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RESEARCH ARTICLE

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Impact performance of egg-box core sandwich panels made from sisal fibers and castor-oil-based polymer

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Abstract

Developing sustainable composites for engineering applications is essential for minimizing environmental impacts and ensuring the long-term viability of infrastructure and technological advancements. In this context, this work focuses on the manufacture and evaluation of the structural integrity of a sandwich structure composed of aluminum faces and egg-box-shaped, sisal fiber-reinforced epoxy (SFE) or castor-oil polyurethane (SFC-O) composites. The sandwich panel is filled with a biobased foam and subjected to dynamic load (drop-tower) test. For comparison, the base materials SFE and SFC-O molded into the egg-box-shaped cores are also evaluated using Charpy impact tests to establish a potential correlation between their Charpy performance and the drop-tower behavior of egg-box sandwich structures. The findings reveal that SFC-O laminates demonstrate superior Charpy impact resistance (∼49%) compared to SFE laminates. Similarly, sandwich structures composed of egg-box-castor-oil composite cores absorb approximately 42.5% more energy than those made with egg-box-epoxy cores. The impact behavior of the sandwich structures correlates directly with the impact resistance of the sisal fiber laminates. Overall, the results indicate that the castor-oil polymer can effectively replace the epoxy polymer matrix phase, enhancing impact absorption and providing an environmentally correct and sustainable solution for fabricating sandwich panels.

Highlights

- Castor-oil polymer provides laminates with lower density relative to epoxy.
- Sisal-castor-oil-based laminates possess higher impact resistance than those based on epoxy.
- Sisal-castor-oil-based panels achieve higher absolute and specific drop-tower impact properties.
- Panels subjected to drop-tower impact tests reveal skin delamination, wrinkling and indentation.
- Debonding between the foam and egg-box core is a typical failure mode for epoxy sandwich panels.

KEYWORDS
bio-based polymer, drop-tower testing, egg-box shaped core, sandwich panels

1 | INTRODUCTION

The growing interest in sandwich composites based on recyclable and natural resources results from increasing environmental concerns.[1–3] The use of natural fibers in the manufacturing process makes these structures more economical and sustainable for civil structural applications in which high strength is not a primary requirement, like roofs, floor panels, and walls. The use of natural fibers is also widespread in the automotive industry, where lightweight materials are nowadays essential to improve fuel efficiency, reduce emissions and enhance the vehicle performance. Additionally, the incorporation of recycled materials into sandwich structures reduces environmental impacts by conserving finite natural resources. It also promotes a circular economy, in which resources can be continuously reused, repurposed, or recycled at the end of their lifecycle. This strategy minimizes waste, reduces the need for virgin materials and fosters more sustainable production and consumption practices.[2,4,5] The urge for biodegradable and ecological structures has boosted the use of recycled materials and the development of composites reinforced with natural fibers, whose low density and considerable specific properties have been explored for core materials for aluminum-sandwich panels.[6–10] Natural fiber-reinforced composites core materials can be beneficial to the use of aluminum-sandwich panels because of their high load-bearing capacity, impact resistance, and lightweight properties.[11] Recycled and reused materials, such as bottle caps, enhance the core mechanical properties, increase the energy absorption and reduce the overall weight. These measures make them viable as secondary structural components in engineering applications, contributing to performance efficiency and sustainability.[3,8]

Sandwich panels are composed of thin, rigid skins and a low-stiffness and lightweight core.[12–17] These structures are primarily designed to safeguard a target structure from undesired impacts and ensure structural integrity.[18–21] Rigid skins are the primary load-bearing component in bending. The skins (faces) must be sufficiently strong to resist tensile and compressive forces along the plane of the sandwich structure. The skins protect the core from mechanical damage, environmental exposure and wear. The core, besides its space-filling properties, distributes forces between the skins, provides shear strength, compressive and impact resistance and improves energy absorption against the propagation of cracks in the skins. At the same time, the core prevents the faces from buckling or separating under load.[4,5,7,10] The stiffness of the sandwich panel can be enhanced by increasing and optimizing the core thickness, which must have low density to maintain a lightweight structure. The primary design goal of sandwich panels is a high stiffness-to-weight ratio.[22]

