Research Article

Influence of Incident Energy on Sisal/Epoxy Composite Subjected to Low Velocity Impact and Damage Characterization Using Ultrasonic C-Scan

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Abstract
Impact resistance is an inevitable characteristic of the composites employed in the high performance structural applications. Due to the growing interest in the use of sisal fibre as reinforcement in the polymer composites, it is required to determine the response of sisal/epoxy composites to low velocity impact at high incident energies where perforation can occur and assess the damage characteristics using a non-destructive technique. In this work, sisal/epoxy composites were subjected to drop weight impact in the velocity range of 3 m/s to 5 m/s at different energy levels between 20 J to 50 J according to the ASTM D7136. Based on the results observed, it is concluded that both the peak load and absorbed energy increased with the increasing incident energy level up to 40 J. At 50 J, perforation occurred and the maximum deformation was approximately 22 mm for the sisal/epoxy composite. Damage characteristics and failure behaviour of the composite at different incident energies was examined from the visual images of the front and back face of the composite. The quantitative assessment of crack propagation in the sisal/epoxy composite and the damage area were determined from the ultrasonic C-scan images of the sample post impact at various energy levels.

Keywords: Sisal, Drop weight impact, Impact damage, Ultrasonic C-scan, Damage area

1 Introduction

Natural fibres extracted from the renewable resources such as plants and trees can be used as reinforcement in the composite material. High material cost, growing concern on the environmental pollution due to the disposal of synthetic fibre-based composites and their limited recycling abilities have turned the focus towards the sustainable, and environmentally friendly natural fibres [1], [2]. Features of the natural fibres such as low density, ease of manufacturing, low cost, and abundant availability to meet the demand suits the application requirement for the lightweight structures [3].

Resistance to sudden impact is critical for materials used in the high-performance applications like automotive and aerospace structures. Impact damage in the aircraft materials can be classified into barely visible impact damage (BVID) and visible damage. Instances such as tools drop from certain height of the aircraft by technician during the maintenance operation [3], small hailstone and tiny debris from the runway can cause the BVID while the collision of birds and larger foreign objects on the nose section, wing leading edge, etc. can cause visible damage. The damages caused due to impact are hairline cracks in case of the BVID while it is matrix cracks, fibre breakage, and delamination in case of the visible damage. These damages can affect the structural integrity of the composite. Thus, it is mandatory to determine the response of the natural fibre reinforced composites and their failure behaviour under the low velocity impact.

Drop weight impact testing is the most commonly used method to predict the low velocity impact properties of the composite intended for application in the aircraft structures. A known weight is allowed to drop from certain height on the composite specimen clamped and supported in a horizontal platform. Load-time history from the data acquisition system provides the impact damage characteristics such as perforation while the parameters such as peak load, absorbed energy and maximum deformation provides the quantitative data for comparison.

Performance of the natural fibre reinforced composite under low velocity impact has been examined by various researchers with fibres such as pineapple leaf fibre (PALF) [4], flax [5], hemp [6]–[8], coir [9], and jute [10], [11]. In the aforementioned studies, low velocity impact behaviour was studied by adding the fillers and as a function of the fibre architecture, thickness, impact energy by varying the impactor drop height, impactor velocity, impactor mass and geometry, fibre loading, hybridization with the synthetic fibre, etc. Among the various natural fibres, sisal fibre extracted from the sisal leaves has been chosen as reinforcement for this study. This is because of their higher cellulose content (60–65%), a critical parameter for impact resistance, low cost, short cultivation span, and abundant availability [12].

Most of the studies existing in the literature have reported impact properties of the sisal/epoxy composite determined from the Izod and Charpy impact tests. In a recent study, Mahesh et al investigated the energy absorption characteristics of the sisal/epoxy composite by varying the thickness of the laminate, velocities between 1 m/s to 3 m/s, and incident energy between 0.5 J to 4.5 J. The composites specimens endured delamination, fibre breakage and matrix cracking. However, the specimens were found to be only partially penetrated in the selected velocity range, and incident energies up to 4.5 J [13]. Impact damage and failure behaviour of the sisal fibre reinforced composite based on the drop weight impact test with respect to higher impact energies was hardly investigated. In another study, sisal/epoxy laminate made up of unidirectional plies, cross-plies, quasi-isotropic plies, and randomly oriented mat type reinforcement were subjected to the low velocity impact. The difference in failure characteristic post impact due to the use of various fibre architectures was examined at energy levels of 5, 10, and 15 J. Cross-ply laminate had superior energy absorption characteristic among the investigated composites and the performance was comparatively better than the other natural fibres such as flax, jute, and hemp-based composites found in the literature [14]. In the above studies, the incident energy at which perforation occurs has not been examined. Hence, in this study, sisal/epoxy composite was subjected to drop weight impact test at high incident energies between 20 J to 50 J by varying the impactor height and the observed results were discussed.

