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Synopsis Of

Comprehensive Characterization of Natural Fiber Composites: Damage Assessment, Fracture Toughness, and Impact Testing

A Thesis

To be submitted by

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Of

DOCTOR OF PHILOSOPHY

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Abstract

The demand for lightweight, sustainable, and high-performance materials has driven the advancement of natural fiber-reinforced polymer composites as eco-friendly alternatives to synthetic counterparts. This study investigates their mechanical performance, fracture behavior, and impact response under quasi-static and dynamic loading conditions. Low and highvelocity impact tests, supported by acoustic emission (AE) monitoring, reveal detailed damage progression mechanisms. Fracture toughness is assessed under Mode I, Mode II, and Mixed-Mode configurations to evaluate delamination resistance and crack propagation. AE signal features such as amplitude, energy, and frequency are linked to failure modes like matrix cracking, fiber pull-out, and delamination. The results demonstrate the structural reliability and energy absorption capabilities of bio composites, offering critical insights for the design of durable and sustainable composite structures.

1   Introduction

The increasing demand for sustainable and lightweight materials has led to a growing interest in natural fiber-reinforced polymer composites (NFRPCs). These eco-friendly composites not only contribute to environmental sustainability due to their biodegradability and renewability but also exhibit competitive mechanical properties such as high specific strength and stiffness Skosana *et al.* (2025). Their cost-effectiveness, low density, and reduced environmental footprint make them promising alternatives to synthetic fiber composites in structural, automotive, aerospace, and defense applications. This research aims to comprehensively investigate the mechanical behavior, damage progression mechanisms, and energy absorption characteristics of laminated hybrid composites under various quasi-static and dynamic loading conditions S. Maiti (2022). Tensile, flexural, and compression tests were conducted to characterize stiffness and failure patterns, while impact loading (both low and high velocity) was employed to assess energy dissipation capabilities. Acoustic Emission (AE) monitoring was utilized as a non-destructive technique to capture real-time damage events, offering insights into microcracking, delamination, fiber breakage, and interfacial debonding. Additionally, advanced fracture tests using Arcan fixtures were performed to evaluate the fracture toughness under mode-I, mode-II, and mixed-mode loading conditions. The outcomes provide a better understanding of the structural integrity and failure mechanisms of natural fiber composites, establishing their potential for durable and reliable engineering application Li.C and Gao.W (2013).

2   Objectives of the research

The primary objective of this research is to address the identified problem through systematic experimental investigation. The research work aims to:

(a) Damage and failure assessment of laminated banana/ramie/epoxy hybrid composites under tensile and compression loading using acoustic emission monitoring.

(b) Acoustic emission characterization of failure modes in banana/ramie/epoxy composites under flexural loading.

(c) Experimental investigation of the orientation of the fibers of normal and inclined planes in sustainable composites to determine the resistance to indentation damage.

(d) Evaluate the impact resistance of natural fiber composites under controlled drop weight conditions.

(e) Assess the fracture toughness of natural fiber composites under loading conditions in mode-I, mode-II, and mixed-mode.

3   Research Gaps

(a) Traditional tensile tests only provide basic properties like strength and stiffness. They do not show how damage begins and spreads inside hybrid composites. Earlier studies did not use real-time tools to detect early damage like micro-cracks or fiber pull-out. This study used Acoustic Emission (AE) during tensile tests to track and classify different types of damage

(b) Earlier flexural (bending) tests mainly focused on maximum strength and ignored different damage types like matrix cracks and delamination. This study used AE during three-point bending to find when and how each type of damage happened, giving a better understanding of flexural behavior

(c) Compression behavior in fiber composites is complicated and not well studied. Damage like fiber buckling and shear failure is hard to detect and was often missed in past work. This study used AE to monitor these failures during compression tests and to better understand how the damage develops

(d) The impact performance of natural fiber composites at both low and high speeds has not been studied enough. Most past work used simple tests and didn't show how damage changes with speed. Low-speed impacts can cause hidden damage, while high-speed impacts create fast and severe failure. This study used drop-weight and ballistic tests on banana/ramie/epoxy laminates to measure peak force, energy absorbed, rebound, and damage area.

(e) The effect of fiber orientation on indentation damage is not well explored. Fiber direction changes how stress moves and how cracks grow. This study tested normal and inclined fiber setups under indentation and found clear differences in strength, deformation, and damage area.

(f) Most fracture studies only looked at Mode-I (opening) type cracks. But real parts face mixed loading with shear and combined forces. This study used Mode-I, Mode-II (sliding), and Mixed-Mode (Arcan) tests to study banana/ramie/epoxy laminates. It measured energy release rates (G_I, G_{II}, G_{mix}) and examined fracture surfaces to understand how fiber layout affects crack growth.

4   Most Important Contributions

The study comprehensively evaluated banana/ramie/epoxy composites using acoustic emission to monitor progressive damage under mechanical loading. Impact and indentation tests revealed superior energy absorption and surface resistance in hybrid laminates. Fracture analysis using the Arcan fixture confirmed enhanced delamination resistance under mixed-mode loading. These results establish the suitability of natural fiber hybrids for sustainable structural applications.

4.1   Damage Assessment of banana/ramie/epoxy hybrid Composites

The damage behavior of laminated banana/ramie/epoxy hybrid composites under tensile, flexural, and compressive loading was systematically assessed using Acoustic Emission (AE) monitoring. The AE data revealed distinct damage progression patterns for each loading type.In tensile tests, low-amplitude signals initially indicated matrix microcracking, followed by high-energy bursts corresponding to fiber breakage near ultimate failure. During flexural loading,

AE activity was more gradual, reflecting sequential matrix cracking, fiber–matrix debonding, and eventual fiber pull-out.Compression tests exhibited moderate AE amplitudes with sustained energy release, attributed to progressive crushing, interlaminar shear, and localized buckling. The cumulative AE energy and amplitude–frequency distributions provided valuable insights into the severity and timing of damage events.Peak amplitudes exceeding 70 dB typically indicated critical damage in all loading conditions.Overall, AE-based evaluation effectively distinguished early micro-damage from catastrophic failure, validating its application in real-time structural health monitoring of natural fiber-reinforced composites.

4.2 Materials and Methods: Testing procedure

Banana and ramie fiber mats were used as reinforcements in this study. Banana pseudo-stems and ramie stalks were cleaned, dried, and processed into fibers, which were then aligned to form mats. These mats were chemically bonded and compressed for stability before being cut to required sizes. LY556 epoxy resin and HY951 hardener were mixed in a 10:1 weight ratio and stirred to uniformity.A fiber-to-resin weight ratio of 30:70 was maintained. The hand lay-up method followed by compression molding in a 50 kN press was employed to fabricate the composites with a 0° fiber orientation. The impregnated laminates were cured at room temperature for 48 hours and later trimmed to 300 mm × 300 mm using a waterjet cutter. The average hardness was found to be 168 HV. Surface profiling revealed roughness values of Sa = 18745.43 nm, Sq = 25401.96 nm, and Sz = 170551.92 nm. The composite plates exhibited a uniform thickness of approximately 3 mm with minimal surface defects. The fiber alignment was verified using optical microscopy, confirming consistent orientation throughout the laminate. Prior to testing, all specimens were conditioned at ambient temperature and humidity for 24 hours to eliminate moisture effects.No delamination or warping was observed post-curing, indicating good interfacial adhesion between fibers and matrix. The physical integrity and edge quality after waterjet cutting were maintained, ensuring specimen suitability for subsequent mechanical and thermal testing. The step-by-step manufacturing process for banana/ramie/epoxy composite preparation is shown in Fig. 1.

