratios (SNR) in fully bonded TCP, whether the defects are perfectly perpendicular or randomly oriented unfavorably to wave propagation [16]. It is worth noting that glass fibers exhibit higher reflectivity of ultrasonic signals than carbon fibers, resulting in more pronounced signal scattering and attenuation [17, 18]. This research further highlights the benefits of employing the TCG method, building upon the work presented in [16], to address the unique and significant challenge of inspecting RTP structures with unbonded reinforcement layers. The presence of unbonded interfaces introduces a high acoustic impedance mismatch, which exacerbates signal attenuation and complicates defect detection. The proposed PAUT optimization aims to mitigate these effects and enhance the reliability of inspection in such structures.

The implementation of full matrix capture and total focusing method when inspecting thick composites provides higher image resolution compared to standard PAUT [19–23]. However, their effectiveness is challenged by high attenuation and the anisotropic nature of the laminate, which limits detection depth and reduces SNR due to increased noise from reflections at ply interfaces [21, 22]. These challenges can be mitigated by using a nonlinear frequency modulation waveform [22] or a combination of the ray tracing method with the appropriate coupling medium [23]. Nevertheless, the unbonded nature of the reinforcement layer in structures like RTP would lead to even greater attenuation, requiring further increases in gain, which would not only increase defect signals but also background noise, internal scattering, and electronic noise. Consequently, this advanced technique may pose additional challenges related to SNR, as compared to the TCG method, which selectively amplifies signals only at specific depths, thereby managing noise more effectively [16].

X-ray computed tomography (CT) is an NDT method that reconstructs multiple two-dimensional (2D) radiographic images of a sample taken from various angles into a volumetric three-dimensional (3D) image. This technique enables the visualization and characterization of internal structures, leading to a more accurate and reliable assessment of internal damage. Limited studies have employed CT specifically on FCP applications [24–26]. CT can differentiate micron-sized fiber damage from the area with a lack of adhesion and quantify voids in the same sample [24]. It can detect microcracks perpendicular to the radiation beam. Tiny delamination of several microns is also visible [25]. Despite CT's superior performance in imaging actual defects, its practicality in field applications

is limited. One of the main challenges is the need to rotate the X-ray source and detector devices around the pipe, which is difficult due to pipeline layout restrictions and geometrical limitations [26].

In this study, impact damages on RTP samples are carefully created to preserve the cylindrical shape of the pipe for the PAUT technique. This paper further addresses the challenge of inspecting such an unbonded structure and proposes a way to make it possible to inspect it. For PAUT, a combination of the TCG method and focusing technique is employed. The results are compared with the cross-sectional images from the reconstructed 3D view recorded by the CT scan, focusing on defect detection and sizing capability.

2 Test Specimens

2.1 RTP Sample

The flexible and non-metallic RTP samples, 150 mm in diameter, were acquired from Solu-Force. They comprise several layers, including a thick thermoplastic liner, dry aramid reinforcement layers, and a thermoplastic cover. The thermoplastic material was high-density polyethylene. The RTP was constructed by helically wrapping two layers of prepreg tapes, made of continuous and twisted aramid yarns, over the thermoplastic liner at $\pm 55^\circ$ angles. Subsequently, these layers were heat-bonded together before the thermoplastic cover layer was extruded over them [27, 28]. The fibers were not bonded to the matrix because the twisted aramid yarns were not impregnated. There are two types of RTP used in this research work, namely standard (ST) and gas-tight (GT) types, as illustrated in Fig. 1. The GT type has an additional bonded aluminum layer designed to prevent the permeation of light components and gases, distinguishing it from the ST type. For experimental purposes, the RTP samples were cut into 150 mm lengths to facilitate ease of handling during impact damage creation using drop weight procedures and subsequent impact damage detection studies utilizing the X-ray CT and PAUT.

2.2 Impact Damage

The impact damage was created using a simple drop weight tower comprising a V-shaped high-strength steel impactor with a mass of 96 kg, dropped from a predetermined height and guided by a rail system. The impactor weight and drop height were carefully selected to ensure that adequate impact energy could be generated to initiate damage on the duc-

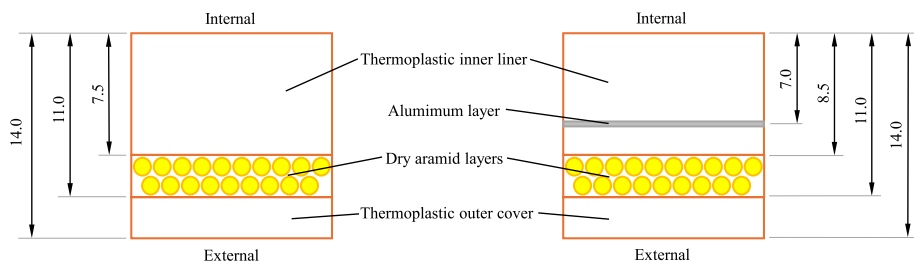
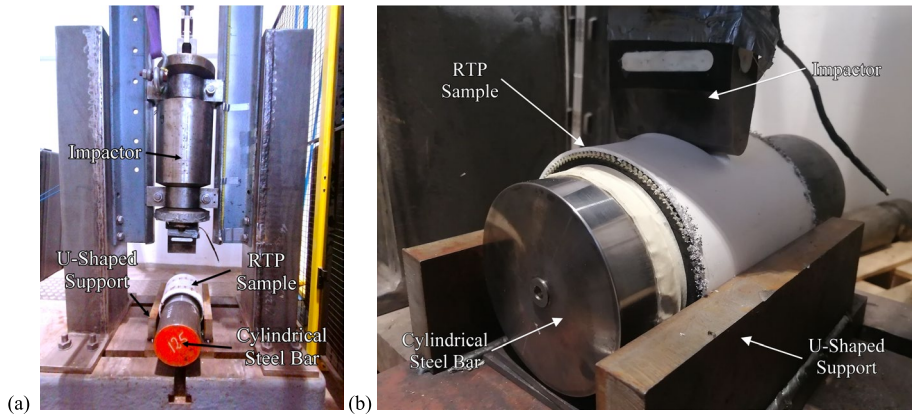


Fig. 1 Cross section of RTP samples: ST type (left) and GT type (right). Measurements are in mm

Table 1 Impact parameters

	Drop height, h (m)	Impact energy, E_i (kJ)	Impact velocity, v_i (m/s)
1		0.94	4.43
2		1.88	6.26

**Fig. 2** Drop weight procedure: (a) just before impact and (b) immediately after impact

tile thermoplastic material, progressing until damage occurred on the aramid layers. High impactor weight was used to produce sufficient impact force that can damage the aramid layers. These layers are recognized for their exceptional toughness, which can absorb significant energy during impact [29]. Additionally, it was intended to damage the aluminum layer in the GT type. The impact energy, E_i , and the corresponding impact velocity, v_i , can be calculated based on energy conservation during free-fall by the relations:

$$E_i = m_i \cdot g \cdot h \quad (1)$$

and

$$v_i = \sqrt{2 \cdot g \cdot h} \quad (2)$$

where m_i is the mass of the steel impactor, g is the gravitational acceleration for an object in free fall, which can be assumed to be constant at about 9.81 m/s^2 , and h is the drop height. These impact parameters are summarized in Table 1.

Figure 2 shows the drop weight setup. The steel impactor was aligned perpendicularly to the axial length of the RTP sample, which was placed in a U-shaped steel support frame and fastened atop the tower floor to prevent unwanted lateral movement during impact. Additionally, a cylindrical steel bar with a diameter matching the inner diameter of the RTP sample was inserted to prevent severe denting post-impact, preserving the cylindrical shape necessary for subsequent PAUT procedure. This bar could simulate the presence of internal pressure during impact. At the same time, the significant weight of the setup could

imitate the drop of a ship anchor in a marine environment, which is relevant to pipe in field applications [30].

