

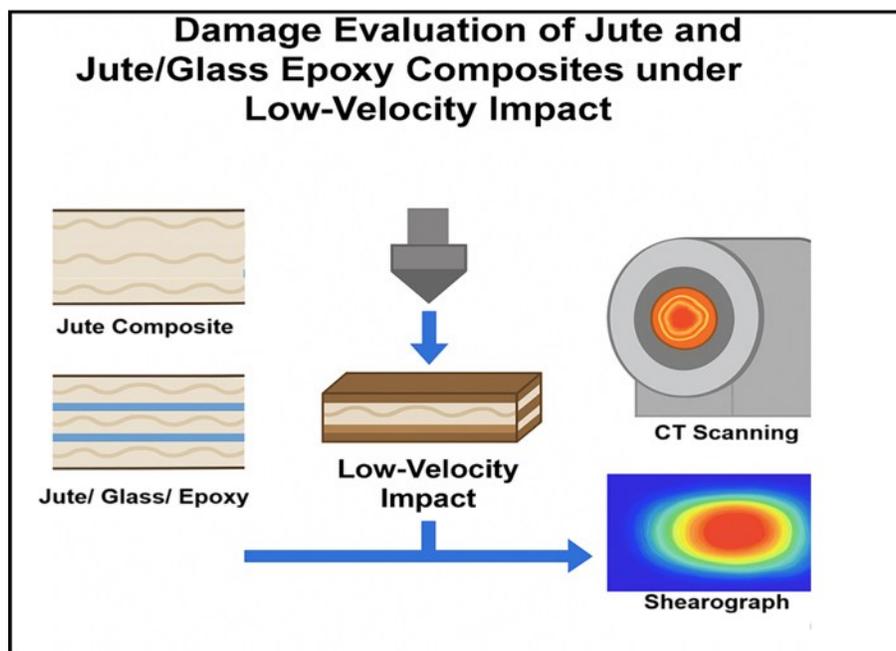
# Damage Evaluation of Jute and Jute/Glass Epoxy Composites under Low-Velocity Impact Using Computer Tomography and Shearography

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## GRAPHICAL ABSTRACT



# Damage Evaluation of Jute and Jute/Glass Epoxy Composites under Low-Velocity Impact Using Computer Tomography and Shearography

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Compressed hybrid composite laminates with a thickness of 3 mm were fabricated using a skin–core configuration, employing jute and glass fabrics as reinforcements and epoxy as the matrix material. The impact performance and damage mechanisms of the jute/glass hybrid composites were compared against jute/epoxy composites with the same and variable thicknesses under varying low-velocity impact energies. The incorporation of glass fabric significantly improved the impact resistance of the thinner hybrid laminates. At a higher impact energy of 15 J, the hybrid composites exhibited a rebounding response, indicating superior energy absorption and damage tolerance. Laser shearography was utilized to examine the internal damage evolution, while computed tomography (CT) scanning was employed to quantitatively assess damage. An increase of up to 86% in the maximum impact load was observed from the hybrid composites with thickness of 3 mm when compared with the jute/epoxy laminates. CT scan analysis revealed completely perforated failure in the jute/epoxy composites with progressive crack propagation at different depths. The hybrid composites primarily exhibited localized sliding damage accompanied by surface denting, as observed through shearography. The findings confirmed that jute/glass hybrid composites offered an enhanced low-velocity impact resistance when compared with the pristine jute composites.

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*Keywords:* Hybrid composites; Jute fibers; Mechanical performance; CT scanning; Product innovation

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## INTRODUCTION

The increasing demand for sustainable materials in various engineering applications has led to a significant interest in natural fiber-reinforced polymer (FRP) composites. Among these, jute fiber has emerged as a prominent material, due to its abundance, biodegradability, and favorable mechanical properties (Bledzki and Gassman 1999). Jute, a lignocellulosic fiber, possesses high tensile strength and low density, making it an attractive alternative to synthetic fibers in composite materials (Mohanty *et al.* 2002).

However, while jute fibers exhibit commendable mechanical properties, their performance can be further enhanced through hybridization with synthetic fibers, such as glass fibers, within a polymer matrix like epoxy (Pickering *et al.* 2015, Irawan *et al.* 2022). The hybrid composites materials, which incorporate two or more types of fibrous materials, have been shown to exhibit superior mechanical performance when compared with their non-hybrid materials (Suriani *et al.* 2021). The combination of jute and glass fibers in an epoxy matrix can leverage the strengths of both materials, resulting in composites that possess improved tensile strength, flexural modulus and impact resistance (Gujjala *et al.* 2013). The synergistic effects of hybridization allow for the optimization of mechanical properties, making these composites suitable for a wide range of applications, including automotive, construction and consumer goods (Kaufmann *et al.* 2025). The advantages of hybridization of jute and glass FRP composite materials possess a higher elastic modulus and strength, enabling efficient load bearing, as jute fibers exhibit high strain to failure and energy absorption capability. The structure of the hybrid jute and glass fibers composite promotes progressive damage mechanism, such as fiber bridging, delayed the crack propagation and improved load and stress distributions evenly to the structures, thereby increasing the force and energy required for fracture under impact loading (Manders *et al.* 1981; Jawaid *et al.* 2011).

The use of epoxy as a matrix material is more advantageous, because of its superior adhesive characteristics, chemical resistance and thermal stability (Tanaka and Sakakibara 2025). Epoxy resins can effectively bond with both natural and synthetic fibers, leading to enhanced interfacial adhesion and consequently, higher mechanical performance of the composite (Tripathy *et al.* 2001). The use of glass fibers enhances the composites strength and stiffness, improving dimensional stability and heat resistance (Morampudi *et al.* 2021). To evaluate the internal structure and performance characteristics of the hybrid composites, advanced imaging techniques, including computed tomography (CT) scanning, have been employed (Paltan *et al.* 2019). CT scanning provides a non-destructive means of analyzing the fiber distribution, orientation and interface quality within the composite material. This methodology enables researchers to get insights into the microstructural features that influence the mechanical behavior of the composites, facilitating the optimization of their design and processing methods (Gao *et al.* 2021).

The ability to visualize the internal structure of composites through CT scanning enables the identification of potential defects, such as voids or fiber misalignment, which can adversely affect mechanical performance (Fracz *et al.* 2021). This information is crucial for fine-tuning fabrication processes and ensuring consistent quality in production (Nurazzi *et al.* 2021). In addition, by employing CT scanning in conjunction with mechanical testing, researchers can correlate microstructural characteristics with macroscopic performance, leading to a more comprehensive understanding of the behavior of material under various loading conditions (Engler *et al.* 1990). As a result, this holistic approach enhances not only the performance of hybrid composites, but also contributes to their wider adoption in industries, such as automotive, aerospace and construction, where reliability and durability are paramount (Mikhaylov *et al.* 2024).