2 Experimental Procedure

2.1 *Materials*

Plain weave sisal fabric was brought from Guntur, Andhra Pradesh, India. The epoxy resin (Araldite LY556) and Hardener (ARADUR HY951) were purchased from the Go Green Products Pvt Ltd., Chennai, India. Properties and specifications of the sisal fibre and epoxy resin is given in Table 1.

Table 1: Material specification of the sisal fabric and epoxy resin

Specification	Sisal Fabric	Epoxy Resin
Density (g/cc)	1.4	1.15–1.20
Tensile strength (MPa)	500–700	3.77
Young's modulus (GPa)	6–7	-

2.2 *Laminate preparation*

Fibre loading of 30 wt. % which equates to 12 layers of sisal fabric was used [Figure 1(a)]. The composite was fabricated by the compression moulding technique. Initially, the resin and hardener were taken in the plastic container at 10 : 1 ratio and mixed thoroughly for few minutes. Then, the prepared resin mixture was spread over the frame of size 300 × 300 × 5 mm^3. The first layer of sisal was placed over the epoxy-hardener layer and subsequent layers were placed one above the other until 12 layers of sisal were placed alternately with the epoxy-hardener being applied on each layer. Air bubbles were removed using a roller to make sure no voids are formed in this process. The setup

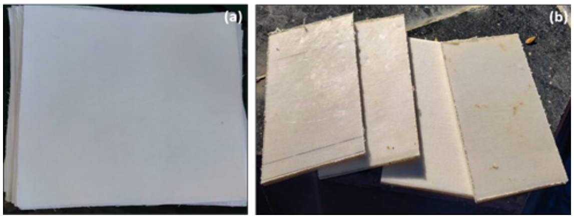

Figure 1: (a) Sisal fabric and (b) Sisal/epoxy laminate.

was then transferred to the hot press machine. In the machine, the pressure was set to 5 bar at a temperature of 35°C for 3 h. After the laminates are completely cured it was removed from the frame carefully and cut to 150 × 100 mm for drop weight impact test according to ASTM D7136 standard [Figure 1(b)].

2.3 *Drop weight impact testing*

The drop weight impact test was carried out in CEAST Fractovis plus machine at MIT campus, Chennai, India according to the ASTM D7136 standards. In this test, a hemispherical mass of 3 kg was allowed to strike from a known height on the composite specimen clamped in a horizontal platform. A specimen of size 150 × 100 × 5 mm were used for each incident energy such as 20, 30, 40, and 50 J respectively. Incident energy was varied by changing the heights of the impactor. Immediately after the impact, force, velocity, energy, and deformation with respect to time were recorded by the data acquisition system. After the first impact on the specimen, a catcher mechanism was used to prevent a second strike.

2.4 *Defect characterization and damage area assessment*

The defect characteristics and damaged area of the impacted specimens were assessed from the images obtained through the immersion type ultrasonic C-scan [Figure 2(a)] using “Through the transmission mode” as shown in Figure 2(b). The transducer frequency was set to 2.25 MHz. The scan resolution was maintained to 0.25 mm in the index axis and the scan axis while the scan length was 115 and 155 mm in the index axis and the scan axis respectively. Damage area was calculated using the digital image processing.

3 Results and Discussion

Table 2 presents the various parameters measured from the drop weight impact test for sisal/epoxy composite specimens at different incident energy levels.

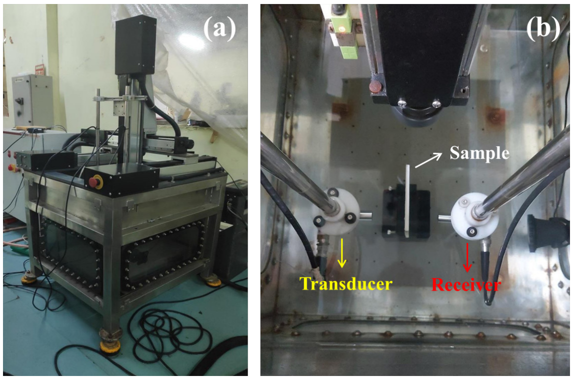

Figure 2: Ultrasonic C-scan (a) Immersion technique and (b) Through the transmission setup.