3 Experimental Method

3.1 X-Ray CT Scan Technique

The X-ray CT scan technique was employed to image and characterize the impact damages on the RTP samples by generating detailed cross-sectional views. This approach facilitated the analysis of through-thickness damage progressions, which was crucial for comparing the results with those obtained using the PAUT technique. The scanning was performed utilizing the Nikon XT h 225 ST scanner. Figure 3 shows the schematic of the X-ray CT setup. The RTP sample was placed between the X-ray source and the flat panel detector type Varex 1620 with an active pixel size of 2000. The longitudinal axis of the RTP sample was aligned perpendicular to the X-ray beam to ensure consistent imaging along the length of the pipe. In this study, the whole length of the RTP sample was set to be within the field of view (FOV) by placing it at approximately 545 mm from the X-ray source to obtain the full 3D image of the sample. With the distance of the detector to be approximately 1125 mm from the X-ray source, the resolution achieved was 97 μm determined by the voxel sizes in the x-, y-, and z-directions, with approximately 8 billion voxels for the scanned sample. For a microscopic analysis of the damage, the resolution could be improved by focusing only on the area of impact damage to be within the FOV. However, this approach was not considered in this study because the results were intended to be compared with the PAUT technique, which focused on the macroscopic analysis of the impact damages.

The measurement principle relied on the attenuation of X-ray radiation, which was influenced by factors such as the wavelength of the incident beam and the atomic number, density, and thickness of the scanned sample. For this study, the X-ray generation settings included an accelerating voltage and a tube current of 160 kV and 77 μA , respectively. Multiple 2D projection images were acquired at various angles around the pipe. With an angular step of approximately 0.115° , a total of 3141 projections were acquired for the scan, encompassing a complete 360° rotation of the RTP sample. These 2D images were processed using the Inspect-X software developed by Nikon to reconstruct a detailed 3D volumetric image of the pipe's internal structure, enabling a thorough analysis of the impact damages. These reconstructed 3D data sets were processed using the VGStudio MAX from Volume Graphics and further analyzed using the open source myVGL software.

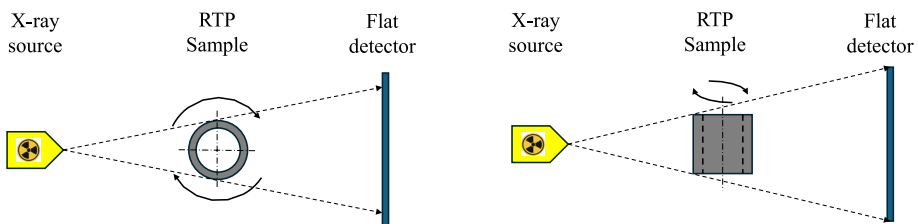


Fig. 3 Schematic of the X-ray CT setup from (left) the top and (right) the side views

3.2 PAUT Technique

Three 64-element linear phase array transducers with center frequencies of 1.5 MHz, 3.5 MHz, and 5.0 MHz of type NW1 from Olympus were used in this research work. These transducers have a total active aperture of 64 mm×7 mm, with 1-mm pitch and 7-mm elevation. Phased array devices can electronically control the incidence angle and focal distance of the ultrasonic beam. A 16-element group configuration and a 1-element step increment were used to produce 49 channels of zero-degree beams. In addition, a classical TCG method was implemented, whereby the signal height of the fiber layer was set to 100% of the full-screen height (FSH), followed by the signal of the back wall being incrementally increased to the same level. It is worth noting that this method is only applicable to multi-layer polymer structures because the second echo of the fiber layer, which would coincide with the first echo of the back wall, experiences severe attenuation due to its exceptionally high attenuation coefficient [16]. Meanwhile, the high attenuation nature of polymer causes the ultrasonic signal beyond the first interface layer of a multi-layer polymer structures to be severely attenuated, which impacts signals from subsequent interfaces, the back wall, discontinuities, and even repeated echoes from the first layer. This research work proves that this inherent limitation regarding high attenuation of sound waves in RTP has made implementing the TCG method in a zero-degree configuration possible.

Figure 4 shows the A- and E-scan views of the ultrasonic signal data captured on a good RTP sample (ST type) using immersion technique. While the A-scan data provides a point measurement comprising the signal amplitude over pulse transit time, the E-scan view represents a cross-sectional view of the RTP sample underneath the entire length of the PAUT transducer without moving it, resembling a typical B-scan view. The inspected part of the sample was submerged in a water tank at a certain distance from the transducer until the first water-sample interface signal appeared at approximately 45 mm in the A- and E-scan views. It was noted that when the testing was conducted from outside the RTP sample, the water-sample interface signal merged with the reinforcement layer signal, the back wall signal was severely attenuated, and the repeated signals were incomprehensible. In contrast, testing from the inside provided clearer and more distinguishable results. Due to the significant increase of gain, the reflected backward signal within the transducer at approximately 16 mm was increased as well. In addition to a factor stemming from the non-bonded fibers and matrix, the curvature geometry of the pipe likely contributed to this severe attenuation. The convex curvature dispersed the signal, hindering its return to the transducer when scan-

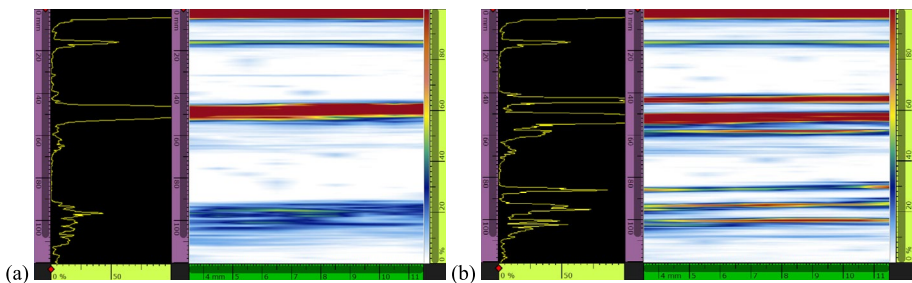


Fig. 4 A- and E-scan views of the ultrasonic signal at 43 dB gain settings when scanning the RTP sample from (a) external and (b) internal sides

ning the RTP sample from external. In contrast, the signal tended to converge more effectively through the transducer after reflecting off the concave curvature when scanning was performed from the internal side.

A combination of a zero-degree Aqualene™ wedge and immersion technique was essential for PAUT from inside the pipe to ensure a consistent distance between the transducer and the RTP sample and maintain sufficient coupling during scanning. The selection of wedge made of this thermoset polymer material is important due to its similar acoustic properties to that of water [31]. This setup ensured that the RTP sample was only partially immersed in water to prevent complete immersion of the transducer, as it was not designed for immersion. While the Aqualene™ wedge provided optimal matching with the transducer, a small water-filled gap existed between the other side of the wedge and the curved internal pipe, as shown in Fig. 5(a). Therefore, selecting the Aqualene™ wedge was crucial because it shares a similar acoustic impedance with water, governed by density and sound velocity, ensuring maximal signal transmission [31–33]. Additionally, Aqualene™ wedge exhibits a lower attenuation coefficient than the other documented elastomers and many plastics commonly used as wedges [34].