The increasing demand for sustainable materials has driven the exploration of natural fiber-reinforced composites. Accordingly, jute fibers, known for its biodegradability and favorable mechanical properties, are used as primary reinforcement element for making composite laminates. By combining glass fibers with the epoxy matrix, the hybrid composites can leverage the strengths of materials, potentially enhancing tensile strength, flexural modulus and impact resistance. Hence, this present study aims to

investigate into the low velocity impact properties of hybrid jute/glass/epoxy composites in comparison with non-hybrid or pristine jute/epoxy composites with different thickness. By utilizing CT scanning, the internal structure of these composites was analyzed to understand the effects of fiber hybridization on their mechanical performance. The findings of this research contribute to the development of sustainable composite materials with enhanced performance characteristics, paving the way for the replacement of lightweight materials in the field of transport industries.

## EXPERIMENTAL

### Materials

The glass and jute fabrics were obtained from Madhu Glasstex Private Limited in Gujarat and Go Green Pvt. Ltd. in Chennai, India, respectively. The epoxy resin series Araldite LY556 with Hardener HY951 was obtained from the Sigma Aldrich, Bangalore and used for the manufacturing of the epoxy/jute composite materials, due to its exceptional impact properties.

### Composites Preparation

Glass fiber and jute mats were combined with epoxy resin to create hybrid epoxy composites. A compression molding technique was used in the fabrication process, which is known for its effectiveness in creating distinct composite structures. The composites were prepared using layer by layer resin application technique, followed by placing the mold in a compression machine. The skin-core type of hybrid composites was fabricated with the layering sequence of placing 3 layers of jute fabric at middle, and 2 layers of glass fabric at the top and bottom of the composites. The stacking sequences consisted of one layer of glass fabric placed first in the mold, followed by three layers of jute fabric stacked. Epoxy resin was applied between each fabric layer to ensure proper bonding. Finally, one more layer of glass fabric was placed on the top. Thus, the glass fabric layers acted as sandwich skins of the fabricated polymer composite materials. The composite material was prepared with 30 wt% of fibers content and 70 wt% of epoxy resin. The density of the fabricated composites was 1.48 g/cm<sup>3</sup>. To examine the effect of thickness on the performance and structural integrity of the composites, only samples with a thickness of 3 mm were manufactured. After fabrication of the composite samples, their mechanical performance to resist penetration was assessed under low velocity impact tests. Important information about the toughness and longevity of both pristine jute epoxy and hybrid jute/glass fiber epoxy composites were obtained from the tests, highlighting the significance of constituent materials and thickness in mechanical properties.

### Low Velocity Impact Test

Low velocity Impact tests were conducted at the Defense Metallurgical Research Laboratory (DMRL), Hyderabad, India, using an advanced instrumented drop-weight impact tester (CEAST-9350 model). A schematic representation of a similar testing set-up has been reported by Reddy *et al.* (2019). Impact energy levels of 5, 10, 15, and 20 J were selected to encompass both non-perforation and perforation regimes. The testing protocol adhered to ASTM D7136 standards, ensuring compliance with established procedures for evaluating the impact behavior of composite materials, as similarly used by Reddy *et al.*

(2019). A minimum of three specimens were tested at each energy level for each composite configuration under room temperature conditions, and the average value was reported.

### Computer Tomography Analysis

Following the impact tests, CT scans were performed on jute/glass/epoxy laminate composites to evaluate internal damage mechanisms. The composite specimens, with dimensions of 150 mm × 100 mm × 3 mm, were analyzed using a CT scanning system interfaced with a computer for detailed visual inspection. This high-resolution imaging technique enabled detailed visualization of the damage in the internal structure of the composites (Safri *et al.* 2017). The software facilitated precise measurement of damaged areas, allowing for a thorough assessment of how varying thicknesses and fiber types affect the structural integrity of the hybrid composites (Braga and Magalhaes 2015).

### Laser Shearography

In this study, a Q-800 Dantec Dynamics shearography system equipped with ISTRA software was used for data acquisition and evaluation. The experimental setup (Fig. 1) was configured, as reported by Guo and Qin (2002). Two laser diodes ( $2 \times 70$  mW) with a wavelength of 653 nm were integrated with the shearographic sensor, which had a resolution of  $1392 \times 1040$  pixels. The camera was fitted with a Tokina 6–15 mm lens operated at an aperture of f/1.4. The measuring sensitivity of the Q-800 system was  $0.03 \mu\text{m}$  per shear distance, calculated as  $0.03/(50/1392)$  based on a shear base distance of 50 pixels. The corresponding theoretical sensitivity was estimated to be  $0.83 \mu\text{m}$  (Kadlec *et al.* 2011). By applying external excitation, such as thermal loading, vibration or pressure, low-level strain was induced in the test specimen, enabling the prediction of the material response. The shearographic camera detected variations in surface strain caused by defects present within the material. A fringe pattern was generated and displayed in real time by comparing interferograms recorded before and after loading. This technique allowed rapid inspection, with an inspection rate of approximately  $1 \text{ m}^2$  per minute and is particularly effective in detecting composite failures, such as debonding, delamination, wrinkling and other subsurface defects.



