Charkaoui et al. J Mater. Sci: Mater Eng. (2024) 19:20
https://doi.org/10.1186/s40712-024-00158-8

Journal of Materials Science: Materials in Engineering

ORIGINAL PAPER

Open Access

Low-velocity impact response of hybrid core sandwich panels with spring and strut cores filled with resin, silicone, and foam

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Abstract

Advancements in the load-bearing capacity of composite panels open doors to high-performance applications. The integration of additive manufacturing allows for the creation of intricate core designs effortlessly. Hybrid cores, combining structural elements with infill materials, play a crucial role in enhancing panel impact resistance while maintaining its low weight. This study compares sandwich panels incorporating spring and octet strut structural elements infused with different materials—silicon, foam, and epoxy resin—evaluating their energy absorption capabilities. Additive manufacturing is employed to produce these panels with structural elements then subsequently filled with infills. The drop tower test is utilized to experimentally assess panel behavior under low-velocity impact. Design of experiments and statistical analysis are used to examine the influence of core height, impact height, core geometry, and filling type on the damaged area and impactor penetration. Results showed that the strut-based structure performed better than other structures in preventing penetration, with a damaged area reduction from 501.45 to 301.58 m^2 compared to the spring core. The addition of foam or silicon reduced the impact damage to the front and the back sheets, with silicon infills proving to be the most effective, reducing penetration by reducing penetration by about 60%. The depth of impact was measured, with results indicating that the truss core displayed the smallest specific depth of penetration. A decision tree model predicted that a sandwich panel with a spring core would have a 100% chance of perforation while a filled core showed a significantly reduced penetration risk.

Keywords Sandwich panels, Low-velocity impact, Composite material, Additive manufacturing, Filling material

Introduction and literature review

An ongoing effort is dedicated to designing structures that are both lightweight and high-strength, incorporating multifunctional features. Sandwich panels have appeared as a central focus in several engineering disciplines because of their exceptional properties. These complex structures, made of three layers with robust outer shells enclosing lightweight cores, result in structures that exhibit durability, impact resistance, and resilience to weather conditions.

The notable strength-to-weight ratios of sandwich panels make them versatile for applications in the construction, automotive, marine, and aerospace industries (Fischer 2015). The sandwich panel's load-bearing capabilities also contribute to high-performance set-ups, and the insulative properties of their cores support energy conservation, promoting sustainability and innovation in a world that increasingly prioritizes efficiency and environmental consciousness.

The structure of the core in sandwich panels significantly affects their mechanical performance, specifically under specific loads (Tran and Peng 2021; Ma

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et al., 2024). While the face sheets contribute to the bending strength and rigidity, the core's primary role is to transmit the shear forces between them. Recent research has focused on optimizing energy absorption and enhancing the resistance of sandwich panels, especially in low-impact loading conditions. Advancements in 3D printing and precision cutting have allowed a new era of structural design, demonstrated by truss core sandwich panels. These panels, with core designs that are cell-based, excel in transferring the loads within outer skins which significantly reduces the shear deflection and yields lightweight, engineered panels (Djama et al., 2020). The development of additive manufacturing and 3D printing technologies enabled the fabrication of complex core geometries, which improves load resistance and energy absorption. Core properties, such as stiffness and robustness, depend on dimensions, design, thickness, and material choice.

This customization allows for the development of lightweight yet mechanically robust materials (Du Plessis et al., 2022). Manipulating the composite's composition and structure supports structural engineering principles like the truss theory, increasing the potential for tailored material designs to meet specific application demands (Wu et al., 2023; Ma et al., 2024) investigated the ballistic impact resistance of PLA 3D-printed sandwich panels with cubic, grid, gyroid, and honeycomb infill patterns and tested them under three impact velocities: 109.95, 173, 97, and 209.48 m/s. The study found that panels with cubic infill patterns exhibited the highest maximum impact load and energy absorption, performing better than the other patterns, Specifically, the cubic and gyroid patterns showed superior impact resistance, with the cubic pattern absorbing the most energy. The research highlights the significant role of infill patterns in enhancing impact resistance and 3D-printed sandwich panels.

Birman and Kardomateas (2018) classified lattice truss cores into five different types: pyramidal, corrugated, X-shaped, tetrahedral, and Kagome. O'Leary et al. (2019) studied the mechanical behavior of these cores, with a focus on shear and compression, of Kagome truss core sandwich panels made from titanium using selective laser melting. In a similar study, Mei et al. (2017) examined carbon fiber-reinforced polymer (CFRP) sandwich panels with a tetrahedral truss core manufactured through thermal welding in a thermoplastic matrix. The authors' main goal was to validate advanced manufacturing methods for such structures. Strut-based designs, including the kelvin cell and the octet truss structures, have shown notable mechanical properties, which enhance energy absorption at high velocities and improve impact resistance (Hawreliak et al., 2016). Hassan et al. (2021) compared the conventional honeycomb structure with the 3D-printed octet structure, proving its potential for the production of composites. The octet structure enhances the composite strength and stiffness which makes it cost-effective for high-strength and impact applications. Liu et al. (2020) developed spring-cylinder, spring-rubber, and spring-aluminum foam isolation devices with damping ratios of 0.125 to 0.132. These devices perform well in resisting explosions and impact loads, achieving over 92% vibration isolation.

The adaptability of sandwich panels allows diverse material combinations that are tailored to meet specific performance requirements (Larsson et al., 2023). This customization includes the introduction of various core fillings (Li et al., 2020) , like foams and resins (Mohammadiha and Ghariblu 2016; Hassanpour Roudbeneh et al., 2019; Deng et al., 2022), for enhancing the mechanical properties, energy absorption, and resistance to external forces. Open-cell truss core configurations provide easy access for integrating lightweight materials to further enhance the panel performance.

Researchers have studied filling metallic sandwich panels with polymer or metallic foams for cost-effectiveness. Foam integrated into the core significantly enhances the compression strength, shear strength, energy absorption, perforation resistance, and blast resistance (Yan et al., 2013; Bin et al., 2015; Karttunen et al., 2017) observed improved fatigue strength in foam-filled sandwich panels. (Najafi and Eslami-Farsani 2021) enhanced the structural and durability properties of PU foam-based sandwich panels without increasing the weight. The design incorporated through-thickness stiffening, core hybridization, and improved core-skin interfaces. This was done through the use of agglomerated cork/PU foam and lattice structures. The novel panels portrayed a 506% increase in the maximum flexural load and an 816% increase in the initial flexural stiffness as compared to traditional panels. Moreover, the novel panels absorbed 21% more impact energy and demonstrated better damage tolerance and energy absorption.

Mei et al. (2022) conducted three-point bending tests on polyurethane foam-filled CFRP X-core sandwich panels and reported a significant increase in the initial failure and peak load. Wang et al. (2021) enhanced the compression strength and bending resistance in lattice truss sandwich panels using polyurethane and concrete foam fillings. Zhang et al. (2023) found that introducing polyurethane foam in Kirigami corrugated core panels increased the energy absorption by 88.5% for blast mitigation.

Deng et al. (2022) assessed the ballistic properties of an S-shaped folded sandwich configuration with micro-bead modified epoxy resin in the core. Yuan et al. (2018) experimented with silicone resin and carbon powder as fillers for enhancing the mechanical properties of the truss. Introducing thermal insulation and ablative materials extended the failure time and reduced the ablation damage. Warren et al. (2021) studied honeycomb core sandwich panels filled with a shear-thickening fluid under hypervelocity impact, significantly decreasing the damage levels and preventing complete perforation. Noor Azammi et al. (2018) blended kenaf fiber with natural rubber and thermoplastic polyurethane to enhance mechanical properties, such as tensile strength and flexural strength. The reinforced specimen outperformed normal composites.

To further explore the enhancement of impact resistance in sandwich panels, Maher et al. (2022) investigated the high-velocity impact behavior of corrugated core composite sandwich panels with composite face sheets reinforced by pseudo-elastic NiTi shape memory alloy (SMA) wires. The study aimed to improve the impact resistance by incorporating SMA wires into the composite face sheets. Results demonstrated that the addition of SMA wires significantly reduced the projectile's residual velocity and that pre-strained wires markedly enhanced energy absorption. The location of SMA wires at the impact site played a crucial role, leading to better energy absorption compared to wires placed away from the impact site. The inclusion of SMA wires enhanced structural integrity and impact resistance, making them suitable for applications requiring high energy absorption and damage tolerance.