The performance of sandwich panels is closely linked to the core-face adhesive strength[23] and inherent mechanical and physical properties of the core,[22,24] prompting substantial efforts to enhance their design, composition, and structure.[15] Cellular structures, including honeycombs, polymer foams, triangular ceramic-filled cores, and truss lattices, fulfill the requirements for strength and low weight, making them common choices for this purpose.[2,13,18,21,22,25,26] The core design must ensure adequate stiffness and enhanced damping properties in view of the lifetime operational loading, availability and cost requirements that these structures must satisfy. The careful selection of the geometric configuration allows for optimized performance tailored to specific application needs. For example, aerospace structures typically use aluminum or Nomex honeycombs, while civil engineering applications often employ closed- or open-cell foams. Balsa is commonly used for sandwich structures in marine applications. Ceramic truss-core structures could be employed in high-temperature applications.[22,27]

Moreover, natural fiber-reinforced polymer composites can be utilized to create cost-effective sandwiches based on fiber metal laminates (FML), exhibiting intriguing mechanical properties, particularly when specific properties are considered.[1,11,28,29] Even though natural fibers are vulnerable to moisture, aluminum skins enhance the structure's rigidity and shield the composite core from deteriorating elements, such as UV light, water, and humidity.[30] Due to their hydrophilic nature, natural fibers absorb water and cause swelling that compromises the structural stability of the composite. The fiber-matrix interface is also affected, reducing adhesion and load transfer capacity.[31] Aluminum acts as a barrier to water diffusion through the material's surface, assuming the material is used in a structure with sealed edges. The shape of the core is contingent on the application, type of loading, and constraints. By customizing the geometric pattern of the corrugations, it is possible to control the material's stress response in different directions, addressing anisotropy.[27] Recently, egg-box-shaped composite structures have attracted attention as sandwich cores due to their significant potential for energy absorption, high strength-to-weight ratio, and acoustic features. The unique geometric configuration of egg-box-shaped composite structures offers excellent energy absorption and impact resistance, effective load distribution and enhanced overall durability. Their lightweight nature and high strength and stiffness make these cores particularly suitable for applications where weight reduction is crucial, such as in the aerospace and automotive industries.[14,15,32–34]

Santos et al.[30] were the first to investigate natural fiber-reinforced composites as an egg-box core for aluminum sandwich panels manufactured with a bio-based castor-oil polyurethane (PU) polymer. Their study assessed the compressive behavior of bio-based corrugated cores and the physical and bending properties of sandwich structures with aluminum skins. The nominal stress of the egg-box-corrugated composites made from sisal fibers and epoxy or castor oil PU is very similar to that observed by[15] for glass-fiber-reinforced epoxy. Although direct comparisons of flexural properties for these new natural-based materials are lacking, Santos et al. reported flexural strength values for sandwich panels with 1200 aluminum faces and egg-box-shaped cores ranging from 47 to 93 MPa. The findings indicated the feasibility of scaling up these sandwich panels for various structural applications.

Understanding the dynamic behavior of sandwich structures is crucial as it influences numerous real-world events in automotive, aerospace, and marine applications. These structures must endure dynamic loads like vibrations, impacts, and fatigue, and accurate performance predictions under such conditions ensure safety, durability, and efficiency.[35] Impact analyses are thus essential to ensure the quality and availability of these materials on the market.

In this context, the current study focuses on the dynamic characterization of the sandwich panels previously examined in[30] via drop-tower impact testing. Sandwich panels are manufactured using aluminum faces and an egg-box-shaped, sisal fiber-reinforced epoxy (SFE) or castor-oil polyurethane (SFC-O) composites filled with a biobased foam. For comparison, the base materials SFE and SFC-O, which were molded into the egg-box-shaped core, are evaluated in Charpy impact tests to establish a potential correlation between their Charpy performance and the drop-tower behavior of egg-box sandwich structures. A statistical design is used to ensure a robust analysis of the results.