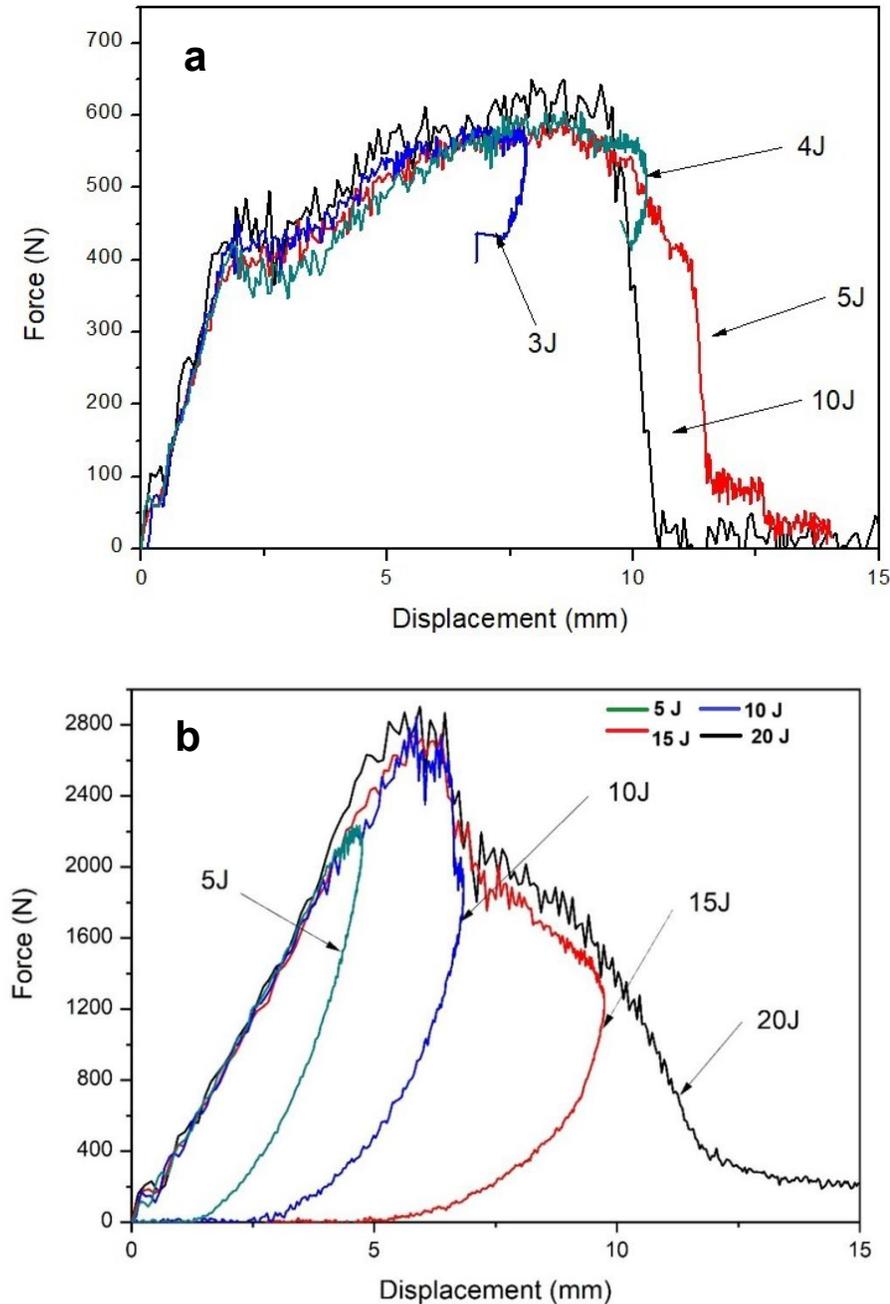
Fig. 1. Photographic image of Q-800 portable shearography system (SQS 2026)

## RESULTS AND DISCUSSION

### Low Velocity Impact Analysis

#### *Force versus displacement*

The force *versus* displacement plots obtained (Fig. 2a and 2b) from the impact tests for the 3 mm thick jute/epoxy (Prabhakar *et al.* 2024) and jute and glass fiber (present study) mat epoxy hybrid composite plates provided valuable insights into the rebound behavior of the composite material under impact loading.



**Fig. 2.** Force *versus* displacement plots obtained from the low-velocity impact tests for (a) 3-mm plate of jute composites (Prabhakar *et al.* 2024) and (b) 3-mm plate of jute/glass/epoxy hybrid composites

The data established distinct differences in the force-displacement response between the hybrid composites and the non-hybrid jute/epoxy composites. These variations reflected differences in material performance and structural integrity, with the hybrid composites demonstrating enhanced resilience and energy absorption capabilities when compared with their non-hybrid counterparts. This comparative analysis highlighted the benefits of hybrid reinforcement in optimizing the impact properties of composite materials.

In Fig. 2a, the curves show a sharp increase in force with displacement at lower impact energies (3, 4, 5 and 10J), peaking between 500 and 600 N before abruptly declining. Since the composite cannot withstand much load after peak load, this suggested brittle failure and limited energy absorption. The force increased to a similar peak at 10 J, but the post-peak drop was slower, indicating the beginning of matrix cracking and fiber breakage, while maintaining some load-carrying capacity. Even 6 mm thick jute/epoxy composite exhibited significant damage, fiber pullout, and delamination at the maximum load of 15 J, exhibiting extended displacement of ~12 mm and reduced maximum force of ~1100 N (Prabhakar *et al.* 2024). The composite experienced progressive damage mechanisms rather than an abrupt brittle failure, as evidenced by the wider displacement range. Overall, at higher impact energies, jute/epoxy exhibited limited energy absorption, but a moderate peak force. Lower impact resistance and toughness were indicated by more catastrophic damage (sudden force drop). This composite can be suitably used where moderate strength is needed, but not high impact loading (Gopinath *et al.* 2014).

Figure 2b depicts force-displacement curves of hybrid composites of jute/glass/epoxy, which increased smoothly at 5 and 10 J, reaching peak forces of about 2500 N, which was much higher than in pure jute FRP composite counterparts. The hybrid composites maintained greater peak loads and wider displacement prior to total failure, even at higher impact energies of 15 and 20 J. The displacement reached about 14 mm at 20 J, indicating significant energy absorption and penetration resistance. In contrast to brittle fracture, the post-peak response exhibited a progressive force reduction, indicating progressive damage mechanisms, including fiber bridging, delamination and matrix cracking (Tang *et al.* 2025). When compared with non-hybrid composites, jute/glass/epoxy hybrid composites exhibited greater energy absorption, a higher peak load capacity and superior impact resistance. Glass fibers increased load-bearing capacity and prevented catastrophic failure (Chandra *et al.* 2025). Because hybrids are more resilient to damage, they can be used in automotive and structural applications, where higher impact loads are anticipated.

