

Research Article

Damage Assessment of Low-Velocity Impacted Sandwich Composite Structures Using X-Ray Micro-Computed Tomography

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Sandwich composite structures offer significant versatility in structural system design but are susceptible to low-velocity impact damage, impacting their structural robustness. This study focused on nondestructive testing, particularly using X-ray micro-computed tomography, to assess damage on these structures, comprised of thin glass fibre reinforced polymer face sheets and a polyvinyl chloride foam core, under low-velocity impacts. Impacts were induced by a constant mass of 5.61 kg, dropped from various heights, generating impact energies between 2 and 22 J. This resulted in varied damage levels, from indentations to full perforations. The X-ray micro-computed tomography technique was chosen for its ability to detect internal damage. However, the system's efficacy in accurately assessing damage depends on numerous factors like focus-to-detector distance, focus-to-object distance, and spatial resolution of the detector, among others. The system yielded an approximated resolution range of 10–25 μm for a focal spot size of 4 μm and the resolution range of 11–26 μm for a spot size of 7 μm . To this end, the system was able to reveal damage inflicted across the specimen through captured and reconstructed images. The quality of the reconstructed images was validated using ImageJ2 software by comparing with the processed images. The median filter was found to deliver images that closely resembled the original ones, albeit with a slight reduction in quality. Damage types varied based on impact energies. Low-level impacts caused matrix cracking and delamination at the foam interface. Medium-level impacts led to intralaminar and interlaminar damage, fibre fractures, and significant damage to the foam core through shearing and crushing. High-level impacts resulted in near or full perforations, with more pronounced delamination at the bottom interface, and fibre fractures in the impact zone, displaying a distinctive diamond-like damage pattern. These findings can be instrumental in developing a predictive impact damage model.

1. Introduction

Within the framework of this study, damage assessment is understood as the evaluation of low-velocity impact damage (LVID) to gather both qualitative and quantitative data on sandwich composite structures. Different damage assessment methods and their advantages are discussed. Many existing studies have primarily focused on damage assessment in laminates, while research on sandwich composite structures remains scarce despite their growing utilisation in various fields. Unlike laminates, which form a simpler monolithic structure, sandwich composite structures are

more prone to LVID, which compromise their load-bearing capacity.

Furthermore, sandwich foam cores are made of different materials. Core materials substantially affect damage initiation characteristics because they have lower mechanical properties than the skins or face sheets due to their low density [1]. This highlights the fact that independent investigations need to be conducted for different core materials to determine their damage initiation thresholds. The sandwich composite structures used in this work consisted of thin glass fibre reinforced polymer (GFRP) face sheets and polyvinyl chloride (PVC) foam core of low density.

2. Background

2.1. Low-Velocity Impact (LVI). The notion of low-velocity impact has been clarified in existing literature to distinctively separate it from other velocity categories. A common consensus among researchers establishes that low-velocity impacts occur at speeds below 10 m/s [2, 3]. This study will adhere to this definition, ensuring that all considered velocities remain within this range, specifically between 0.9 m/s and 2.8 m/s. In practical scenarios, sandwich composite structures can be subjected to low-velocity impacts in numerous ways, such as tool drops during servicing or routine maintenance, hailstorms, bird strikes for moving objects in space, during transportation and handling prior to installation, and part installation whether standalone or in assembly [3, 4]. For this study, low-velocity impact damage was induced on the sandwich composite structures by utilising the Instron Dynatup Impact Testing Machine. Notably, recent research regarding sandwich composite structures primarily concentrated on understanding the effects of extremely low temperatures on carbon fibre reinforced polymers [5]. This highlights the many factors that can influence the impact behaviour of these complex structural materials.

2.2. Damage Assessment Methods. Damage assessment methods are techniques that aim to detect, locate, quantify, and characterise damage in structures. There are different types of damage assessment methods, such as non-destructive testing (NDT), structural health monitoring (SHM), and numerical modelling and simulation. The application and the available resources determine the advantages and disadvantages of each method.

2.2.1. Nondestructive Testing (NDT). These techniques assess damage without causing further harm or altering the structure being inspected. Examples include ultrasound, radiography, X-ray micro-computed tomography (X-ray μ -CT), acoustic emission, shearography, and thermography [6]. Each of the mentioned technique has its own advantages and disadvantages that are not covered in this work except X-ray μ -CT that is the focus of this study and presented in detail as an isolated subsection. Some advantages of NDT methods are as follows:

- (i) They are fast and reliable, as they can provide immediate results without affecting the structure's performance or service life.
- (ii) They are cost-effective, as they can reduce the need for destructive testing, repair, or replacement of the structure or its parts.
- (iii) They are versatile, as they can be applied to various materials, shapes, sizes, and conditions of the structure.

2.2.2. Structural Health Monitoring (SHM). These are monitoring techniques that continuously or periodically measure and analyse the structural responses to external stimuli, such as loads, vibrations, temperature, and strain [6]. They can provide information about the structural behaviour, performance, and condition of the structure. The advantages include the following:

- (i) They are proactive, as they can detect and identify damage before it becomes critical or catastrophic and provide early warning and diagnosis.
- (ii) They are adaptive, as they can adjust to the changing environmental and operational conditions of the structure and provide updated and accurate information.
- (iii) They are comprehensive, as they can provide a global and holistic view of the structure and capture the interactions and interdependencies among the structural components and systems.

Efforts from researchers are currently underway to create hybrid systems that combine the strengths of nondestructive testing (NDT) and structural health monitoring (SMH) approaches, aiming to enhance the monitoring and assessment of damage.

2.2.3. Numerical Modelling and Simulation. These are computational techniques that use mathematical models and algorithms to simulate the physical phenomena and processes that affect the structure. They can provide information about the structural response, damage evolution, and failure mechanisms of the structure [7]. Although not discussed in the current work, this approach is slated for exploration in subsequent studies. Some advantages are as follows:

- (i) They are predictive, as they can forecast the future behaviour and performance of the structure and provide optimal design and maintenance strategies.
- (ii) They are flexible, as they can incorporate various parameters, scenarios, and uncertainties of the structure and provide sensitivity and robustness analysis.
- (iii) They are innovative, as they can explore new and complex phenomena and mechanisms that are difficult or impossible to observe or measure experimentally and provide novel and creative solutions.

2.3. X-Ray Micro-Computed Tomography (X-Ray μ -CT). Initially, the primary utilisation of X-ray μ -CT was in the realm of medical applications. However, over time, enhancements in the technique have broadened its application to nonmedical fields. X-ray μ -CT introduces a novel possibility of measuring internal geometries that surpasses the capabilities of optical measuring techniques [8]. In their study on the CT Scanner Facility at Stellenbosch, the researchers highlighted emerging applications in material science, wood science, and industrial applications, owing to the developments in computer power, hardware, and software advancements [9]. Evidently, there is a vibrant research effort to leverage the capabilities of X-ray μ -CT, with explorations extending to areas such as industrial non-destructive testing [10], dimensional metrology [11], additive manufacturing [12], food science [13], and biological sciences [14]. Within the scope of this study, the limitations of optical methods in generating reliable

qualitative and quantitative data on internal damage led to the choice of X-ray μ -CT as the preferred technique.