Table 2: Parameters measured from the impact test

Impact Energy (J)	Peak Load (N)	Peak Deformation at Load (mm)	Energy Absorbed (J)	Peak velocity (m/s)
20	2863.96	9.25	11.68	2.83
30	2930.11	13.34	18.41	3.48
40	2933.78	16.89	25.86	4.01
50	2872.53	22.40	46.27	4.49

3.1 *Velocity-time plot*

In general, velocity-time plot gives information on the free fall, stop, rebound and perforation conditions [15], [16]. Figure 3(a), and (b) presents the velocity-time plot and peak velocity attained just before strike at each incident energy level.

From Figure 3(a), it can be observed that velocity decreased with time for all incident energies and reached zero on impact with the composite specimen. Since the catcher mechanism does not allow rebound or upward travel of the impactor, negative velocity can’t be seen in the graph. As the impactor travels downward, velocity is represented by positive value. On impact, the velocity becomes zero. If the rebound occurs with or without penetration into the composite, velocity becomes negative and negative value indicates upward motion of the impactor [16]. It can be noticed from Figure 3(b) that peak velocity increased with the incident energy which corresponds to the change in height of the impactor mass. A maximum velocity

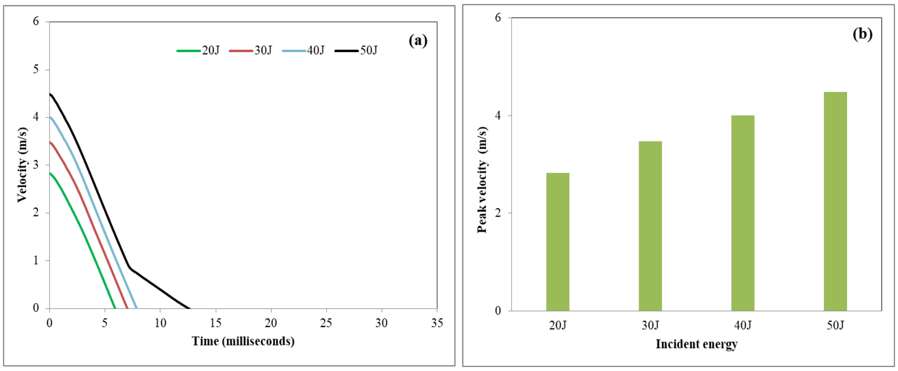

Figure 3: Sisal/epoxy composite at different incident energies (a) Velocity vs Time and (b) Peak velocity attained.

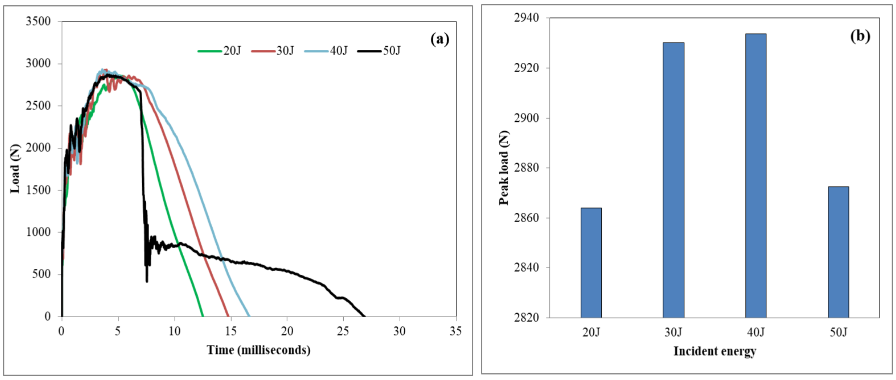

Figure 4: Sisal/epoxy composite at different incident energies (a) Load vs Time and (b) Peak load.

of 4.49 m/s was obtained at 50 J energy level. At 50 J energy level, the slope of the velocity-time plot changes after approximately 6 ms. This change was mainly due to the perforation of the impactor into the sample at that energy level [Figure 6(e) and (f)] which didn't occur in the other energy levels employed.

