Low-velocity Impact Response of Jute/Banana Fiber in Natural Rubber-Based Hybrid Composites: FE Approach

Kartik Kumbhare, Vishwas Mahesh, and Sharnappa Joladarashi

Abstract Green composites are proposed as environmentally friendly, easily recycled, and reusable advanced composite materials. The present study aims at studying the damage done by low-velocity impact (LVI) of jute and banana fiber-based green composites using commercial finite element (FE) software. The LVI response is evaluated for flat, hemispherical, and conical impactors at three velocities of 5, 10, and 15 m/s. Hybrid composites are modeled in two stacking sequences: jute-rubber-banana-rubber-jute (JRBRJ) and banana-rubber-jute-rubber-banana (BRJRB). These hybrid green composites are compared to their pure fiber counterpart composites, i.e., jute-rubber-jute-rubber-jute (JRJRJ) and banana-rubber-banana-rubber-banana (BRBRB). The ABAQUS Finite Element Modeling software is used to model, and the explicit dynamic solver is used to simulate these proposed composites. The absorbed energy at 5 m/s for flat impactor for JRJRJ and BRBRB is 3.5 J and 0.52 J, respectively, whereas for JRBRJ and BRJRB is 2.3 J and 1.4 J, respectively. Similar results are obtained for 10 and 15 m/s. The energy absorbed follows a sequence JRJRJ > (JRBRJ, BRJRB) > BRBRB. The flat impactor has more damage due to its larger contact area and high energy absorption at higher velocities. Impact due to conical impactor shows local penetration and lower energy absorption. Results show that the proposed composites exhibit better energy absorption due to a flexible matrix and more resistance to damage due to the involvement of a hybrid structure which makes the composite stiffer.

Keywords Banana-Jute hybrid · Low-velocity impact · Natural rubber · Damage study · Green composites

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1 Introduction

A composite material is formed with a combination of two or more distinct materials to create a new material with enhanced properties. Composites consist of two or more compatible materials that may differ in constitution and attributes embedded in a continuous phase. The embedded materials are usually more rigid and more robust than the continuous phase, called the reinforcing material, whereas the continuous phase is termed the matrix. Although lightweight, composites are prone to impact damage, which severely degrades the structural stiffness, firmness, and load-carrying capacity. In prevailing times, composite structures subjected to impact loads have been widely examined through experiments and mathematical models [1]. As we expand our use of composite structures in engineering applications, their relatively poor resistance to impact load is an area of research that has been and is still being pursued. The composite structures consisting of two or more discontinuous phases are defined as hybrid composites or more than one type of fiber (in the case of fiber-reinforced composites). Different methods combine these fibers, which involve stacking layers of fibers, coalescing fibers, selective placements of fiber in a layer or in the matrix itself, and in a specified orientation [2]. In recent years, rigid composites have substantially improved their physical and chemical characteristics, but they are inflexible, which negatively influences their impact behavior. Rigid composites are generally made with thermosetting materials, which cannot be restructured as per our needs. As a result, to improve the impact characteristics, flexible matrices such as rubber or a combination of other materials are being explored. Natural rubber (N.R.), which is inherently flexible, might be a possible substitute for thermosetting materials. Natural rubber is a polymeric substance that possesses visco-elastic properties. Mahesh et al. 2019c successfully validated that N.R. could be effectively used as a core material to improve the impact response of jute-epoxy and jute-epoxy-rubber sandwich composite [3]. Natural and synthetic rubbers are used in a wide range of applications and are not limited to shock absorbers and impact-resistant panels [4–8]. The "flexible composites" are based upon elastomeric polymers of which the operating range of deformation is very high than those of the conventional thermoset or thermoplastic composites [9].