X-ray μ -CT technique uses X-ray radiation to capture 2D images of an object in many positions about the axis of rotation on which the platform is mounted. In this work, the specimen underwent a complete 360° revolution while the X-ray generator emitted X-ray beams that passed through the specimen and reflected on the digital detector in the form of radiographs (projected 2D images) as shown in Figure 1. The 2D images were subsequently transformed into 3D images using specific algorithms included in the Volume Graphics software. This conversion was done to provide qualitative and quantitative data for more in-depth analyses.

The calibration of the X-ray μ -CT system for dimensional metrology entails optimising key geometric parameters, including the source-to-detector distance, source-to-object distance, detector resolution, detector tilt angle, and rotation centre offset. These parameters are critical for ensuring the accuracy and quality of the reconstructed images and must be meticulously established. However, the focus of this study is not to explore the calibration process in depth or to examine all potential sources of uncertainty that may arise during the measurement process. The system resolution for this study was estimated from the formula provided in [15].

$$r_s \approx \frac{1}{M_g} \sqrt{D_r^2 + \left(S \frac{d_{OD}}{d_{SO}}\right)^2}, \quad (1)$$

where r_s is the system resolution; M_g is the geometrical magnification; D_r is the resolution of the detector; S is the size of the X-ray focal size; d_{OD} is the distance of the object to the detector; and d_{SO} is the distance of the source to the object.

The geometrical magnification:

$$M_g = \frac{FDD}{FOD}. \quad (2)$$

The typical pixel resolutions of commercial flat panel detectors are within the range of 75–200 μ m [16]. The detector resolution is primarily determined by the pixel size of the detector. A detector with a smaller pixel size will have a higher resolution, as it can capture more detail. Conversely, a detector with a larger pixel size will have a lower resolution.

The smallest focal spot sizes for X-ray μ -CT system using a microfocus and nanofocus tubes are 7 μ m and 3 μ m, respectively [17]. The focal spot size in an X-ray μ -CT system plays a vital role in determining the resolution and contrast of the X-ray beam. The smaller the focal spot size, the greater the resolution and contrast of the X-ray beam. This high resolution and contrast would allow for the detection and quantification of the elemental composition and distributions in the sample with greater detail.

The detector resolution and focal spot size are not the only relevant parameters in estimating the overall system resolution, but they are among the most important ones.

3. Experimental Methodology

This section deals with the steps and procedures that were followed to carry out the different tests. The construction of the sandwich panel involved an autoclave process using preimpregnated resin (prepregs) with glass fibers for the outer layers, and a foam material at its core. The arrangement of the prepregs followed a symmetrical and balanced pattern, with the sequence being [(0/90), (+45/-45)] for the top face sheet, followed by the foam core, and then mirrored by [(+45/-45), (0/90)] for the bottom face sheet. A cross-linked and closed-cell polyvinyl chloride foam of density 80 kg/m³ was used in the construction of the panel. The planar dimensions of the specimens were 150 mm $\times$ 100 mm, selected in accordance with the ASTM D7136/7136M-15 standard for drop weight impact testing.

3.1. Impact Tests. Low-velocity impact tests were conducted on an Instron Dynatup Impact Testing Machine equipped with a hemispherical impactor of diameter 12.5 mm. Various levels of impact energy were applied to the specimens, ranging from barely visible impact damage (BVID) to the point of achieving complete penetration. The total impact mass of 5.61 kg was used. All tests were conducted at a room temperature of 21°C. The testing machine was equipped with a data acquisition device as depicted in Figure 2. The specifications of the testing machine are provided in Table 1.

Impact damage was induced by varying the drop height of the impactor so that the desired impact energy levels were reached. In this study, the selected energy levels do not necessarily represent specific industrial applications except to understand the impact responses aimed at optimising the use of sandwich structures in identified industrial applications. The impacted specimens were then taken for damage analysis using X-ray μ -CT.

3.2. X-Ray Experimental Setup. The setup of an X-ray micro-computed tomography (μ -CT) scanner is essential in ensuring accurate and precise measurements. The micro-CT scans were conducted on the General Electric Phoenix V-Tome-X L240 scanner with the following specifications as presented in Table 2.

The setup steps are summarised as follows:

- (1) Positioning of the X-ray source, the detector, and the specimen: The X-ray source, the detector, and the specimen were positioned as illustrated in Figure 3, to optimise the geometric parameters. The detector was positioned at an angle perpendicular to the X-ray beam to prevent image distortion.
- (2) Specimen mounting: Each specimen was mounted on a rotating stage located between the X-ray source and detector. It was placed in such a way that the centre of rotation was aligned with the axis of the X-ray beam to avoid reconstruction errors. Each specimen was secured on a low-density floral foam

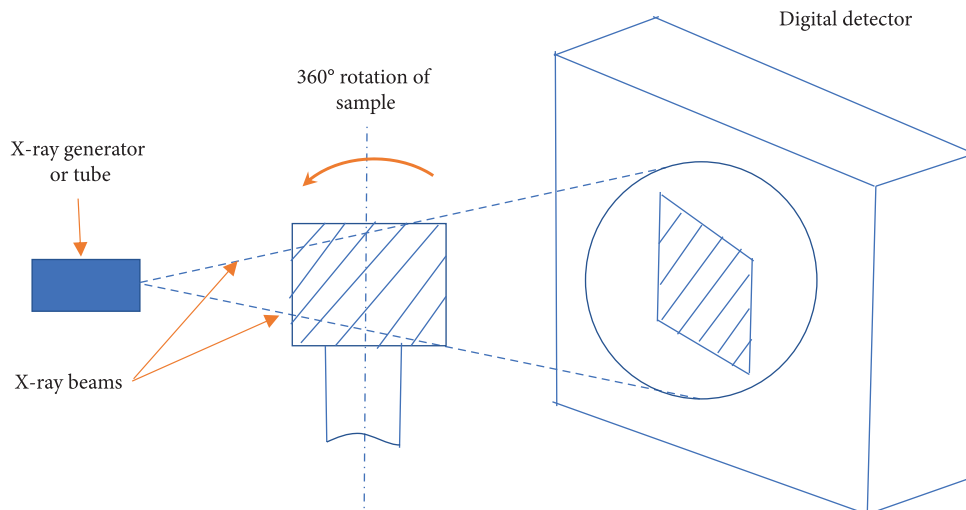


FIGURE 1: Schematic representation of the X-ray micro-computed tomography.