4.3 Testing procedure and setup

Tensile tests were conducted using a 100 kN Tinius Olsen universal testing machine (Model 100ST). Composite specimens (250 mm × 25 mm × 4 mm) were prepared as per ASTM D3039. Each sample was equipped with two piezoelectric acoustic emission (AE) sensors placed 150 mm apart. AE sensors (75 kHz resonance, 80 dB sensitivity) were bonded using ultrasonic grease. The test was performed at a displacement rate of 0.5 mm/min. The samples were clamped with self-aligning jaws to ensure a uniform load distribution. AE data acquisition was used to monitor internal damage and fiber–matrix bonding during loading.

4.4 Acoustic emission monitoring

Acoustic emission (AE) monitoring was used to assess damage progression in natural fiber composites during quasi-static tensile, flexural, and compression tests. AE sensors were bonded using ultrasonic vacuum grease to ensure optimal signal transmission and minimize interface attenuation. Tensile specimens (150 mm gauge length) were tested under displacement control at 0.5 mm/min using a universal testing machine. An 8-channel PCI-8™ AE system (Physical Acoustics Corp., USA) captured real-time signals associated with internal damage events.
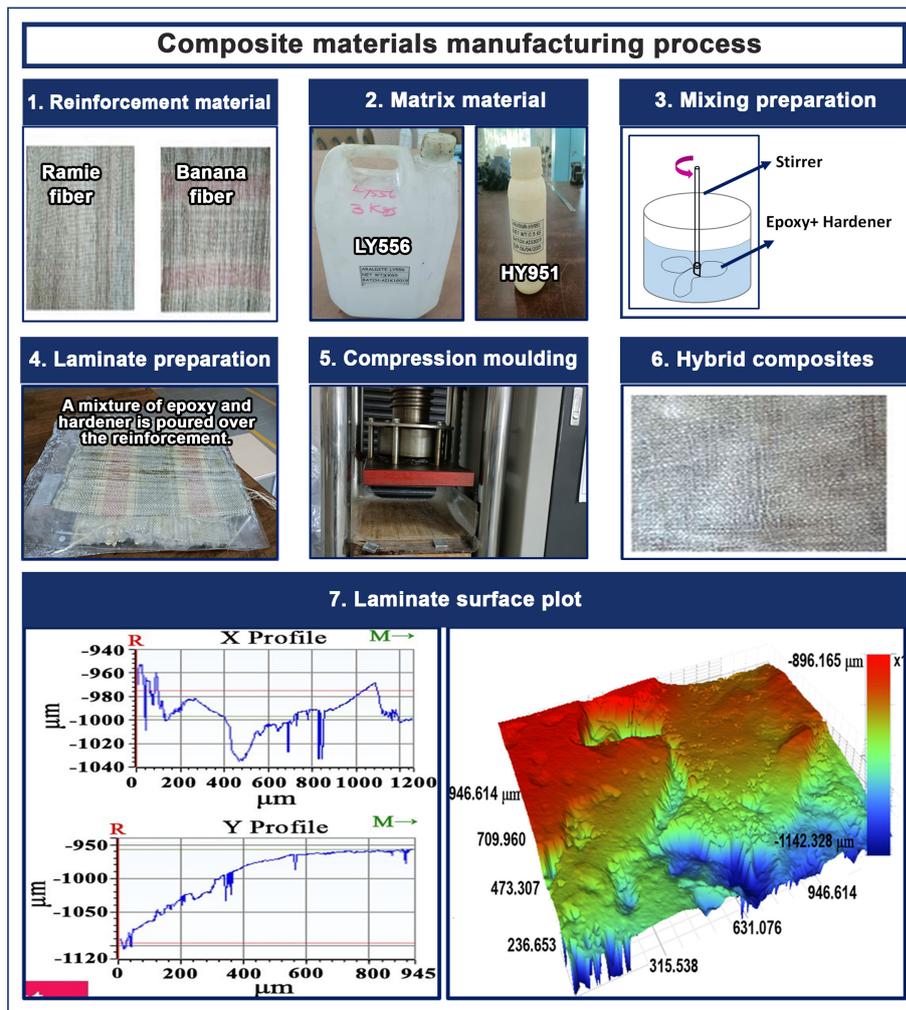
Fig. 1. Composite materials manufacturing process: (1) Reinforcement materials (ramie and banana fibers), (2) Matrix materials (epoxy resin LY556 and hardener HY951), (3) Mixing preparation of epoxy and hardener, (4) Laminate preparation with resin poured over fiber layers, (5) Compression moulding of the laminate, (6) Final hybrid composite laminate, and (7) Laminate surface topography analysis using X-Y profiles and 3D surface plot.

The system operated with a 40 dB gain, a 45 dB threshold to suppress background noise, and recorded frequencies up to 3 MHz. Key signal parameters included a 32 μs peak definition time, 150 μs hit lockout time, and signal duration filtering to isolate relevant events. System calibration was performed using the pencil lead break (PLB) method to ensure accurate wave detection and sensor response. AE signals were generated by various failure mechanisms such as matrix cracking, fiber fracture, and interfacial debonding. Tests were conducted at 0°, 45°, and 90° fiber orientations to evaluate the influence of anisotropy on damage mechanisms. A longitudinal wave velocity of 300 m/s was used for event localization and spatial tracking of damage initiation points. Cumulative AE energy and hit count data were synchronized with load–displacement curves to study damage evolution. Spatial and temporal clustering techniques enabled identification of localized failure zones, offering insights into the damage sequence. AE effectively detected early-stage micro-failures and internal flaws not visible through conventional methods, reinforcing its utility in real-time structural health monitoring. As shown in Fig. 2, the experimental setup facilitated correlation between AE features and mechanical behavior. Combined with strength data, AE allowed damage mode differentiation: low- to mid-amplitude signals were linked to matrix cracking and interfacial failure, while high-energy, high amplitude bursts signified fiber breakage. Frequency-domain analysis further refined failure mode classification, providing a comprehensive view of structural degradation Awerbuch *et al.* (2016).