Figure 5(b) shows the PAUT testing setup. The wedge stabilized the transducer, ensuring it remained fixed in distance and angle and preventing complete submersion of the transducer underwater while the pipe underwent rotation for scanning purposes. A mini-wheel encoder from Olympus having a resolution of 16 step/mm was mounted on the test bench above the RTP sample in a way that the wheel rotates in tandem with the pipe rotation, recording the scanning positions and damage dimensions along the scan axis, thereby synchronizing data acquisitions with the pipe rotation. The scanning was performed twice to demonstrate data repeatability. In the first set of measurements, the ultrasonic beam was unfocused. Then, the ultrasonic beam was focused at the reinforcement layers and back wall to improve the detection and characterization accuracy of the impact damage. The electronic gates were positioned at the reinforcement layer and the back wall signals.

The focusing distance of the ultrasonic beam in the test object would change in the presence of an intervening material used as the coupling medium, which, in this case, was the combination of wedge and water. Previous studies demonstrated how the algorithm of calculating the time delays used in the focal law calculator of the instrument, considering the different sound velocities in those two mediums, led to the difference in the resulting focusing

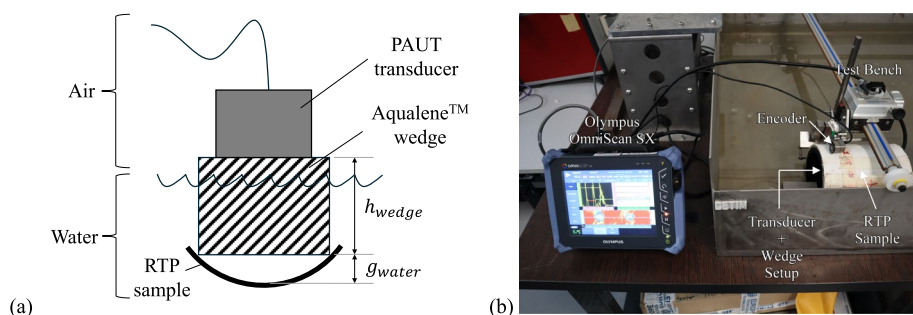


Fig. 5 (a) Schematic diagram of the small water gap, g_{water} , between the Aqualene™ wedge and the internal surface of the RTP sample and (b) the PAUT testing setup implementing partial immersion of the sample

depth [35, 36]. Hence, the benefit of using the Aqualene™ wedge, due to its similar acoustic properties with water, is that the wedge height settings in the instrument can be assigned as the sum of the physical height of the wedge itself and the small water gap between the wedge and the RTP sample, denoted as h_{wedge} and g_{water} in Fig. 5(a), respectively.

Several strategies were employed to characterize the defect, including assessing the signal attenuation of the back wall and reinforcement layers. The B- and C-scan data for the RTP were obtained and analyzed. While the B-scan data offers a 2D cross-sectional view of the sample, facilitating the analysis of the defect morphology in the through-thickness plane, the C-scan data provides a 2D planar view of the sample projected upon the scanning surface essential for assessing the extent of damage across the sample area. Due to the smaller damage size than the ultrasonic beam size used in this study, only one-line scan was performed per sample. The raw data was acquired using the Olympus OmniScan SX flaw detector and subsequently transferred to a PC for post-inspection data analysis utilizing the OmniPC 5 software, which is a complimentary companion software for the Olympus OmniScan series [37].

4 Results

4.1 X-Ray CT Scan Results for Impact Damage Analysis

Figure 6(a) shows the 3D reconstructed radiographic image of the RTP sample, highlighting the impact damage near the center. Cross-sectional images of the sample thickness are acquired from multiple planes in all directions to thoroughly assess the damage within the reinforcement layers and, specifically for the GT type, the aluminum layer. The central

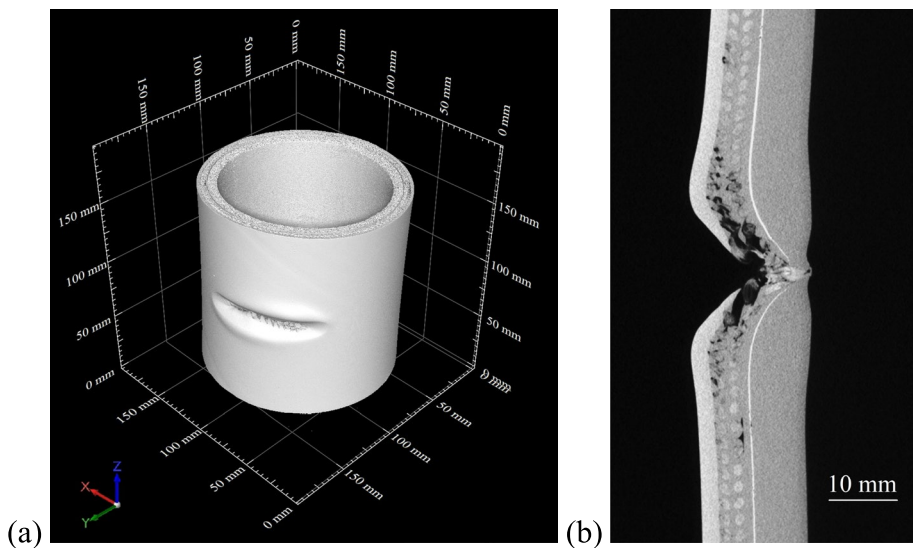


Fig. 6 (a) 3D radiographic image of the RTP sample and (b) the representative cross-sectional view of the GT type at the damage central position parallel to the yz-plane

point of the damage is identified from the cross-sectional view in the yz-plane, depicted in Fig. 6(b).

There are 2000 planes showing the cross-sectional view of the RTP sample in each x, y, and z direction. Adjacent planes within the same direction are spaced approximately 97 μm apart. However, due to space constraints on paper, only 7 cross-sectional views in the xy-plane per impact damage for both types of samples are presented in this section, as schematically shown in Fig. 7.

Cross-sectional radiographic images parallel with the xy-plane for the RTP sample are presented in Fig. 8. The reconstructed radiographic images reveal the different components of the sample. These components include two aramid layers, a thermoplastic outer cover, and an inner liner in both RTP types. Additionally, the aluminum layer in the GT type is identifiable. Each component produces different density images because of different X-ray absorption rates. Damage mechanisms, primarily dominated by fiber breakage, matrix degradation and deformation, and aluminum damage, are prominently identified in these images. The central region of impact emerges as the locus of most severe damage across all specimens, notably observed in Slice 4. Slice 1 is one of the outmost points of the impact damage, at which the matrix deformation starts to create a gap with the fiber, extending until Slice 7. Slice 2 and Slice 6 mark the boundaries of the V-shaped notch damage, while Slice 3 and Slice 5 represent regions within this damage zone.