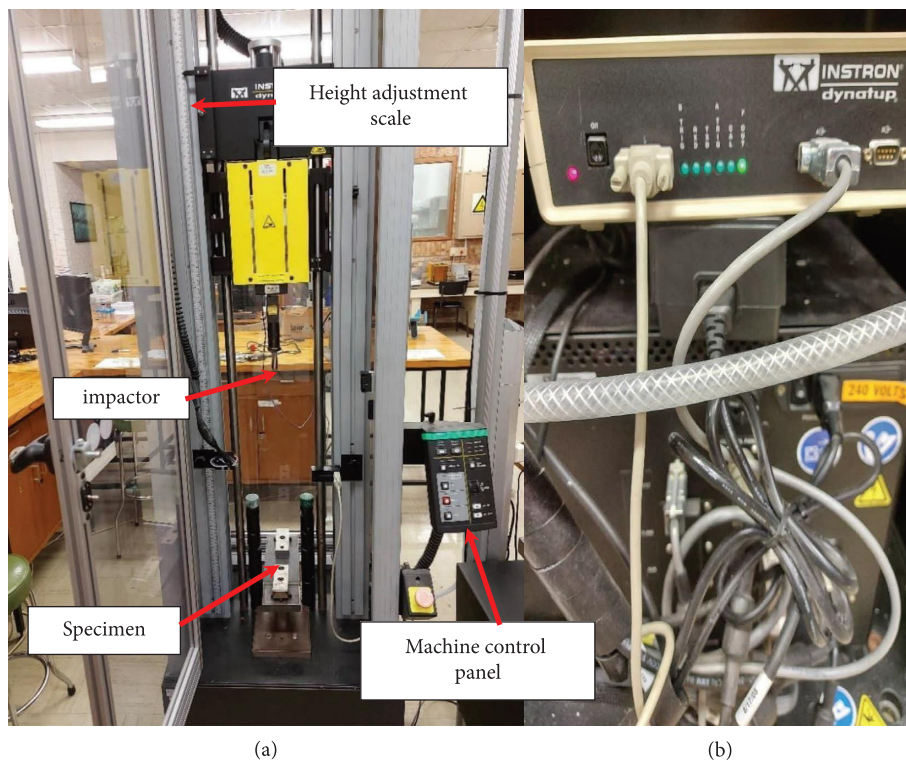


FIGURE 2: (a) Instron Dynatup Impact Testing Machine. (b) Data acquisition equipment.

so that its image would not interfere with that of the tested specimen. Because the sizes of the tested specimens were too long in relation to the detection spectrum, part of either side of the specimen length from the centre was covered. The covering was aided by a sticky stuff that can be observed on the scan. Thus, the focus of inspection was concentrated on the impacted zone around the centre.

- (3) Selection of scanning parameters: Important scanning parameters that were selected include the X-ray tube voltage and current, the exposure time, the

number of projection images, and the rotation step. These parameters can affect the quality of the images and the time it takes to complete the scan.

- (4) Calibration of the detector: the detector's pixel size, linearity, and uniformity were calibrated to ensure accurate intensity readings.
- (5) Test scan and adjustment: A test scan was performed to check and adjust the setup. The resulting images were examined for artifacts, distortions, or misalignments, and adjustments were made as necessary.

TABLE 1: Instron Dynatup Impact Testing Machine specifications.

Nominal load limit capacity	100 kN
Maximum tup capacity	88.964 kN
Load cell accuracy	0.07%
Ringing frequency	8600 Hz

TABLE 2: Scanner specifications.

Voltage (kV)	10–240
Current (μ A)	5–3000
Max. voxel resolution	1 μ m
Typical best voxel size	5 μ m
Beam angle	Approx. 30°
Max. sample weight	50 kg
Max. sample height	320 mm
Max. sample width	300 mm
Sample max. wall thickness	
Steel	10 mm
Rock	40 mm
Plastic	100 mm
Wood	200 mm

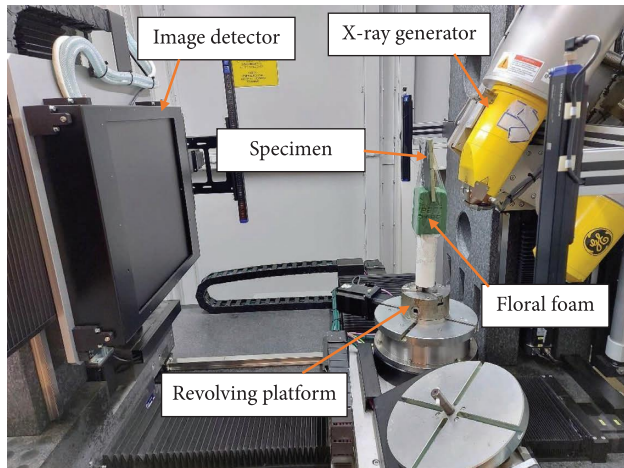


FIGURE 3: Experimental setup for the X-ray micro-computed scanner.

- (6) Actual scanning: Once all parameters were set and the test scan results were satisfactory, the actual scanning process began. The specimen was rotated 360 degrees while the X-ray source and detector remain fixed. The detector captured a series of 2D X-ray images (projections) from different angles.
- (7) Image reconstruction: The captured 2D images were then reconstructed into a 3D volume using specific algorithms. The quality and accuracy of the reconstructed image depend on the accuracy of the setup and calibration.

It is worth noting that the setup and calibration of the X-ray μ -CT scanner are critical steps that directly influence the quality and precision of the measurements, thereby necessitating meticulous attention.

The μ -CT scanner was operated in a temperature-controlled environment to prevent thermal drifts that could affect the accuracy of the scans. The scanner boasts

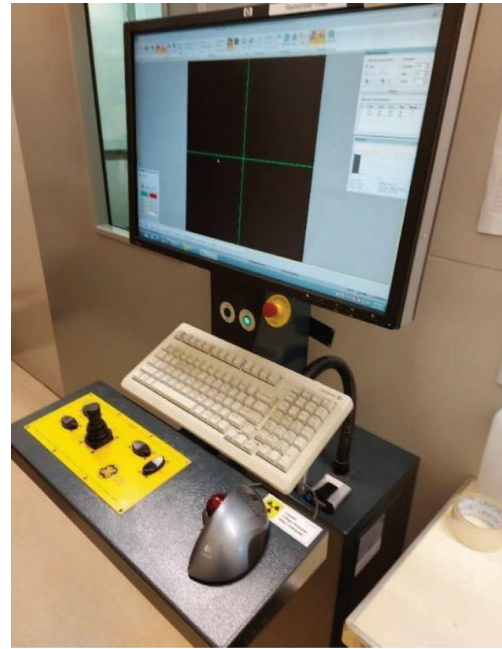


FIGURE 4: Personal computer desktop for data acquisition installed outside the scanner room.

robust shielding designed to impede radiation leakage effectively. This includes enclosures fortified with lead lining, complemented by observation windows crafted from leaded glass, which allow for secure monitoring of the scanning procedure. As an additional safety measure, the computer utilised for data capture is stationed externally to the scanner chamber, as depicted in Figure 4.

The scanning time lasted for about 2 hours per specimen. Important parameters for the X-ray settings are provided in Table 3.