This research proposes an innovative composite structure using 3D additive manufacturing to integrate a structural core with a polymeric filling, aiming to enhance the performance and redefine composite design. Physical experiments will compare the impact of spring and strut core structures with polyurethane foam, epoxy resin, and silicone rubber fillings on the performance of composites. A drop tower test will evaluate the panel's behavior under low-velocity impact, assessing the impact absorption capabilities of various sandwich panels with different core designs and fillings. Regression analysis is applied to model and predict panel behavior, providing insights for material design in critical industries like aerospace and automotive. Classification modeling with decision trees is used to predict the penetration probability, highlighting safety implications for practical applications. Traditional materials often struggle to meet the combined requirements of strength, weight, and functionality.

By taking advantage of advancements in additive manufacturing and new materials, this study explores novel design possibilities, pursuing performance enhancements through customized core geometries and fillings.

Materials and methods

Figure 1 shows the sandwich panel dimensions, with a fixed length and width of 80 mm. The core height (h) varied, while the upper and lower face sheet thickness were constant at 1 mm. A cellular core volume fraction of 15% was maintained for all core designs. The study explored two core structures: octet strut and spring, as shown in Fig. 2. The octet truss and spring core designs were selected for this research due to their unique structural properties, important for enhancing the performance of sandwich panels. The octet truss core is known for its exceptional strength and stiffness and can efficiently distribute the loads and reduce shear deformation, making it ideal for high-strength and impact-resistant applications. Its compatibility with additive manufacturing processes allows for the accurate fabrication of complex shapes. The spring core, on the other hand, is chosen for its ability to absorb and redistribute impact energy, due to its high in-plane elastic modulus. This core design spreads the shear forces and compression across neighboring cells which results in effective energy dissipation.

To study the cellular core's effect on energy absorption in the sandwich panels, three variables were examined: the core height, core filling type, and the impact height. A full factorial design in Table 1 established the experimental runs, including two core heights (10 mm and 20 mm), three reinforcement fillings (foam, silicon, and epoxy

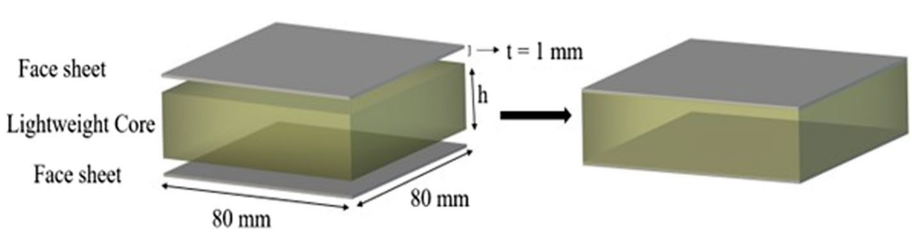

Fig. 1 Sandwich panel dimensions

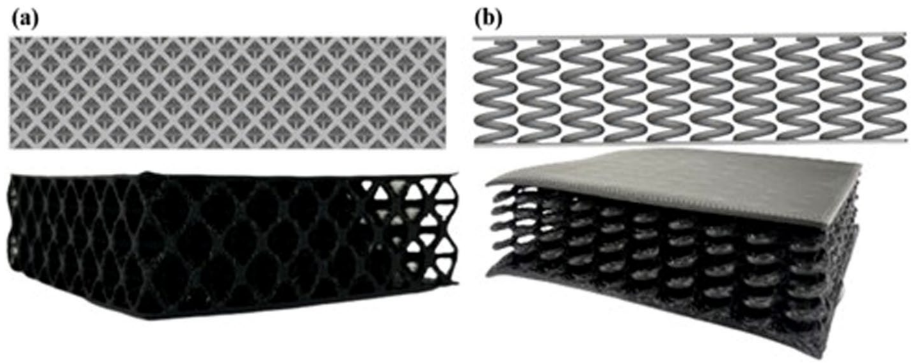

Fig. 2 Schematic and 3D printed sandwich panels for an **a** octet truss core and **b** spring core

Table 1 Factorial design for experimental study

Factor	Levels	Values
Core geometry	3	None, spring, strut
Core height (mm)	2	10, 20
Impact height (cm)	2	15,25
Filling type	4	Foam, silicon, resin, none

resin), and two impact energies achieved by changing the drop height (15 mm and 25 mm).

Additionally, a control sample without a core, assuming a rectangular configuration, served as a scale for all variable conditions. The study investigated a total of 48 unique combinations of these variables.

Architected sandwich panels were 3D printed using a Flash Forge printer (Fig. 3), which uses fused deposition modeling (FDM) technology for creating polylactic acid (PLA) polymer samples. This process is aligned with ASTM standard F2792 (MIT 2012). FDM, involves the extrusion of heated polymeric filaments in the x- and y-coordinates, while the build table lowers the object layer by layer in the z-direction. The orientation and toolpath of each layer, as prescribed by ASTM F2792 (Baich et al., 2015), affect the mechanical properties of the printed structures.

PLA was chosen due to its simplicity and accessibility which aligns with the study's focus on topological attributes and diverse fillings. The filament diameter used was 1.75 mm from Filatech UAE. Three fillings, epoxy resin, foam, and silicon, were strategically selected for their varied mechanical properties and impact behaviors.

Polyurethane foam from Hi Stick® expanded by 50% during curing and was contained within the panel using tape (Fig. 4b). EL160 high-temperature epoxy laminating resin from Easy Composites® was carefully mixed at a ratio of 1:0.35 (resin: hardener) and injected into the cellular cores using a syringe, taped from three sides (Fig. 4a), and required 24 h to cure. Silicon from Sikasil® was chosen for its one-component nature and resistance to cracking applied using a sealant gun and to cure through atmospheric moisture. Table 2 presents the

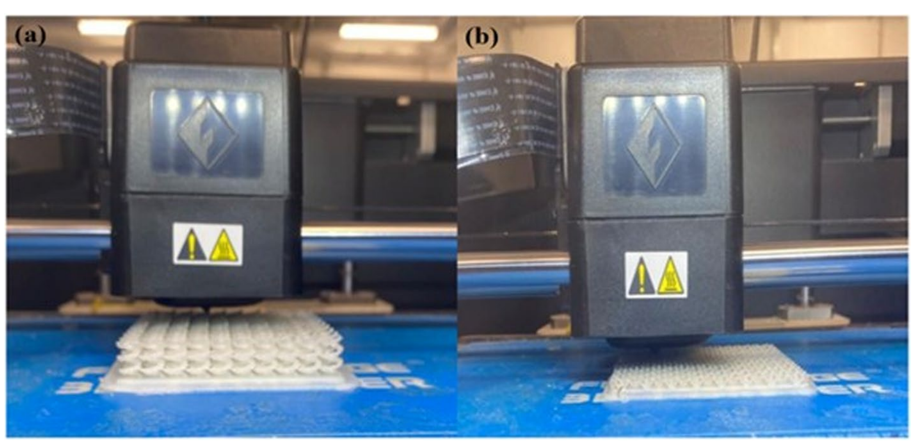

Fig. 3 3D printing of **a** spring core and **b** strut core sandwich panel

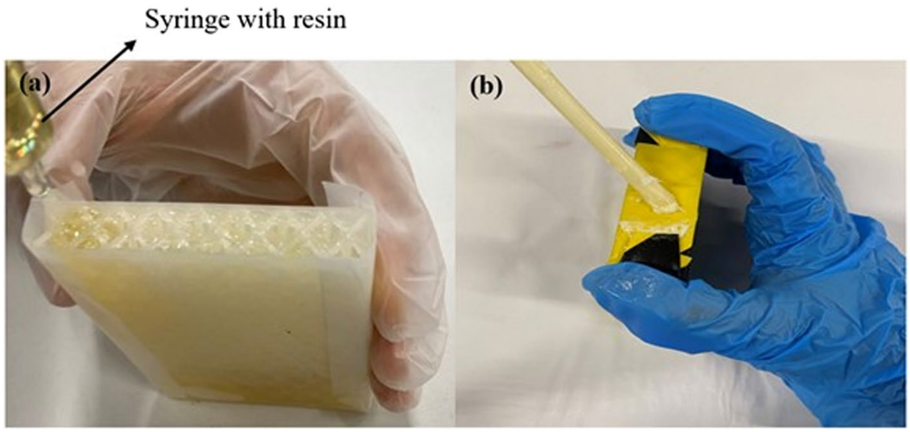

Fig. 4 Core filling process **a** resin and **b** polyurethane foam

Table 2 Material properties

	Density (g/cm^3)	Tensile strength (MPa)	Elongation at break (%)	Impact strength (kJ/m^2)
PLA	1.25	55	100	3.5
EL160 high-temperature epoxy laminating resin	1.18	25	2	–
Polyurethane foam	0.01	1.03	78	14
Silicon	0.95	1.5	500	–