It is observed that the distance between Slice 1 and Slice 7 increases with higher impact energy, indicating that doubling the impact energy increases the damage progression in the axial direction. While the distance between Slice 2 and Slice 6 is relatively consistent across all samples, damage progression beyond the boundaries of the V-shaped notch damage going further away from the impact location in the GT type exceeds that of the ST type. The reason behind these phenomena is that the presence of an aluminum layer in the GT type separates the total thickness of the specimen into two thicknesses, resulting in a lower homogeneous thickness than the ST type. The thinner sample under impact exhibits a lower resistance to deformation, resulting in a larger in-plane damage progression than the thicker sample, which dissipates energy over a larger area and volume [38–40]. However, it is observed that the damage mechanism beyond the V-shaped notch damage area is mainly a

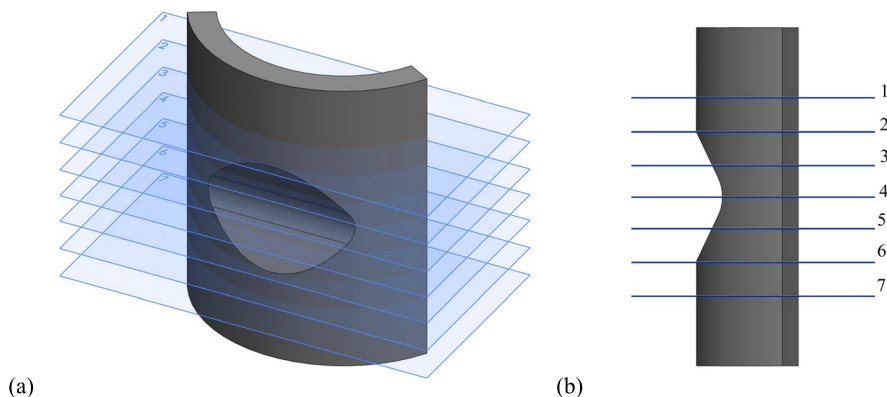


Fig. 7 (a) Trimetric and (b) side views of the schematic drawing showing the impact damage on the RTP sample, with the locations of slices for cross-sectional images parallel with the xy-plane

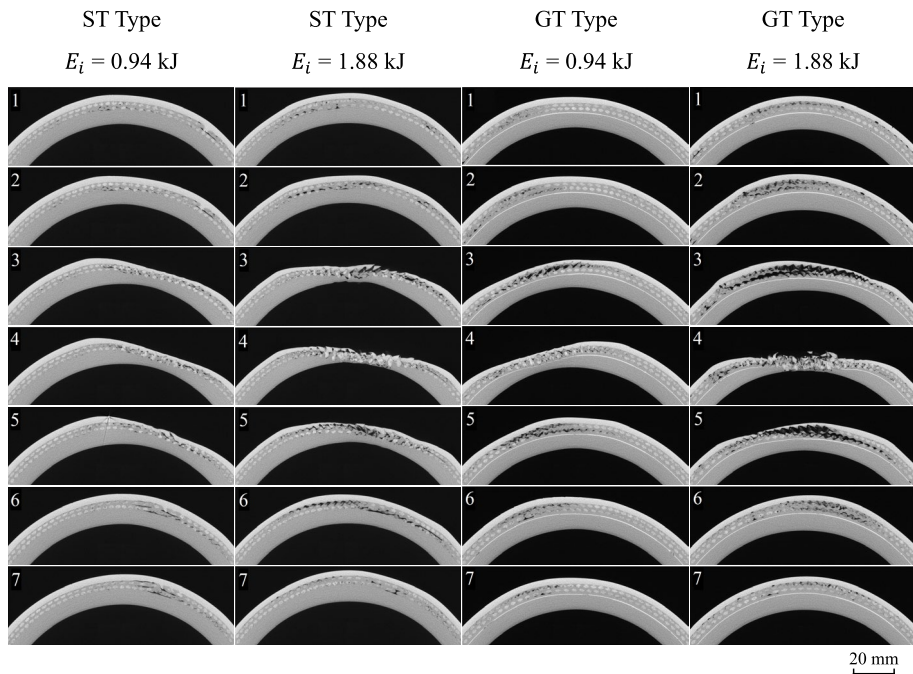


Fig. 8 Cross-sectional radiographic images of the RTP sample in parallel with the xy-plane

small gap between the matrix and fiber attributed to the slight matrix deformation, with no significant fiber breakage or matrix degradation, as evident in Slice 1 and Slice 7.

Referring to Slice 4, the two aramid layers in the ST type under 0.97 kJ impact energy are still distinguishable. In contrast, the specimen under 1.88 kJ impact energy exhibits complete damage concentrated around the center. In addition to similar damage mechanisms involving fiber and matrix that occurred in the ST type, the aluminum layer under 0.97 kJ impact energy in the GT type shows minor cracks and dents. When subjected to 1.88 kJ impact energy, the aluminum layer suffers extensive damage and severe denting. At the boundaries of the V-shaped notch damage, the material deforms by outward stretching due to the ductile behavior of the thermoplastic material and the presence of the cylindrical steel bar inserted during impact, preventing inward deformation [41], as shown in Fig. 6(b) as viewed in the yz-plane and in Slice 2 and Slice 6 as viewed in the xy-plane.

4.2 PAUT Results

4.2.1 Sound Velocity Calibration in Immersion Technique

Before conducting the test, the sound velocity calibration was performed on the RTP sample immersed underwater. The calibration involved five different thicknesses, t_{RTP} , of 8.4 mm, 10.0 mm, 10.4 mm, 12.0 mm, and 14.5 mm by removing the liner thickness accordingly. Initially, the calibration sample was fully immersed underwater at three depths to implement a complete immersion technique. Considering the relatively lower acoustic impedance at the sample-water interface of the back wall, which led to the reduced amount of received

signals, three water columns with heights similar to the depths used in the complete immersion technique were additionally utilized, representing a one-sided immersion technique to maximize signal reflection at the sample-air interface of the back wall. In both methods, the distance between the transducer and the surface of the calibration sample, d_w , was maintained at 22.85 ± 0.35 mm, 32.30 ± 0.62 mm, and 42.62 ± 0.40 mm. Measurements were conducted using four different beam sizes by grouping and pulsing 4, 8, 12, and 16 elements to generate a single ultrasonic beam profile, and data from all beams were considered. This approach made the signal travel through both the water and the calibration sample, covering a distance twice the path length of both mediums, each with different velocities, as illustrated in Fig. 9.

The time of flight, T_{bw} , from the transducer to the back wall of the RTP sample and back at the transducer can be calculated by the relation:

$$T_{bw} = 2 \cdot \left(\frac{d_w}{v_w} + \frac{t_{RTP}}{v_{RTP}} \right) \quad (3)$$

where d_w is the distance between the transducer and the RTP calibration sample, t_{RTP} is the thickness of the RTP calibration sample, v_w is the sound velocity in water, and v_{RTP} is the sound velocity in the RTP sample. It is worth noting that the velocity value applied for the RTP sample was considered an average velocity since the sound wave was traveling in two different compositions, which are the dry bundle of aramid fiber and thermoplastic material constituting the liner and cover layers [16]. The following relation is obtained by rearranging Eq. (3):

$$t_{RTP} = \frac{v_{RTP}}{2} \cdot T_{bw} - \frac{v_{RTP}}{v_w} \cdot d_w \quad (4)$$

Data was plotted for t_{RTP} as a function of T_{bw} . The three different d_w produces three graphs, as shown in Fig. 10.

The linear trendline was obtained with its corresponding linear equation, allowing us to derive the line's slope and y-intercept value. Comparing the general linear equation in the form of $y = m \cdot x + C$ with Eq. (4), it is evident that the gradient of the graph, m , equates to half the velocity of the RTP sample. Similarly, the y-intercept value of the linear trendline, C , corresponds to the product of the distance between the transducer and the RTP sample underwater and the ratio between the velocity of the RTP sample and the velocity of water, which is known to be 1.480 mm/ μ s. The calculated velocity values were reported in Table 2, resulting in an average velocity of 2.282 mm/ μ s with a standard deviation of 0.033 mm/ μ s, subsequently utilized in the PAUT experimental procedure.