3.2 *Load-time plot*

Figure 4(a) presents the overall load-time history of the sisal/epoxy composite at different incident energy levels. It can be seen that at initial stage below 3 ms, load almost increased linearly as shown in Figure 4(b). Sudden increase in the load at the beginning occurs due to the contact of the impactor with the composite [15]. After the sudden increase, the load was found to drop at different intervals before reaching the peak value between 5 to 7 ms. According to Ahmed *et al.* [17], the initial drop in load is a sign of damage initiation in the composite laminate and the first inflection point is often referred to as incipient damage load. The damage onset occurs in the form of matrix crack and delamination within the laminate while the subsequent drops in load is associated with the fibre breakage, propagation of matrix crack, and extensive delamination [18].

In this study, incipient load occurred between 500–1000 N at all the incident energy levels. The incipient damage then propagates with the further increase in incipient load until a peak load which is the maximum load-carrying capability of the laminate. It can be observed from Figure 4(b) that peak load increases with the increase in incident energy level from 20 J to 40 J. A maximum peak load value of 2934 N was observed for 40J. However, at 50 J, a slight decrease in the peak load was seen. This was due to the perforation of the composite. On reaching the peak load, the force then decreases with time. This is particularly due to the reduction in stiffness of the composite caused by the impact damage at maximum load [4].

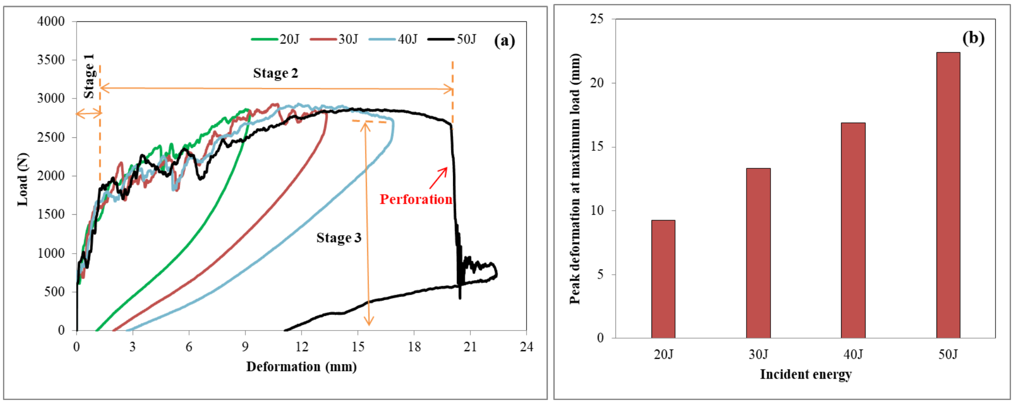

Figure 5: Sisal/epoxy composite at different incident energies (a) Load vs Deformation and (b) Peak velocity attained.

In general, drop weight impact happens in a shorter timescale involving ms. Time scale is generally influenced by the thickness, fibre architecture and areal weight of the fibres [10]. In this study, it was found that incident energy level could also influence the time duration of the impact event. Total time taken from the beginning to the end of the impact event was 12 to 26 ms at the incident energy level between 20 to 50 J. It can be noticed that timescale at 50 J for the perforated composite specimen was unusually longer than the non-perforated specimens showing the severity of the impact on the sisal/epoxy composite.

3.3 *Load-deformation graph*

Load-deformation plot from the drop weight impact test is shown in Figure 5(a) and (b). It is evident that impact failure due to impactor mass occurred in 3 stages: Stage 1 is the damage initiation zone, stage 2 is the damage propagation zone and stage 3 is the force unloading part in case of the non-perforation or decline in the load without strain recovery due to the perforation [19], [20].

In stage 1, load increases sharply due to the impactor strike on the composite leading to onset of matrix crack and delamination in the laminate. It is the then followed by maximum deformation in the stage 2 where the fibre breakage occurs while the matrix cracks as well as delamination continue to grow until the impactor stops. The influence of incident energy level was visible in the stage 3. For energy level between 20 J to 40 J, force unloading part was observed. The force unloading part which forms a closed loop implies recovery of elastic energy that helps the impactor to rebound without perforation [21]. At 50 J energy level; the impactor was found to completely penetrate the composite specimen and the maximum deformation was approximately 22 m as shown in Figure 5(b). The damage due to complete penetration at 50 J is visible from the front and back face of the impacted area as shown in Figure 6(g) and (h).