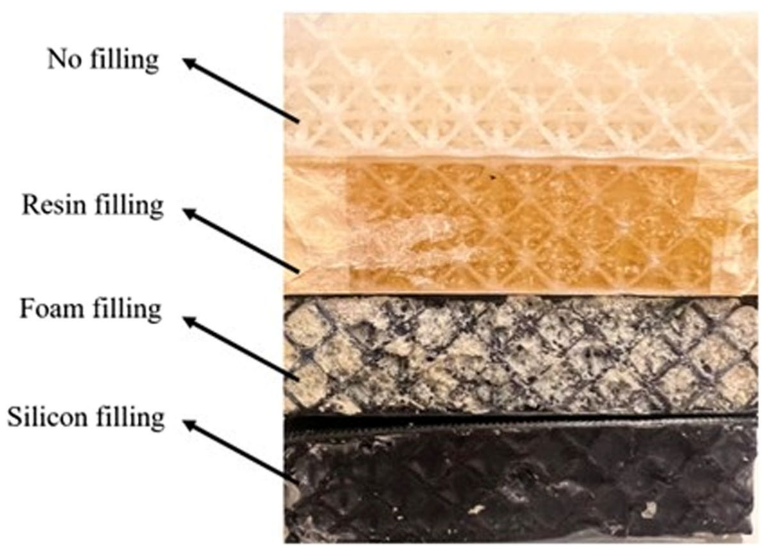

Fig. 5 Different filling types in the octet truss core sandwich panels

mechanical properties of these materials. Figure 5 shows the three filling types in the octet truss sandwich panel.

This study analyzed mass changes in various samples, considering core topology and filling type. Spring and strut cores had the least mass increase with resin, foam, and silicon compared to the hollow panel. The panel with no core showed the highest mass increase, as expected with an initial volume fraction of 0%. Foam had the least impact on the mass increase, while resin had the most substantial increase due to its higher density. These findings reveal the complex relationship between core topology, filling type, and mass changes, offering insights into sandwich panel materials and design considerations.

Experimental setup

Figure 6a shows the drop test tower setup for low-velocity impact experiments. It uses a 0.18 kg steel impactor connected to a 15-kg plate, dropped from 15 and 25 cm heights. Raising the drop height increases the impact energy. Impact velocities just before contact were 1.7 m/s and 2.2 m/s for the 15 cm and 25 cm heights, respectively. The impactor drops on a simply supported beam. Two responses evaluated were damaged area and impact indentation depth on both the front and back sides of the panel. To ensure reliability and consistency, two identical samples were made for each of the 48 configurations, totaling 96 tests. Results were averaged, with a third test conducted in cases of deviations exceeding 5% for accuracy.

Results and discussion

The damage area on the face sheets was measured using Adobe Photoshop Lasso's tool which traces the damage outline, records the pixel dimensions using the measurement log, and converts the measurements to real-world for precise quantification.

During low-velocity impact tests, some samples fully penetrated while others showed partial damage without perforation. For non-penetrating specimens, the depth of impact was precisely measured using a vernier depth gauge, indicating the panel's ability to withstand penetration and endure deformation. A smaller depth indicates higher resistance to penetration and greater capacity for energy absorption and deformation. A larger impact area suggests more extensive damage and can be correlated with the transferred energy during impact. Smaller impact areas signify effective energy dissipation and force absorption. These measurements of impact area and depth provide valuable insights into damage patterns, energy absorption capabilities, and overall mechanical behavior of sandwich panels under low-velocity impact.

Surface response analysis was used to study the results of the damaged area and depth of impact using Minitab software. The main effects plot shows the average response for each level of a factor, irrespective of the levels of other factors. Each point on the plot represents the average outcome for a particular level of a factor, averaged across all other factors included in the analysis. Figure 7 depicts the main effect plots revealing the correlation between the design variables and their impact on the average damaged area on the back face sheets of the sandwich panels. The plot for the core height shows the mean damaged area for different core heights, averaged over all impact heights, core geometries, and filling types. Similarly, the plot for the impact height shows the mean damaged area for different impact heights, core geometries, and filling types. This approach provides a clear understanding of how each factor independently influences the mean damaged area. The same trend can be seen for both the front and back face sheets of the sandwich panels. As illustrated in Fig. 7, there exists a linear inverse relationship between core height and damaged area. As the core height increases, material stiffness also increases, resulting in a reduction in the damaged area at the back of the panel compared to a panel with a shorter core height. This is also depicted in Fig. 8 showing the damaged area on the front and back face sheet of a truss core sandwich panel with foam core filling. It is

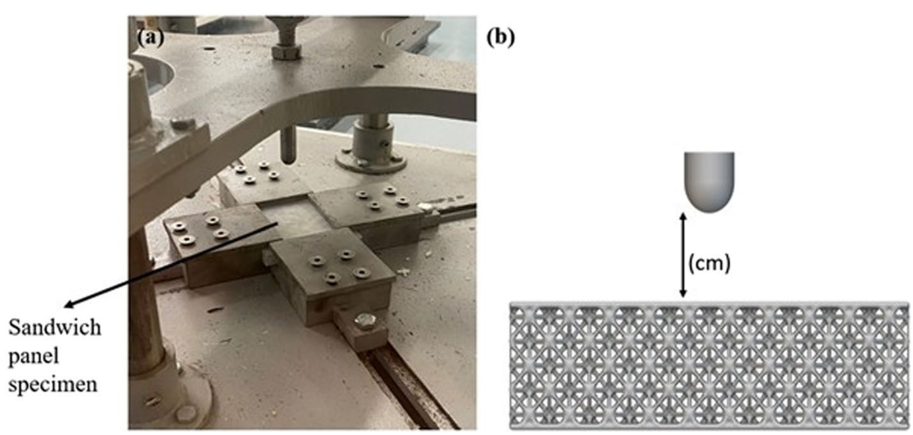

Fig. 6 **a** Experimental setup for low-velocity impact tests. **b** 2D schematic illustrating sandwich panel and impactor height