4.2.2 PAUT Results for Impact Damage Analysis

Figure 11 shows the typical UT A-scan data and E-scan views of the RTP sample inspected from the internal side. The three significant ultrasonic signals correspond to the water-sample interface, the reinforcement layers, and the back wall. Meanwhile, the relatively weaker signal before the water-sample interface signal represents the Aqualene-water interface signal, indicating that most of the ultrasonic energy passes through the interface due to similar

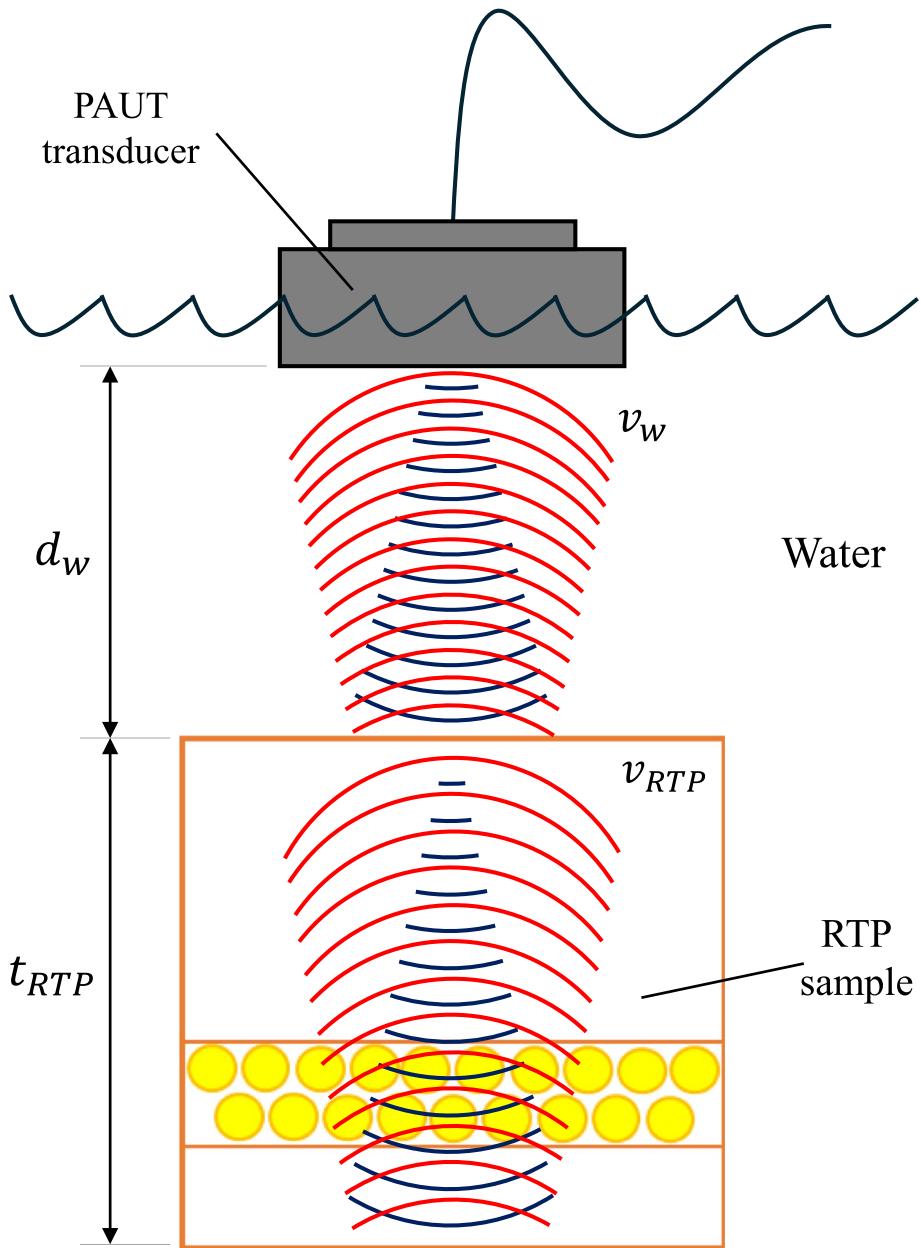


Fig. 9 Schematic diagram of sound wave travelling in water and RTP sample with different velocities

acoustic properties, as described in Sect. 3.2. Partially increasing the back wall signal using the classical TCG method does not increase the second (repeated) signal of the reinforcement layers, which is assumed to be severely attenuated due to the considerable attenuation coefficient of the polymer [16]. Implementing the TCG method in a zero-degree configura-

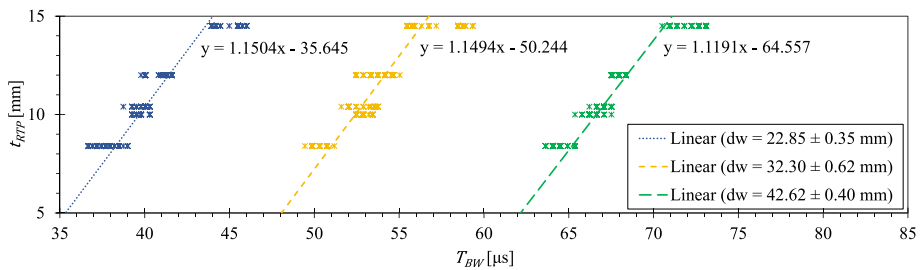


Fig. 10 Calibration thickness, t_{RTP} , as a function of time of flight, T_{BW} , for three different distances between the transducer and the surface of the calibration sample, d_w

Table 2 Sound velocities of RTP sample calculated from the gradient and y-intercept values of the trendlines

d_w [mm]	Gradient, m [mm/ μ s]	y-intercept, C [mm]	v_{RTP} calculated from the m -value [mm/ μ s]	v_{RTP} calculated from the C -value [mm/ μ s]
22.85	1.1504	-35.645	2.3008	2.3091
32.30	1.1494	-50.244	2.2988	2.3024
42.62	1.1191	-64.557	2.2382	2.2420

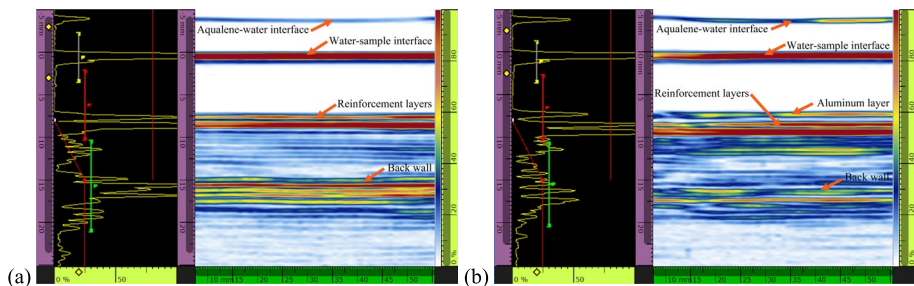


Fig. 11 Typical A- and E-scan views of the (a) ST and (b) GT type when inspecting from internal

tion is possible due to this inherent limitation regarding high attenuation of sound waves in multi-layer polymer structure like RTP. Consequently, no unwanted signal overlaps with the back wall signal, which would cause erroneous interpretation of the results.

Looking at the signal of the reinforcement layers, the two signals from the reflection of the two Aramid layers are distinguishable, demonstrating a high signal resolution in discriminating against two closely positioned reflectors. Additionally, the signal from the aluminum layer before the aramid layers for the GT type can also be differentiated from the signal of the aramid layers, as shown in Fig. 11(b). Conversely, the pulse width of the back wall signal is relatively huge, approximately 5 mm, posing challenges in detecting defects closer to the back wall. The signals from these adjacent reflectors would merge into a single, indistinct signal, complicating defect detection [9, 42]. Furthermore, the ultrasonic energy coming back from the back wall of the GT type is much lower than that of the ST type, which indicates a smaller amount of energy penetrating the aluminum layer due to high difference in acoustic impedance.