2 | MATERIALS AND METHODS

2.1 | Fabrication

Sisal fibers are sourced from Sisal Sul (Brazil). The Huntsman thermosetting epoxy system, consisting of the M-type resin and HY-956 hardener, is mixed in a 5:1 ratio. A bio-based castor-oil polyol (AGT 1315) and methylene diphenyl diisocyanate (MDI) are supplied by Imperveg (Brazil) to produce a PU elastomer. According to the suppliers, the castor oil and epoxy systems require 14 and 7 days of curing, respectively. The core filler agent, Mamonex RD 70™, is a bicomponent bio-PU foam also supplied by Imperveg. Both PU polymers are prepared by mixing the MDI (component A) and polyol (component B) in a mass mixing ratio of 1:1.2 (A:B), according to the fabricant. A 0.5 mm-thick 1200 (BS-1C) aluminum alloy from Belmetal (Brazil) is utilized as the skins. This alloy exhibits higher ductility in its annealed state and excellent corrosion resistance. The aluminum skins are prepared by sandpapering (80 grit) and bonded to the core material using the 3 M Hi-Strength 90 Contact Adhesive™.

Laminate composites measuring $200 \times 200\ mm^2$ are produced via uniaxial cold pressing considering a 900 g/m^2 sisal fiber mat and a matrix volume of 80%. The sisal mat comprises randomly distributed fibers of different sizes, measuring approximately 20–180 mm (Figure 1A). A metal mold (Figure 1B) is employed to compress the sisal mat and matrix phase at 645 kPa for 15 h under controlled ambient conditions at $22 \pm 1°C$ and $55\% \pm 5\%$ humidity (Figure 1C), as detailed in previous work.[11,36] Similarly, the sandwich egg-box structure core is fabricated through cold pressing at 645 kPa for 15 h under controlled ambient conditions at $22 \pm 1°C$ and $55\% \pm 5\%$ humidity, using a Nylon (666) mold measuring $150 \times 90 \times 10\ mm^3$. After opening and demolding, the egg-box structures are subjected to 3.7 kPa of pressure for 14 days to ensure the complete curing of the castor oil resin. The epoxy resin is maintained under the same conditions to ensure statistical consistency. The entire process is detailed in Figure 2. The sandwich panel is fabricated by compacting the aluminum skins (with adhesive), the cured egg-box core and the liquid castor-oil foam using a wooden mold wrapped with plastic film to prevent leakage. The PU foam expands within the mold under pressure. Controlled ambient conditions of $22 \pm 1°C$ and $55\% \pm 5\%$ humidity are maintained throughout the manufacturing process. The entire production process is shown in Figure 2. The experimental conditions and respective nomenclature are presented in Table 1.

FIGURE 1 Sisal fiber-reinforced polymer composites manufacturing process: (A) randomly distributed sisal fibers, (B) metal mold, and (C) uniaxial cold pressing under ambient conditions.