The ratio of the distance of the detector from the X-ray source to the distance of the sample or specimen stage from the X-ray source determines the magnification, which in this case was 8 (refer Table 1). Voxel size was set at 25 μ m. Voltage and current were 130 kV and 150 μ A, respectively. The acquisition time per image was 333 ms carried out during the full rotation of the specimen on which 3000 images were captured.

The 2D images acquired through the detector were stored in the memory of the personal computer desktop stationed outside the X-ray room. The CT scans were reconstructed and visualised in a 3D graphic software called Volumetric Graphics VGStudio Max. Complimentary viewer program myVGL 3.5 was used to interactively view the analysis results and 3D visualisations of the impacted zones of specimens. The 3D reconstruction allowed for the impacted zones to be examined without morphological ambiguities.

The resolution of the cone-beam X-ray μ -CT system depends on the geometrical magnification as illustrated in Figure 5.

The graph shows a steep reduction of system resolution up to a geometrical magnification of 5 for the range of commercial flat panel detectors. The system resolution curves then decreased gradually as the geometrical

TABLE 3: X-ray machine test settings.

Geometry	Detector	X-ray excitation
FDD = 800 (mm)	Timing value = 333.1 (ms)	Voltage = 130 (kV)
FOD = 100 (mm)	Avg = 1	Current = 150 (μ A)
Magnification = 8	Skip = 0	
Voxel size = 25 (μ m)		

FDD and FOD are the positions of the detector and sample stage, respectively, from the X-ray source.

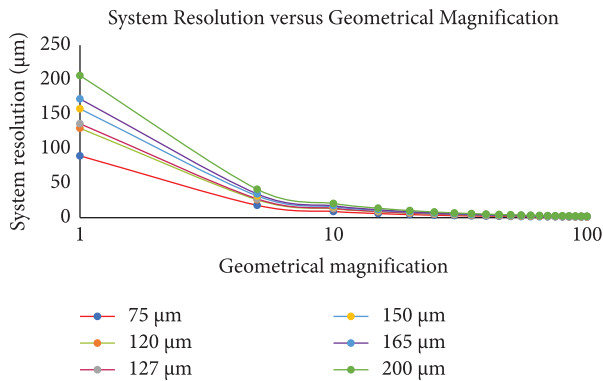


FIGURE 5: System resolution versus geometrical magnification for spot size of $7 \mu\text{m}$.

magnification increased, approaching the minimum system resolution. Given a focal spot size of $7 \mu\text{m}$ and a detector resolution range of $75\text{--}200 \mu\text{m}$, the system produced a resolution range of $11\text{--}26 \mu\text{m}$. This suggests that the system's resolution is more influenced by the detector resolution than the focal spot size or any other parameters. When the focal spot size was changed to $4 \mu\text{m}$, the system resolution was estimated between 10 and $25 \mu\text{m}$ for the same range of flat panel detector resolution. In other words, even with the very small focal spot size ($4 \mu\text{m}$), it is the detector's resolution that primarily determines the system resolution. It is also worth noting that the system resolution is much smaller than the detector resolution, which indicates that the reconstruction algorithm and system geometry successfully resolved details smaller than a single detector pixel. This setup, with a high-resolution detector and small focal spot size, provides the capacity to image fine details within the specimens being examined.

4. Results and Discussion

4.1. Impact Test Results. The specimens subjected to impact were examined to assess their responses to such events. Barely visible impact damage was scrutinised using X-ray micro-computed tomography. Following each impact occurrence, notes were recorded regarding the condition of each specimen, as detailed in Table 4. The accepted margin of error for both velocity and impact energy measurements is within $\pm 0.1\%$.

The impact responses were observed on load-time curves. The area under each curve is representative of the total energy absorbed during the impact event. For all curves, the load increased linearly with the increase in time before the peak load was reached. The time to reach the peak load depended on the impact energy values. Thus, the higher the impact energy, the shorter the time to reach peak value. For barely visible impact damage, two cases exist. (1) The impact energy is completely dissipated throughout the specimen, as reflected on a load-time graph with a smooth curve. For this loading profile, the peak load was reached at 6 ms . (2) The profile depicting a sharp drop in load by approximately 18% is a manifestation of damage initiation as well as a reduction of stiffness in the structure. In this case, the peak load was reached at only 3 ms . From the sharp bottom end, the load increased nonlinearly to below the initial peak load. The second peak load was followed by a smooth curve to zero load at the end of the impact event that lasted for a total 13 ms , as shown in Figure 6. The first notable damage mechanism to manifest was delamination (interfacial debonding or debonding of the face sheet and the foam core). However, delamination is preceded by matrix cracking caused by shear and tensile stresses during impact.

The reduction in stiffness continued until the top face sheet was completely perforated with a sharp drop of the load to approximately 75% of the peak load. This drop in load suggests a minimum contact force recorded at the impactor at the time of perforation. When the impactor regained full contact with the foam core, it occurred at a lower load in comparison to the peak load before another slight sharp increase. The load then gradually decreased from a lower peak load to zero and remained constant, as illustrated in Figure 7.

In the near penetrated specimen, the foam core was crushed immediately after the top face sheet was penetrated. This resulted in a decrease in load before the densification of the foam core due to load increase as shown in Figure 8. The second sharp curve shows that the back face sheet was nearly perforated because it did not reach the zero load. At this stage, the perforated foam core remained in contact with the impactor. The load started to decrease gradually from a point above the end point to indicate a complete perforation of the foam core. The decrease reached the zero load, remained constant for a while before a gradual increase, and then became constant again. The gradual increase is perhaps an indication of residual energy before full penetration.

It was important to carry out visual inspections for the impacted sandwich composite structures for the different impact energies. However, visual inspection failed to identify the delamination inflicted on the specimen, as shown in Figure 9.

Near penetration and its corresponding damage morphology suggested a dent diameter to impactor diameter ratio of $1:2$ as depicted in Figure 10. The fully perforated damage morphology served as an indicator of the specimen's impact response for the utilised stacking sequence, as demonstrated in Figure 11.

TABLE 4: Impact energies and statuses of impacted specimens.

Drop height (m)	Impact velocity (m/s)	Impact energy (J)	Remark on status
0.02	0.9	2	BVID
0.03	1	3	BVID of delamination
1	2	11	Top face sheet penetrated
1.15	2.6	19	Near full penetration
1.2	2.8	22	Full penetration

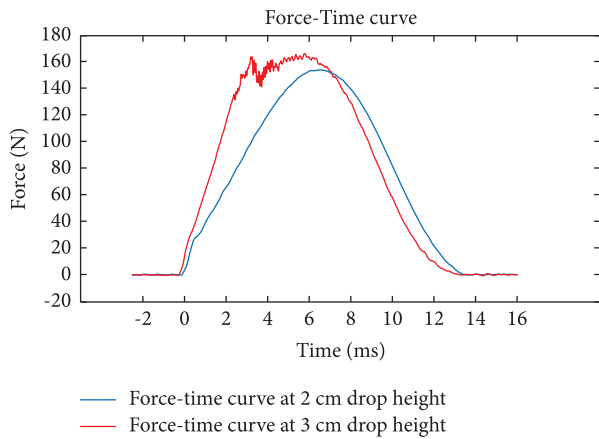


FIGURE 6: Damage initiation at the second lowest drop height.