Gate A (red) and B (green) in Fig. 11 are positioned at the reinforcement layers and back wall signals, respectively. Employing a signal attenuation strategy facilitates the generation of corresponding C-scan amplitude images, depicting the impact damage area represented by the bluish-white region where the amplitude falls below 50% of the FSH, as shown in Fig. 12 and Fig. 13 for ST and GT types, respectively. C-scan images of the same damage obtained from multiple measurements demonstrate good repeatability, confirming the consistency and reliability of the inspection results. Due to space constraints, this paper presents results from the two extremes of the test parameter as representative. The x-axis and the left y-axis represent the damage sizes in the circumferential and axial directions, respectively. The other y-axis on the right side indicates the signal amplitude height. While it is evident from the C-scan images that the damage size of the impacted sample with higher energy is larger, there is no significant difference between the damage sizes impacted by the same energy for both types. Additionally, the C-scan images of the GT type show more bluish-white regions outside the damage area, indicating lower ultrasonic energy penetration due to the presence of the aluminum layer. This layer introduces a high acoustic impedance mismatch, resulting in reduced transmission of ultrasonic energy through the layer.

Initially, the test was conducted without focusing the ultrasonic beam. The results show that increasing the frequency yields slightly more refined images with evidence of fiber direction. Then, the signal is consecutively steered and focused at the back wall and rein-

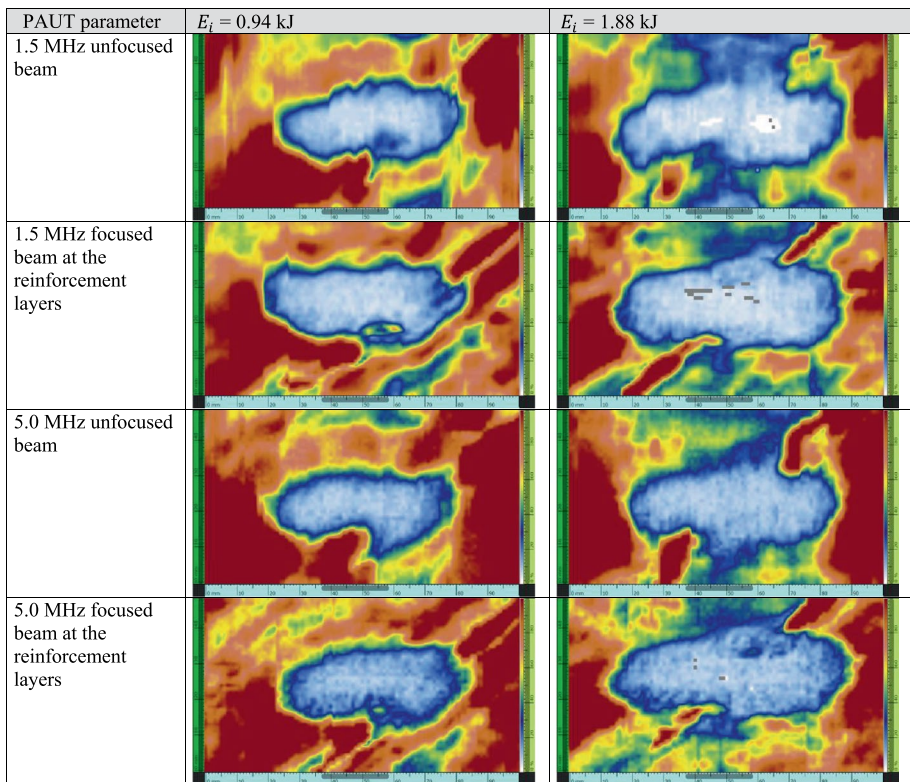


Fig. 12 PAUT C-scan amplitude images for the ST type with the gate placed at the back wall echo

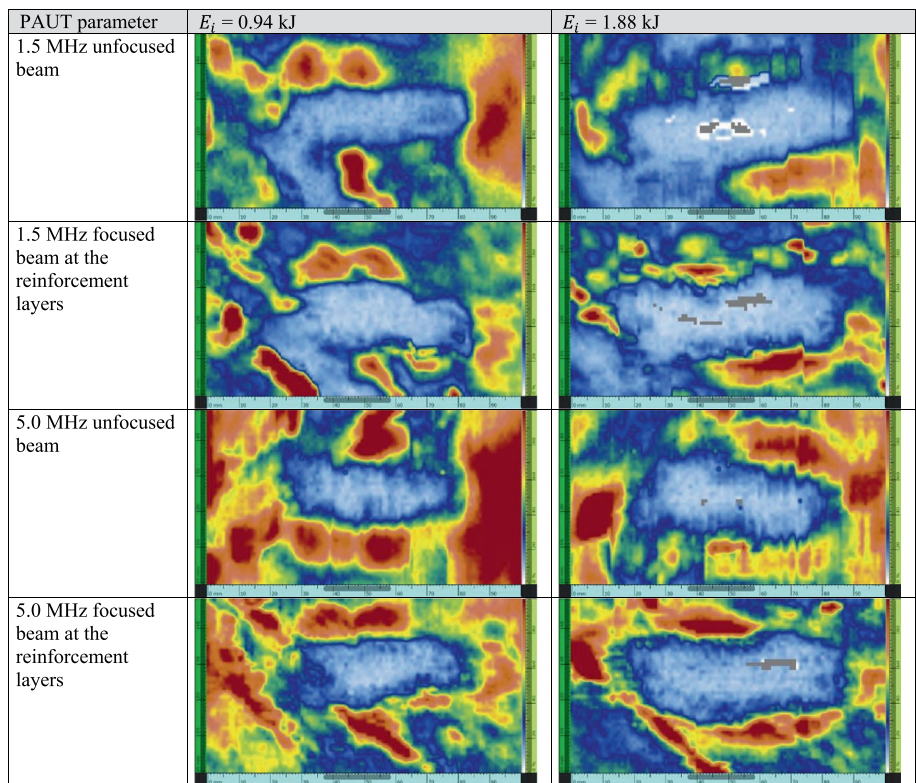


Fig. 13 PAUT C-scan amplitude images for the GT type with the gate placed at the back wall echo

forcement layers to enhance damage characterization. When the ultrasonic beam is focused, the results yield even more confined images due to reduced signal distortion and more energy reacting at the damaged area. Moreover, the image quality improves when the ultrasonic beam is focused at a lower frequency, revealing the image of the fiber direction.

5 Discussions

When impact energy increases, the degree of impact damage typically intensifies. However, the visible signs of damage remain minimal or barely noticeable on the surface, even though internal damage could be significant. This type of damage, especially in composite materials, is often called barely visible impact damage (BVID). Since BVID can mask severe internal damage that is difficult to detect visually, using NDT, like X-ray CT and PAUT, is crucial in assessing the full extent of the damage.