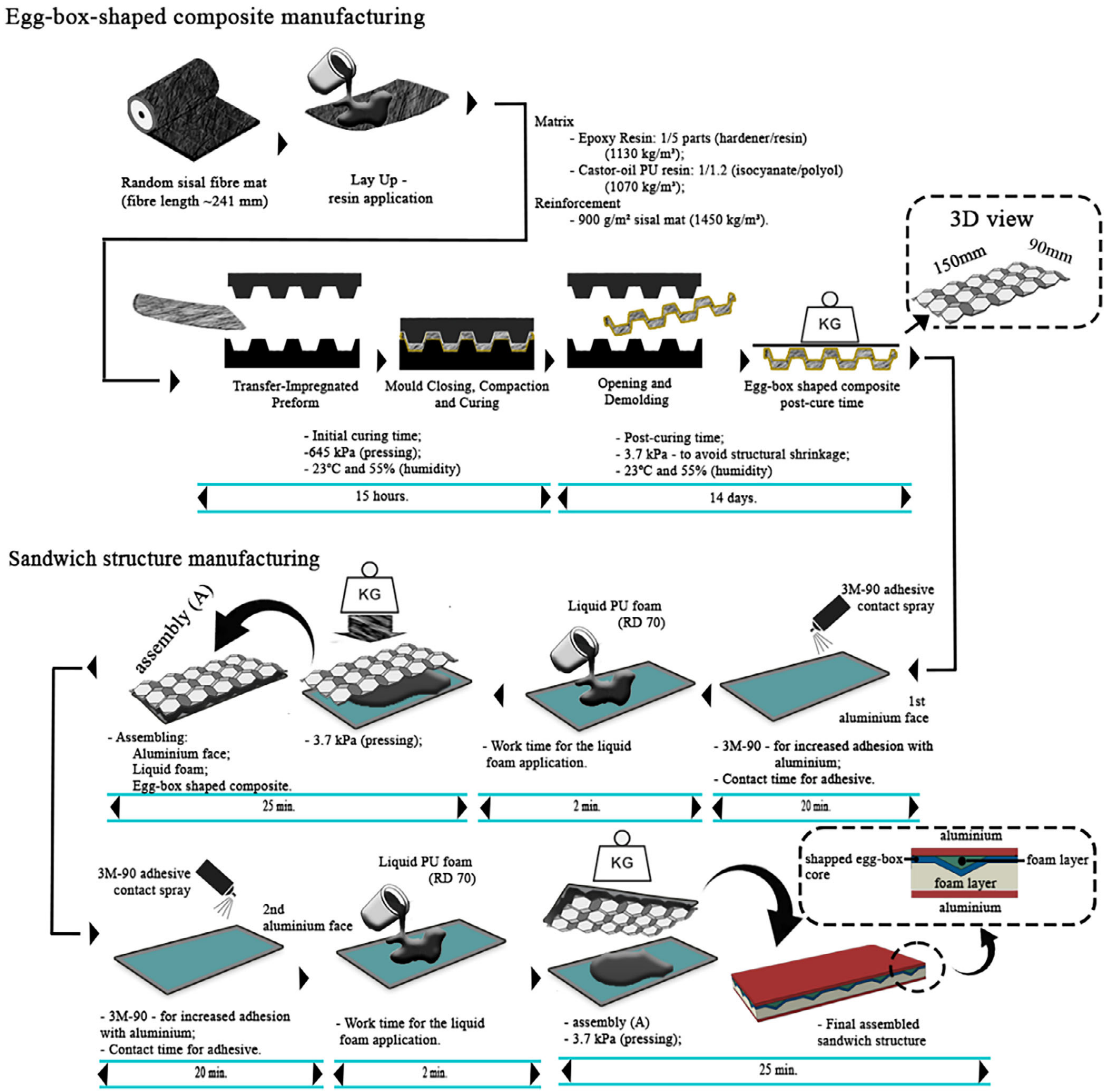

FIGURE 2 The manufacturing production process of sandwich structures.

2.2 | Characterization

Sisal-fiber laminate composites, produced with epoxy (SFE) or castor oil (SFC-O) polymers, are characterized through bulk density and Charpy impact tests. Ten specimens per condition are tested, and two replicates are considered. A Charpy Impact Tester (XJJ Series) is used at 15 J according to the guidelines of the ISO 179-1 standard.[37] The bulk density is determined following ASTM D792.[38]

The drop-tower impact test is performed following the ASTM D7136[39] using an Instron-Dynatup 9250 HV machine, with five replicates considered. The impact support fixture has a cut-out of $75 \times 125\ mm^2$, and four clamps are used to restrain the specimen during impact. The impact energy is determined based on the specimen thickness that is, 6.7 J/mm. The equivalent density values of the sandwich panels are derived from the drop-tower test specimens, calculated by dividing the mass by the volume of the samples. Each sample, with dimensions of approximately $150 \times 90\ mm^2$, is designed to fit the impact test support, as specified by ASTM D7136.[39]

The impact resistance of sisal-fiber composites (SFE and SFC-O), as well as the specific and absolute properties of the sandwich panels (S_SEp and S_SCo), are compared using analysis of variance (ANOVA) and Tukey's test within a 95% confidence interval ($p \leq 0.05$). The Anderson-Darling test is employed to verify the normality of the data. In Tukey's test, the experimental conditions that do not share the same letter group are considered statistically different.[6,40,41] All statistical analyses are performed using the Minitab® 18 software.

3 | RESULT AND DISCUSSION

3.1 | Drop-tower impact properties

Table 2 presents the descriptive statistics and ANOVA of the drop-tower impact properties for the sandwich structures. Panels with egg-box-castor-oil cores (S_SCo) absorb approximately 10.60% more total energy than those composed of egg-box-based-epoxy cores (S_SEp). The typical impact force–deflection curves for S_SEp and S_SCo panels are shown in Figure 3A,B. At the maximum impact load (indicated by the black horizontal dashed line), castor-oil-based panels absorb approximately 57 J. In comparison, epoxy-based panels absorb around 40 J (see blue dashed horizontal lines), representing a 42.5% increase in impact energy absorption. In addition, the maximum load deflection of the S_SCo panels (19.43 mm) is nearly 23% greater than the S_SEp panels (15.84 mm), as shown in Table 2 and Figure 3A,B.

