https://doi.org/10.3311/PPme.39914

Periodica Polytechnica Mechanical Engineering, 69(2), pp. 129–135, 2025

An Experimental Investigation of Natural-fibre/Rubber Reinforced Bio-composites under Low-velocity Impact Analysis

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Received: 19 January 2025, Accepted: 22 April 2025, Published online: 09 May 2025

Abstract
Natural fibers are renewable, inexpensive, and environmentally friendly; they have become a viable material for a wide range of uses. These composites consist of a natural fibre matrix modified with flax, hemp, sisal, jute, and bamboo. The aim of this present investigation is to explore the existing research, which focuses on examining the influence of natural fibre's absorbed energy and peak force on hemp rubber hemp (HRH), jute rubber jute (JRJ), hemp rubber jute (HRJ), and glass rubber glass (GRG) composite laminates under Low-velocity impact (LVI) analysis. The LVI test results affirmed that the HRH laminates have more energy absorption and elastic energy by 44.34%, 10.6%, and 80% as compared to other configurations due to their stiffness and robustness. The free vibrational analysis shows that the HRH samples have the highest natural frequency of 526.9 Hz compared to JRJ, HRJ, and GRG. The Field Emission Scanning Electron Microscopy (FESEM) discloses the failure mechanisms of the tested samples, including interlaminar failure, delamination, and matrix cracking due to the stress concentration in the impacted region.

Keywords
biomaterials, composite materials, low-velocity-impact, modal analysis, failure analysis

1 Introduction

Natural fibre-reinforced composites are said to be the most widely used type due to their outstanding durability and compact design. The composites firm was dominated by synthetic, non-biodegradable fibers like carbon, aramid, carbon, and glass. The production of these artificial fibers requires a substantial amount of energy and fossil fuels, which means they cannot be recycled in the natural world. Considerations about sustainability have prompted further study on sustainable fibre derived from renewable sources for use as reinforcements in composite components [1–5].

The development of biodegradable materials for tackling the present problems with the environment and ecology may heavily rely on natural fibers. In industries like consumer products, affordable housing, and civil construction, among many others, natural fibre composites present a vast array of possibilities in which the use of traditional lightweight reinforced plastics is currently limited by the exorbitant cost of the reinforcements. Over the last ten years, a variety of organic fibers, including ramie, hemp, jute, sisal, bamboo, banana, oil palm, and others, have been produced as reinforcing for the installation of fibers made from glass in composites made of natural fibers [6–9]. A variety of natural fibers, including flax, hemp, jute straw, wood, rice husk, and many more, have been investigated for use as plastic reinforcement. Natural fibers provide numerous significant benefits over synthetic alternatives. Thermoplastics supplemented with certain wood fillers exhibit rapid development due to their lightweight nature, suitable durability, and stiffness. Certain plant proteins, including wheat gluten, have thermoplastic qualities and are used to make recyclable, sustainable film and packaging supplies. Biodegradable polymers have made use of hemp, a bast lignin fibre derived from the plant Cannabis sativa. Mechanical, water-resistant, and compostable characteristics have been investigated in composites made of cotton and flax fibers with compostable polyester amide [10–13].

Throughout the course of their functional lives, Low-velocity impact (LVI) degrading is a common and commonly seen type of deterioration in composites built with fiber reinforcing [14–18]. Catastrophic destruction can arise from LVI, which causes substantial structural

Cite this article as: Erannagari, S., Reddy, D. M. "An Experimental Investigation of Natural-fibre/Rubber Reinforced Bio-composites under Low-velocity Impact Analysis", Periodica Polytechnica Mechanical Engineering, 69(2), pp. 129–135, 2025. https://doi.org/10.3311/PPme.39914

instability [19–21]. Failure mechanisms, including delamination, matrices failing, and fiber failure, expose the FRP materials to damage and will impact [10, 22]. Fiber orientation is utilized in material selection with thermoplastic polymers to increase the impact durability of FRP composites. Ply direction, thickness, and specimen shape will all have an impact on the FRP materials' performance [23–26].