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4.5 Acoustic emission activity & Load response

The acoustic emission (AE) response recorded during tensile testing offered detailed insights into the progressive failure mechanisms of banana/ramie/epoxy hybrid composites. As depicted in Fig. 3a and Fig. 3b, AE activity began at low stress levels, significantly prior to visible failure, emphasizing its effectiveness for early-stage damage detection. During initial loading, low-energy AE signals—typically in the range of 35–50 dB and frequencies between 100–200 kHz—were predominantly linked to matrix micro-cracking and early fiber–matrix interfacial debonding.
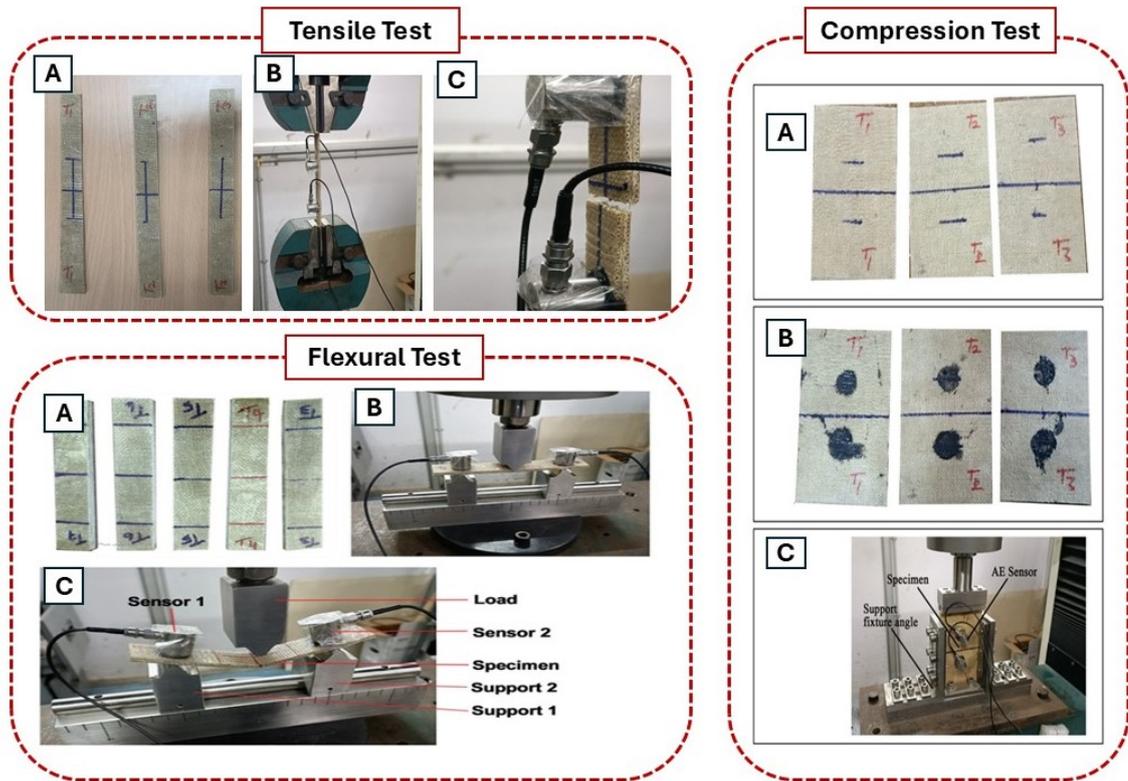

Fig. 2. AE-assisted mechanical testing setups for natural fiber composites: (A) Test specimens, (B) Specimen fixed in fixture, and (C) Complete experimental setup.

These early emissions were sporadic but steadily increased in density, especially as the applied stress approached 60–70% of the peak load. At this stage, localized interfacial friction and delamination between adjacent fiber layers were initiated, as reflected by moderate AE bursts (200–300 kHz).As the specimens approached ultimate tensile strength, a sharp rise in AE hit rate and amplitude was observed, often exceeding 70 dB. These signals corresponded to fiber breakage events (typically above 300 kHz) and catastrophic failure mechanisms. The AE energy values also peaked sharply in this region, with cumulative energy reaching up to 1.5×10^5 aJ for certain stacking configurations, particularly **B/B/R/R** and **B/B/H/H** laminates.

Fig. 3c illustrates the corresponding tensile stress–strain behavior, highlighting the elastic, damage initiation, and failure regions. In parallel, Fig. 3d presents amplitude, energy, and hit count evolution throughout the tensile test. A clear correlation was found between AE activity spikes and slope changes in the stress–strain curve, underscoring the strong interdependence between mechanical response and acoustic events.Moreover, the cumulative AE energy curve plateaued post-peak load, indicating that most energy-releasing damage mechanisms had concluded. This trend, when analyzed in conjunction with load-displacement behavior, reinforces the utility of AE as a non-destructive, real-time diagnostic technique for tracking the full damage lifecycle in natural fiber-reinforced composites.These findings align well with prior literature, where AE amplitude

and frequency were shown to distinguish between matrix cracking, delamination, and fiber rupture events in bio-composites Masmoudi *et al.* (2014).