Figure 3C shows the mean effect plot for the Charpy impact resistance of the sisal-fiber laminate composites. The castor-oil composite (SFC-O) exhibits a higher impact resistance (+48.71%) compared to the epoxy-based composite (SFE). Additionally, SFC-O laminates provide a 132.4% increase in specific impact resistance relative to SFE. The equivalent density of SFC-O composites is 22.48% lower than that of the SFE composites, resulting in an 18.50% reduction in the equivalent density of S_SCo sandwich structures (Table 2). This reduction in density leads to an increase of approximately 35%, 54.4%, and 34.02% in the specific properties of total energy, energy to maximum load, and maximum load, respectively, of sisal-castor oil-based sandwich structures (Table 3).

TABLE 1 Sandwich panels composition.

	Egg-box core composition				
Nomenclature	Type	Fiber	Polymer type	Filled with foam	Skin thickness (mm)
S_SEp	SFE	Sisal	Epoxy	Yes	0.5
S_SCo	SFC-O	Sisal	Castor-oil	Yes	0.5

TABLE 2 Equivalent density and drop-weight impact properties (mean [SD])—analysis of variance (ANOVA).

Setup		Equivalent density (kg/m^3)	Total energy (J)	Total deflection (mm)	Energy to max load (J)	Deflection at max load (mm)	Maximum load (kN)
S_SEp		589 (7)	66.4 (2.8)	30.2 (1.8)	44.3 (3.9)	15.8 (2.4)	3.60 (0.58)
S_SCo		480 (8)	73.09 (0.95)	26.84 (0.87)	55.8 (1.4)	19.43 (0.04)	3.94 (0.07)
ANOVA	p value	0.000	0.004	0.055	0.032	0.098	0.463
	R^2 (adj)	91.44%	80.56%	–	76.96%	–	–
	AD	0.295	0.490	–	0.522	–	–

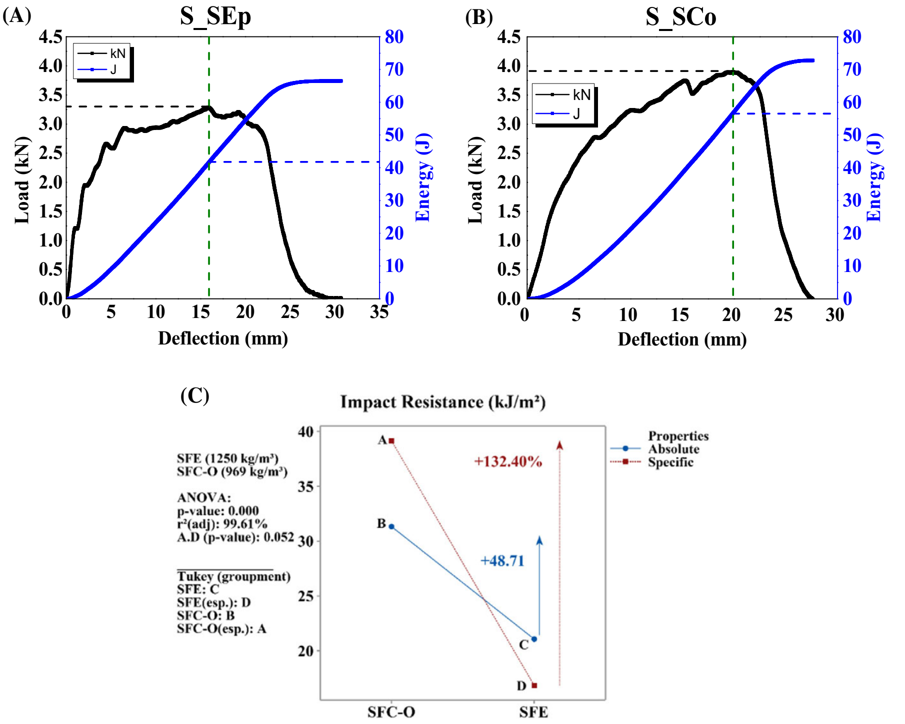

FIGURE 3 Load-deflection curves for egg-box sandwich subjected to drop-weight testing (A) S_SEp and (B) S_SCo and (C) ANOVA and Tukey test results for Charpy impact resistance (absolute and specific) of laminate composites.

