

Article

Experimental and Numerical Analysis of the Impact Resistance of Polyurethane Foam Aluminum-Concrete Sandwich Structures

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Abstract: The objective of this research paper is to examine the shock-absorption capabilities of sandwich structures that utilize polyurethane foam and aluminum as energy-absorbing materials. A series of drop weight impact tests were conducted on sandwich structures comprising polyurethane foam, aluminum, and concrete. The investigation encompasses variations in the thickness of the polyurethane foam-aluminum absorption layer, the impact height, and different structural combinations, coupled with numerical simulations. Results indicate that as the thickness of the polyurethane foam-aluminum energy absorption layer increases, the energy absorbed by the composite structure also increases. However, the rate of this increase tapers off as the layer thickness continues to grow. The impact height influences energy absorption within a defined range, enabling optimal utilization of the deformation and energy absorption capacities of the polyurethane foam-aluminum layer. Notably, the double-sandwich structure outperforms the single-sandwich structure in terms of impact resistance. The incorporation of the polyurethane foam-aluminum sandwich structure significantly enhances the impact resilience of concrete. Among the tested configurations, the double-sandwich structure composed of polyurethane foam, aluminum, and concrete exhibits the optimal absorption performance. Nevertheless, the layered nature of the structure significantly increases its construction complexity, potentially impacting the practical feasibility of utilizing the polyurethane foam-aluminum-concrete composite structure in real-world applications.



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Keywords: polyurethane foam-aluminum; concrete; sandwich structure; impact test; numerical simulation

1. Introduction

A variety of approaches are available for examining the impact resistance characteristics of concrete structures. One sophisticated method involves improving the mechanical properties of cement by incorporating other materials to formulate cement nanocomposites [1]. Another technique to enhance the mechanical properties of concrete involves utilizing carbon fiber-reinforced polymer (CFRP) grids and engineered cement-based composites (ECC) [2]. Furthermore, the addition of materials such as silica fume, bentonite, and recycled clay brick aggregates to concrete can significantly elevate its compressive strength, splitting tensile strength, and flexural strength [3–5].

In addition to the incorporation of various admixtures into the concrete mix, a notable research direction and trend involves the design of sandwich concrete structures that feature innovative energy-absorbing layers.

Metallic foams, particularly, have gained widespread adoption as energy-absorbing materials. Several researchers have conducted explosion tests on aluminum foam and its sandwich panels to investigate the wavefront effect under shock-wave compression [6,7]. Additionally, theoretical analyses and numerical simulations have been performed to explore the dynamic compression behavior of metallic foams, leading to the establishment of

constitutive models [8,9] and finite element models [10,11]. Guo Kailing et al. [12–14] examined the impact resistance of aluminum foam sandwich structures and correlated their findings with numerical simulations. Shokrieh M M et al. [15] formulated a three-dimensional constitutive model based on load-time and energy-time curve analyses. Cooper V and Michailidis N et al. [16,17] validated, through finite element calculations of impact tests, that the predicted load, energy, and deformation outcomes aligned with experimental results. Eva Kasperek et al. [18] conducted impact tests and three-dimensional numerical simulations on polyurethane foam, meticulously analyzing the impact of temperature, strain rate, and specific stress states on load-deformation. Rostamiyan, Y. et al. [19] found that polyurethane foam-filled sandwich panels exhibit greater load-bearing capacity than the sum of unfilled samples and samples filled with polyurethane blocks. Meanwhile, research by Shen Mingjie et al. [20] indicated that the stress-strain response of rigid polyurethane foam was sensitive to strain rate, and demonstrated excellent energy absorption capabilities. Wang Jie [21] and I. Ivanez [22] respectively conducted low-speed and high-speed impact tests, and related numerical simulations on polyurethane sandwich structures reinforced with glass fiberboards and carbon fiberboards, delving into the correlation between impact energy and sandwich panel damage, as well as energy absorption by the interlayer. Sunith babu Loganathan et al. [23] studied the low-speed drop hammer impact response of glass fiber-sandwiched polyurethane boards, focusing on factors such as interlayer thickness and density. Zhang Wei et al. [24] analyzed the static mechanical properties of aluminum foam-polyurethane composites, while Xie Weihong [25,26] and Zhang Yong et al. [27] conducted relevant experimental investigations into the dynamic properties of polyurethane foam-aluminum composites.

This article presents a novel composite material achieved through the infill of open-cell aluminum foam panels with polyurethane foam, significantly augmenting the energy-absorbing capabilities of aluminum foam. This composite material serves as an innovative energy-absorbing interlayer. A drop hammer impact test is conducted to assess its performance in absorbing energy within concrete plate composite structures during impact tests. Subsequently, numerical simulation techniques are employed to iterate on relevant test parameters, aiming to optimize the composite structure further.