4.6 Damage mode identification & Microscopy correlation

Understanding damage mechanisms is essential for assessing the structural reliability of natural fiber composites. In this study, Acoustic Emission (AE) monitoring was used to track real-time damage evolution in banana/ramie/epoxy composites under tensile loading. AE parameters—amplitude, energy, duration, and frequency—were analyzed to classify failure modes: low-amplitude signals indicated matrix micro-cracking; mid-range signals reflected fiber–matrix debonding; and high-amplitude bursts corresponded to fiber breakage.To validate AE interpretations, Scanning Electron Microscopy (SEM) was conducted on fractured surfaces. As shown in Fig. 4, SEM confirmed matrix cracking, fiber pull-out, and breakage, correlating well with AE signals. Voids and weak interfacial bonding contributed to early damage, leading to stress concentration and premature failure. Additionally, fiber misalignment and poor resin infiltration were observed in some regions, exacerbating crack propagation. The AE–SEM correlation provides a robust framework for identifying damage modes, monitoring internal deterioration, and improving composite design for structural applications Hamdi *et al.* (2021).
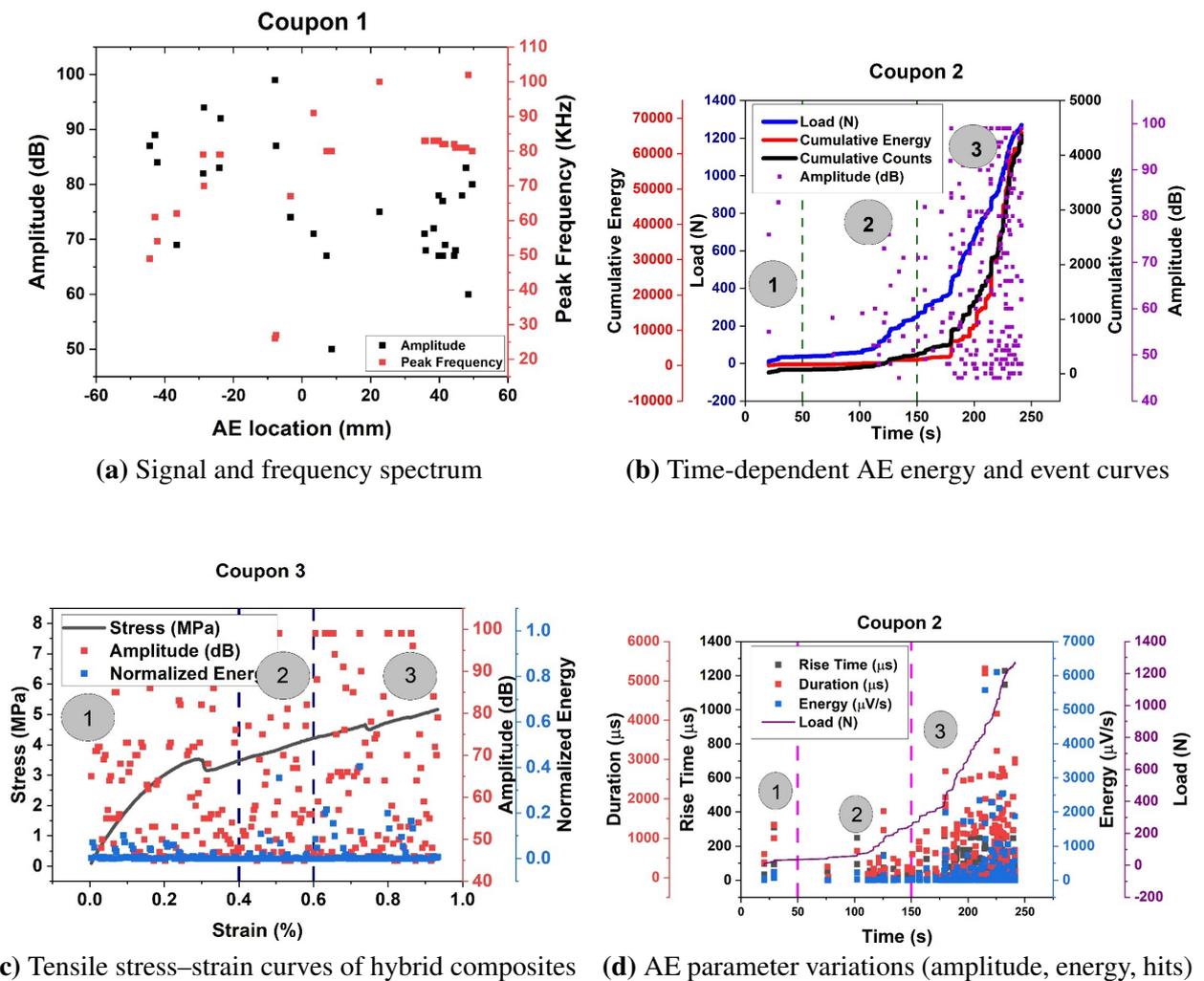

(a) Signal and frequency spectrum

(b) Time-dependent AE energy and event curves

(c) Tensile stress–strain curves of hybrid composites

(d) AE parameter variations (amplitude, energy, hits)

Fig. 3. Acoustic emission activity correlated with tensile load response in banana/ramie/epoxy composites
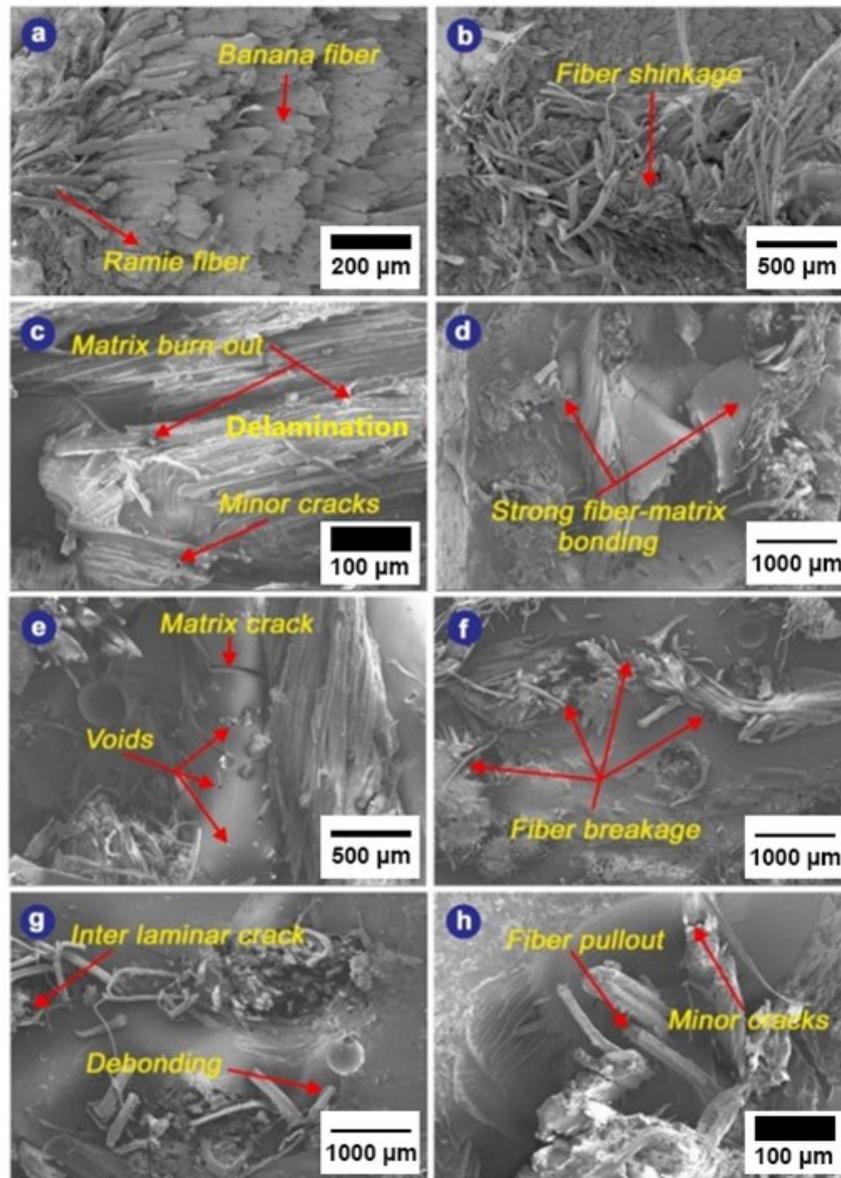
Fig. 4. SEM observation of tensile-tested specimen showing matrix cracking and fiber pull-out, validating AE-detected failure mechanisms.