Various researchers have carried out studies on natural and synthetic fiber reinforced with epoxy and poly-lactic acid [10]. Mahesh et al. 2019a [11] studied the impact behavior of jute epoxy (J.E.) composite and experimented to understand the influence of various parameters such as the thickness of the composite plate, impactor velocity, and shape of the impactor. The J.E. composite laminate with thicknesses ranging from 6 to 10 mm, subjected to low-velocity impact (LVI) at 2 to 8 m/s velocities using conical shaped, hemispherical, and flat impactors that the thickness of the composite laminate might affect the energy absorption and impact resistance. Thicker composites showed a high impact resistance to the impact. Another study [12] looked at the LVI response of a flexible green composite made of sisal and N.R., as well as the influence of impactor profile. The same author also conducted a parametric FE investigation on the impact behavior of sisal and cenosphere-reinforced

N.R.-based hybrid composites [13]. They came to the conclusion that the contact area has a direct impact on the energy absorption potential and the level of damage to the composite laminate when it comes to LVI. Few investigations on jute and banana hybrids using N.R. fiber composites have been conducted, particularly for impact studies. Jute and banana fibers have better mechanical properties than other natural fibers and can be used to replace synthetic fibers. They have good specific mechanical characteristics, notably in terms of stiffness and their low density. Epoxy resin is used as the matrix material in almost all polymer matrix composites. Despite its high energy absorption capacity and excellent puncture and tear resistance, there are limited studies on natural rubber-based matrix material composites, especially for impact applications.

A thorough literature survey on topics such as LVI, impact studies, and FE modeling of impact was done, and it is found that not much work has been reported on the FE analysis of impact behavior of the flexible composites with jute and banana fiber hybrid and natural rubber subjected to LVI. There also have been reports on enhancing the bond between the fibers and the matrix by various methods but not specifically for impact studies. The authors tried to explore only naturally available materials for the green composites, thereby taking care not to harm nature.

2 Modeling

The simulation was created using ASTM D7136/7136 M-07 standards, which is a standard test procedure for determining a fiber-reinforced polymer matrix composite's damage resistance to a drop-weight impact event. Several factors influence the damage resistance properties generated by this test method, including geometry, layup, impact energy, impactor shape, and boundary conditions. As a result, results are rarely transferrable to different configurations and are typically limited to the geometric and physical characteristics studied [14]. We modeled the composite laminates to be deformable bodies with dimensions of 125 mm × 75 mm. The deformable or rigid characteristic of a body is defined at the start of the modeling. The impactors (conical, flat, and hemispherical) are modeled as rigid bodies with dimensions according to [15]. The impactor is placed just 1 mm above the laminate. The composite laminates are assigned an encastered boundary condition at the edges such that they are constrained with all degrees of freedom (DOF). Material properties of both the impactor and the laminate are defined in the "property" section of ABAQUS. Firstly, each material is created with the defining properties. The laminate has a 5-layer stack, as seen in Fig. 1c. Secondly, each layer of the stack has been specified as a material accordingly. The impactors travel only in one direction, which is in the normal direction of the laminate plane. All composite laminates are modeled with the thickness of fibers as 1 mm, and Natural rubber as 2 mm. So, the volume fraction of the fibers (V_f) in the proposed composite is 43%, and the volume fraction of Natural rubber (V_m) is 57%. The tensile strength and tensile modulus are directly dependent on the fiber volume fraction. Thus, it is kept constant for each composite so as to compare the composites effectively. Necessary constraints are defined for the laminate and impactors. Step size is taken as 10–20 ms. Step size is intentionally kept small to reduce the simulation time. The front surface of the laminate and the outer surface of the impactors are defined by contact interaction properties. A contact interaction property is something that defines tangential behavior, i.e., friction, and normal behavior, i.e., hard or soft contact. A friction-tangential behavior with a friction coefficient of 0.3 and a hard contact normal behavior is defined for the fiber-matrix interaction. Surface-to-surface contact is considered here that describes contact between two deformable bodies or between a deformable surface and a rigid surface. All the rotational and translational DOFs have been constrained except for directions normal to the plane of the laminate for the impactor. While modeling, a reference point (RP) is set on the impactor, which will be constrained in every direction except in the direction to assign velocity. A point mass of 1 kg is also given to the RP. After all of the boundary conditions have been established, the impactor's reference point is given a preset field of velocity.