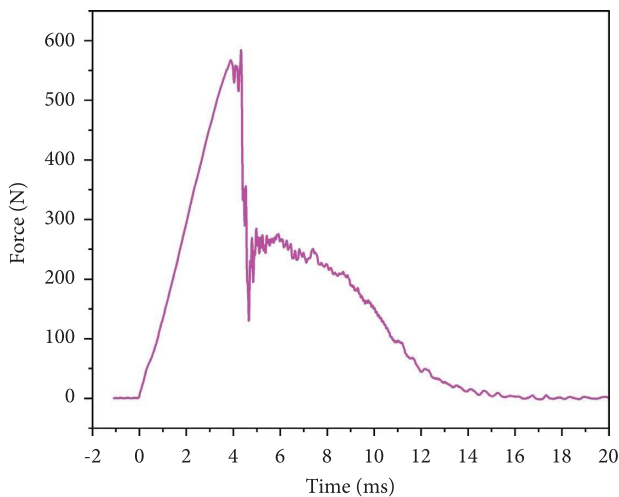


FIGURE 7: Damage evolution with top face sheet penetrated.

4.2. Damage Assessment on the Impacted Specimens Using X-Ray Micro-Computed Tomography. Figure 12 shows the position of impact with respect to the orthogonal views, while Figures 13 and 14 are surface and profile plots, respectively, for the 2 J impact energy.

The plot was generated using data from the impacted zone and its peripheries. It reveals that within the region of interest (the impacted zone), there is a notable and consistent decline in gray values when contrasted with the adjacent areas.

The first impact energy induced an indentation that was only visible through a CT scan. The second impact energy (3 J) resulted in further stretching of fibres and propagation

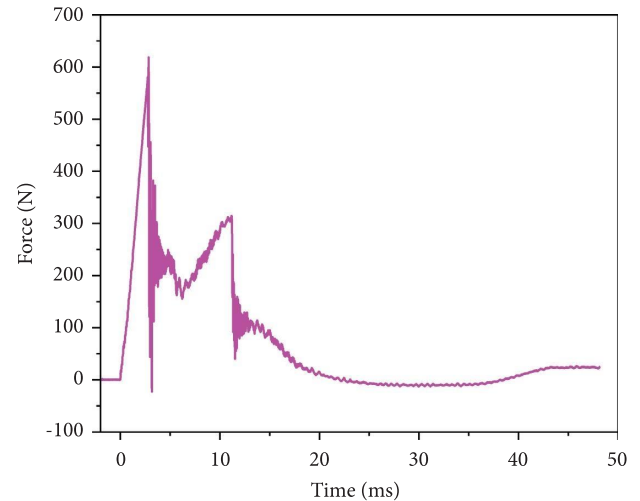


FIGURE 8: Damage evolution for a nearly perforated specimen.

of crack tips in the matrix along different stacking sequence orientations. An indentation was observed at the impacted zone that resulted in initiation of delamination that could not be visually noticed, as illustrated in Figure 15. The respective surface and profile plots for the 3 J impact energy are depicted in Figures 16 and 17.

The intensity-distance plot shows a drop in intensity as the depth of penetration increases. Thus, the lower gray values were identified at the impacted zone.

The observed consistent reduction in intensity towards the centre of the impacted area suggests the presence of valuable data that could be extracted. This finding necessitates additional research to ascertain whether the grayscale profile within the impacted zone could yield insights into the penetration depth and the characteristics of the impactor employed when inducing the damage.

4.3. Validation of Quality of Reconstructed Images. The reconstructed images were further refined using ImageJ 2.9.0/1.54h software, a widely used tool for image processing. The objective was to enhance the quality of the images. An iterative process was employed, removing outliers and applying various filters to find the ones that offered the best improvements. Interestingly, by visual means, the median filter was found to deliver images that closely resembled the original ones, albeit with a slight reduction in quality. This outcome supports the quality and accuracy of the images produced by the X-ray μ -CT. The images revealed both internal and external features with precision, demonstrating the effectiveness of the adjustments made to the

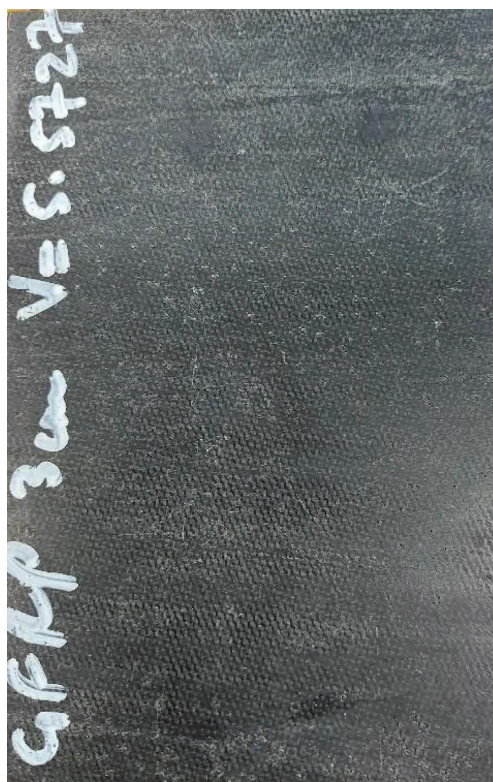


FIGURE 9: Front face sheet of impacted specimen with delamination BVID.

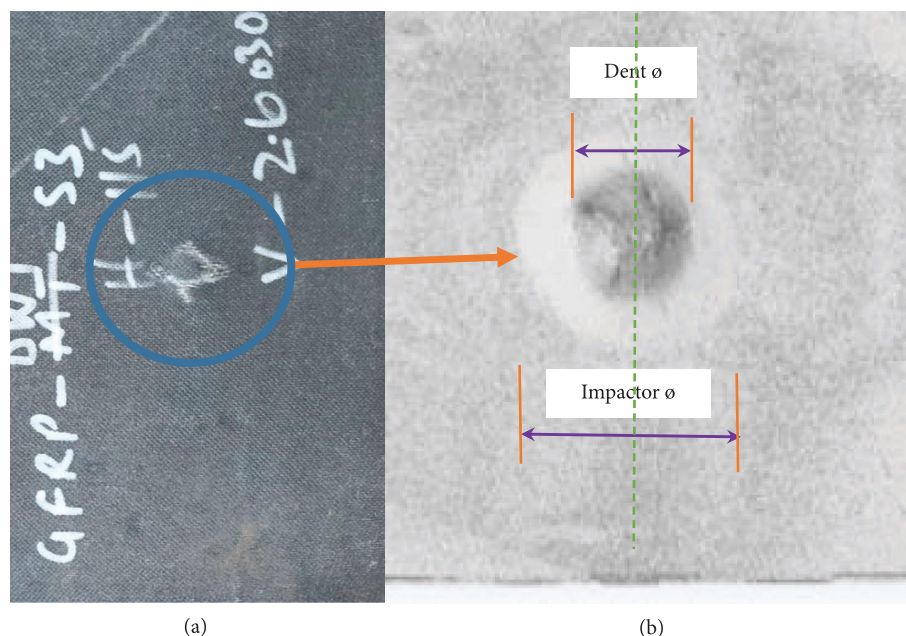


FIGURE 10: (a) Specimen showing the state of closer to full perforation. (b) Specimen illustrating the relative damage morphology tomogram.