Figure 6(a) and (b) shows the front and back face of the specimen subjected to 20 J impact. It is clear that damage initiated on the backside in the form of matrix crack in the warp and weft direction. The front face showed only a sign of indentation. According to Kumar *et al.* [22], at low incident energy level, the failure initiates on the back face since it experiences tension. As the impact energy was raised to 30 J, matrix crack occurred on both the faces of the specimen [Figure 6(c) and (d)]. Maximum deformation at peak load was 13 mm compared to 9 mm at 20 J indicating substantially higher damage at 30 J as shown in Figure 5(b). At 40 J, maximum deformation increased to nearly 17 mm and the matrix crack in the warp direction was larger than the crack in the weft direction.

3.4 *Impact energy-time plot*

Figure 7(a) and (b) illustrates the energy-time plot and energy absorbed by the composite specimens at different incident energy levels. Energy absorbed by the composite is computed from the area under the load-deformation plot [5].

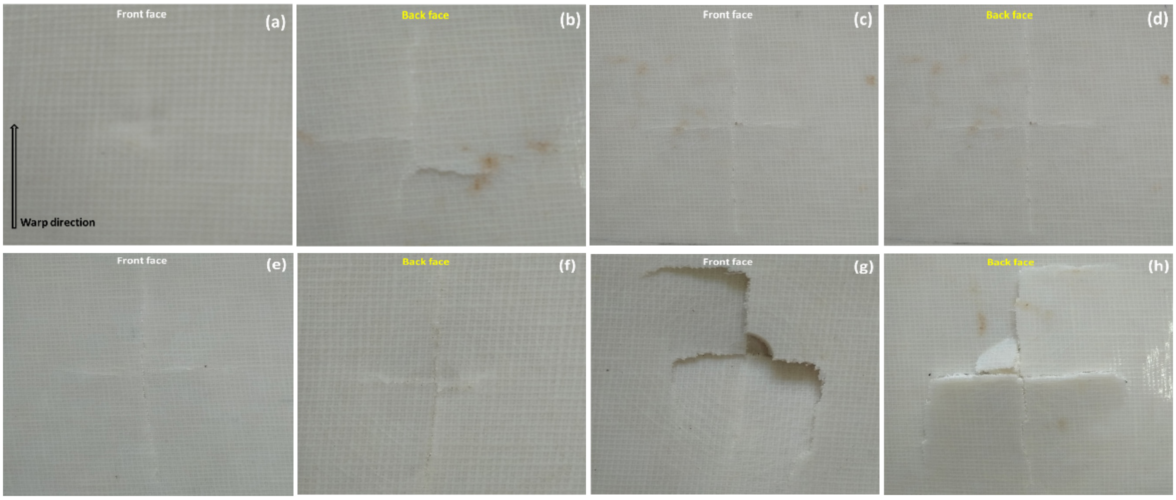

Figure 6: Composite specimens subjected to impact at different incident energies (a) 20 J – Front face (b) 20 J – Back face (c) 30 J – Front face (d) 30 J – Back face (e) 40 J – Front face (f) 40 J – Back face (g) 50 J – Front face and (h) 50 J – Back face.

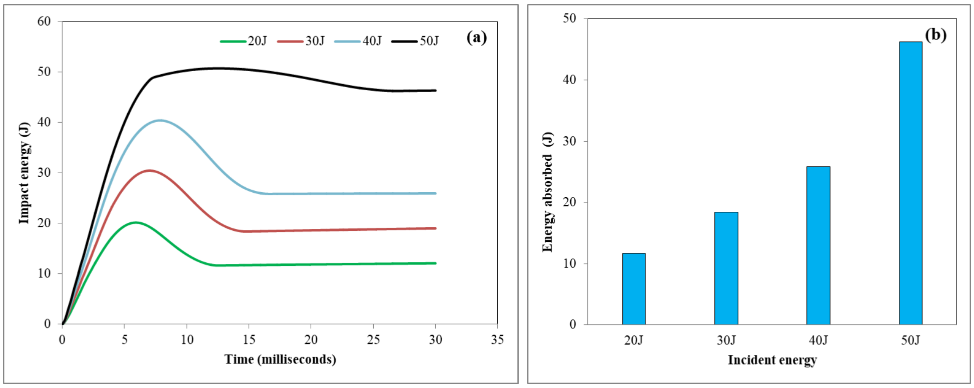

Figure 7: Sisal/epoxy composite at different incident energies (a) Impact energy vs Time and (b) Energy absorbed.