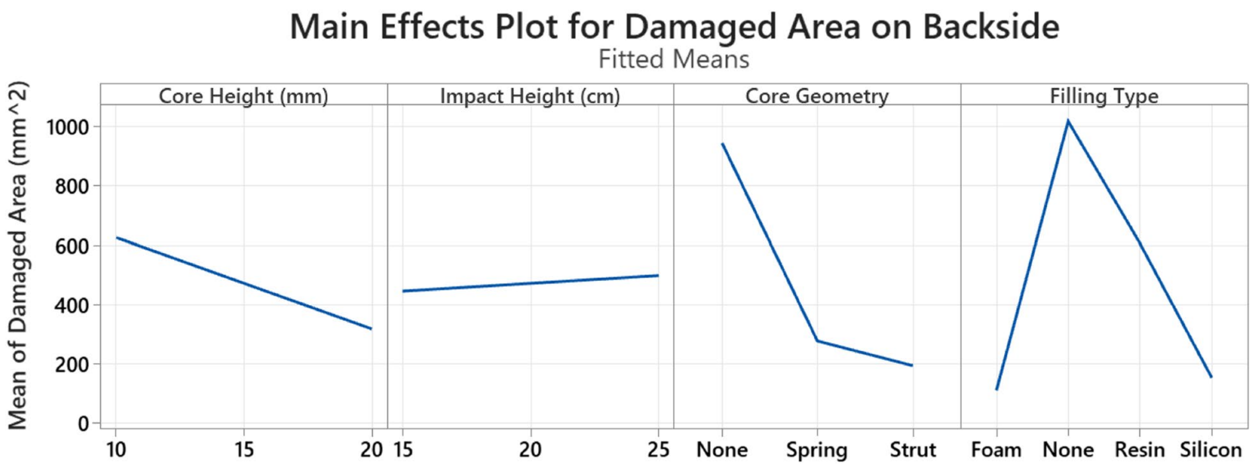

Fig. 7 Main effect plot for the damaged area (mm^2) on the back face sheet

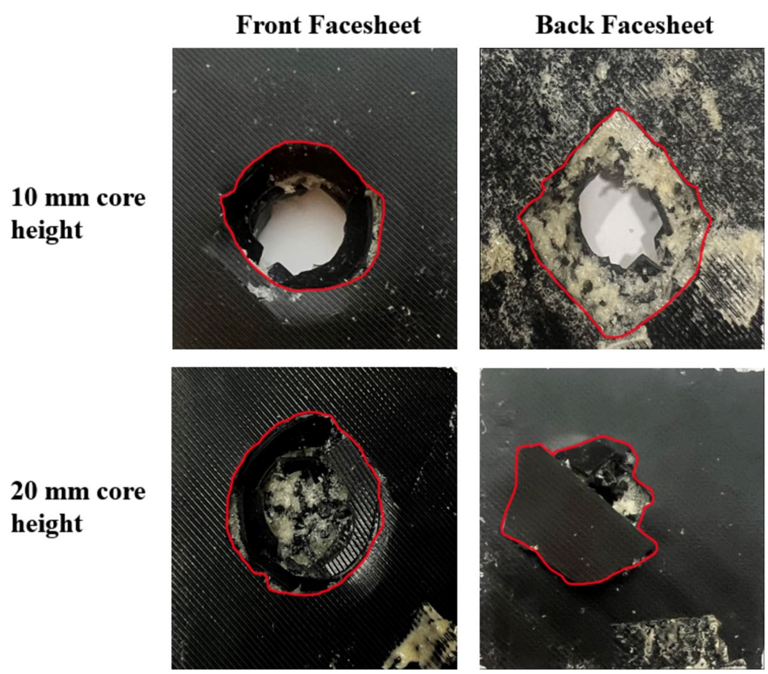

Fig. 8 Truss core sandwich panel with foam filling at impact height 15 cm

evident that as the core height increases, irrespective of the impact height, the damaged area decreases.

An interaction plot visualizes the interaction effects between two or more factors on a response variable. These plots show how the mean response (damaged area) changes with the levels of one factor while considering different levels of another factor. Each line in the interaction plot represents a different level of one factor, showing how the response variable changes with the levels of another factor. Analysis of the interaction plots in Fig. 9 shows a significant interaction between core geometry and filling material. Panels with no core filling have the highest damage, while those with a strut core show the lowest face sheet damage, regardless of filling type. Foam and silicon are the most robust fillings, consistent with the back face sheet damage.

Changing the impactor's drop height to vary the impact velocity causes a slight increase in the mean

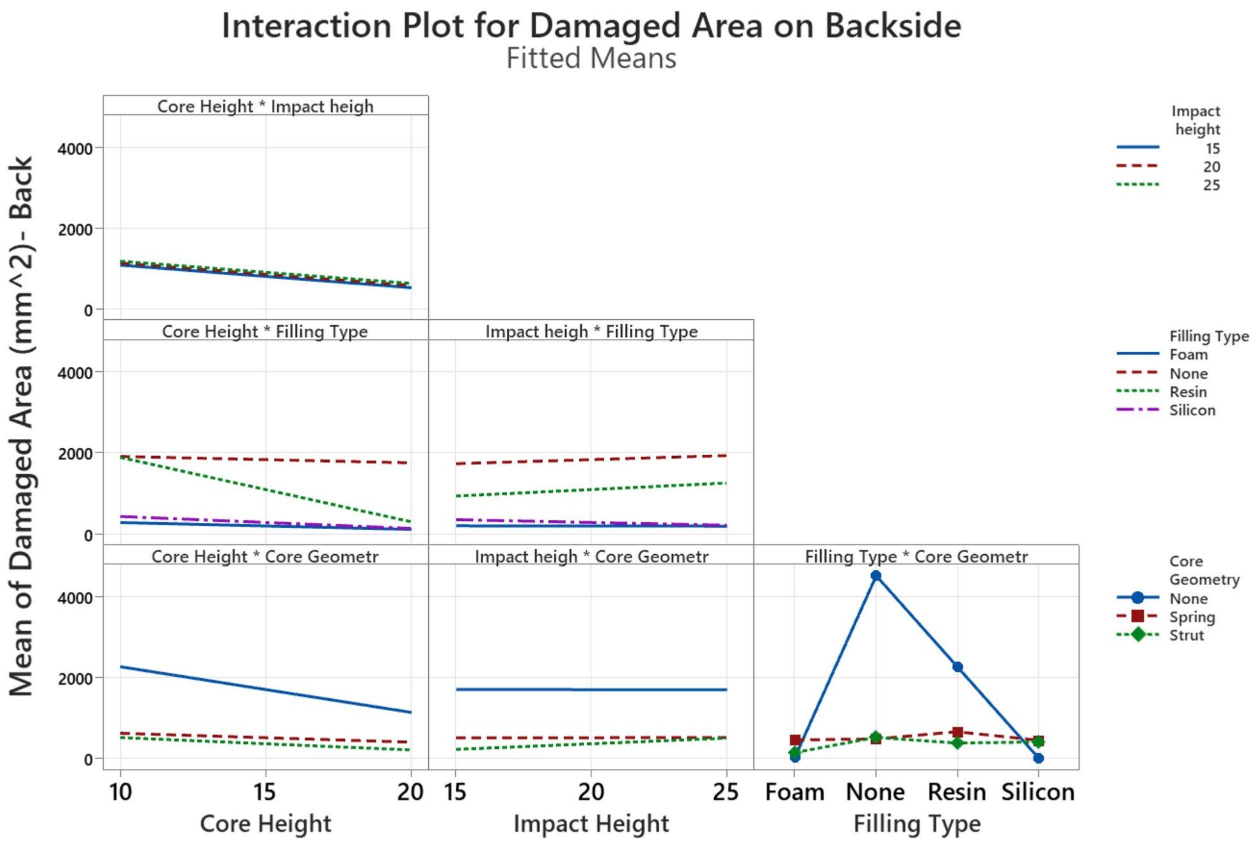

Fig. 9 Interaction plot of damaged area (back) with core height, impact height, and core geometry

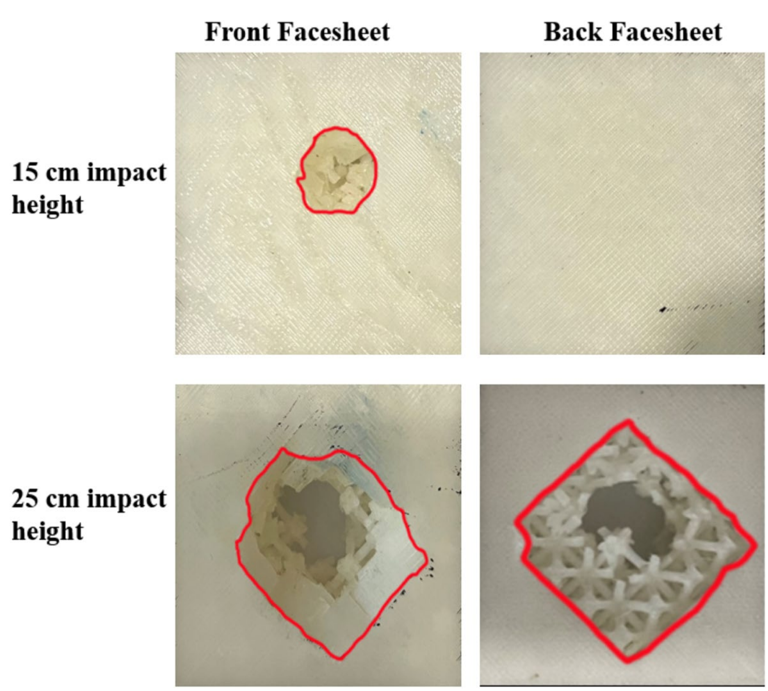

Fig. 10 Truss core sandwich panel (20 mm core height) with no filling

damaged area, from 805.77 to 897.88 mm^2, as shown in Fig. 7. This increase is due to the greater impact force at higher velocities. However, it is not the most significant factor, as indicated by the main effect plot. Higher impact energy would ensure penetration but not necessarily lead to a further extension of the damaged area, as will be demonstrated later in the study.