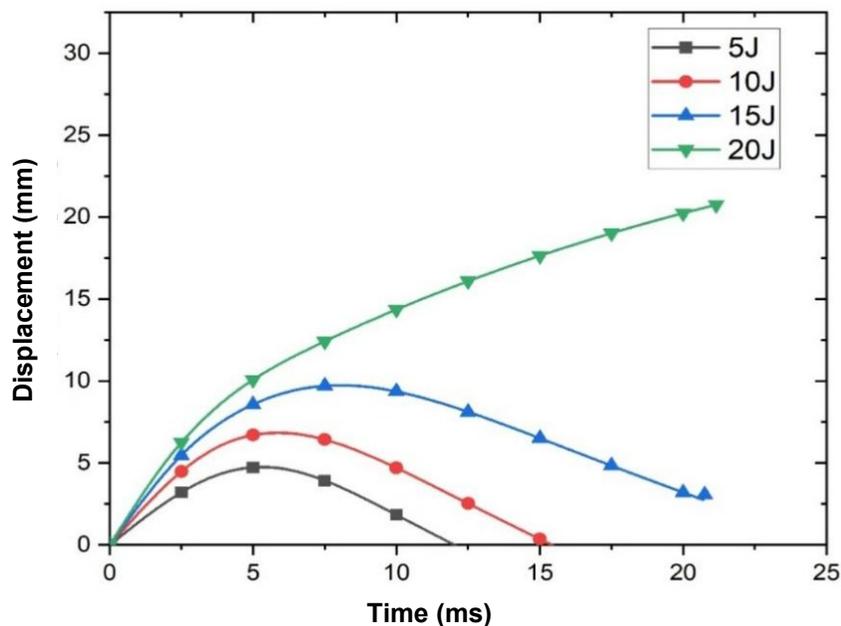
The comparative analysis of the force *versus* displacement plots for the 6-mm thick hybrid epoxy composites underscored the influence of thickness on impact resistance and damage characteristics. The 3-mm hybrid jute and glass fibers mat epoxy plates demonstrated superior performance in terms of both peak force and energy absorption capacity, which is consistent with the expectation that increased thickness (6 mm) enhanced ability of the composite to withstand and absorb impact forces. In contrast, the non-hybrid jute/epoxy composites exhibited lower peak force and energy absorption, indicating a reduced capacity to manage impact loading (Gopinath *et al.* 2014). This improved performance in the hybrid composites can be attributed to the additional material, providing increased structural support and a greater capacity to accommodate deformation and energy dissipation.

The enhanced damage tolerance of the hybrid composites highlighted the advantages of incorporating multiple fiber types, allowing for better overall mechanical

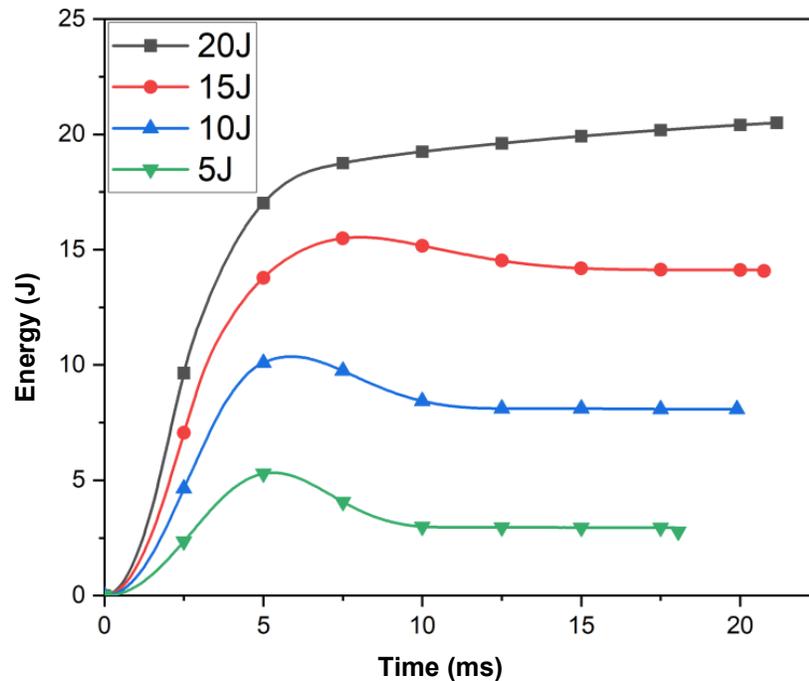
performance under impact conditions when compared with their non-hybrid counterparts (Wang *et al.* 2020).

Prabhakar *et al.* (2024) investigated that, for increasing impact energy (5 → 7 → 8 → 10 → 15 J), the jute/epoxy composites showed more displacements and longer periods to reach the displacements. Small displacement at 5 J rapidly peaked and then fell back toward zero, primarily elastic reaction with minimal irreversible damage (rebound). There was continuous deformation and damage, due to matrix cracking, fiber matrix debonding at 7 and 8 J, along with significant displacement and a propensity to plateau. At 10 J, the displacement was bigger, the climb was slower, and there was post peak drop before more serious internal damage (fiber breakage/delamination). Ultimately, under 15 J testing conditions, the structure of the composites might experience the largest, steadily increasing displacement over the entire measured time (no discernible rebound), but also significant permanent deformation and progressive damage, as a result of extensive delamination, fiber pull-out and potential perforation. In the end, the pure jute/epoxy laminate had permanent damage instead of elastic recovery and was comparatively compliant for higher energies, allowing for considerable larger displacement.

The hybrid composites (Fig. 3) demonstrated considerable displacement while retaining load-carrying behavior; progressive damage rather than rapid failure. At impact test under 20 J, with the greatest displacement among hybrid cases, the rise was smoother and more gradual. When compared with pure jute/epoxy laminate, the hybrid was stiffer and more impact resistant. Early on, it showed lesser displacements; the composite resisted indentation for the same or higher energies. When damage occurred, it progressed more gradually. In addition, Fig. 4 depicts 3-mm thick plates of jute/glass epoxy hybrid composites at varying energy levels.



**Fig. 3.** The displacement *versus* time plots obtained from the low-velocity impact tests for the 3-mm plate of Jute/Glass/Epoxy hybrid composites



**Fig. 4.** Energy versus time for a 3 mm thick plate of jute/glass epoxy hybrid composites at varying energy levels

The corresponding energy–time histories obtained from the experiments indicate that the hybrid composites significantly influenced the energy absorption characteristics. At all impact energy levels, the specimens exhibited a stable response with respect to time. A maximum impact energy of 20 J was recorded, showing a nearly linear increase trend over time, as illustrated in Fig. 4. Notably, the 3-mm hybrid composites exhibited an energy absorption range comparable to that of the 6-mm jute/epoxy composites. The greater energy absorption by the hybrid implied an improved performance, due to structural strengthening with glass fibers, making it more effective in dynamic loading circumstances. Previous research reported similar findings, demonstrating that jute/glass composites have better mechanical characteristics than pure jute composites (Braga and Magalhaes 2015). The findings emphasized the potential of hybrid composites for applications that require increased mechanical strength and durability, necessitating additional research into their mechanical properties. Enhanced energy absorption in jute/glass hybrids has been connected to improved load distribution and lower stress concentrations (Gujjala *et al.* 2013). Understanding how these composites behave under dynamic situations is critical to maximize their use in practical applications, including automotive and construction materials.