The medium-mesh composite plate has SC8R elements, which illustrates an 8-node hexahedron, general-purpose, finite membrane strain conventional shell. Meshing is done independently on the plate and impactor and is defined as is while modeling. The impactor also has a medium-mesh with R3D4 elements, which illustrates a 4-node 3D bilinear rigid quadrilateral. A medium-size mesh is used for both the impactor and the laminate as it reduces the simulation time. The (a) assembly and the boundary conditions (BCs), (b) the meshing of the laminate, and (c) a common ply-stack plot of the proposed composites are shown in Fig. 1a–c, respectively. The material properties used in the FE analysis are taken from the [8, 16, 17] and are

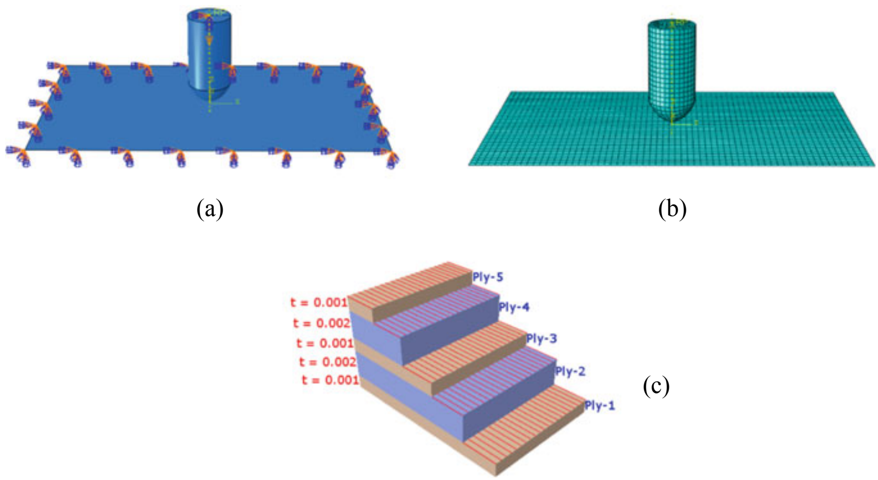

Fig. 1 **a** Assembly with BCs, **b** Mesh of the assembly, **c** A common ply-stack of the proposed composites

Table 1 Material properties [8, 16, 17]

Properties	Banana	Jute	Natural rubber
Density (kg/m^3)	1300	1400–1500	987.18
Youngs modulus (GPa)	28–29	10–30	4.5 × 10–4
Elongation at break (%)	2–5	1.8	11.1
Tensile strength (MPa)	200–800	300–700	0.05

Table 2 Nomenclature of the proposed composites

Proposed composites	Nomenclature
Jute + N.R	JRJRJ
Banana + N.R	BRBRB
Jute/banana hybrid _1	JRBRJ
Jute/banana hybrid _2	BRJRB

tabulated in Table 1. The terminologies of the proposed composites are provided in Table 2.

3 Analysis Results

The results of the energy absorbed by the JRJRJ, BRBRB, JRBRJ, and BRJRB composites at $V = 5$, 10, and 15 m/s when impacted by the three impactors (conical, hemispherical, and flat) are shown graphically in Figs. 2, 3, and 4, respectively.

3.1 Effect of Hybridization

The JRJRJ laminate absorbed the maximum energy for all velocities, as we can see from the peaks of Figs. 2, 3, and 4, while the BRBRB laminate absorbed the least. The hybrid laminates absorption capacity was that between the pure fiber counterpart laminates. The JRJRJ composite absorbed on an average 12% more than the hybrid laminates and 20% more than the BRBRB laminate. At the same time, the hybrid laminates absorbed on an average 11% more than the BRBRB laminate. This suggests that pure jute laminate is superior in absorbing energy to pure banana laminate and hybrid laminates. These results indicate that the hybridization of jute and banana fiber decreases the absorption capacity while increasing the stiffness. This might be because jute fibers have better mechanical properties than banana fibers.