Due to the irregular shape of impact damage, it is difficult to determine the exact damage size from the X-ray CT and the ultrasonic C-scan images. Hence, the damage size was measured in the axial direction at five roughly equidistant positions. Given that each damage underwent two ultrasonic scans, a total of ten measurements were obtained per damage. Subsequently, the mean values and standard deviations were computed and plotted

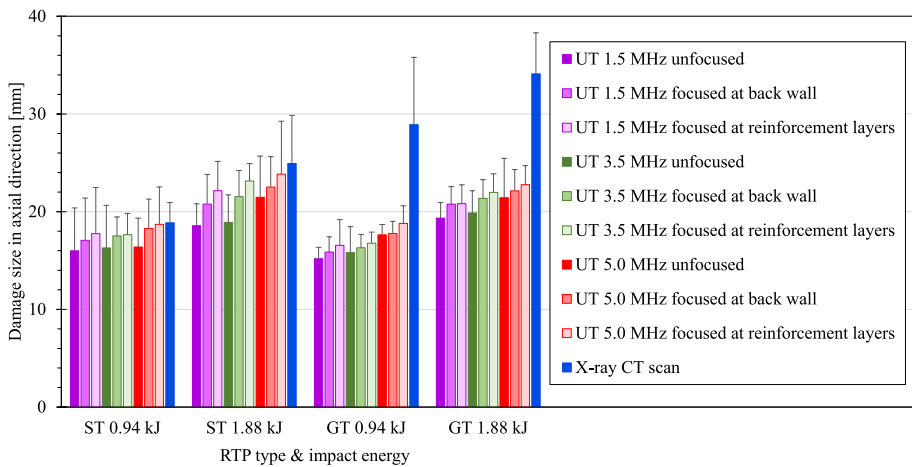


Fig. 14 Damage size in the axial direction recorded by PAUT technique based on the attenuation of the back wall signal as compared to the X-ray CT scan technique. The solid bar represents the mean damage size in the axial direction from ten measurements each, while the error bar indicates the standard deviation from these repeated measurements

in Fig. 14 and Fig. 15 for C-scan images based on attenuation signals of the back wall and reinforcement layers, respectively. These values are then compared with those measured from the radiographic images.

In general, higher impact energy tends to result in larger damage sizes. It is observed that the damage area at the reinforcement layers is smaller than that at the back wall, consistent with the morphology of the V-shaped notch damage type. PAUT results report almost simi-

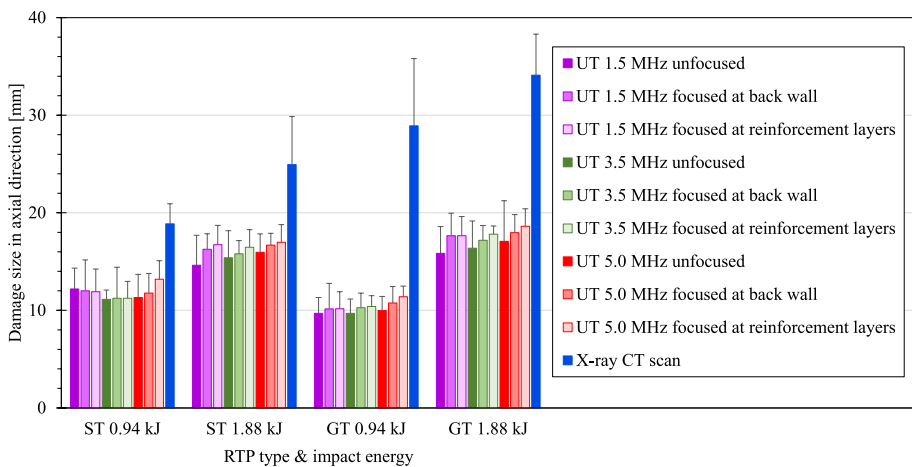


Fig. 15 Damage size in the axial direction recorded by PAUT technique based on the attenuation of the reinforcement layer signal as compared to the X-ray CT scan technique. The solid bar represents the mean damage size in the axial direction from ten measurements each, while the error bar indicates the standard deviation from these repeated measurements

lar damage sizes for both RTP types impacted by the same energy, contrary to the X-ray CT scan results, which show a larger damage area for the GT type. This discrepancy is attributed to the damage mechanism beyond the V-shaped notch area comprising small gaps between the matrix and fibers due to matrix deformation with no fiber breakage and matrix degradation, which still allows the ultrasonic energy to pass through them and reach the back wall, as shown in Slice 1 and Slice 7 in Fig. 8.

Furthermore, PAUT results show that the damage sizes increase with increasing frequency of the unfocused ultrasonic beam. Additionally, employing the focusing technique reveals a further increment in damage sizes, aligning more closely with the results obtained by the X-ray CT scan method, especially for the ST type. This sizing improvement shows the efficiency of the focusing technique in enhancing signal detection and characterization capability [43]. Increasing frequency reduces the wavelength, resulting in a better sensitivity and more accurate detection capability. Focusing the beam at the position of interest increases the amount of energy that reacts with the reflectors and provides more accurate information from the reflected energy.

The radiographic technique offers distinct advantages over ultrasonic methods when characterizing damage shapes and sizes due to its similarity to an optical image derived from density differences, as opposed to the ultrasonic C-scan amplitude images. Although both techniques can reliably characterize damage at the impact location, only the CT technique allows for precise imaging of the small fiber-matrix gap beyond the impact location, resulting in a more accurate assessment of damage progression. This disparity can lead to significant undersizing when inspecting impact damage on the GT type using the PAUT technique, as damage progression beyond the edges of the V-shaped notch comprises more extension of the small gaps between the matrix and the fiber than in the ST type. Therefore, reliance solely on the PAUT technique may compromise the accurate evaluation of damage extent.

Furthermore, it is advisable to refrain from cutting impacted samples into smaller test pieces to determine the actual damage size destructively, as this could jeopardize the original damage state. Additionally, the dry fibers in RTP could easily be pulled out when the sample is cut into smaller pieces [44]. Based on previous studies, X-ray CT scan results are assumed to have less than 10% errors compared to the actual damage dimensions, further highlighting this technique's reliability in accurately characterizing damage [43]. The relative errors are used to compare the result of the PAUT with the X-ray CT scan method as reference using the following relation:

$$e_{rel} = \frac{|l_{axial,UT} - l_{axial,CT}|}{l_{axial,CT}} \times 100 \quad (5)$$

where $l_{axial,UT}$ and $l_{axial,CT}$ are the damage sizes in the axial direction measured by the PAUT and X-ray CT scan methods, respectively, and plotted in Fig. 16 considering the C-scan images based on the back wall attenuation only.

In general, relative errors are improved not only through increasing the transducer's frequency but also the focusing technique at the position of interest enhances accuracy. Notably, this improvement is evident in the ST type, reducing the relative error from a little over 25% to less than 5%, showing a good agreement with measurements from the X-ray CT scan method. However, for the GT type, despite enhancements in relative error achieved

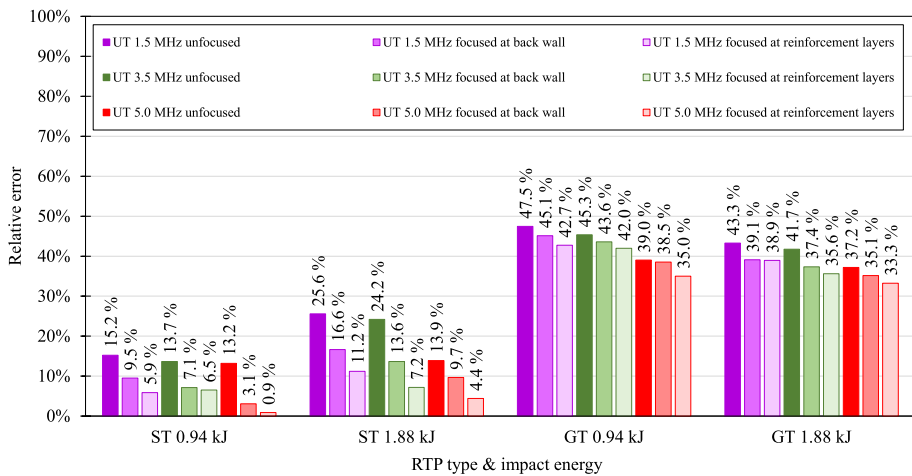


Fig. 16 Relative errors of the damage measurement using the PAUT technique based on the attenuation of the back wall signal as compared to the X-ray CT scan technique

through frequency increase and focusing technique implementation, the relative errors are more than 30%. Consequently, while PAUT results for the ST type indicate high reliability in damage detection and characterization, cautious interpretation is required when analyzing PAUT results for the GT type, representing a relatively thinner RTP due to the presence of the aluminum layer. The impact on this RTP type can lead to large damage areas consisting of small fiber-matrix gaps due to matrix deformation post-impact, which are inaccurately recorded by the PAUT technique.