3.5 *Impact failure characterization using ultrasonic c-scan and damage area assessment*

Figure 8 shows the ultrasonic C-scan image and Amplitude vs Depth plot from the ultrasonic A-scan. The flaws or discontinuity or damages in a composite material can be assessed from the strength of the amplitude signal. In a typical A-scan image the defect echo from the damaged region has lower amplitude than the area that remains intact [23]. The amplitude signal obtained in the damaged area is weaker than the amplitude signal obtained from the area without damage.

Figure 9(a)–(d) presents the ultrasonic C-scan images of the sisal/epoxy composite at different impact energy levels. It can be noticed from the images that as the impact energy is increased the crack propagation in the scan-axis as well as index axis increased (Table 3). Specifically, the maximum crack length was higher in magnitude in the scan-axis than the index axis at each impact energy level. Similar extension in crack length with increase of impact energy was reported in a recent study on the jute/polylactic acid composite subjected to the low velocity impact [24]. However, sisal/epoxy composite exhibited complete penetration at 50 J with multiple cracks as shown in [Figure 9 (d)] compared to the jute/polylactic acid composite which underwent penetration at less than 20 J.

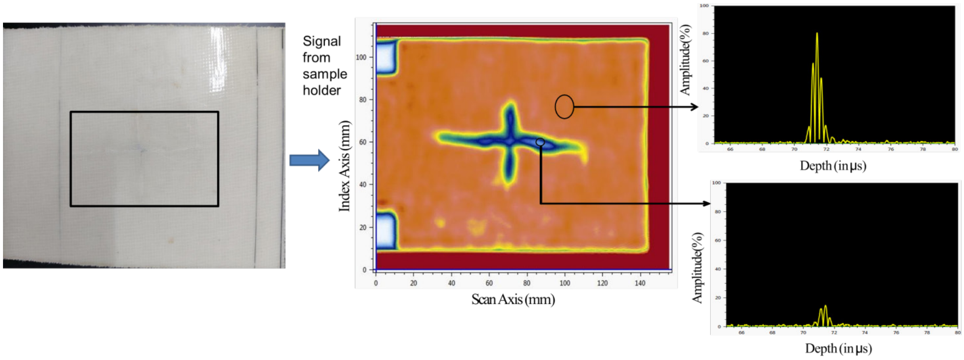

Figure 8: Defect characterization (a) Defective area, (b) Ultrasonic C-scan image and (c) A-scan signal from the unimpacted and impacted area.

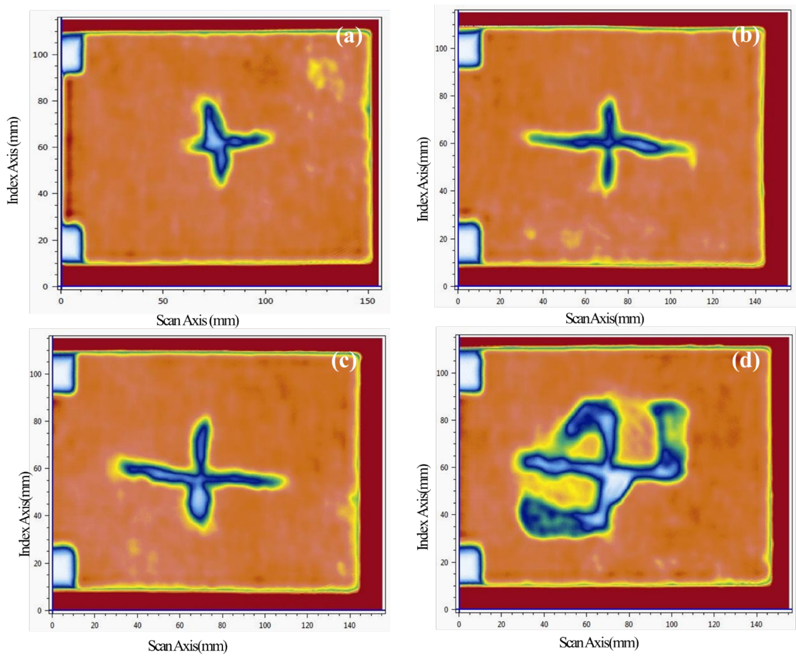

Figure 9: Ultrasonic C-scan images (a) 20 J, (b) 30 J, (c) 40 J and (d) 50 J.