X-ray μ -CT system. Figure 18 shows the comparison of reconstructed (raw) and processed images for 2 J and 3 J impact energies.

Barely visible impact damage was observed at low-level impact energies. Progressive damage was attained through increasing the drop heights and observing the damaged areas until

full perforation. The area of complete penetration displayed a diamond shape, as shown in Figure 11. This shape could have been influenced by the stacking sequence which featured $0/90^\circ$ at the outer surface. In a nearly perforated specimen, all failure damage mechanisms were vividly visible using X-ray micro-computed tomography, as featured in Figure 19.

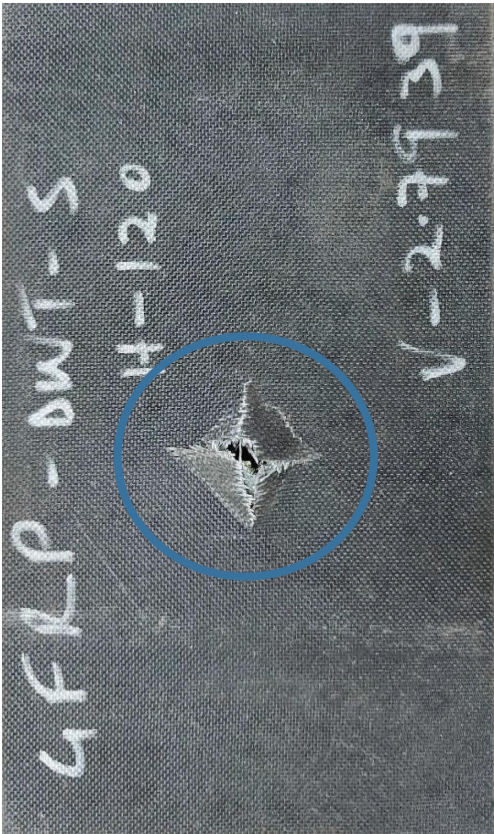


FIGURE 11: Fully penetrated bottom side of the impacted specimen.

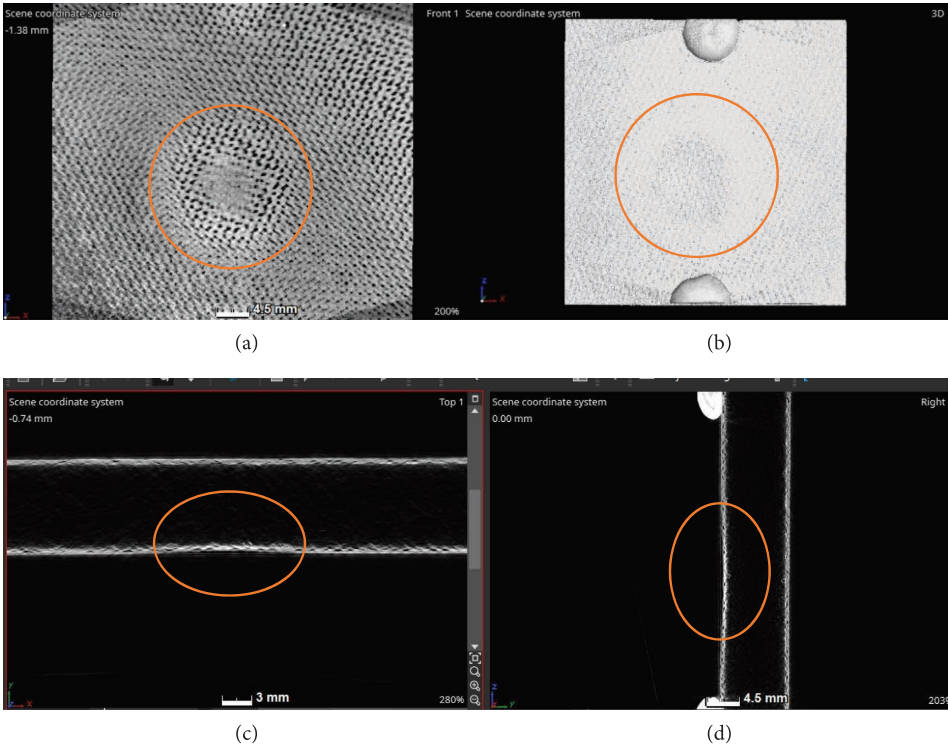


FIGURE 12: (a) Front view. (b) Front (original view). (c) Top view. (d) End view.

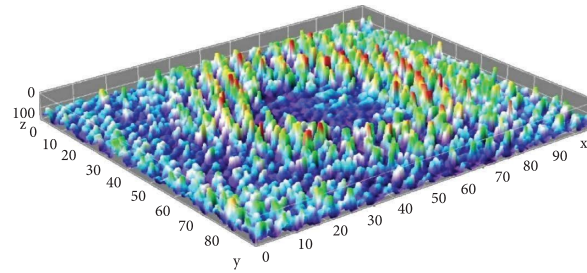


FIGURE 13: Surface plot around the impacted zone for 2 J impact energy.

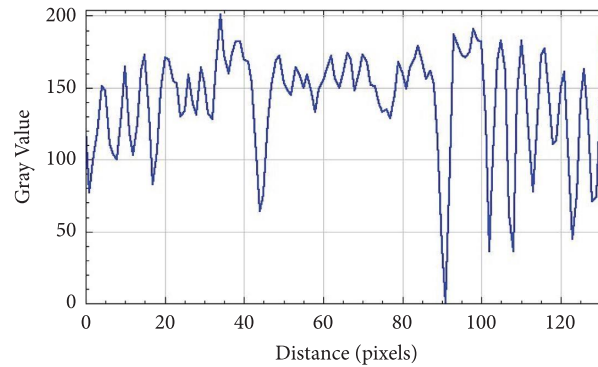


FIGURE 14: Profile plot around the impacted zone for 2 J impact energy.