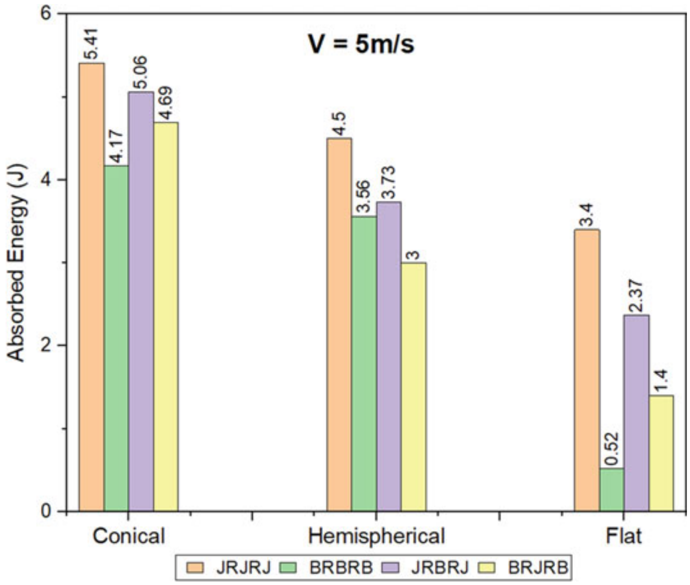

Fig. 2 Absorbed energy at $V = 5$ m/s

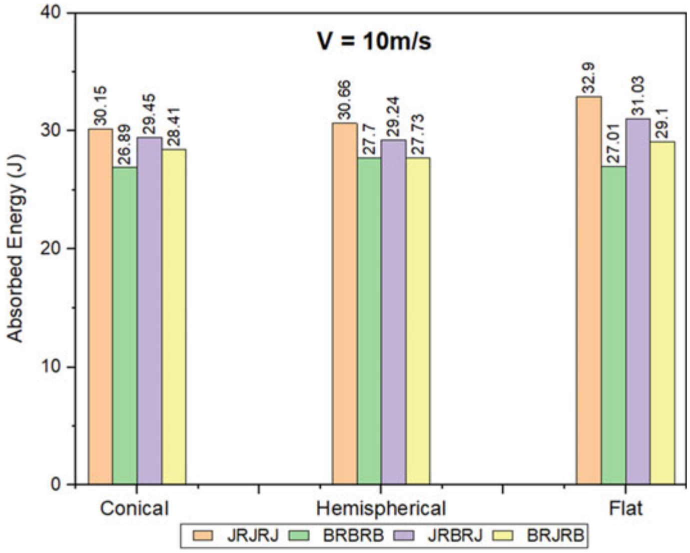

Fig. 3 Absorbed energy at $V = 10$ m/s

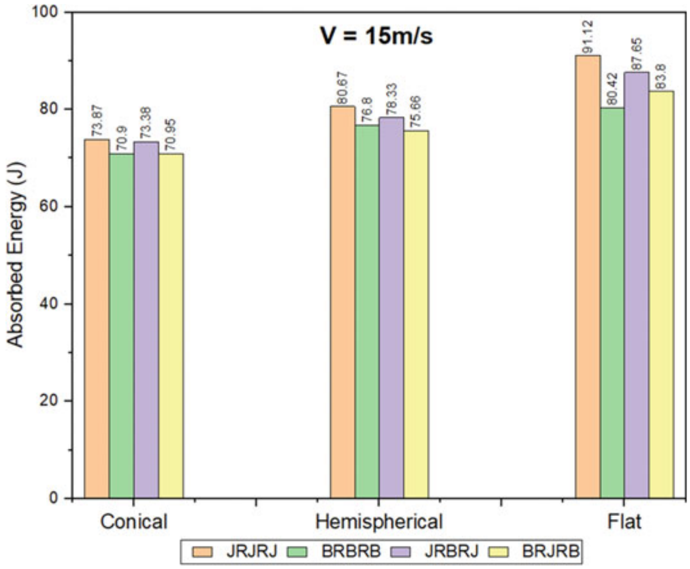

Fig. 4 Absorbed energy at $V = 15$ m/s

3.2 Effect of Impactor Shape

We found that the energy absorption capacity of the proposed composites is affected by the impactor shape and is shown graphically in Figs. 2, 3, and 4. The energy absorbed is maximum for conical impactor for $V = 5$ m/s (Fig. 2), but the energy absorbed is maximum for flat impactor at increased velocities, i.e., $V = 10$, 15 m/s (Figs. 3 and 4). This suggests that the impactor's energy absorption capacity and the level of damage to the laminate may be affected by the impactor's contact area with the laminate [13]. At 5 m/s, the conical impactor absorbed 1.2–8 times the energy absorbed by flat and hemispherical impactors. At 10 m/s, the flat impactor absorbed 1.1–1.25 times the energy absorbed by conical and hemispherical impactors.