2. Experimental Program

2.1. Materials

The cement utilized in the experiment is the high-strength PII525 cement, manufactured by Jiangnan-Onoda Cement Co., Ltd., located in Nanjing, China. The fine aggregate comprises washed river sand, characterized by a bulk density of 1480 kg/m³, an apparent density of 2650 kg/m³, a void ratio of 42%, a minimal moisture content of 0.3%, and a fineness modulus of 2.5. The coarse aggregate consists of locally sourced crushed stone used within the laboratory, featuring a maximum particle size of under 20 mm, and adhering to the criteria for continuous grading. The experiment employs neutral purified water. The water-reducing agent is a naphthalene-based reducer, effective in reducing water by a rate of 18 to 25%. The silica fume used is 98-micron grade, specifically for experimental purposes, while the fly ash is of Yuanheng Brand Grade 1. The definitive mix proportions of the concrete are outlined in Table 1.

Table 1. Concrete proportion table (kgm^{−3}).

Water	Cement	Silica Powder	Fly Ash	Sand	Crushed Stone	Water Reducer
150	370	80	50	595	1155	9

The aluminum foam used in this project is the open-cell aluminum foam manufactured by Shanghai Zhonghui Aluminum Foam Material Co., Ltd. (Shanghai, China). The specific parameters of this material are detailed in Table 2.

The polyurethane foam material consists of a two-component agent, achieving a density of approximately 0.3 g/cm³ once foamed.

Table 2. Foam aluminum performance parameters.

Pore Size	Porosity	Open Cell Content	Bulk Density	Compressive Strength σ_c	Flexural Strength σ_w	Tensile Strength σ_b
1.66 mm	68~78%	90~95%	0.60~0.85 g/cm ³	8.61 MPa	8.06 MPa	3.41 MPa

The drop hammer test utilizes a circular hammer head with a diameter of 50 mm. To mitigate boundary and size effects, the test panel dimensions are set at 300 mm × 300 mm. For this test, a total of 10 concrete panels, each with a thickness of 100 mm, 3 concrete panels with a thickness of 66 mm, and 12 polyurethane foam-aluminum panels, each with a thickness of 8 mm (intended to be combined into various thickness energy-absorbing layers), were produced.

The aluminum foam panels, supplied by the manufacturer, measure 500 mm × 500 mm, and have a thickness of 8 mm. These panels were cut down to 300 mm × 300 mm using a cutting machine for testing purposes. The polyurethane foam material is a blend of black and white components for foaming, and the detailed production process of the specimens is illustrated in Figure 1.

**Figure 1.** Polyurethane foam-aluminum case diagram.

2.2. Drop Hammer Impact Test

This test utilizes the JLW-800 drop hammer impact testing machine, manufactured by Jinan Shangtai Company (Jinan, China). The device, along with its schematic diagram, is depicted in Figure 2. The experiment was conducted in accordance with the requirements of GB/T 8363-2007 [28], “Drop-weight Tear Test Method for Ferritic Steels”. The instrument provides a versatile display of nine types of curves, including the original curve, force-time, acceleration-time, force-displacement, and several other types.

**Figure 2.** Drop hammer test machine.

To examine the impact of varying thicknesses of polyurethane foam-aluminum energy-absorbing layers on the energy absorption capabilities of composite structures, the most widely studied sandwich structure was chosen. This structure comprises 100 mm thick concrete panels for the top and bottom layers, with polyurethane foam-aluminum panels serving as the middle. Under a constant external impact load, the thickness of the intermediate energy-absorbing layer was adjusted for testing purposes (as illustrated in Figure 3). Given that each foam aluminum panel has a thickness of 8 mm, the energy-absorbing layer thickness was set at 8 mm, 16 mm, and 24 mm to streamline the experimental process. Table 3 outlines the specific experimental schemes employed.



Figure 3. 24 mm specimen test images.

Table 3. Specimen table.

Test Group	Number	Number of Concrete Structural Layers	Concrete Structure Thickness/mm	Number of Polyurethane Foam Aluminum Interlayers	Polyurethane Foam Aluminum Interlayer Thickness/mm	Drop Hammer Height	Impact Energy	Impact Velocity
1	A	2	100	1	8	—	—	—
1	B1	2	100	2	16	—	—	—
2	B2	2	100	2	16	—	—	—
3	B3	2	100	2	16	—	—	—
3	C	2	100	3	24	—	—	—
1	D	3	66	2	16	—	—	—

2.3. Numerical Simulation Test

Using the ANSYS/LS-DYNA 17.0 software, a numerical simulation was performed for the drop hammer test of the polyurethane foam-aluminum sandwich concrete composite structure. After validating the accuracy of the simulation outcomes, a supplementary analysis was carried out on the experimentally selected variables.

2.3.1. Material Property Definition

In consideration of the practical scenario where concrete material loses its overall functionality upon experiencing through-cracking damage, for computational simplicity, both the concrete and polyurethane foam-aluminum materials were modeled as homogeneous materials during the simulation. The hammer head utilized the *MAT_JOHNSON_COOK model. The weight of the drop hammer tester's hammer head was primarily augmented through the addition counterweight, achieving the necessary mass by adjusting its density. The concrete employed the *MAT_JOHNSON_HOLMQUIST_CONCRET model, while the polyurethane foam aluminum utilized the *MAT_CRUSHABLE_FOAM model. Tables 4 and 5 provide specific parameters for these models.