TABLE 3 Drop-tower impact specific properties.

	Specific total energy (J/g cm^{-3})	Specific energy to maximum load (J/g cm^{-3})	Specific maximum load (kN/g cm^{-3})
S_SEp	112.78	75.21	6.11
S_SCo	152.27	116.14	8.20
Percentage increase (%)	35.0	54.4	34.2

A correlation between the Charpy impact test results obtained for sisal fiber laminates and the drop-tower impact test results of sandwich panels can be established. Egg-box cores with larger Charpy impact resistance composites (SFC-O composites) improve the drop-tower impact resistance performance of sandwich structures. Therefore, the composition of the core significantly influences the effective properties of the sandwich panels obtained under drop tower testing. It is also worth noting that the matrix phase directly impacts the mechanical properties of these composites, as well as the interface conditions, which may affect additional impact energy dissipation mechanisms, such as fiber-matrix debonding, fiber bridging, sliding, and pull-out.[30,42–45]

Both sandwich structures exhibit top skin wrinkling, aluminum fracture, and debonding under drop-tower impact, corroborating findings by Beharic et al.[18] The indentation resulting from impact loading is localized, primarily confined to the vicinity of the impacted region, as depicted in Figure 4 (items a1 and b1). Top skin wrinkling is a failure mode where the outermost layer (the 'top skin') deforms or buckles under compressive forces. Such behavior occurs when compressive stresses exceed the critical buckling stress of the skin material, causing it to wrinkle. These wave-like patterns can be observed in Figure 4 (items a1 and b1). The aluminum sheet folds transversely in the vicinity of the impact area, leading to a noticeable local stress concentration and the formation of a plug, which is associated with permanent skin deformation. When the stress exceeds the material's strength, the aluminum fracture tends to be localized in the generated plug, as observed in Figure 4 (items a1 and b1).[16] Notably, no bottom skin perforations or cracks are observed after penetration, as shown in Figure 4 (items a2 and b2). When the core absorbs significant energy during crushing, the bottom skin experiences less damage and failure.[9] According to Yoo, Chang, and Sutcliffe,[32] corrugated structures filled with low-density foams serve as an ideal energy absorber, maximizing energy absorption at a given stress level. The debonding region for both panels (Figure 4, items a3 and b3) differs: S_SCo panels experience debonding between the foam and skins, while S_SEp panels exhibit adhesion failure between the egg-box core and the foam (Figure 4, b3). Sandwich structures with hard cores are generally more susceptible to debonding under impact load than those with soft