Natural materials have benefits, including being readily available, recyclable, acoustically insulated, biodegradable, renewable, and requiring less money to manufacture. The majority of plant fibers, such as flax, hemp, sisal, and kenaf, are used to reinforce composite structures in place of artificial fibers. Compared with various fibers, hemp fibers have a higher percentage of cellulose and are stronger [27–29]. Cannabis composites with fibre reinforcement are typically employed in the construction of car body sheets, door panels, and goods floors [30, 31]. The researchers examined the physical and mechanical features of several raw hemp fibers and came to the conclusion that hemp fibre is just as strong as artificial fibers [32]. All the mechanical tests are conducted on natural fibres, and it performs equal to the synthetic fibres [10, 33]. Further, experiments has been carried out on model analysis to evaluate the natural frequency of the laminates for better enhancement [34].

The current work discloses the investigation of different natural fibers with natural rubber and hybrid composite laminates under low-velocity-impact analysis. Further model analysis has been carried out to evaluate the natural frequency, and the Field Emission Scanning Electron Microscopy (FESEM) has been adopted to analyse the failure mechanism.

2 Materials and methodology

2.1 Materials and sample preparation

The natural hemp, jute, and glass fibers are used along with the natural rubber to make the composite laminates. The laminates are fabricated using epoxy LY556 and hardener HY951 with a ratio of 10:1. The specimens were prepared using the hand layup technique in four different variants such as hemp rubber hemp (HRH), jute rubber jute (JRJ), hemp rubber jute (HRJ), and glass rubber glass (GRG). The specimens consist of 1.5 mm of fibre layers and 8 mm of rubber layer, and the average thickness of the specimens is 11 mm. Later, the specimens were cut at 150 × 150 mm as per the ASTM D3039/D3039M-08 standard [35], the different nnatural-fibre/rubber reinforced specimens as shown in the Fig. 1.

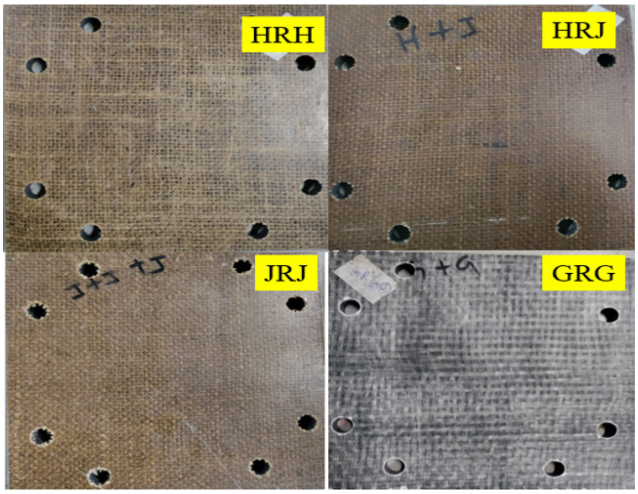

Fig. 1 Natural-fibre/rubber reinforced specimens

2.2 Testing of samples

The laminates underwent an impact test using a drop-weight configuration using a conical impactor, as shown in Fig. 2, with an 8 kg impactor unit. The investigations were conducted in accordance with the ASTM D7136/D7136M-15 standard [36]. Three different velocities such as 9, 11, and 15 m/s with different heights like 1000, 1200, and 1500 mm have been used, and the average of three samples is considered. The specimens are shown in Fig. 3 before and after impact testing.

3 Modal analysis

An investigation was conducted to see how laminates behave under free vibrational characteristics within free initial conditions. The frequency response was determined using modal analysis. Utilizing a small impulse sledgehammer with modally modified calibration movement data was obtained using a 0.5 g small, tiny porcelain shear