Figure 10 shows the damaged area of the truss core sandwich panel with no filling. It can be seen that the damage area increases as the impact height increases. A similar trend is observed in all samples regardless of core topology or filling material.

Regarding core geometry, it is evident that when a sandwich panel features an entirely hollow core, it cannot withstand damage as well as other panels with cellular cores. However, it is used as a control specimen for the purpose of comparison. In the case of the strut and spring topologies, the core's volume fraction remained the same. However, the spring core resulted in a higher damaged area, decreasing from 501.45 to 301.58 mm^2 compared to the strut.

When comparing the topology of the strut and spring core, results showed the spring has the ability to effectively withstand impact forces by absorbing energy, primarily due to its higher in-plane elastic modulus. Moreover, the spring topology exhibits higher flexural stiffness than that of the strut. Therefore, in terms of the damaged area, the spring core redistributes both shear forces and out-of-plane compression forces across neighboring cells, which results in a larger damaged area.

As a result, the impact forces are transmitted not just to the immediate vicinity of the point of impact but also to neighboring cells within the core. This widespread load distribution causes neighboring cells to deform, resulting in a more extensive area of damage on the face sheets. In contrast, the strut core, with its higher flexural strength, confines the damage to a localized region, resulting in a smaller affected area that is not spread across the panel. Figure 11a–c shows the damaged area of the void core, spring core, and strut core sandwich panels with no filling, respectively. It can be seen that the lowest damage was observed in the front and back face sheets of the

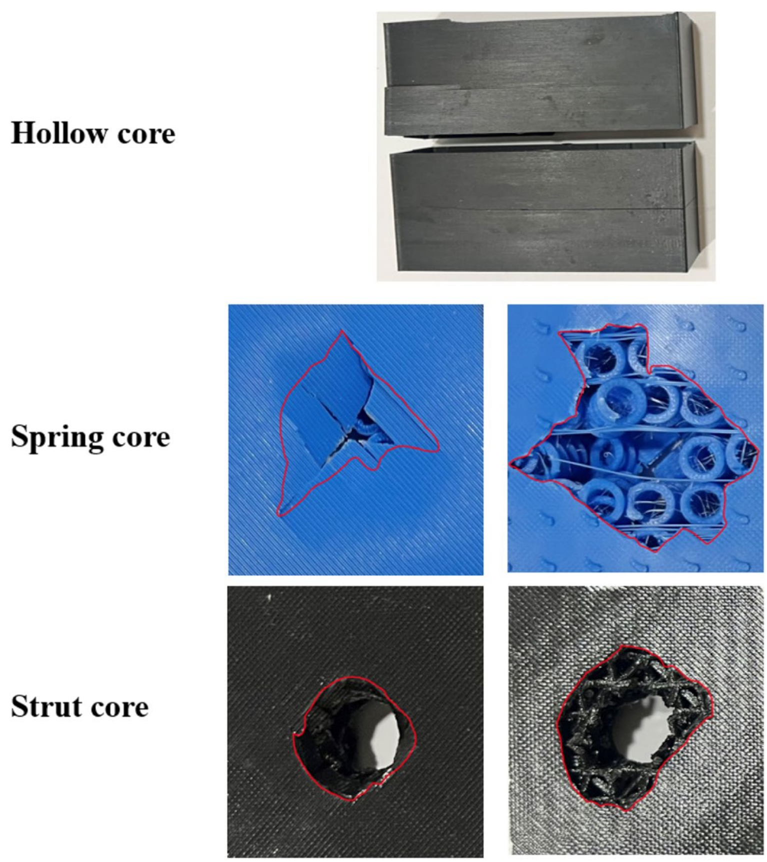

Fig. 11 Sandwich panels with a 20-mm core at an impact height of 15 cm. Note: all sandwich panel samples are manufactured from the same spool

truss core while the void core has the highest damage since the specimen broke in half.

While examining the effect of different fillings, it is observed that the absence of fillings results in the greatest damage as seen in Fig. 7. This is primarily due to the minimal material stiffness within the cellular core. The inclusion of fillings serves the purpose of introducing an additional layer of damping material to the cellular core, contributing to its overall energy absorption capabilities.

The foam-filled samples demonstrate superior performance compared to sandwich panels filled with silicon and resin. Specifically, the damaged area at the back side in the foam-filled sandwich panel is significantly reduced compared to that in the resin-filled panel, with values of 995.5 mm^2 and 201.34 mm^2, respectively. This improvement can be attributed to the reinforcement of specimen stiffness achieved through foam filling. The crushable nature of polyurethane foam plays a crucial role in mitigating damage and dissipating the energy applied in crushing the foam inside rather than the back sheet of the panel. On the other hand, silicon outperforms epoxy resin as a core filler, even though the resin can withstand higher in-plane forces due to its superior strength, but the superiority of silicon is attributed to its greater ductility exhibiting a higher toughness than that of the resin.

Figure 12a–d shows the damaged area of the truss core sandwich panel with no filling, resin filling, foam filling, and silicon filling, respectively. It is evident that the foam and silicon filling have the lowest damage on both face sheets while unfilled panels have the highest damage.

To assess impact depth more effectively, variations in mass were considered, especially due to density differences in the fillings. Samples with resin and silicon showed a significant mass increase, particularly those without a core. This analysis determines the optimal sandwich panel configuration by evaluating the penetration depth relative to the weight of the samples. The optimal sample is identified as the one with the least penetration per gram of material, indicating higher impact resistance and efficiency. To normalize the depth of impact, a specific depth was used which indicates the depth of impact per unit mass (Eq. 1).