The damaged area computed from the ultrasonic C-scan images [Figure 9(a)–(d)] is displayed in Table 3. The damage area was initially smaller with a magnitude of 607 mm^2 at 20 J followed by linear increase until 50 J where the maximum damage of 3733 mm^2 was observed. Both the increase in crack length along the scan-axis and index axis as well damage progression shows the severity of the impact on the sisal/epoxy composite at higher impact energy levels.

Table 3: Crack length and damaged area computed from C-scan images

Impact Energy (J)	Maximum Crack Length in Scan Axis (mm)	Maximum Crack Length in Index Axis (mm)	Damaged Area (mm^2)
20	47	43	607.5
30	85	43	854.5
40	85	50	1168.5
50	82	64	3733

4 Conclusions

An experimental investigation on the low velocity impact properties of the sisal reinforced composite was carried out at different incident energy levels between 20 J to 50 J. Following are the observations from the study:

- Significant increase in the energy absorption and peak load was observed with the increase in incident energy.
- At 50 J, the composite specimen was found to be completely penetrated and peak load dropped slightly compared to 40 J. This clearly shows that load-bearing capability of the sisal/epoxy composite decreases beyond the 40 J energy level.
- Typical impact failures such as the indentation, matrix crack, and fibre breakage were observed from the visual images of the impacted specimens.
- Failure occurred in the form of matrix crack at the bottom face of the composite at 20 J and indentation in the top surface.
- As the incident energy was increased, matrix cracks initiated on both the faces of the composite. Crack propagation was higher in the warp direction than the cracks in the weft direction.
- In this study, impact event occurred in a infinitesimally smaller time scale between 12 to 26 ms for energy levels between 20 J to 50 J. It is clear from this trend that at the higher incident energy level, the contact time of the impactor increases. Thus, initiated crack propagates further leading to greater deformation.
- The increase in crack propagation and damage area with respect to the increasing impact energy level was also evident from ultrasonic C-scan images of the specimens subjected to low velocity impact.

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References

[1] K. Lau, P. Hung, M.-H. Zhu, and D. Hui, "Properties of natural fibre composites for structural engineering applications," *Composites Part B: Engineering*, vol. 136, pp. 222–233, 2018.

[2] S. M. Rangappa, S. Siengchin, and H. N. Dhakal "Green-composites: Ecofriendly and sustainability," *Applied Science and Engineering Progress*, vol 13, no. 3, pp. 183–184, 2020, doi: 10.14416/j.asep.2020.06.001.

[3] M. M. Kabir, H. Wang, K. T. Lau, and F. Cardona, "Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview," *Composites Part B: Engineering*, vol. 43, no. 7, pp. 2883–2892, 2012.

[4] S. H. S. M. Fadzullah, S. N. N. Ramli, Z. Mustafa, A. S. Razali, D. Sivakumar, and I. Ismail, "Low velocity impact behaviour of pineapple leaf fibre reinforced polylactic acid biocomposites," *The International Journal of Advanced Manufacturing Technology*, vol. 14, no. 1, pp. 1–12, 2020.

[5] T. Q. T. Hoang and F. Touchard, "Non-woven flax fibre reinforced polypropylene: Static and low velocity impact behaviour," *Polymers and Polymer Composites*, vol. 21, no. 5, pp. 287–298, 2013.

[6] C. Scarponi, F. Sarasini, J. Tirillo, L. Lampani, T. Valente, and P. Gaudenzi, "Low-velocity impact behaviour of hemp fibre reinforced bio-based epoxy laminates," *Composites Part B: Engineering*, vol. 91, pp. 162–168, 2016.

[7] H. N. Dhakal, Z. Y. Zhang, M. O. W. Richardson, and O. A. Z. Errajhi, "The low velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites," *Composite Structures*, vol. 81, no. 4, pp. 559–567, 2007.

[8] H. N. Dhakal, Z. Y. Zhang, N. Bennett, and P. N. B. Reis, "Low-velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites: Influence of impactor geometry and impact velocity," *Composite Structures*, vol. 94, no. 9, pp. 2756–2763, 2012.

[9] A. R. A. Hani, M. S. Hashim, T. Y. Lim, M. Mariatti, and R. Ahmad, "Impact behaviour of woven coir-epoxy composite: Effects of woven density and woven fabric treatment," *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 230, no. 1, pp. 240–251, 2016.