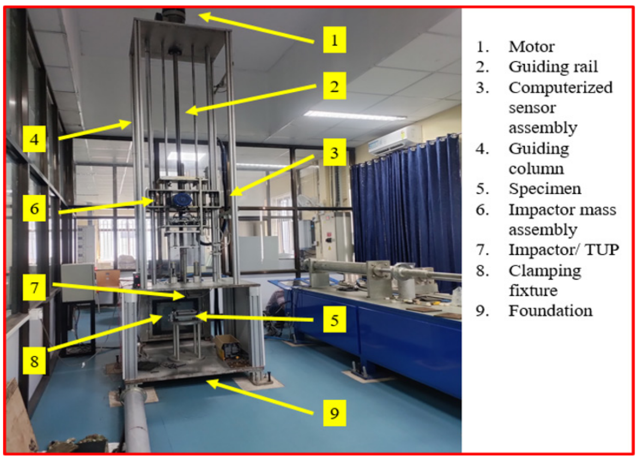

Fig. 2 Experimental LVI test rig

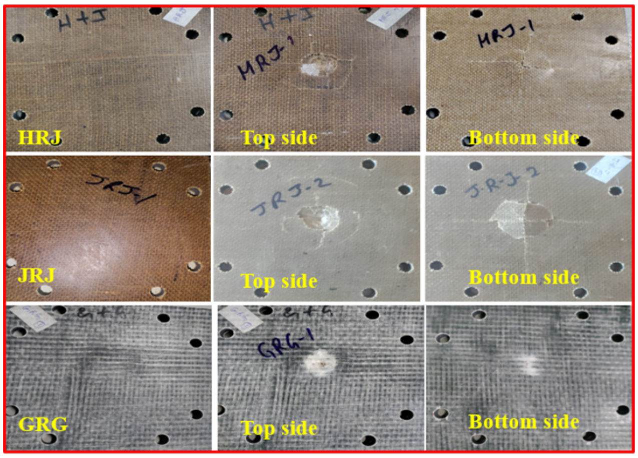

Fig. 3 Specimens with before and after impact testing

ICP accelerometer. The acquired signals were fed into a four-channel data-gathering system, which converted this time-domain information into frequency-domain signals using the Rapid Fourier Transformation (FFT) technique. The entire setup for modal analysis is shown in Fig. 4. And the nomenclatures are used as:

1. Specimen,
2. Accelerometer,
3. Impact hammer,
4. Data acquisition system,
5. PC analyser.

4 Results and discussion

4.1 Effect of impact energy and peak force

The experimental outcome showed that the energy absorption ratio is higher in hemp-based laminates as compared to jute and glass fibers, as illustrated in Table 1. HRH laminates that are more unlikely to distort under impacts tend to retain less energy because they can bear impact forces effectively in all directions of the fibre. Delamination reduces the laminate's total energy absorption capacity because of the larger interlaminar strains caused by the impact on laminates. Additionally, because thicker laminates have more fibers and rubber bridging the gaps, the matrix portion receives less energy.

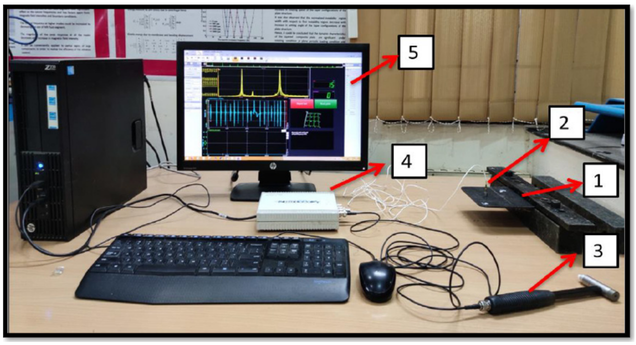

Fig. 4 Experimental setup for conducting modal analysis

Whereas, the JRJ and GRG have less energy absorption compared to HRH because the laminates are stiffer and harder. This includes the more elastic energy in the laminates that will rebound the impact load due to direct impact on the rubber material. Later HRJ has a similar energy absorption ratio compared to hemp fibre, which will absorb the impact load within it and provide both transversal and fibre dimensions with a blend of toughness and flexibility. The impact force may result in specific stresses in the matrix substance, which could cause the laminated material to delaminate or micro crack. JRJ and GRG have undergone fibre fractures that may result from tensile or shear loading on fibers brought on by high stress levels at the impacted point. Fibre separation or breaking could occur as a result of a breakdown spreading throughout the entire length of the strands.