3.3 Damage Studies

Figures 5, 6, and 7 present the damage induced by the three different impactors (conical, hemispherical, and flat) in some of the proposed laminates. Three different impactor velocities, i.e., 5, 10, and 15 m/s with a mass of 1 kg, are assumed for the damage study. The results reveal that the penetration by the conical impactor is much more than H.S. and flat impactors (Fig. 5). This could be because of the less area at the point of contact of the conical impactor. Flat impactor has the largest area of impact when compared to H.S. and conical impactors, which can be clearly seen in Fig. 6.

For the conical impactor, the damaged area is the least owing to local penetration. It can be summed up as follows: the more the contact area between impactor and laminate, the more the damage and vice versa.

As the velocity increases, the damaged area also increases. But there must be a limit to which the laminate can deform and will start to break apart as a result of high velocity. This can be a future scope of this study.

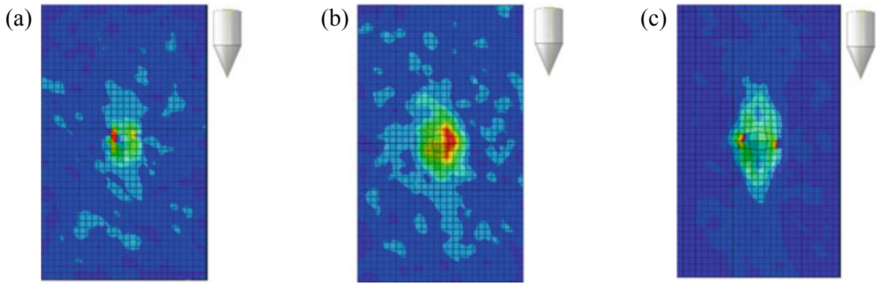

Fig. 5 Damage in laminate by conical impactor for velocities **a** 5 m/s **b** 10 m/s **c** 15 m/s

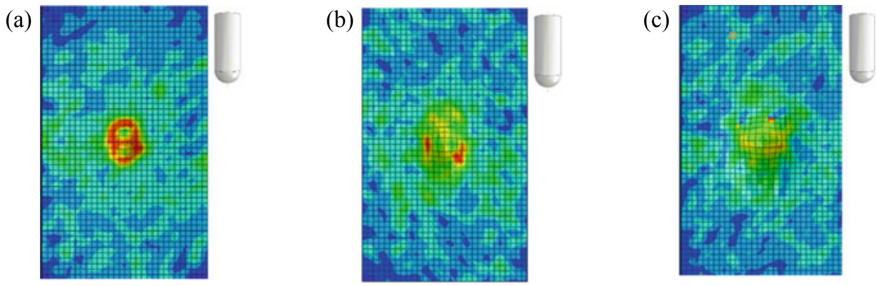

Fig. 6 Damage in laminate by hemispherical impactor for velocities **a** 5 m/s **b** 10 m/s **c** 15 m/s

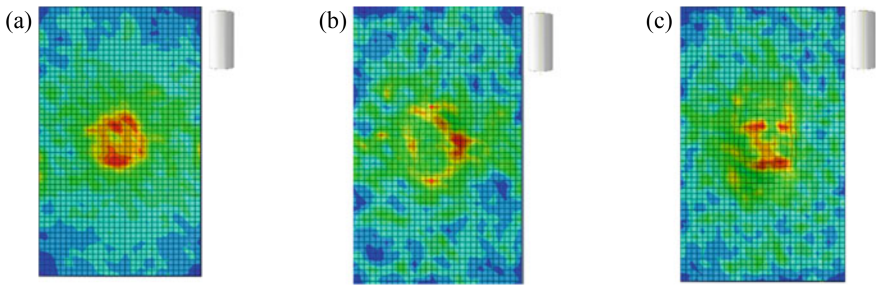

Fig. 7 Damage in laminate by flat impactor for velocities **a** 5 m/s **b** 10 m/s **c** 15 m/s

3.4 Coefficient of Restitution (CoR)

The coefficient of restitution is described as the ratio of the residual velocity of the object after the impact and the initial velocity of the object [18]. CoR can be expressed as

$$\text{CoR} = Vr/Vi \tag{1}$$

where Vr and Vi are the residual and initial velocities, respectively.