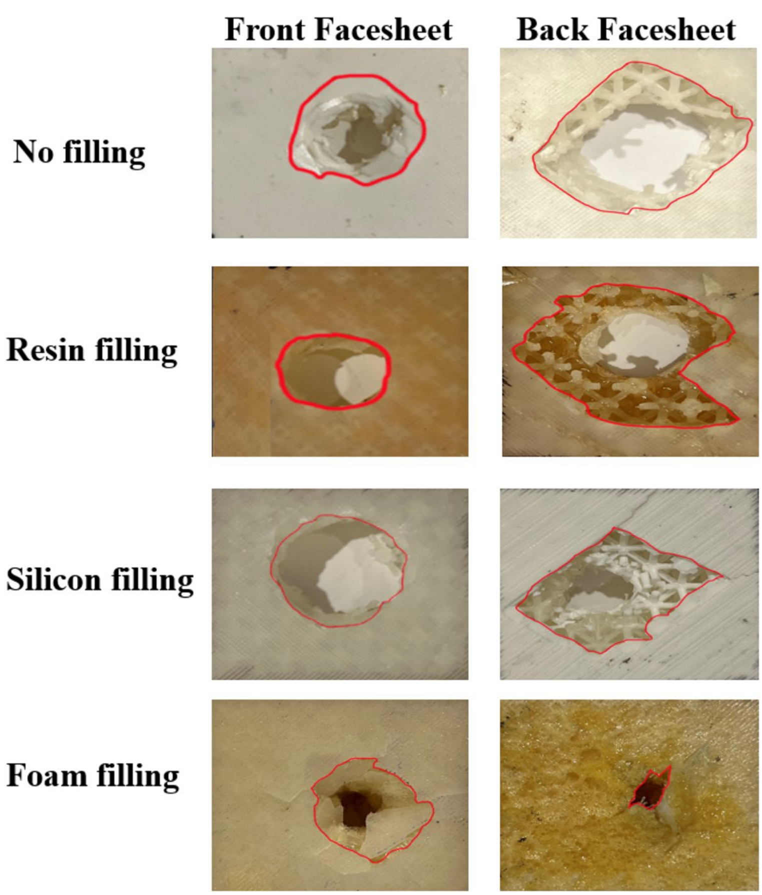

Fig. 12 Sandwich panels at impact height 15 cm

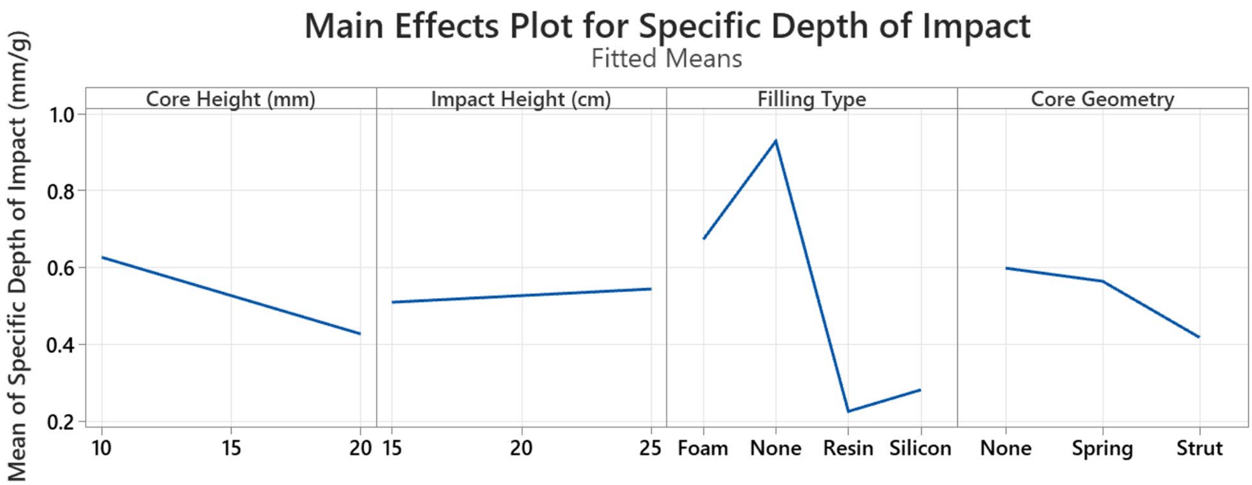

Fig. 13 Main effects plot for specific depth of impact

$$\text{Specific depth of impact} = \frac{\text{Depth of impact (mm)}}{\text{Mass after filling (g)}} \tag{1}$$

Figure 13 shows the influence of the core height on the specific depth of impact, decreasing from 0.583 to 0.42 mm/g as the core height increased from 10 to 20 mm. A similar trend is seen in Fig. 15 for the change of specific depth with the change of impact height, where higher energy results in deeper penetration and a larger damaged area.

Analyzing Fig. 13 shows that the truss core displayed the smallest specific depth of penetration. The truss core's superior energy absorption capacity and stiffness differentiated it from the spring core, which distributed impact depth along the sandwich panel's height. Figure 13 shows that resin and silicon fillings provided the lowest depth of impact followed by foam core and then the empty core.

Comparing Figs. 13 and 7, it can be analyzed that the mean damage area with resin filling was high when compared to the case where the mean specific depth was notably low. This change comes from cases where low-velocity impact did not lead to perforation of the sandwich panels. In such cases, the impact depth was much lower than that observed in samples filled with either silicon or foam.

Figure 14 shows the interaction plot for specific depth involving the core geometry and filling type, showing their significant interaction. Pareto analysis in Fig. 15 proves this interaction, with silicon and resin fillings not making a difference for strut elements, whereas foam improves the structure for strut elements but not for spring elements. Figure 15a indicates that the core geometry is the most influential factor for the damaged area in the front face sheets, with increased effects from second-order interactions. Figure 15b shows core height's second-order interactions for the damaged area in the back face sheets. For specific depth, the filling type is the primary factor, followed by its second-order interaction with core geometry.

Regression analysis

Statistical analysis was conducted evaluating the impact of core topology, core filling, and core height on the damaged area of the front and back face sheets, and the specific depth of impact. Regression analysis plays an important role in understanding the impact on sandwich panels by quantifying the effects of variables like core geometry, filling type, and impact height on panel damage.

Response surface methodology was used for building a regression model, excluding terms with high P values in the analysis of variance, resulting in linear terms and their interactions. The model achieved a good fit with R^2 values of 88.46% for the damaged area front, 87.45% for the damaged area back, and 93.74% for specific depth. Regression equations (Tables 3, 4, and 5) describe how core height and impact height influence damage area and depth of impact, presented in a linear format as follows:

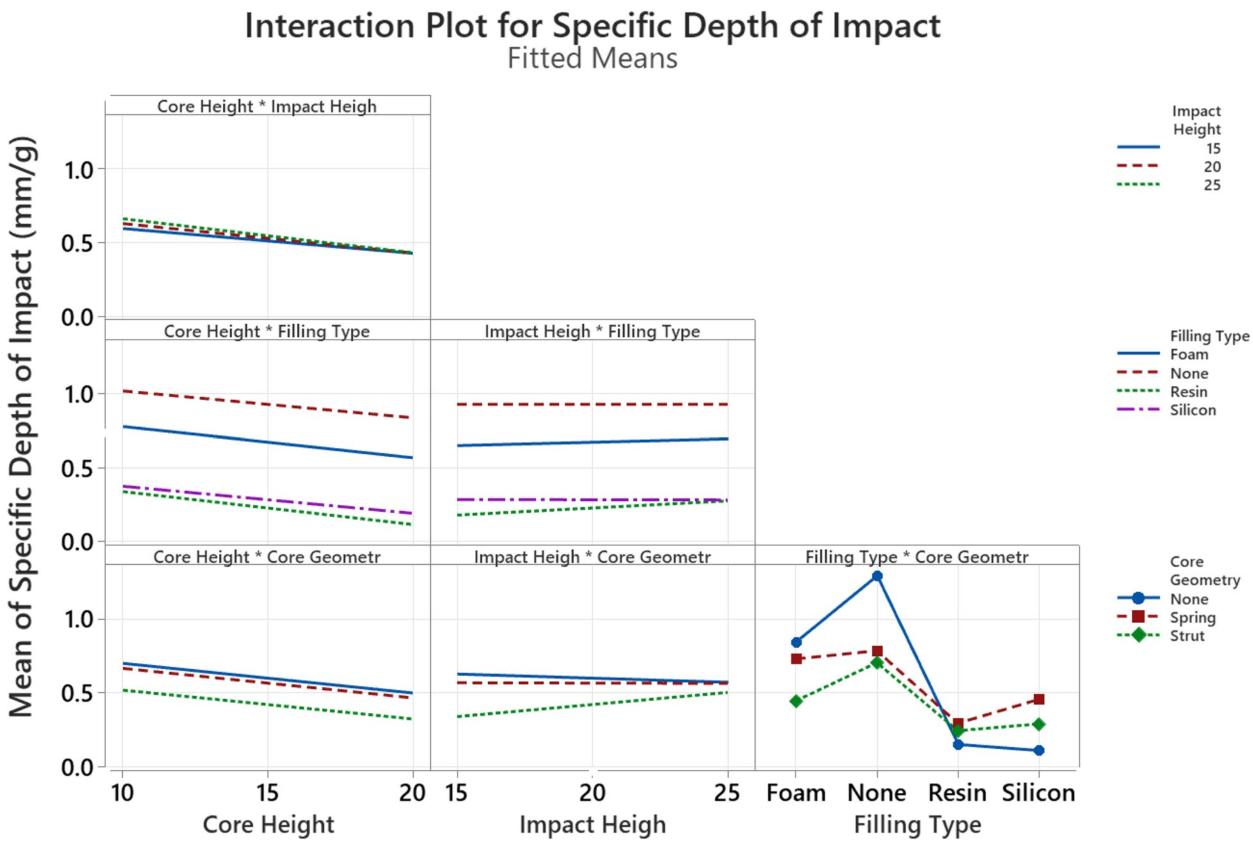

Fig. 14 Interaction plot of specific depth with core height, impact height, and core geometry

$$R = a + b(H_C) + c(H_I) + d(H_C)(H_I) \quad (2)$$

where H_C and H_I are the core height (mm) and impact height (cm), respectively. a is the constant, b is the linear coefficient of core height, c is the linear coefficient of impact height, and d is the two-way interaction coefficient between core height and impact height. The values of these terms are provided in Tables 3, 4, and 5 for each of the response variables.