[10] H. N. Dhakal, M. Skrifvars, K. Adekunle, and Z. Y. Zhang, "Falling weight impact response of jute/methacrylated soybean oil bio-composites

under low velocity impact loading," *Composites Science and Technology*, vol. 92, pp. 134–141, 2014.
[11] H. N. Dhakal, V. Arumugam, A. Aswinraj, C. Santulli, Z. Y. Zhang, and A. Lopez-Arraiza, "Influence of temperature and impact velocity on the impact response of jute/UP composites," *Polymer Testing*, vol. 35, pp. 10–19, 2014.
[12] K. Senthilkumar, N. Saba, N. Rajini, M. Chandrasekar, M. Jawaid, S. Siengchin, and O. Y. Alotmane, "Mechanical properties evaluation of sisal fibre reinforced polymer composites: A review," *Construction and Building Materials*, vol. 174, 2018, doi: 10.1016/j.conbuildmat.2018.04.143.
[13] V. Mahesh, A. Nilabh, S. Joladarashi, and S. M. Kulkarni, "Analysis of impact behaviour of sisal-epoxy composites under low velocity regime," *Revue des Composites et des Matériaux Avancés*, vol. 31, pp. 57–63, 2021.
[14] C. Militello, F. Bongiorno, G. Epasto, and B. Zuccarello, "Low-velocity impact behaviour of green epoxy biocomposite laminates reinforced by sisal fibers," *Composite Structures*, vol. 253, p. 112744, 2020.
[15] K. I. Ismail, M. T. H. Sultan, A. U. M. Shah, M. Jawaid, and S. N. A. Safri, "Low velocity impact and compression after impact properties of hybrid bio-composites modified with multi-walled carbon nanotubes," *Composites Part B: Engineering*, vol. 163, pp. 455–463, 2019.
[16] G. Belingardi and R. Vadori, "Low velocity impact tests of laminate glass-fiber-epoxy matrix composite material plates," *International Journal of Impact Engineering*, vol. 27, no. 2, pp. 213–229, 2002.
[17] K. S. Ahmed, S. Vijayarangan, and A. Kumar, "Low velocity impact damage characterization of woven jute—glass fabric reinforced isothalic polyester hybrid composites," *Journal of Reinforced Plastics and Composites*, vol. 26, no. 10, pp. 959–976, 2007.
[18] F. Sarasini, J. Tirillò, S. D'Altilia, T. Valente, C. Santulli, F. Touchard, L. Chocinski-Arnault, D. Mellier, L. Lampani, and P. Gaudenzi, "Damage tolerance of carbon/flax hybrid composites subjected to low velocity impact," *Composites Part B: Engineering*, vol. 91, pp. 144–153, 2016.
[19] I. Fahmi, M. S. A. Majid, M. Afendi, E. A. Helmi, and J. A. M. Haameem, "Low-velocity impact responses of Napier fibre/polyester composites," *International Journal of Automotive and Mechanical Engineering*, vol. 13, p. 3226, 2016.
[20] M. Ravandi, W. S. Teo, L. Q. N. Tran, M. S. Yong, and T. E. Tay, "Low velocity impact performance of stitched flax/epoxy composite laminates," *Composites Part B: Engineering*, vol. 117, pp. 89–100, 2017.
[21] V. Fiore, T. Scalici, F. Sarasini, J. Tirilló, and L. Calabrese, "Salt-fog spray aging of jute-basalt reinforced hybrid structures: Flexural and low velocity impact response," *Composites Part B: Engineering*, vol. 116, pp. 99–112, 2017.
[22] C. S. Kumar, V. Arumugam, H. N. Dhakal, and R. John, "Effect of temperature and hybridisation on the low velocity impact behavior of hemp-basalt/epoxy composites," *Composite Structures*, vol. 125, pp. 407–416, 2015.
[23] T. Segreto, R. Teti, and V. Lopresto, "Non-destructive testing of low-velocity impacted composite material laminates through ultrasonic inspection methods," in *Characterizations of Some Composite Materials*. London: IntechOpen, 2018, pp. 45–66.
[24] I. Papa, V. Lopresto, G. Simeoli, A. Langella, and P. Russo, "Ultrasonic damage investigation on woven jute/poly (lactic acid) composites subjected to low velocity impact," *Composites Part B: Engineering*, vol. 115, pp. 282–288, 2017, doi: 10.1016/j.compositesb.2016.09.076.