The hybrid composites of 3-mm thick, while exhibiting significant stiffness, demonstrated enhanced capacity to sustain high impact forces when compared with the non-hybrid jute/epoxy composites. The force-displacement plot for the hybrid plates showed a sharper peak followed by a more gradual decline, indicating that they could better manage impact loads and were less susceptible to rapid damage and failure. In contrast, the non-hybrid jute/epoxy composites exhibited a more abrupt drop in force after reaching peak levels, reflecting their vulnerability to failure under similar conditions. This observed behavior underscored the trade-off between stiffness and impact resistance, where the

hybrid composites provided not only superior energy absorption, but also exhibited greater damage tolerance when compared with the non-hybrid counterparts. The incorporation of glass fibers into the hybrid matrix enhanced overall performance, allowing for improved structural integrity and resilience during impact loading (Prabhakar *et al.* 2024). The force *versus* displacement data aligned with findings from similar studies, which reported that composite thickness plays a crucial role in determining the impact performance of hybrid materials (Sethu *et al.* 2024). The ability of the thicker composite to spread the impact force over a larger area and through multiple layers resulted in enhanced performance, making it more suitable for applications that require higher impact resistance and durability.

The results confirmed that optimizing composite thickness is critical for balancing stiffness, impact resistance and overall material performance. The findings indicated that hybrid epoxy composites could achieve enhanced mechanical strength and energy absorption capabilities through appropriate thickness selection. In contrast, non-hybrid jute/epoxy composites, while simpler in construction, could not provide the same level of performance, due to their inherent limitations in energy absorption and damage tolerance. This underscored the importance of designing hybrid composites with tailored thicknesses to meet specific application requirements, ensuring an effective balance between structural integrity and impact resilience.

### Damage Analysis of Composite Laminates

#### *Macroscopic observation of impact damage*

Photographic images of the impacted jute/glass fiber reinforced epoxy hybrid composite laminates subjected to varying impact energies of 5, 10, 15, and 20 J are presented in Fig. 5.



**Fig. 5.** Photographic images of fabricated jute/glass fiber reinforced composites plates after low velocity impact test with varying loads

The extent and morphology of the surface damage clearly indicated the progressive nature of the impact-induced failure mechanisms with increasing impact energy. At 5 J, the laminate showed a slight indentation at the impacted site without any visible cracks or fiber breakage, signifying that the energy was primarily absorbed elastically through local matrix deformation. When energy was increased to 10 J, the indentation became more pronounced, accompanied by the initiation of surface microcracking around the impact core. The damage zone remained localized, suggesting that the hybrid laminate effectively

dissipated moderate impact energy through interfacial friction and limited delamination (Garcea *et al.* 2017). These findings are in strong agreement with previously reported studies on the hybrid composites structures in terms of enhanced impact tolerance and controlled damage mechanism, as sustainable energy absorption behavior improved (Mahmud *et al.* 2025; Das *et al.* 2021), and the delamination under low velocity impact loading delayed. Overall, the results confirmed that sandwich type jute/glass hybrid composites offered better mechanical performance that is suitable for lightweight structural engineering applications (Mahmud *et al.* 2023).

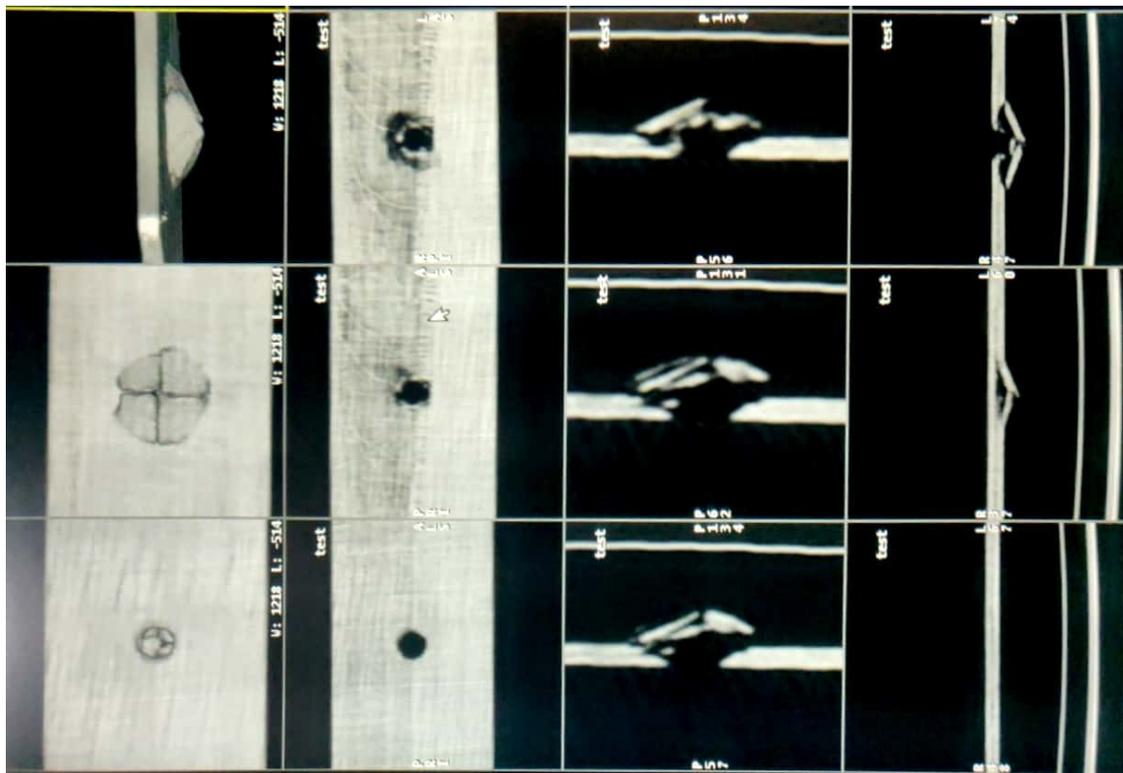
At 15 J, visible matrix cracks and slight fiber breakage appeared at the impact center, indicating the onset of interlaminar delamination and plastic deformation. The extent of the whitened region surrounding the impact site increased considerably, representing fiber–matrix debonding and subsurface delamination growth. At the highest impact energy of 20 J, severe surface damage was evident with prominent matrix fracture, fiber breakage, and partial perforation at the center. The increased damage diameter and exposed fiber bundles reflected transition of the laminate from localized deformation to significant structural degradation. Overall, it was evident through surface morphology that damage severity and affected areas expanded with an increasing impact energy. The hybrid configuration of jute and glass fibers provided an effective balance between stiffness and energy absorption at lower impact energies. At higher energies, the mismatch in fiber mechanical properties and interfacial adhesion led to progressive delamination and fiber rupture. These macroscopic observations were in good agreement with the subsurface damage characteristics obtained from laser shearography, confirming a strong correlation between visual surface damage and internal failure progression. It was clearly observed that an increase in impact energy resulted in complete perforation of the 3 mm jute/epoxy laminates only at an impact energy of 20 J. A similar trend was reported by Reddy *et al.* (2017, 2019), where the perforation behavior varied with laminate thickness under fixed impact loading conditions. The study showed that thicker E-glass/epoxy laminates exhibited less damage when compared with thinner laminates under impact energy of 100 J. Moreover, complete perforation of the 3 mm E-glass/epoxy laminates occurred, due to fiber breakage in both warp and weft directions, which is comparable to the damage mechanism observed in the present study for jute/epoxy hybrid composites at 20 J. Delamination between the plies was not observed in the impacted specimens. The same study also employed infrared (IR) thermography on both the front and rear surfaces of the impacted laminates and reported that the rear-side damage area was consistent with visual observations.