The values of the coefficient of restitution for velocities 5, 10, and 15 m/s are shown graphically in Fig. 8.

It is found that CoR is reduced when the impact velocity increases. The trend for all impactors in Fig. 8 shows just this. This indicates that the composite goes under plastic deformation and absorbs more energy. Also, for all composites and for all velocities, the conical impactor has the least CoR, which suggests that the energy absorbed is high for the conical impactor, around 25% more than the HS impactor and 40% more than the flat impactor. For the hemispherical impactor, the CoR follows Hybrid laminate > Pure fiber laminate, 30% more, which indicates that the hybrid composites show more resistance to the impactor with minor damage. Whereas, for conical and flat impactors, the CoR is greatest for BRBRB laminate.

The energy absorbed can be found by knowing the impactors' initial velocity, residual velocity, and mass. Energy absorbed can then be expressed as

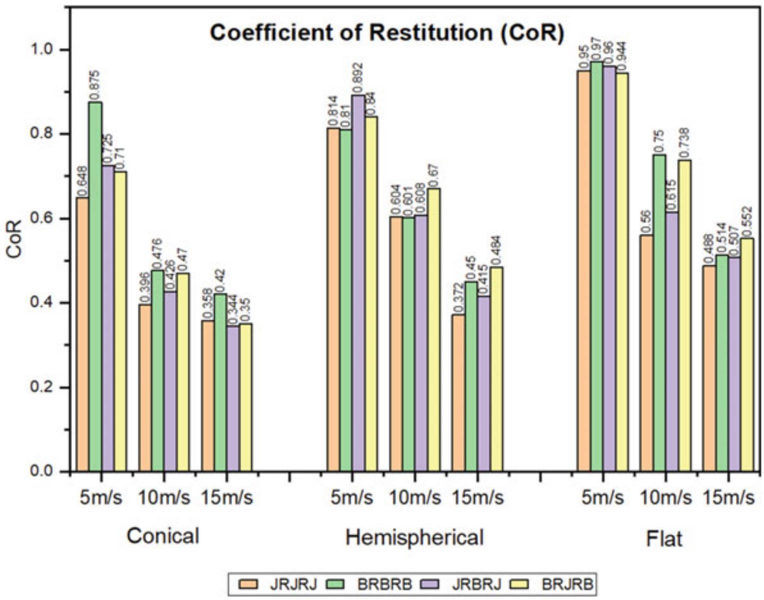

Fig. 8 Coefficient of restitution (CoR) for all impactors

$$\text{Energy Absorbed} = 0.5 * m * \left(Vr^2 - Vi^2\right) \quad (2)$$

where Vr and Vi are the residual and initial velocities, respectively, and m is the mass of the impactor

4 Conclusions

This study used FE analysis to investigate the low-velocity impact response of jute, banana, and their hybrid composite with natural rubber as a matrix, using three different impactors: flat, conical, and hemispherical.

When the laminates are impacted at higher velocities (10, 15 m/s) by a flat impactor, it shows 1.1–1.25 times energy absorption. Thus, the energy absorption capability depends on the area of contact. The JRJRJ composite absorbed, on average, 12% more than the hybrid laminates and 20% more than the BRBRB laminate. The hybrid laminates absorbed an average of 11% more than the BRBRB laminate, which shows that the hybridization of jute and banana fiber decreases the absorption capacity while increasing the stiffness. The CoR of the conical impactor is 25% more than the HS impactor and 40% more than the flat impactor, which suggests that the energy absorbed is more for the conical impactor. The CoR is up to 30% more for the hybrid composites than the pure fiber composites, suggesting that hybrid composites resist more damage.

As a result, the contact area between the impactor and the composite laminate is shown to have a substantial influence on the energy absorption capacity and the damage extent for low-velocity impacts. And the hybridization of the jute and banana fibers makes the composite stiffer and can be used for sacrificial structural applications. At the same time, there are other ways to make the composite stiffer such as using a stronger fiber material and making sandwich panels, which can be explored ahead.

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