4.7 Acoustic emission characterization under flexural loading

The flexural behavior of banana/ramie/epoxy hybrid composites with different stacking sequences was assessed using Acoustic Emission (AE) monitoring for real-time damage evaluation. Figure 5 shows both the AE amplitude distribution and corresponding stress–strain curves.In the initial linear-elastic region, AE amplitudes ranged from 30–45 dB, typically linked to matrix micro-cracking and brittle epoxy failure due to stress concentrations. As loading progressed into the non-linear phase, amplitudes rose to 50–65 dB, indicating more severe damage such as fiber–matrix debonding and delamination. This shift coincided with deviations from linearity in the stress–strain response, confirming progressive internal damage Alander *et al.* (2004).A sharp increase in AE hit count and energy near peak stress reflected the build-up of critical damage. Post-peak, stress dropped suddenly, indicating catastrophic failure due to fiber breakage and layer separation, accompanied by high-amplitude AE bursts representing rapid energy release.Specimens with outer ramie layers showed higher flexural strength and delayed AE onset, attributed to ramie's stiffness and better load transfer. In contrast, outer banana layers resulted in earlier AE activity and lower strength, due to weaker interfacial bonding and less effective stress distribution.
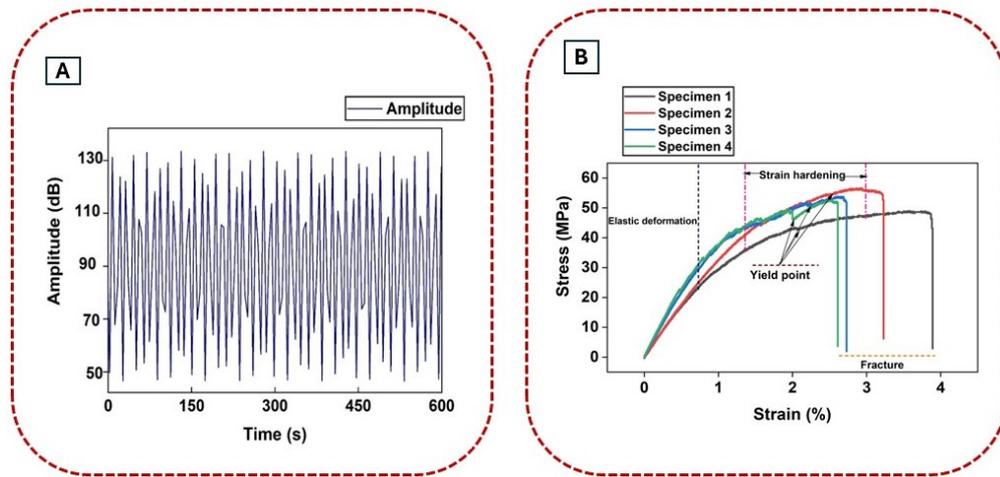
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Fig. 5. Flexural behavior of banana/ramie/epoxy hybrid composites: (A) Amplitude distribution of AE signals recorded during flexural loading, reflecting the damage initiation and progression; (B) Flexural stress–strain curves for various stacking sequences, illustrating differences in strength, stiffness, and failure strain influenced by fiber arrangement.

4.8 Damage and failure under compression

Acoustic Emission (AE) monitoring was used to evaluate damage initiation and progression in banana/ramie/epoxy hybrid composites under uniaxial compression. Broadband piezoelectric AE sensors were symmetrically mounted on specimens during quasi-static loading at 0.5 mm/min. Key AE parameters—hit count, amplitude, duration, rise time, energy, and frequency—were recorded to characterize the damage mechanisms. The AE hit count profile (Fig. 6a) revealed that hybrid laminates generated more events (750–820) than pure ramie (560) or banana (490) composites, indicating more extensive damage due to matrix shearing, fiber kinking, and interfacial delamination from heterogeneous stacking. The frequent AE events imply prolonged damage evolution and improved energy dissipation.

The amplitude–time response (Fig. 6b) further revealed the severity and timing of damage. Early-stage signals (0–40% peak load) were mostly low amplitude (<50 dB), linked to matrix micro-cracking. Mid-stage (40–60%) showed increased amplitude and density, indicating interfacial decohesion and matrix yielding. Beyond 60%, high-amplitude bursts (>70 dB) marked catastrophic events like macro-cracks and fiber buckling. The spatial AE energy distribution (Fig. 6c) highlighted energy concentration in high-stress zones, matching visual inspections and confirming AE's effectiveness in detecting internal damage zones.

Hybrids exhibited more distributed energy patterns, implying gradual energy release and higher damage tolerance. Notably, AE activity continued post-peak, indicating delayed failure through mechanisms like stress redistribution, crack bridging, and fiber pull-out. This supports the benefit of hybridization in promoting progressive rather than sudden failure, enhancing compressive load reliability. Furthermore, the correlation between AE features and mechanical response demonstrates AE's capability as a real-time diagnostic tool for structural health monitoring of natural fiber composites. These insights confirm that hybrid laminates provide a balanced failure mode with improved damage resistance and service reliability. In addition, the ability of AE to distinguish between early micro-cracking and catastrophic fracture events offers valuable information for predicting remaining service life. The findings suggest that integrating AE-based monitoring with design strategies can further optimize hybrid composite architectures for enhanced safety, durability, and sustainability in practical engineering applications.
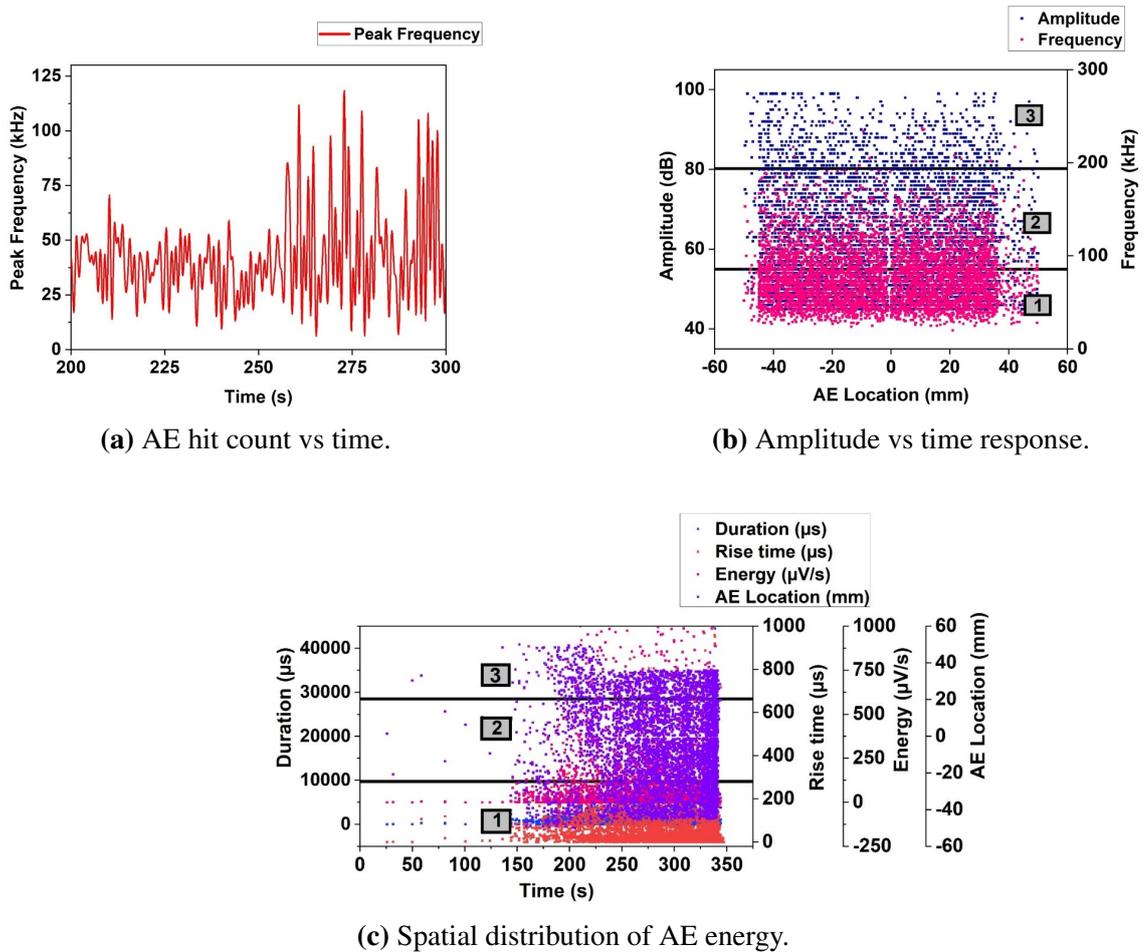
(a) AE hit count vs time.