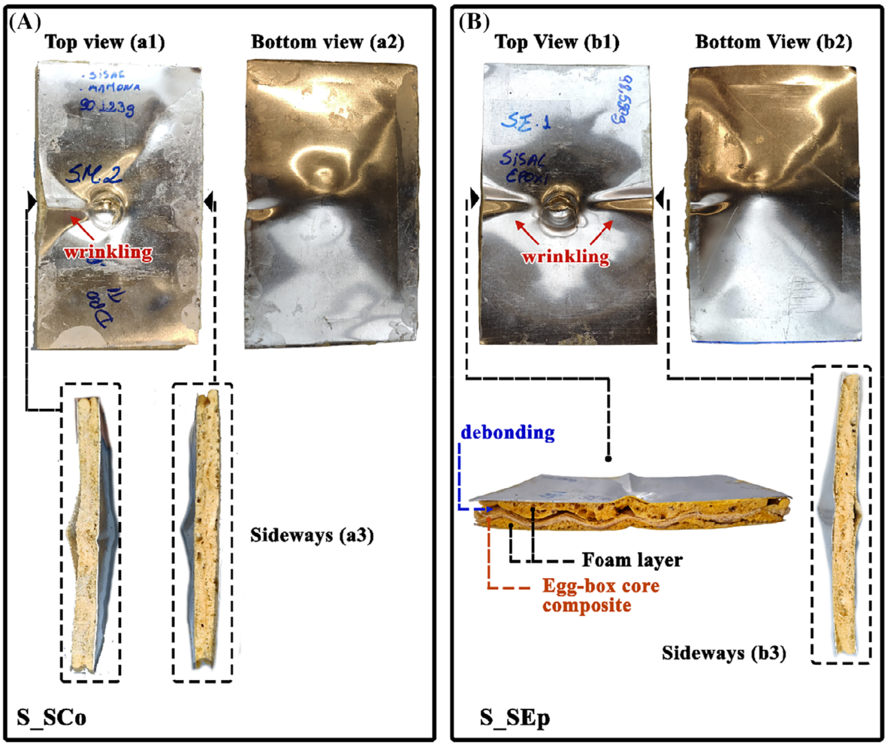

FIGURE 4 Fracture modes of the sandwich panels after drop-weight impact testing: (A) S_SCo-a1 (top), a2 (bottom), a3 (sideways); (B) S_SEp-b1 (up), b2 (bottom), b3 (sideways).

cores.[12] Despite this local delamination, both panels maintain strong core-skin adhesiveness and manual skin separation is difficult even after impact damage.

4 | CONCLUSIONS

Sisal fiber composites are evaluated under impact loadings, both individually, as a laminate composite and as a corrugated core integrated into sandwich panels with aluminum skins. Epoxy and biobased PU systems are utilized as the matrix phase and compared. The castor-oil polymer produces laminate composites with a lower density (−22.48%) compared to the epoxy polymer, resulting in an 18.50% reduction in the equivalent density of the produced S_SCo sandwich structure. Sisal-castor-oil-based composites exhibit increased Charpy impact resistance: 48.71% higher than sisal-epoxy-based composites. The higher Charpy impact resistance of sisal-reinforced castor-oil laminates is correlated with a better impact performance of sandwich panels made with its corrugated composite counterpart, highlighting the importance of its matrix composition. Due to the low density of castor oil-based composites, the specific impact strength was shown to be superior (+132.40%) relative to sisal-epoxy-based composites. The sisal-castor-oil-based sandwich structures achieved higher drop-tower impact properties, such as total energy (+10.6%), energy to maximum load (+25.8%), deflection at maximum load (+22.7%) and maximum load (+9.4%). Sisal-castor-oil-based sandwich structures achieved higher specific properties of total energy (+35%), energy to maximum load (+54.4%), and maximum load (+34.2%) owing to the lower density of the biobased matrix phase. Sandwich panels subjected to drop-tower impact tests reveal delamination and indentation in the skins, particularly in the top area surrounding the impact center where bending occurs. Debonding between the foam and egg-box core is a typical failure mode for epoxy sandwich panels. Overall, sandwich panels made with egg-box-castor-oil composites demonstrated higher impact properties than egg-box-epoxy composites.

The impact properties of sisal-castor-oil-based sandwich structures show notable improvements compared to the analogous sisal-epoxy-based configurations. The castor oil PU matrix enhances the energy absorption capacity, resulting in superior impact resistance and reduced damage under load. This improved performance is attributed to the increased toughness and flexibility of the castor oil-based resin, which provides better resilience and structural integrity during impact events. Castor-oil PU is therefore a promising alternative for applications requiring high impact resistance and a green alternative for various structural engineering applications, offering both performance and sustainability benefits over traditional epoxy-based systems.

Based on these interesting impact properties, future investigations should include a vibration damping analysis to understand how effectively the materials absorb and dissipate energy during both impact and vibration loading. This analysis could enhance the knowledge about the overall performance and durability of structures made with these materials. Additionally, a comprehensive evaluations of the effects of aging on the mechanical performance, along with thermal and acoustic analyses, will be crucial for further studies. These investigations will provide a more comprehensive understanding of the materials' long-term behavior and their suitability for various structural applications.

AUTHOR CONTRIBUTIONS

Júlio Cesar dos Santos: Conceptualization, investigation, methodology, data curation, validation, formal analysis, visualization, writing – original draft. Rodrigo José da Silva: Writing – review & editing. André Luis Christoforo: Methodology, writing – review & editing. Rodrigo Teixeira Santos Freire: Formal analysis, writing – review & editing. José Ricardo Tarpani: Writing – review & editing, supervision. Túlio Hallak Panzera: Writing – review & editing, visualization, validation, supervision, resources, project administration, methodology, conceptualisation. Fabrizio Scarpa: Resources, writing – review & editing.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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