Classification modeling

Decision tree analysis was used to model whether penetration will occur for that panel or not. Classification tree model (CART®) in Minitab statistical software was used for that purpose. The Classification tree model (CART) serves a pivotal role in predicting penetration events in sandwich panels, functioning as a binary classification tool to discern the conditions leading to material failure or impact resistance. This model's utility extends significantly into safety-critical applications, particularly in sectors like the aerospace industry. Understanding the probability of penetration is key to making informed design choices that bolster aircraft safety. Manufacturers can leverage this model to identify optimal combinations of core materials and fillers, effectively minimizing penetration risks and thereby upholding higher safety standards. This practical application of the CART model demonstrates its importance in enhancing material safety and reliability in critical environments.

Results reveal the most crucial variables among the input parameters within the tree. Results of the model are given in Fig. 16, indicating which conditions would result in penetration. It shows that a sandwich panel with a spring core will have a 100% chance of perforation while a strut core and a void core will have a 52.4% chance of perforation. However, if these cores are filled with either resin, silicon, or foam, they will have a 41.2% chance of penetration while it will be 100% if no fillers are used. Tables 6 and 7 present a detailed overview of the confusion matrix and its associated statistics, providing valuable insights into the model's classification performance. Notably, the highest level of accuracy was achieved for the "no penetration" event, with a perfect accuracy rate

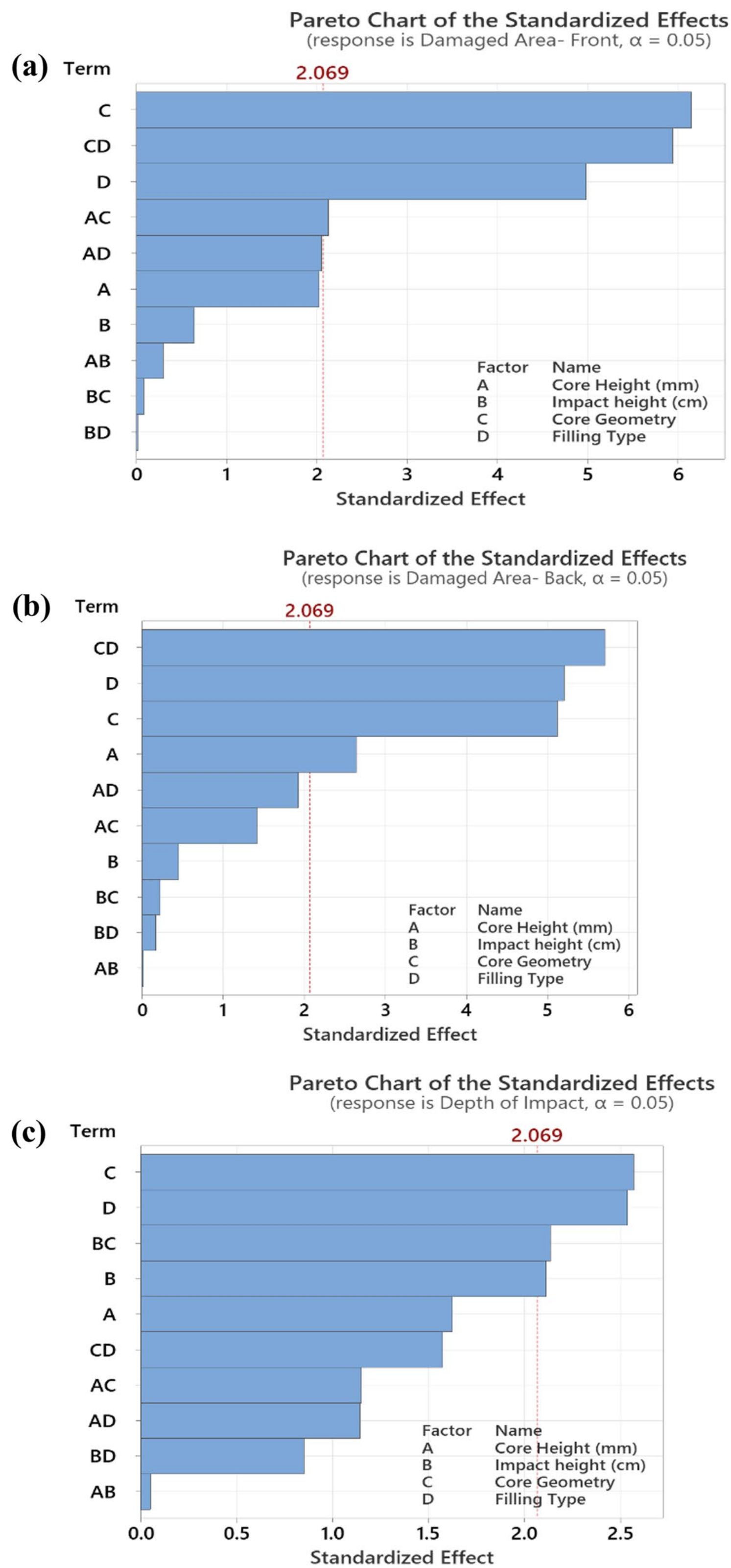

Fig. 15 Pareto charts for **a** damaged area on front face sheets, **b** damaged area on back face sheets, and **c** impact depth

Table 3 Regression analysis equations for damage area on front face sheets

Core geometry	Filling type	*a*	*b*	*c*	*d*
None	Foam	2278	124	− 24.9	1.31
Spring	Foam	283	3	− 4.6	1.31
Strut	Foam	20	6	− 12.9	1.31
None	None	6492	120	− 3.2	1.31
Spring	None	-285	0	17.1	1.31
Strut	None	-263	10	8.8	1.31
None	Resin	6445	268	13.8	1.31
Spring	Resin	2225	148	6.4	1.31
Strut	Resin	1968	138	− 1.9	1.31
None	Silicon	1803	105	− 23.1	1.31
Spring	Silicon	-286	15	− 2.8	1.31
Strut	Silicon	17	24	− 11.1	1.31

Table 4 Regression analysis equations for damage area on back face sheets

Core geometry	Filling type	*a*	*b*	*c*	*d*
None	Foam	1553	85	− 12.9	0.09
Spring	Foam	461	17	− 11.9	0.09
Strut	Foam	− 350	7	18.4	0.09
None	None	6054	− 84	10.1	0.09
Spring	None	10	18	11.1	0.09
Strut	None	− 407	8	41.4	0.09
None	Resin	5657	− 243	23.7	0.09
Spring	Resin	2327	− 142	24.8	0.09
Strut	Resin	1554	− 151	55.1	0.09
None	Silicon	2007	− 99	− 27.4	0.09
Spring	Silicon	956	2	− 26.4	0.09
Strut	Silicon	448	− 7	3.9	0.09

Table 5 Regression analysis equations for specific depth of impact

Core geometry	Filling type	*a*	*b*	*c*	*d*
None	Foam	0.247	0.023	0.00119	0.000243
Spring	Foam	0.125	0.022	0.00191	0.000243
Strut	Foam	0.058	0.0136	0.00553	0.000243
None	None	0.307	0.0346	0.00036	0.000243
Spring	None	− 0.035	0.0336	0.00347	0.000243
Strut	None	− 0.054	0.0252	0.00708	0.000243
None	Resin	− 0.009	0.0041	0.00419	0.000243
Spring	Resin	0.023	0.0032	0.00730	0.000243
Strut	Resin	0.092	0.0052	0.01091	0.000243
None	Silicon	0.140	0.0048	0.00154	0.000243
Spring	Silicon	0.235	0.0038	0.00157	0.000243
Strut	Silicon	0.147	0.0046	0.00518	0.000243

of 100%. Conversely, the event of "penetration" exhibited the lowest accuracy during the training phase, reaching 65%.