(b) Amplitude vs time response.

(c) Spatial distribution of AE energy.

Fig. 6. AE signal characteristics during compression testing of natural fiber-reinforced composites.
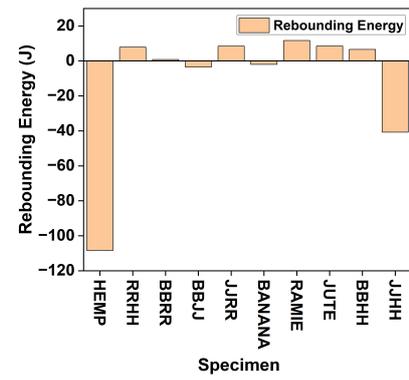
4.9 Impact performance under low-velocity loading

Low-velocity impact response is crucial for applications in transportation, construction, and consumer goods where composites must withstand accidental drops or mechanical shocks. In this study, drop-weight impact tests (ranging from 5–25 J) were conducted on banana, ramie, and hybrid banana/ramie fiber-reinforced epoxy laminates. Hybrid composites exhibited improved impact resistance due to synergistic energy absorption and enhanced crack arrest capability. As illustrated in Fig. 7, contact force–deformation behavior (Fig. 7a) revealed that hybrid specimens withstood higher peak loads and showed more gradual force decay, indicating efficient stress redistribution. Post-impact evaluation highlighted damage mechanisms such as matrix cracking, delamination, fiber pull-out, and localized fiber fracture Safri *et al.* (2014). Rebounding energy analysis (Fig. 7b) further supported the superior energy dissipation ability of hybrid laminates.

Hybrids also displayed smaller permanent indentation depths and reduced delaminated areas compared to single-fiber composites, confirming their ability to maintain structural integrity after repeated impacts. The incorporation of ramie improved stiffness and load-bearing capacity, while banana fibers contributed to ductility and energy absorption, thereby producing a balanced hybrid response. These results demonstrate that hybrid stacking architecture, along with better fiber–matrix bonding, significantly enhances energy absorption and reduces permanent damage, making these composites suitable for sustainable impact-resistant applications. Furthermore, the gradual failure evolution observed in hybrids suggests their potential for real-time monitoring and safer design in lightweight structural components.

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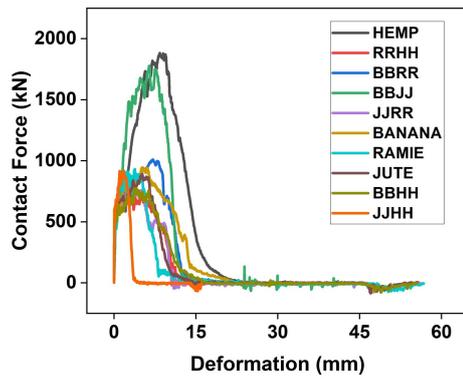
(a) Contact Force vs Deformation   **(b)** Rebounding Energy vs Sample Type

Fig. 7. Low-velocity impact response of natural fiber-reinforced composites.

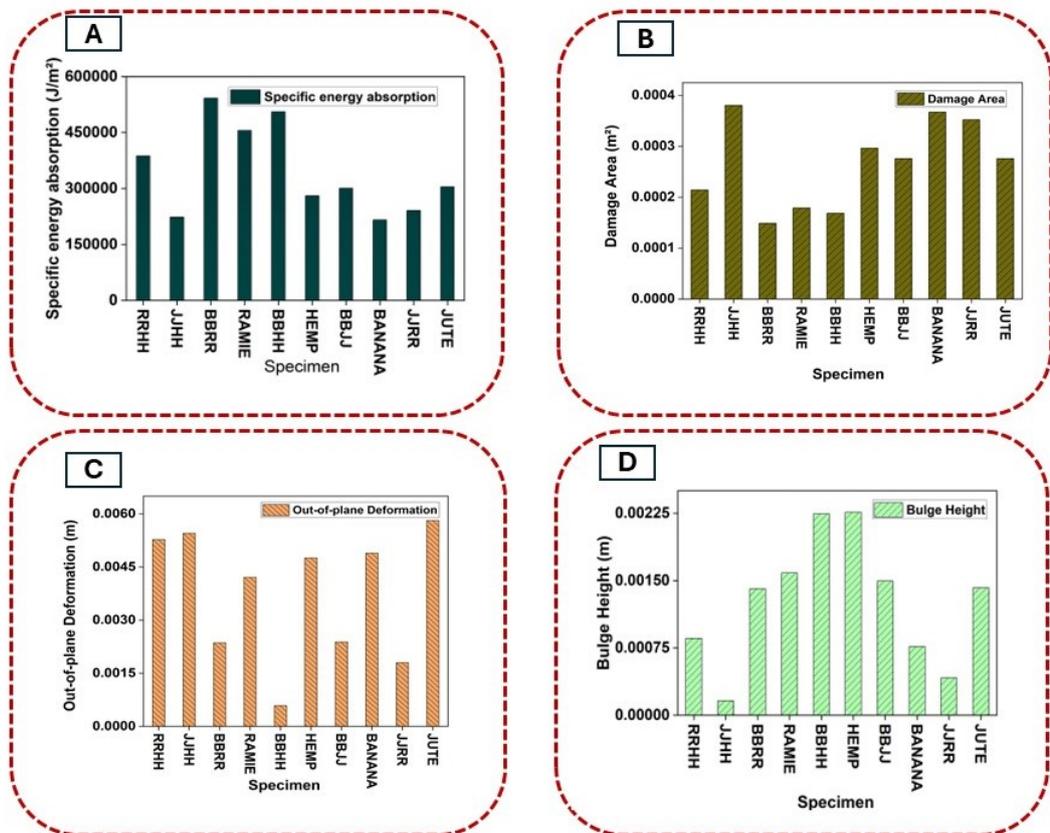**Fig. 8.** Ballistic performance metrics of various composites: (a) Specific energy absorption, (b) Damage area, and (c) Out-of-plane deformation.