It is worth noting that while higher-frequency PAUT transducers demonstrate improved sizing and detection capabilities, further increasing the frequency may not necessarily yield better results due to the higher attenuation caused by shorter wavelengths. Previous works highlight challenges even with a 5 MHz single-element UT transducer with a relatively larger element size, which is 12.7 mm in diameter when scanning thick thermoset composite materials of 8–14 mm thick. Ultrasonic signals were highly attenuated in such cases, making thickness measurement impossible, and fabricated defects remained undetected [45, 46].

The C-scan results only provide information about the in-plane extension of damage. However, looking into the E-scan or B-scan data obtained through a single or multiple-line scanning reveals a more nuanced characterization of damage morphology, particularly with focused ultrasonic beams, as shown in Fig. 17. In scenarios where the ultrasonic beam is not focused, only reflectors perfectly perpendicular to wave propagation efficiently reflect off energy. Conversely, reflectors unfavorably positioned to the wave propagation reflect off ultrasonic waves in random directions, resulting in signal loss. However, with a focused ultrasonic beam, reflections of some amount of energy occur even from reflectors positioned unfavorably to the wave propagation, in this case, the slanted areas within the V-shaped notch damage zone. This reflection produces a cross-sectional view akin to that imaged by the X-ray CT scan method, providing essential out-of-plane information about the depth of impact damage alongside in-plane damage area assessment. The impact energy of 0.94 kJ penetrates until a few millimeters before reaching the back wall, while the impact energy of 1.88 kJ penetrates the entire thickness of the RTP. This E-scan data shows good agreement

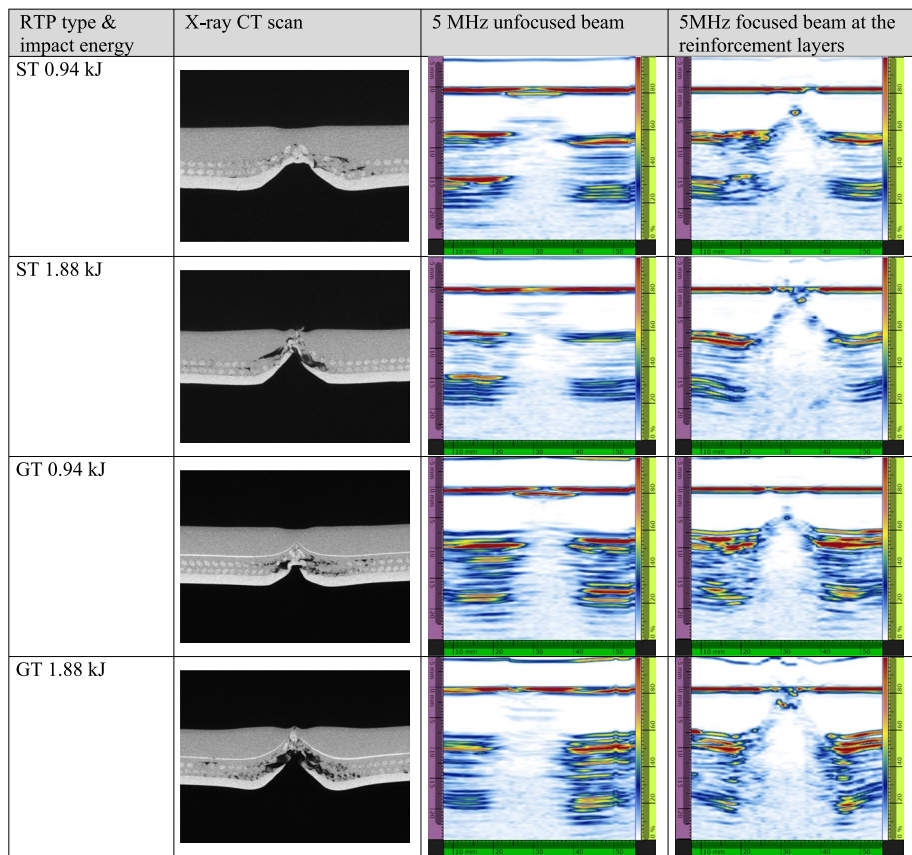


Fig. 17 Comparison of through-thickness radiographic images of impact damage in parallel with the yz-plane with the PAUT L-scan views of unfocused and focused beam at the reinforcement layers

with the cross-sectional radiographic images. Such insights are invaluable for understanding damage penetration depths and extent, aiding in comprehensive damage assessment.

This study successfully demonstrates that the proposed technique utilizing PAUT with the TCG method in a zero-degree configuration provides reliable detection of severe impact damage. Future research should explore lower impact energies that result in less extensive damage to determine the minimum detectable damage threshold using this technique. Such investigations would help assess the capability of early-stage damage detection before it progresses to a critical state.

6 Conclusions

This study presents a comprehensive analysis of impact damage in RTP using X-ray CT scan and PAUT techniques implementing the TCG method. The RTP samples are subjected to controlled impact using a drop-weight tower. X-ray CT scan and PAUT techniques are employed to visualize and characterize the impact damage.

The X-ray CT scan provides detailed cross-sectional images revealing damage mechanisms such as fiber breakage, matrix degradation, matrix deformation, and aluminum layer damage. It is observed that doubling the impact energy results in increased damage extension. Furthermore, the presence of the aluminum layer in the GT type influences damage progression, leading to larger damage areas beyond the impact location than in the ST type.

The PAUT technique demonstrates its capability in detecting and characterizing impact damage. While the PAUT can accurately detect and size the impact damage in the ST type with less than 5% relative error, challenges arise in accurately sizing the damage in the GT type with a relative error of more than 30% due to the presence of the aluminum layer that separates the entire thickness into two. Various strategies are employed to improve the detection and sizing capabilities of PAUT, considering the transducer's frequency and beam focusing.

Higher frequencies and focused ultrasonic beams enhance sizing and detection capabilities, aligning more closely with the X-ray CT scan results. However, caution is advised when interpreting PAUT results for the GT type due to potential inaccuracies in characterizing the impact damage. This discrepancy is due to the damage mechanism beyond the impact location, which consists of small gaps between the matrix and fibers caused by matrix deformation without any significant fiber breakage and matrix degradation but still allowing ultrasonic energy to pass through them and reach the back wall. Additionally, the through-thickness damage morphology is better characterized by the focusing technique, which produces cross-sectional views similar to radiographic imaging.

In conclusion, X-ray CT scan and PAUT techniques show different capabilities in assessing the impact damage in RTP. While X-ray CT scan provides detailed imaging for precise damage characterization, PAUT offers real-time inspection and reliable detection capabilities. Future research should focus on further refining PAUT techniques to improve accuracy, particularly in thinner RTP samples with complex damage mechanisms. Overall, this study contributes to the advancement of nondestructive evaluation methods for assessing impact damage in RTP, aiding in developing more reliable pipeline integrity management systems.

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Authors Contributions Mohd Fadzil Mohd Tahir: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. Andreas T. Echtermeyer: Conceptualization, Funding acquisition, Resources, Writing – review & editing.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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