However, the quantitatively measured damage areas from IR thermograms were higher than those obtained through manual measurements, indicating the presence of internal debonding between laminae that was not detectable by visual inspection. Similarly, S2-glass/epoxy composite laminates with varying nanoclay contents of 0 to 12 wt% have been fabricated and subjected to low-velocity impact tests at incident energies of 50, 110 and 150 J (Reddy *et al.* 2017). The incorporation and uniform dispersion of nanoclay enhanced the energy absorption capability of the laminates up to an optimum level, beyond which an increase in displacement was observed. Furthermore, the fractured area of the impacted laminates was evaluated, and the results indicated a reduction in the fractured area with increasing nanoclay content.

### Damage analysis using computer tomography

X-ray CT is a well-established non-destructive technique for revealing the internal damage and microstructural features of composite materials (Qu *et al.* 2023; Alahmed *et al.* 2022). In recent years, both *in-situ* and *ex-situ* X-ray CT approaches have been increasingly employed to investigate damage initiation and evolution in fiber-reinforced composites, as they enable direct visualization of internal cracks, delamination, and matrix damage without sectioning the specimens (Gao *et al.* 2021; Xu *et al.* 2023). Several studies have demonstrated the effectiveness of *in-situ* X-ray CT for tracking damage under various loading conditions, including tension, compression, bending, fatigue and elevated temperatures (Srisuriyachot *et al.* 2023), highlighting its capability for comprehensive damage identification.

Similarly, attempts have been made to explore the internal failure mechanism of fiber reinforced composite materials in different studies. For example, Wright *et al.* (2008) investigated the microstructural damage modes and interactions of carbon fiber/epoxy composites, using high resolution synchrotron radiation computed tomography (SRCT). Scott *et al.* (2011) visualized progressive damage of carbon/epoxy cross-ply laminates with the *in-situ* loading and high resolution SRCT. Garcea *et al.* (2016) proposed to combine the *in-situ* and *ex-situ* fatigue experiments through SRCT to assess the microscopic failure mechanisms of fiber reinforced thermoplastic carbon/epoxy composites. Watanabe *et al.* (2020) and Kimura *et al.* (2022) explored the nanoscale damage mechanisms in carbon fiber/epoxy composites, using *in-situ* nanoscopic synchrotron radiation X-ray computed tomography (nanoscopic SR X-CT). In this present work, CT scans were acquired and reviewed as three orthogonal views: top (planar/XY), front (cross-section through width/XZ) and side (through-thickness/YZ), as shown in Fig. 6.



**Fig. 6.** A typical damage analysis using CT scan at different depths in thickness in top, front and side views of jute/epoxy composite laminate

The specimen thickness was 3 mm. The CT montage (three rows of images) shows the impacted region across sequential slices from the surface into the thickness. Visual inspection confirmed an approximately circular indentation/perforation in the top view, with radial cracking and progressive subsurface delamination visible in front and side views.

Moving forward, CT analysis of the impacted 3-mm jute/epoxy laminate revealed a centrally located, roughly circular indentation accompanied by radial matrix cracks and pronounced subsurface delamination. The top-surface slices showed matrix crushing and fiber fracture confined to a central patch, with radial crack initiation visible as low-attenuation streaks. In progressively deeper slices, the impact core transitioned into a subsurface zone of fiber pull-out and void coalescence. Cross-sectional (front and side) views exposed multiple interlaminar delamination beneath the impact zone that propagate radially and followed ply interfaces, producing a characteristic mushroom-shaped intrusion in the through-thickness profile. Quantitative segmentation indicated that the major delaminated volume was concentrated between the mid-plane and the surface ply interfaces; cumulative delamination volume and maximum delamination radius (measured from the impact center) were suggested metrics to compare damage severity across specimens. The failure mechanisms observed, including surface matrix crushing, fiber breakage, interlaminar delamination and fiber pull-out, were consistent with low-velocity impact-induced bending and shear in natural fiber composites, while fiber debonding and lumen collapse exacerbated energy dissipation and created larger subsurface damage zones than typically observed in synthetic fiber laminates.

**Table 1.** Comparison of Damage Areas Measured from Pristine Jute/epoxy Composite with Thickness of 3 mm and Jute/glass/epoxy Hybrid Composite Samples at Different Layer Thicknesses

No	Type of Composite	Damaged Areas (mm <sup>2</sup> )					Prabhakar <i>et al.</i> (2024) and Present work
		Layer					
		1	2	3	4	5	
1	Jute / epoxy	180	190	283	386	412	
2	Jute / glass / epoxy	73	56	48	47	71	

The assessment of damaged areas in the 3 mm thick hybrid of jute/glass-epoxy and non-hybrid or pristine jute/epoxy composites involved a comprehensive and multifaceted analysis, which was aimed at elucidating the effects of different fiber reinforcements on impact performance and structural integrity. In the hybrid composite, which strategically combined jute and glass fibers within an epoxy matrix, quantifying various types of damage was a focus, including fiber breakage, matrix cracking, and interfacial debonding. Advanced CT imaging techniques were employed, complemented by specialized image-analysis software, to meticulously identify and quantify damaged regions across multiple layers of the composite. These results revealed that the top layer of the hybrid composite sustained a higher damage area, due to direct impact forces, characterized by significant fiber breakage and extensive matrix cracking. In contrast, the middle layer exhibited moderate damage, manifesting some degree of delamination and interfacial debonding, while the bottom layer displayed minimal damage, suggesting effective load distribution and enhanced capacity for energy absorption. Despite an increasing use of various X-ray CT techniques in carbon FRP composites, the characterization of damage in X-ray tomograms is not always straightforward. The carbon fibers and most polymer resins have

similar X-ray absorption coefficients, making it difficult to generate clear phase-contrast imaging (Guo *et al.* 2021).