4.10   Response of natural fiber-reinforced composites under ballistic loading

The ballistic response of various natural and hybrid composite laminates was evaluated using four key parameters: specific energy absorption, damage area, out-of-plane deformation, and bulge height, as illustrated in Fig. 8(a–d). Fig. 8(a) presents the specific energy absorption. The **BBRR** and **RAMIE** laminates exhibited the highest absorption capacity (above 450,000 J/m^2), indicating superior ability to dissipate impact energy. On the other hand, **BANANA** and **JRR** specimens showed lower absorption values. Fig. 8(b) shows the damage area distribution. **BBRR** and **JJHH** specimens demonstrated limited damage spread (below 0.0002 m^2), while **BANANA** and **JUTE** exhibited significantly larger damaged regions, indicating higher crack propagation

tendency.Out-of-plane deformation results in Fig. 8(c) show that **BBRR** and **BBJJ** had the least deformation (under 0.002 m), implying enhanced stiffness and localized resistance. In contrast, **JUTE** and **JJHH** experienced larger displacements.The bulge height after impact, shown in Fig. 8(d), was lowest for **BBRR** and **JJHH**, suggesting minimal back-face deformation. Higher values for **HEMP** and **BBHH** indicated greater rear-face protrusion and energy transfer through the thickness Gupta *et al.* (2023).
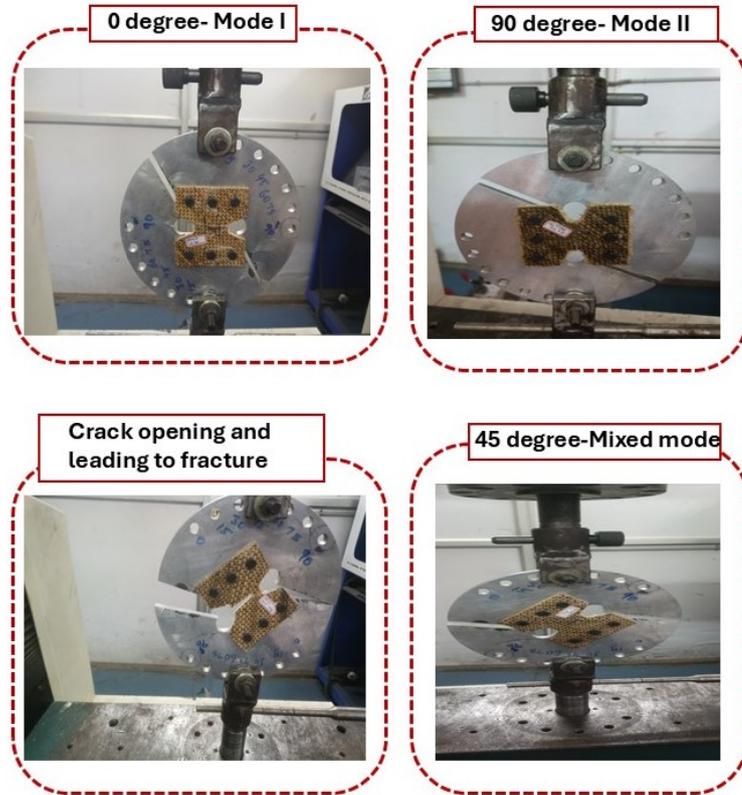

Fig. 9. Experimental setup for Arcan fixture testing: (a) Mode I—opening mode, (b) Mode II—shear mode, and (c) mixed-mode. Loading angle is varied to control the mode mixity.

4.11 Interlaminar fracture behaviour under mode I, mode II, and mixed-Mode loading using arcan fixture

The interlaminar fracture behaviour of banana/ramie/epoxy hybrid composites was examined using an Arcan fixture at loading angles of 0°, 15°, 30°, and 45°, representing Mode I, mixed-mode, and Mode II fracture conditions. This setup (Fig. 9) enabled precise control of loading orientation to study delamination under varied tensile–shear combinations. The test configuration ensured uniform stress distribution at the crack tip and minimized secondary bending effects, thereby improving the reliability of fracture toughness measurements.As shown in Fig. 10, the critical strain energy release rate (G_c) increased with loading angle, from approximately 120 J/m^2 in pure Mode I to over 130 J/m^2 at 45°, indicating enhanced resistance to shear-dominated crack propagation. Mode I failures were characterized by fiber bridging, matrix cracking, and crack opening, while mixed-mode and Mode II conditions revealed interfacial sliding, fiber pull-out, and matrix shear deformation.Crack paths shifted progressively with loading angle due to fiber–matrix interactions and the anisotropic nature of the laminate, influencing delamination resistance.The hybrid architecture enhanced toughness through synergistic mechanisms such as crack deflection, fiber bridging, and frictional resistance along the delamination front. These findings validate the Arcan fixture as an effective tool for evaluating multiaxial delamination and provide design insights for improving interlaminar strength in sustainable composite structures Hao *et al.* (2019).
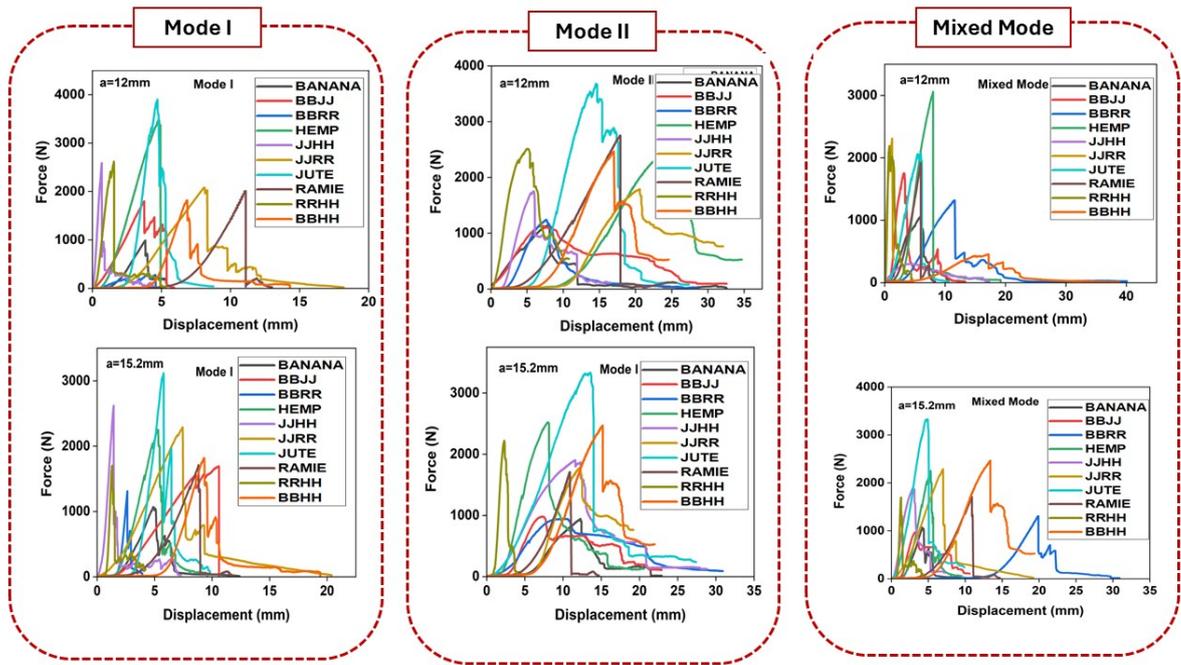
Fig. 10. Force–deflection and critical strain energy release rate (G_c) curves of banana/ramie/epoxy hybrid composites under Mode I, Mode II, and mixed-mode loading using the Arcan fixture. Increasing G_c with loading angle indicates higher resistance to shear-driven delamination.