4.2 Failure analysis

Natural fibers that have broken are frequently seen in the affected area, suggesting that the applied load caused the fibre to fail. Particularly in fragile rubber products, small cracks or matrix fractures have been seen inside the rubber structure. When impact occurs, significant regional stress may surpass the rubber matrix's elasticity restriction, causing cracks to start and spread. Fibre braking lowers the material's ability to support loads and could be a factor in regional stress levels and deboning occurs often at the fibre-matrix contact, especially in areas where the level of stress is significant. Interfacial separation decreases the effectiveness of load transfer and can cause fractures in the matrix or fibre separation as illustrated in Fig. 5 (a) and (b).

Excessive regional stress upon impact may surpass the rubber matrix's flexibility limit, causing the start and spread of cracks. Matrix splitting weakens the laminate's ultimate rigidity and durability and undermines the load transmission among the fibers. So the debonding occurs often at the fibre-matrix contact. Delamination, which appears as a discontinuity among the latex matrix as well as natural fibre layers, is frequently seen in the affected area. Interfacial separating, inadequate adhesion among the latex matrix and material, or significant shear stresses generated upon impact can all result in delamination. Finally it lowers the laminate's strength and flexibility by compromising the integrity of its structure as shown in Fig. 5 (c) and (d).

Table 1 LVI test results

Sample	Height of fall (mm)	Energy (J)			Peak force (N)	Energy absorption ratio (E_a/E_i)	Indent damage	
		Impact (E_a)	Elastic (E_r)	Absorbed (E_i)			Front	Back
	1000	303.67	257.32	46.35	7215.4	0.152	Yes	Yes
HRH	1200	478.91	380.79	98.12	12124.6	0.204	Yes	Yes
	1500	907.92	741.29	166.63	16012.5	0.183	Yes	Yes
	1000	303.67	269.24	34.42	5213.1	0.113	Yes	No
JRJ	1200	478.91	404.30	74.60	8215.2	0.155	Yes	Yes
	1500	907.92	792.89	115.03	13239.8	0.126	Yes	Yes
	1000	303.67	285.67	18.01	5208.3	0.059	Yes	No
HRJ	1200	478.91	413.71	65.19	8215.2	0.136	Yes	Yes
	1500	907.92	537.77	150.19	14092.2	0.207	Yes	Yes
	1000	303.67	284.01	19.65	4753.18	0.064	Yes	No
GRG	1200	478.91	434.76	44.15	6812.6	0.092	Yes	Yes
	1500	907.92	819.29	88.63	9603.7	0.097	Yes	Yes