When examining the non-hybrid jute/epoxy composite, the damage profile revealed distinct differences when compared with hybrid configurations. The top layer exhibited extensive damage, indicating rapid matrix failure and fiber fracture, which resulted in a significant reduction in structural integrity. This behavior was particularly a concern, as it demonstrated vulnerability of the composite under impact loading conditions. The middle layer primarily displayed fiber-matrix debonding, leading to limited energy dissipation, which further compromised overall performance of the material during impact loadings. While the bottom layer showed minimal damage, it still lacked the resilience observed in hybrid composites, underscoring a critical disparity in performance. The findings established the essential role that hybridization played towards enhancing the durability and impact resistance of the composite materials. The incorporation of additional fibers, such as glass, in the hybrid configuration not only improved energy absorption, but also contributed to better load distribution and damage tolerance. Conversely, structural limitations of the non-hybrid jute/epoxy composite were evident, emphasizing the need for optimization in composite design. This analysis reinforced the advantages of hybrid composites in applications where mechanical performance and impact resilience are paramount, providing valuable insights for future research and material development in the field of composite engineering.

The comparative analysis of damage areas presented in Table 1 across these layers emphasized not only the mechanical advantages of hybrid composites but also suggested pathways for optimizing composite designs tailored to specific applications. The findings indicated that hybrid composites can effectively balance essential attributes, such as mechanical strength and energy absorption capabilities, making them particularly suitable for applications where impact resistance is crucial. This research contributed valuable insights into the design considerations for composite materials, advocating for the incorporation of hybrid fiber reinforcements to enhance performance metrics in various engineering contexts. By understanding how different fiber compositions and thicknesses influence damage behavior, engineers can develop more resilient composite structures capable of meeting the demanding requirements of modern applications in several industries, including automotive and aerospace, to mention but a few.

#### *Damage analysis using laser shearography*

Although, several non-destructive testing (NDT) techniques, including ultrasonic testing (Groves *et al.* 2025), thermography (Montanini and Freni 2012), and X-ray inspection (Tan *et al.* 2011), have been widely employed for defect detection in composite materials, their applicability can be limited when inspecting thick composite structures. Among the available non-destructive inspection (NDI) methods, digital shearography is a non-contact, full-field optical technique that has gained significant attention, particularly for the inspection of aerospace and marine composite structures (Groves *et al.* 2025). Shearography-based NDI provides an effective approach for identifying both manufacturing- and service-induced defects in composites, such as delamination, fiber breakage and impact damage (Newman *et al.* 2018).

Laser shearography was employed to qualitatively evaluate the damage morphology of jute/glass fiber reinforced epoxy hybrid composites subjected to low-velocity impact at 5 and 10 J energy levels. The images obtained are depicted in Fig. 7. The shearographic fringe patterns distinctly revealed the extent and nature of internal

defects, such as matrix cracking, delamination, and fiber–matrix debonding induced by the impact loading. At impact energy of 5 J, the observed fringe pattern exhibited a relatively compact and symmetric deformation zone concentrated around the point of impact. The bright interference fringes near the core indicated localized strain accumulation associated primarily with matrix cracking and limited interfacial separation between the jute and glass layers. The surrounding region appeared dark with sparse fringes, suggesting that the deformation remained confined within a small area, and the laminate largely retained its structural integrity. This behavior signified that at lower impact energies, the composite predominantly exhibited elastic–plastic deformation with minimal delamination growth.