5   Conclusions

In this study, a comprehensive experimental investigation was carried out to evaluate the damage mechanisms, energy absorption characteristics, and failure modes of natural fiber-reinforced polymer composites. The primary focus was on understanding the behavior of banana/ramie/epoxy hybrid composites under various mechanical loading scenarios. A combination of quasi-static, dynamic, and fracture tests were conducted, with real-time damage monitoring achieved through Acoustic Emission (AE) techniques. The key findings of the research are summarized as follows:

- Acoustic Emission (AE) monitoring was successfully employed as a real-time, non-destructive technique to detect and track damage mechanisms during all mechanical tests.The AE signals provided critical insights into failure modes: matrix cracking (100–200 kHz), delamination (200–300 kHz), and fiber breakage (above 300 kHz). AE effectively distinguished between micro-failure initiation and catastrophic fracture.

- During quasi-static indentation, banana/ramie/epoxy composites withstood peak loads of approximately 4500 N and absorbed up to 220.5 J of energy. AE activity initiated around 60% of the peak load, indicating early micro-crack formation.

- In low-velocity impact tests, the **B/B/R/R** laminate demonstrated superior performance, absorbing approximately 18.7 J and exhibiting damage areas between 350 and 570 mm^2. AE captured the entire damage progression, including matrix cracking, fiber pull-out, and delamination.

- During high-velocity impact testing, the **B/B/H/H** configuration achieved the highest energy absorption, ranging from 180 to 220 J. Residual projectile velocities were recorded between 39 and 51 m/s. AE bursts corresponded to critical damage events such as fiber rupture and laminate perforation.

- A series of fracture toughness tests were conducted using the Arcan fixture to evaluate Mode I, Mode II, and mixed-mode delamination resistance. The **B/B/R/R** configuration exhibited the highest resistance to crack growth, with Mode I and Mode II fracture energies measured at 1.32 and 2.87 kJ/m^2, respectively. Mixed-mode fracture energy averaged 2.18 kJ/m^2, indicating enhanced interlaminar toughness.

6   Organization of the Thesis

The thesis is organized into ten chapters, as outlined below:

- **Chapter 1: Introduction** Presents the motivation, objectives, scope, and methodology of the study, emphasizing the potential of banana and ramie fibers for sustainable composite applications.

- **Chapter 2: Literature Review** Reviews existing research on natural and hybrid fiber composites, including AE monitoring, impact testing, and fracture analysis, and identifies gaps in AE-based mechanical characterization.

- **Chapter 3: Tensile Damage Assessment Using AE** Investigates tensile behavior using AE signals, correlating amplitude, energy, and frequency with matrix cracking, fiber breakage, and debonding.

- **Chapter 4: AE-Based Flexural Failure Characterization** Analyzes flexural response through three-point bending and AE monitoring, identifying failure modes such as delamination, interfacial debonding, and fiber pull-out.

- **Chapter 5: Compression Failure Assessment via AE** Evaluates compressive behavior using AE monitoring to detect microbuckling, crushing, and the influence of stacking sequence on damage progression.

- **Chapter 6: Indentation Response and Fiber Orientation Effects** Examines local mechanical behavior under quasi-static indentation, focusing on the effects of fiber orientation and stacking on resistance and energy absorption.

- **Chapter 7: Low-Velocity Impact Behavior** Assesses drop-weight impact performance through force, displacement, energy data, and post-impact damage analysis across various stacking sequences.

- **Chapter 8: Ballistic Resistance Evaluation** Investigates high-velocity impact behavior by determining ballistic limit, residual velocity, and damage zones, highlighting the effect of fiber type and hybridization.

- **Chapter 9: Fracture Toughness Under Mixed-Mode Loading** Uses the Arcan fixture to evaluate fracture behavior under Mode-I, Mode-II, and mixed-mode loading, with analysis of crack propagation and delamination resistance.

- **Chapter 10: Conclusions and Future Work** Summarizes key findings from mechanical tests and AE studies, emphasizing the effects of stacking sequence and fiber orientation, and proposes future research directions.

7 List of Publications

I. **Refereed Journals Based on the Thesis**

1. **Saleem M**, **Kashfull Orra**, and **Arumugam V**, "Structural health monitoring of natural fiber-based hybrid composites," *Polymer Composites*, Wiley (Q1, SCI, IF: 4.7), pp. 1–12, 2023.

2. **Saleem M**, **Shahul Hamid Khan B**, and **Arumugam V**, "Acoustic emission characterization of failure modes in banana/ramie/epoxy composites under flexural loading," *Cellulose*, Springer (Q1, SCI, IF: 4.9), pp. 10423–10444, 2024.

3. **Saleem M**, **Shahul Hamid Khan B**, and **Arumugam V**, "Damage and failure assessment of banana/ramie/epoxy composites using acoustic emission monitoring," *Construction and Building Materials*, Elsevier (Q1, SCI, IF: 8.0), Article ID: 138489, 2024.

4. **Saleem M**, **Shahul Hamid Khan B**, and **Arumugam V**, "Energy absorption and damage characteristics of natural fiber composites under low-velocity impact," *International Journal of Impact Engineering*, Elsevier (Q1, SCI, IF: 5.4), 2025. *(Under review)*

5. **Saleem M**, **Shahul Hamid Khan B**, and **Arumugam V**, "Investigation of high-velocity impact characteristics in sustainable natural fiber composites," *International Journal of Damage Mechanics*, Sage (Q1, SCI, IF: 4.0), 2025. *(Submitted)*

6. **Saleem M**, **Shahul Hamid Khan B**, and **Arumugam V**, "Assessment of delamination resistance in fiber-reinforced composites under Mode I, Mode II, and mixed-mode loading using an Arcan test setup," *Engineering Fracture Mechanics*, Elsevier (Q1, SCI, IF: 5.3), 2025. *(Under review)*

II. **Presentations/Publications in Conferences Based on the Thesis**

1. **Saleem M**, **Kashfull Orra**, **Prasant Rawat**, and **Arumugam V**, "Experimental investigation of fiber orientation of normal and inclined planes in sustainable composites to determine resistance to indentation damage," *International Conference on Sustainable Materials for Engineering Applications (ICSMEA 2024)*, Indian Institute of Technology Madras, Chennai, India, 1–3 February 2024.

References

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