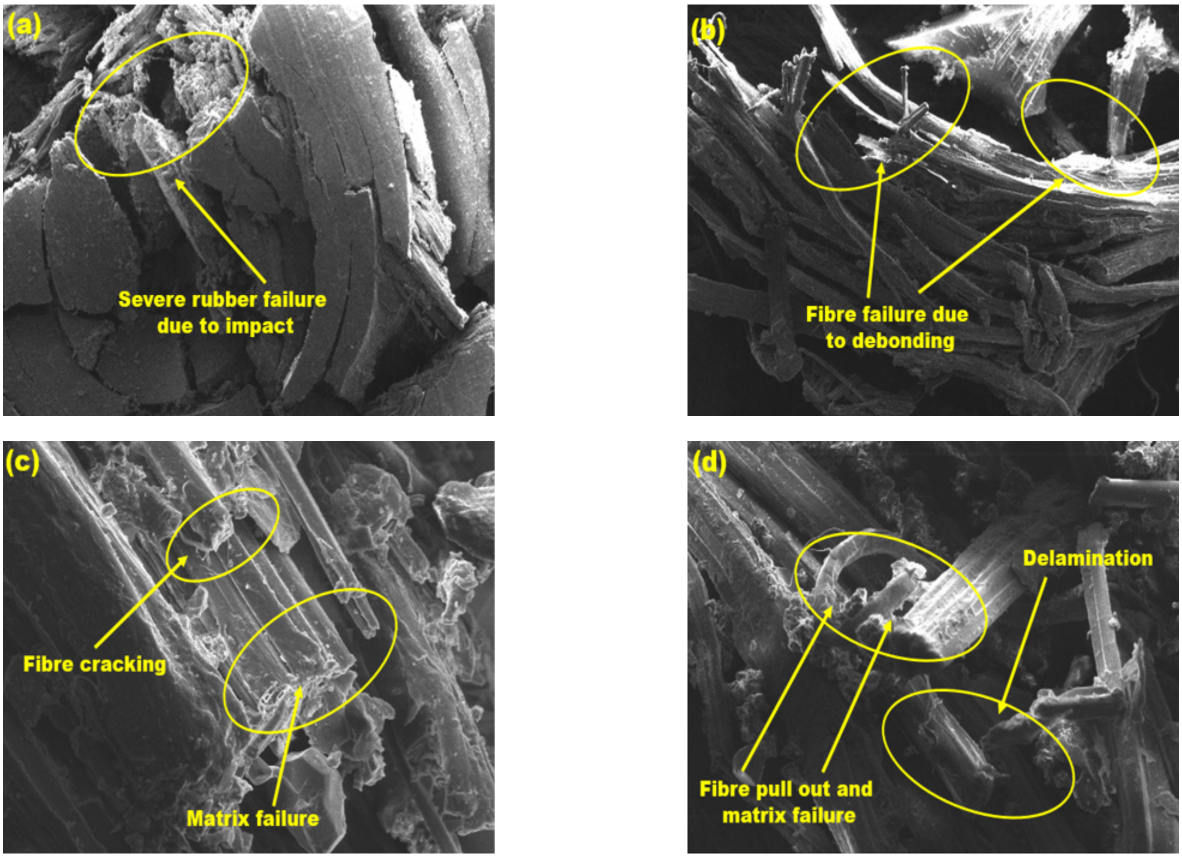

Fig. 5 FESEM images of tested samples of: (a) Rubber, (b) HRH, (c) GRG, (d) HRJ

4.3 C-scan analysis

LVI-induced subsurface damage is visible in C-scan pictures. These pictures display regions of delamination, which is matrix splitting and fibre breaking, indicating variances in material strength. Depends on the material's characteristics and impact energy, the damage usually manifests as elliptical or spherical areas. Delamination zones may be precisely mapped using C-scan imaging. Darker patches in the scan often show regions with decreased density or material separation, which confirms delamination brought on the impact loading stress concentrations. Impact energy and laminate thickness are correlated with the extent of these zones, as shown in Fig. 6.