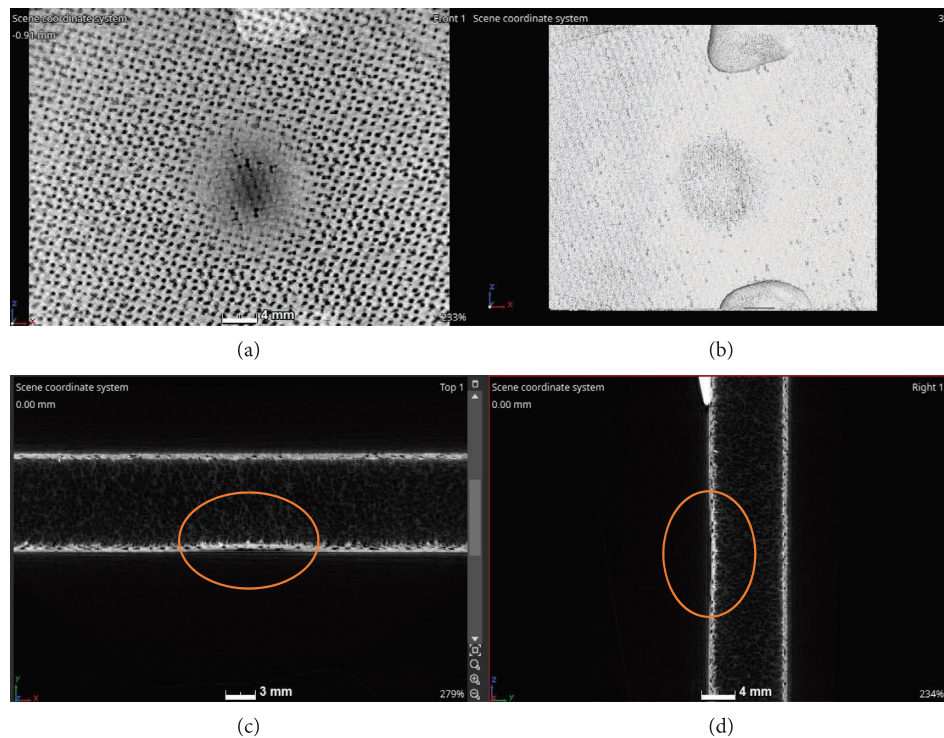


FIGURE 15: (a) Front view. (b) Front (original view). (c) Top view. (d) End view.

The top face sheet underwent delamination, matrix cracking, and fibre fractures. It was also subjected to interlaminar debonding prior to penetration. The debonding between the foam and top face sheet was localised within the

impact area. The foam core failure damage mechanisms included shearing and densification. Shear action originated from the penetrated top face, forming shear bands of almost 45° angle. Densification was a result of the foam core's

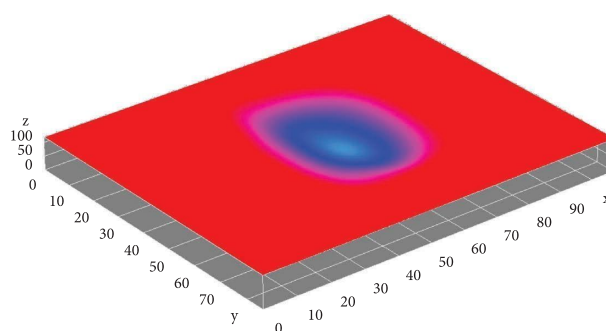


FIGURE 16: Surface plot around the impacted zone for 3 J impact energy.

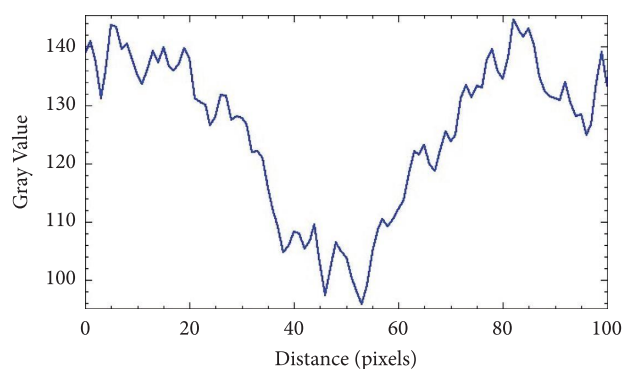
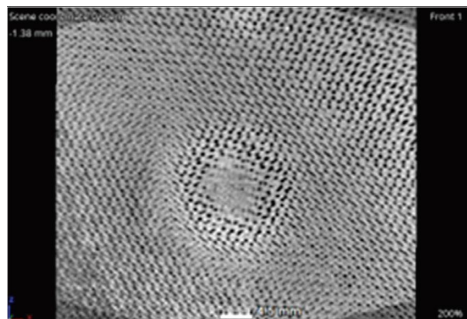
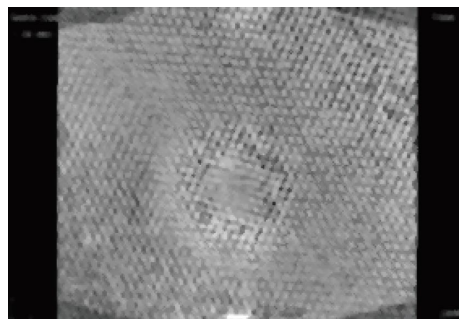


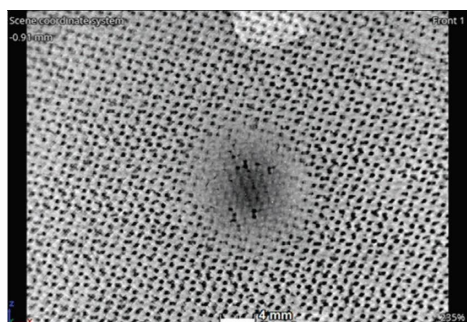
FIGURE 17: Profile plot around the impacted zone for 3 J impact energy.



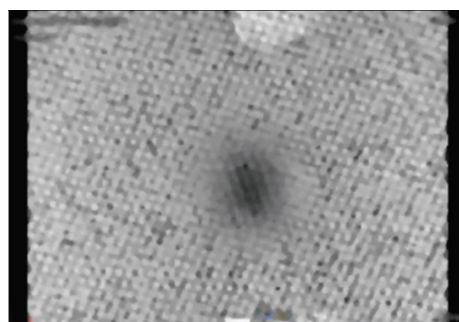
Unprocessed 2 J image



Processed 2 J image



Unprocessed 3 J image



Processed 3 J image

FIGURE 18: Comparison of raw (unprocessed) and processed images.

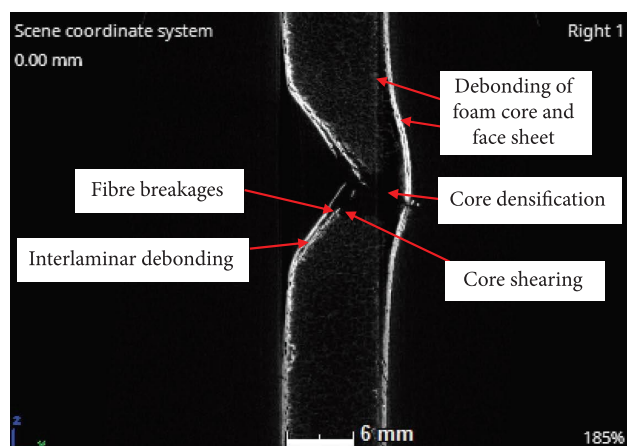


FIGURE 19: Failure modes for the near penetrated specimen.

compression from the top face sheet to the bottom face sheet due to the impactor. The back face sheet experienced delamination as the primary failure damage mechanism. Fibre breakages occurred at the point of impact, as there was no complete penetration of the impactor at the bottom face sheet.