However, when considering the overall performance of the model, particularly its ability to accurately classify the "penetration" event, it is found that it performs commendably. During the training phase, the model achieved an accuracy rate of 76.7% in classifying penetration events, and this performance was maintained at 72.2% accuracy during the testing phase. These results are promising, especially when considering the size of the sample dataset, and they underscore the model's potential for robust classification in scenarios involving penetration events.

Conclusion

In this research, a comprehensive experimental analysis was conducted to assess the energy absorption capabilities of various sandwich panels under low-velocity impact conditions. These panels featured distinct core topologies and filling materials, incorporating two cellular core designs- namely, spring and octet truss. The panels were filled with silicon, foam, or epoxy resin. A total of 48 individual samples were tested, each subjected to various combinations of independent variables. The experiments, conducted through drop tower tests, examined the impact of core geometry, core height, filling type, and impact height on the performance of the sandwich panels. Fused deposition modeling (FDM) technology was utilized to print PLA panels. Three different fillings (i.e., polyurethane foam, epoxy resin, silicon) were selected as infills due to their unique mechanical properties. Polyurethane foam exhibits high thermal stability, epoxy resin offers high performance, and silicon possesses high toughness.

Results indicated that core height, filling type, and core geometry significantly influenced the damaged area and depth of impact. Core height exhibited a linear inverse relationship with the damaged area, attributed to increased core stiffness with higher core heights. Core geometry played a role in the damaged area, with the spring core recording the highest damage for panels without fillings. In terms of depth of impact, core height had the most pronounced effect, followed by impact height. The spring core results in a larger damaged area compared to the strut core since the spring core redistributes forces, leading to a more extensive area of damage. Sandwich panels filled with polyurethane foam outperformed those filled with resin and came very close to silicon in terms of reducing the damaged area at the back face sheet. However, they failed to reduce the depth of penetration compared to the resin and silicon-filled structures.

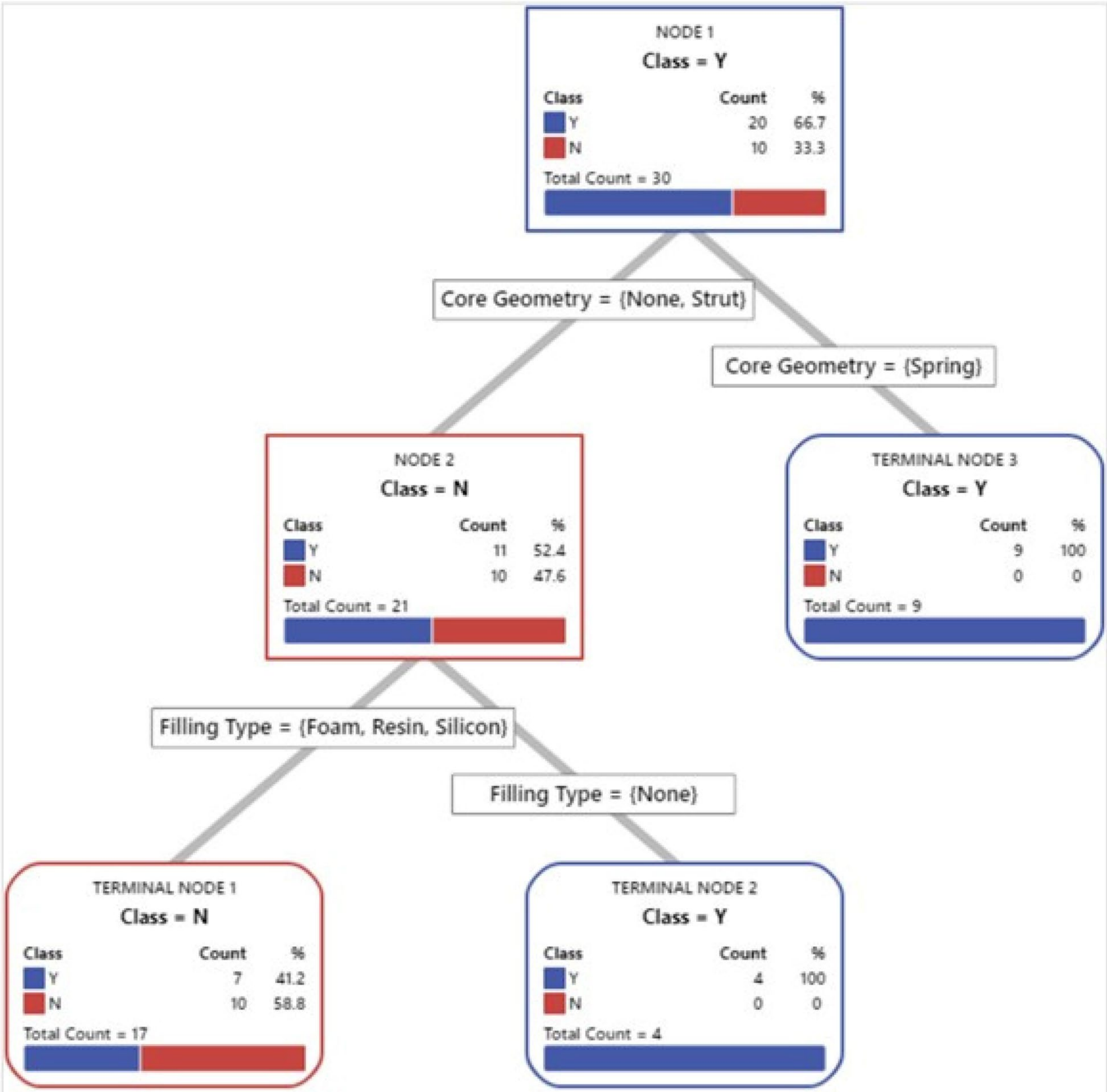

Fig. 16 Decision tree for penetration of sandwich panels

Table 6 Confusion matrix for 3 node CART

	Predicted class (training)				Predicted class (test)			
Actual Class	Count	Penetration (Y)	No Penetration (N)	%Correct	Count	Y	N	%Correct
Penetration (Y)	20	13	7	65	14	10	4	71.4
No penetration (*N*)	10	0	10	100	4	1	3	75
All	30	13	17	76.7	18	11	7	72.2

Table 7 Statistics for the confusion matrix

Statistics	Training (%)	Test (%)
True positive rate (sensitivity or power)	65	71.4
False positive rate (type I error)	0	25
False negative rate (type II error)	35	28.6
True negative rate (specificity)	100	75

Regression analysis was used to model the damaged area and depth of penetration in terms of the design factors. The models were able to predict the behavior with a high level of accuracy, achieving the largest R^2 of 93.74%. Decision trees were also utilized to predict the probability of penetration occurrence based on the structural element shape and filling type yielding a confusion matrix, with an accuracy of 72.2% during the testing phase. Designers can employ the developed model to assess penetration outcomes for a particular application.

Abbreviations

CFRP Carbon-fibre reinforced polymer
FDM Fused deposition modeling
PLA Polylactic acid

Authors' contributions

AC worked on methodology, investigation, experimentation, data Analysis, and writing the first draft. NMH worked on conceptualization, methodology, formal analysis, supervision, and editing and revision of final version. ZB worked on conceptualization, methodology, investigation, supervision, and editing and revision of the final version. MI worked on methodology and experimentation. All authors read and approved the final manuscript.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: this work was supported by the American University of Sharjah [FRG Grant No FRG21-M-E82]. The authors acknowledge the support of the American University of Sharjah under the Open Access Program. This paper represents the opinions of the authors and does not mean to represent the position or opinions of the American University of Sharjah.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

Received: 31 March 2024 Accepted: 19 July 2024
Published online: 22 August 2024

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