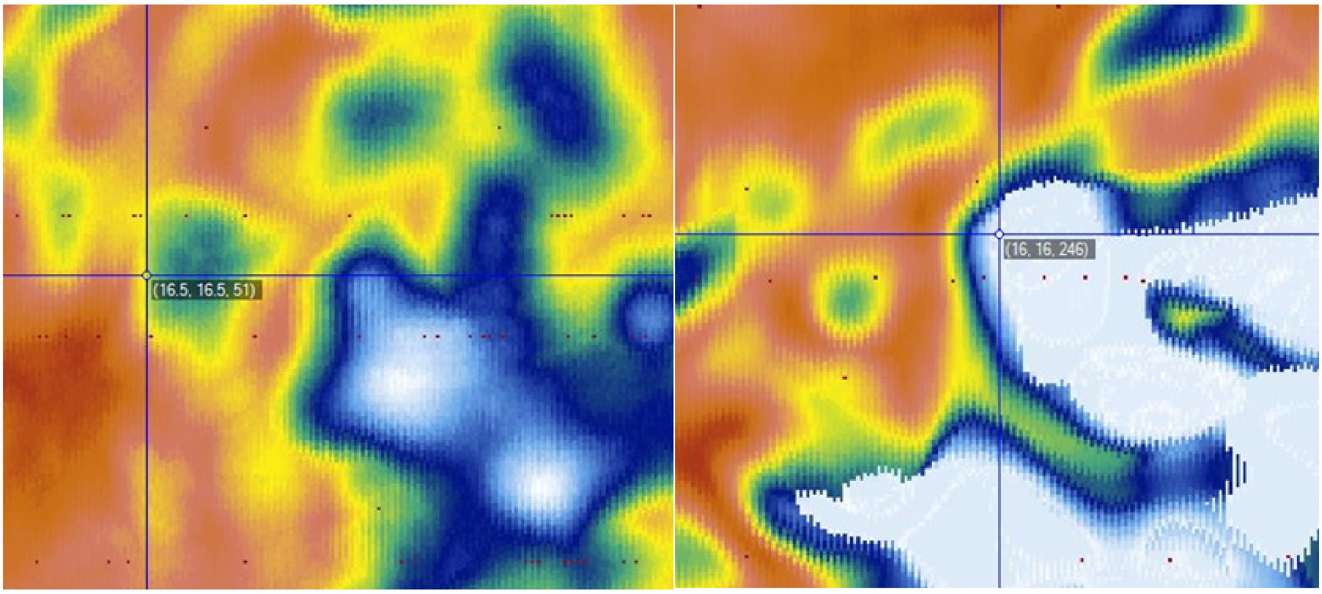

Fig. 6 C-scan images of tested samples

Matrix cracking is indicated by linear or branching patterns in the C-scan picture. Stress redistribution throughout the structure is shown by these fractures, which frequently spread outward from the impact site. Inconsistent patterns or areas with strong reflectivity might be signs of fibre breakdown. These failures can have a major influence on load-bearing capacity and are frequently confined close to the place of contact. In LVI situations, C-scan pictures are a non-destructive assessment method for determining failure processes. They make it easier to identify flaws early on, which makes maintenance plans more efficient and increases the dependability of composite structures in structural, automotive, and aerospace applications.

4.4 Free vibrational behaviour

The effect of using natural fibers and natural rubber as composite laminates under LVI conditions followed that the overall natural frequency of HRH is high in all three modes as compared to all other combinations. This is due to the stiffness and flexibility of hemp fibre. It is possible to see fibre spanning over broken surfaces, which suggests that fibers have a function in preventing crack progression. As reinforcing factors, fibers that bridge broken regions prevent cracks from spreading and increase their resilience to fractures. This shows the variation in the natural frequency ranges before and after impact testing of the laminates. Whereas GRG laminates have a lower natural frequency compared to natural fibre-based laminates due to the continuity of the fibers in the laminates and adhesive bonding between them. Hence the natural frequencies and damping factor of the laminates are in acceptable margin and the overall natural frequencies of all three modes of each configuration is shown in Table 2. The natural frequency of a laminate is influenced by its stiffness, mass, and damping characteristics. The HRH laminate exhibits higher natural frequencies in all three modes compared

Table 2 Modal analysis of the laminates under LVI loading

Sample	Sample	Mode 1		Mode 2		Mode 3	
		Natural frequency (Hz)	Damping factor	Natural frequency (Hz)	Damping factor	Natural frequency (Hz)	Damping factor
HRH	Intact	163.2	0.035	348.6	0.028	526.9	0.021
	Tested	111.5	0.038	265.3	0.029	412.0	0.030
JRJ	Intact	148.3	0.045	341.9	0.041	488.3	0.038
	Tested	108.3	0.047	248.1	0.039	385.6	0.033
HRJ	Intact	135.5	0.056	345.2	0.051	496.3	0.048
	Tested	88.3	0.052	288.3	0.046	402.3	0.038
GRG	Intact	98.2	0.068	216.5	0.066	443.6	0.061
	Tested	65.6	0.059	186.4	0.057	368.9	0.048

to JRJ, HRJ, and GRG because of HRH laminates have a higher stiffness-to-mass ratio, leading to higher natural frequencies in all modes, and have a higher flexural modulus and better load-bearing capacity. Jute fibers are more flexible and lower in stiffness, leading to lower natural frequencies. Glass fibers are brittle and heavy, which reduces the overall stiffness-to-weight ratio in GRG laminates. The same has been updated in the manuscript.

5 Conclusion

The present experimentation aims to identify and evaluate the energy absorption and peak force under LVI analysis of different natural fibre laminates. The outcome of the experiments reveals that the HRH laminates can efficiently withstand impact stresses in all directions of the fibre, they tend to hold less energy than laminates that are more inclined to bend under impact. It enhances the impact properties by 44.34%, 10.6%, and 80%, respectively, as compared to other configurations. The modal analysis describes the efficacy of hemp fibre laminates with the highest natural frequency of 526.9 Hz compared to jute fibre and glass fibre laminates. The FESEM shows the different failure mechanisms of samples under LVI, such as matrix cracking, fibre breakage, drastic rubber failure, and moreover, delamination, during the impact analysis.

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