5. Conclusions

The X-ray micro-computed tomography system with an estimated resolution of up to $26\ \mu\text{m}$ successfully revealed the severity of damage induced on sandwich composite structures. The findings indicate an immediate reduction in strength and load-bearing capacity upon the onset of damage. Even low-level impact energies can cause barely visible yet structurally significant damage, including matrix cracking, delamination, and fibre breakage in the top face sheet, stemming from shear and tensile stresses. The foam core experienced shear and crushing from the impactor's penetration. Delamination was especially pronounced at the bottom interface, highlighting the vulnerability of sandwich composites to impact damage and their potential for premature failure. The X-ray micro-computed tomography technique offers potential opportunities for use in various fields such as engineering, manufacturing, medicine, and biology due to its nondestructive nature and its ability to provide highly detailed internal images of objects without the need for disassembly or destruction.

Despite the benefits that this technique offers, there is need for further resolution improvements. Improving the resolution and sensitivity of micro-CT systems can be accomplished by using novel X-ray sources, detectors, algorithms, and reconstruction techniques. This could lead to better characterisation of microstructures in materials science or more detailed inspections of small components. Furthermore, enhancing the speed at which micro-CT scans are conducted would make the technology more suitable for high-volume production. Another potential area of research involves developing hybrid techniques through combining micro-CT with other nondestructive testing methods such as ultrasonics, acoustic emission, or thermography, to provide

complementary data, leading to a more comprehensive analysis of the specimen under review. Detailed analysis could also be aided by coupling micro-CT systems with mechanical testing rigs to allow for the observation of material behaviour under different loads or environmental conditions, thereby offering insights into material properties and failure mechanisms. In a broader sense, tailoring micro-CT systems to meet the unique needs of specific industries, such as electronics, automotive, marine, or aerospace, could lead to custom solutions that address industry-specific challenges.

Nomenclature

ASTM:	American Society for Testing and Materials
BVID:	Barely visible impact damage
CT:	Computed tomography
FDD:	Focus-to-detector distance
FOD:	Focus-to-object distance
GFRP:	Glass fibre reinforced polymer
LVID:	Low-velocity impact damage
NDT:	Nondestructive testing
PVC:	Polyvinyl chloride
SHM:	Structural health monitoring
VID:	Visible impact damage
μ -CT:	Micro-computed tomography.

Data Availability

The data used in this paper are available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] G. Zhou, M. Hill, J. Loughlan, and N. Hookham, "Damage characteristics of composite honeycomb sandwich panels in bending under quasi-static loading," *Journal of Sandwich Structures & Materials*, vol. 8, no. 1, pp. 55–90, 2006.
- [2] A. Ahmed and L. Wei, "The low-velocity impact damage resistance of the composite structures- a review," *Reviews on Advanced Materials Science*, vol. 40, pp. 127–145, 2015.
- [3] S. N. A. Safri, M. T. H. Sultan, M. Jawaidd, and K. Jayakrishna, "Impact behaviour of hybrid composites for structural applications: a review," *Composites Part B: Engineering*, vol. 133, pp. 112–121, 2018.

- [4] B. W. Jang and C. G. Kim, "Real-time detection of low-velocity impact-induced delamination onset in composite laminates for efficient management of structural health," *Composites Part B: Engineering*, vol. 123, pp. 124–135, 2017.
- [5] M. H. Khan, M. Elamin, B. Li, and K. T. Tan, "X-ray micro-computed tomography analysis of impact damage morphology in composite sandwich structures due to cold temperature arctic condition," *Journal of Composite Materials*, vol. 52, no. 25, pp. 3509–3522, 2018.
- [6] P. Duchene, S. Chaki, A. Ayadi, and P. Krawczak, "A review of non-destructive techniques used for mechanical damage assessment in polymer composites," *Journal of Materials Science*, vol. 53, no. 11, pp. 7915–7938, 2018.
- [7] A. Sellitto, S. Saputo, F. Di Caprio, A. Riccio, A. Russo, and V. Acanfora, "Numerical-experimental correlation of impact induced damages in CFRP laminates," *Applied Sciences*, vol. 9, no. 11, p. 2372, 2019.
- [8] J. Hiller, M. Maisl, and L. M. Reindl, "Physical characterization and performance evaluation of an x-ray micro-computed tomography system for dimensional metrology applications," *Measurement Science and Technology*, vol. 23, no. 8, Article ID 85404, 2012.
- [9] A. du Plessis, S. G. le Roux, and A. Guelpa, "The CT Scanner Facility at Stellenbosch University: an open access X-ray computed tomography laboratory," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 384, pp. 42–49, 2016.
- [10] L. De Chiffre, S. Carmignato, J. P. Kruth, R. Schmitt, and A. Weckenmann, "Industrial applications of computed tomography," *Chartered Insolvency Resolution Professionals Private Limited Annals*, vol. 63, no. 2, pp. 655–677, 2014.
- [11] J. P. Kruth, M. Bartscher, S. Carmignato, R. Schmitt, L. De Chiffre, and A. Weckenmann, "Computed tomography for dimensional metrology," *Chartered Insolvency Resolution Professionals Private Limited Annals*, vol. 60, no. 2, pp. 821–842, 2011.
- [12] S. Senck, M. Hapfl, M. Reiter et al., "Additive manufacturing and non-destructive testing of topology-optimised aluminium components," *Non-destructive Testing and Evaluation*, vol. 35, no. 2, pp. 1–13, 2020.
- [13] S. Olakanmi, C. Karunakaran, and D. Jayas, "Applications of X-ray micro-computed tomography and small-angle X-ray scattering techniques in food systems: a concise review," *Journal of Food Engineering*, vol. 342, Article ID 111355, 2023.
- [14] H. Zhang, H. He, Y. Gao et al., "Applications of Computed Tomography (CT) in environmental soil and plant sciences," *Soil and Tillage Research*, vol. 226, Article ID 105574, 2023.
- [15] M. Feser, J. Gelb, H. Chang et al., "Sub-micron resolution CT for failure analysis and process development," *Measurement Science and Technology*, vol. 19, no. 9, Article ID 94001, 2008.
- [16] H. Villarraga-Gómez, N. Kotwal, R. Parwani et al., "Improving the dimensional accuracy of 3D x-ray microscopy data," *Measurement Science and Technology*, vol. 33, no. 7, Article ID 74002, 2022.
- [17] A. Singhal, J. Grande, and Y. Zhou, "Micro/nano-CT for visualization of internal structures," *Microscopy Today*, vol. 21, no. 2, pp. 16–22, 2013.