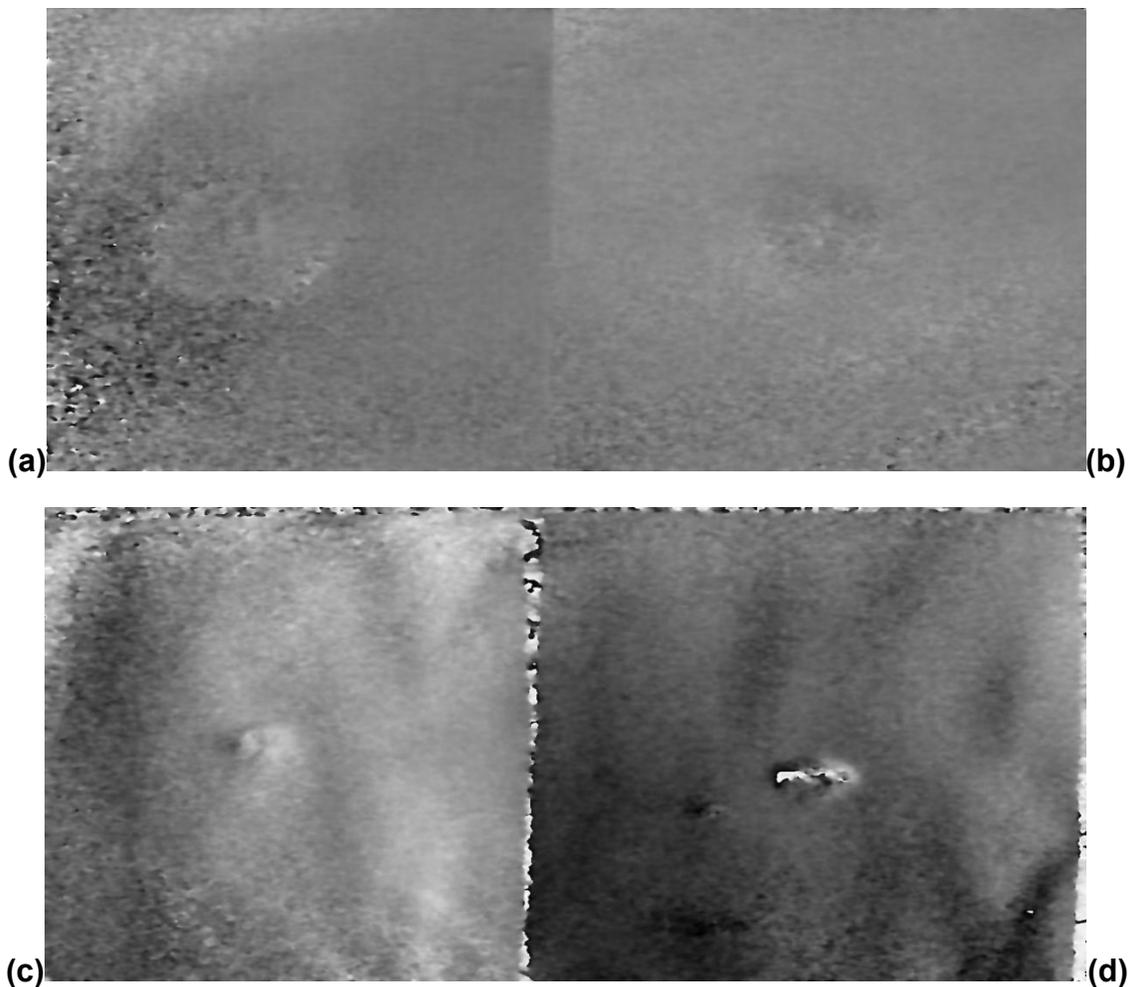


**Fig. 7.** Fringe phase images of jute/glass hybrid epoxy composites (top layer) at 5 and 10 J loading conditions

In contrast, the specimen impacted at 10 J exhibited a pronounced and irregular fringe distribution, extending over a wider area. The increased fringe density and asymmetry of the pattern reflected the presence of extensive interlaminar damage and progressive delamination propagation across the hybrid interfaces. The broad dark zones interspersed with dense fringe bands correspond to large out-of-plane displacement gradients, confirming significant subsurface ply separation and fiber–matrix debonding. The enlargement of the damaged area with increasing impact energy indicated that energy absorption mechanisms transition from localized matrix deformation at lower energies to delamination-driven failure at higher energies. Liu *et al.* (2011) investigated shearographic fringe patterns in PVC specimens, containing surface-breaking holes and reported observations similar to those obtained in the present study. The cracks detected can be quantitatively characterized based on the observed shearographic fringe patterns. For thin plate specimens, the crack tips can be identified through variations in fringe spacing or changes in fringe orientation. Overall, the shearographic observations established a clear correlation between impact energy and the degree of damage in hybrid composites. The hybridization of jute with glass fibers contributed to improved resistance at moderate energy levels. However, at higher energies, the mismatch in stiffness and interfacial properties between the two fiber systems promoted non-uniform delamination and complex damage growth. The results affirmed that laser shearography served as an effective non-

destructive tool for visualizing and differentiating energy-dependent failure modes in natural/synthetic fiber FRP hybrid composites.

Laser shearography fringe phase images captured at 5, 10, 15, and 20 J impact energy levels were analyzed to examine the progressive evolution of damage in jute/glass fiber reinforced epoxy hybrid composites in the inner region, as shown in Figs 8(a)-(d), respectively. The fringe patterns provided qualitative insight into the deformation field and subsurface defects, such as matrix cracking, fiber–matrix debonding and interlaminar delamination developed under increasing energy levels. At 5 J, the specimen exhibited a localized and symmetric fringe concentration around the impact site. The deformation zone was limited in area with well-defined fringes, indicating minor matrix cracking and elastic deformation without significant delamination. This confirmed that the laminate can effectively dissipate low-level impact energy through localized matrix response and minimal interfacial separation. When the impact energy increased to 10 J, a clear expansion of the fringe pattern was observed with the emergence of irregular fringes, extending radially from the impact core. The central bright region corresponded to high strain localization, while the surrounding irregular fringes reflected the initiation of delamination between the jute and glass layers. The asymmetry of the pattern suggested non-uniform stiffness distribution at the hybrid interfaces, resulting in partial interfacial debonding.



**Fig. 8.** Fringe phase images of jute/glass hybrid epoxy composites (inner layers) at (a) 5, (b) 10, (c) 15 and 20 J loading conditions

At 15 J, the shearographic response showed a substantially larger affected region with dense and distorted fringe contours. The increased fringe density and irregular distribution signified severe internal deformation accompanied by widespread delamination propagation. The non-uniform phase contrast implied the coexistence of multiple damage mechanisms, such as matrix cracking, fiber pull-out, and delamination overlap, indicating that energy absorption mechanisms of the laminate had transitioned from localized plastic deformation to progressive interlaminar failure. Finally, at 20 J, the fringe phase image displayed a pronounced and highly disturbed pattern with broad dark zones, indicating complete delamination and fiber–matrix debonding across the hybrid interfaces. The deformation field extended well beyond the primary impact zone, confirming severe structural degradation. The optical fringe discontinuities established that the laminate reached its damage saturation limit, where further impact loading would result in catastrophic failure or complete layer separation. Overall, the laser shearography results established a clear correlation between increasing impact energy and the expansion of the damage-affected area. The jute/glass FRP hybrid composite exhibited improved impact tolerance at lower energy levels. However, at higher energies, the mismatch in fiber stiffness and poor interfacial adhesion promoted complex delamination and interlaminar cracking. Thus, shearography effectively revealed the progressive transition from localized matrix damage to large-scale delamination, validating its capability as a non-destructive tool for impact damage characterization in FRP hybrid composite laminates.

## CONCLUSIONS

1. The study of hybrid jute and glass fiber epoxy composites, incorporating varying thicknesses were assessed through CT scanning, established important insights into the impact performance and structural integrity of the materials, as subsequently summarized.
2. The results demonstrated that increasing thickness of the composite plates significantly enhanced their ability to absorb and distribute impact forces. Specifically, the thicker composites with thickness of 6 mm exhibited a broader and more uniform distribution of damage when compared with the composites with thickness of 3 mm, which showed more concentrated damage in the central layers. This improved performance in thicker composites can be attributed to their greater energy absorption capacity and consequently, a better overall durability.
3. The force *versus* displacement analysis further supported the afore stated findings, highlighting that thicker composite sustained higher impact forces and exhibited more gradual damage progression. These insights underscored the critical role of composite thickness in optimizing material performance, making thicker hybrid composites more suitable for applications that require high impact resistance and enhanced energy dissipation.
4. Besides, hybridization by adding synthetic glass fibers as sandwich skins on both sides of the composite materials significantly improved the impact load resistance when compared with the pristine jute fiber composite materials. The jute/glass hybrid composite materials also exhibited reduction in both damage and crack propagation

under impact loading. Therefore, the hybrid composites structures provided better impact performance and enhanced their structural integrity when compared with the conventional jute counterparts.

5. Evidently, the results of this study provide valuable guidance for the design and application of fibers/epoxy hybrid composites, emphasizing the benefits of increased thickness to achieve superior impact performance and structural resilience.

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