Table 4. Concrete material parameter.

Parameter	Density/gcm ⁻³	Shear Modulus/GPa	A	B	C	N	T/Mpa	EPSO/10 ⁻⁶	EFMIN	SFMAX
Values	2.4	17.80	0.79	1.60	0.007	0.31	4	1	0.01	7.00
Parameter	PC/MPa	UC/MPa	PL/GPa	UL	D1	D2	K1	K2	K3	
Values	20	1.17	0.80	0.10	0.04	1.0	85	−171	208	

Table 5. Parameters of polyurethane-aluminum foam materials.

Parameter	Density/gcm ⁻³	Poisson's Ratio	Young's Modulus E/MPa	Tensile Strength TSC/MPa	Damping Factor DAMP
Values	0.8	0.3	130	0.10	0.10

2.3.2. Establishment and Meshing of the Specimen Solid Model

Utilizing cm-g-us modeling, the simulation encompasses the hammer head metal material, concrete, and polyurethane foam aluminum. To optimize computation time, the

model was constructed using 1/4 symmetry, as shown in Figure 4. This approach allows for an efficient representation of the full structure while reducing the computational burden.

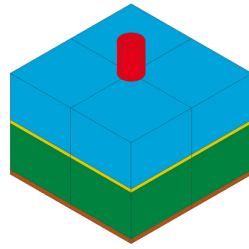


Figure 4. Structure modeling.

The hammer head is designed with a height of 70 mm and a bottom radius of 25 mm. A simple support is positioned at the bottom edge of the composite structure, and its three-dimensional configuration is illustrated in Figure 4. The contact surface between the specimen and the support measures 10 mm on each side. During the experiment, the composite structure employs a simple support method at the base; therefore, no constraints are imposed on the free interface. Given that the structure is modeled using the 1/4 method, the internal interface restricts movement in the vertical direction. This setup ensures that the simulation accurately reflects the experimental conditions while minimizing computational complexity.

3. Results

3.1. Impact Test Results

As illustrated in Figure 5, the energy curves of composite structures featuring various thicknesses of the energy-absorbing layer under an identical impact load are presented. The peak energy points of these three curves consistently hover around 900 J, which corresponds to the total impact energy. Figure 6 depicts the energy curves of an identical composite structure subjected to different impact loads. By comparing these curves, it is evident that when the composite structure with a 16 mm polyurethane foam-aluminum interlayer is impacted by drop hammers from heights of 1.8 m and 1.5 m, the structure undergoes severe damage, with the majority of the impact energy being absorbed. Conversely, when impacted by a drop hammer from a height of 1.2 m, the rebound energy is more pronounced, suggesting that under this impact condition, the structure remains partially intact and retains a certain level of functionality.

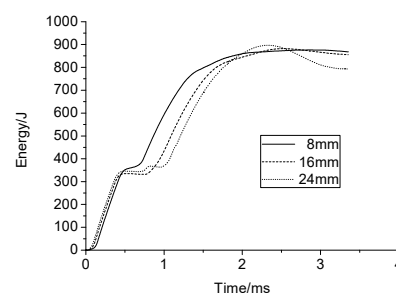


Figure 5. Energy time curve of different energy absorption impact energy layers of various thicknesses.

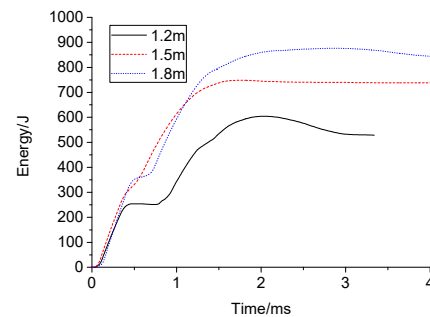


Figure 6. Energy time curve of different impact loads of the structure.

3.2. Accuracy Validation of Numerical Simulation Data

The JLW-800 drop hammer impact testing machine operates based on the principle of collecting experimental data through sensors attached to the hammer head. It records the load-time history curve by measuring the reaction force exerted on the hammer head by the specimen. Additionally, the displacement-time history curve of the hammer head is derived by integrating the corresponding acceleration of the load. Given that the time points for measuring both load and displacement coincide, a computer calculates the integral of the load-displacement curve to obtain the energy-time history curve. This energy-time history curve of the structure is chosen as the primary analysis target to validate the modeling accuracy.

Figure 7 showcases the stress contour maps of polyurethane foam-aluminum sandwich structures with varying thicknesses during the impact process, specifically at the moment when the peak load on the hammer head is reached. The distinct colors depicted in the figure represent the magnitude of stress in each component. Since the impact direction of the hammer head is aligned with the negative direction of the y -axis, warm colors signify lower stress levels, whereas cool colors indicate higher stress levels.

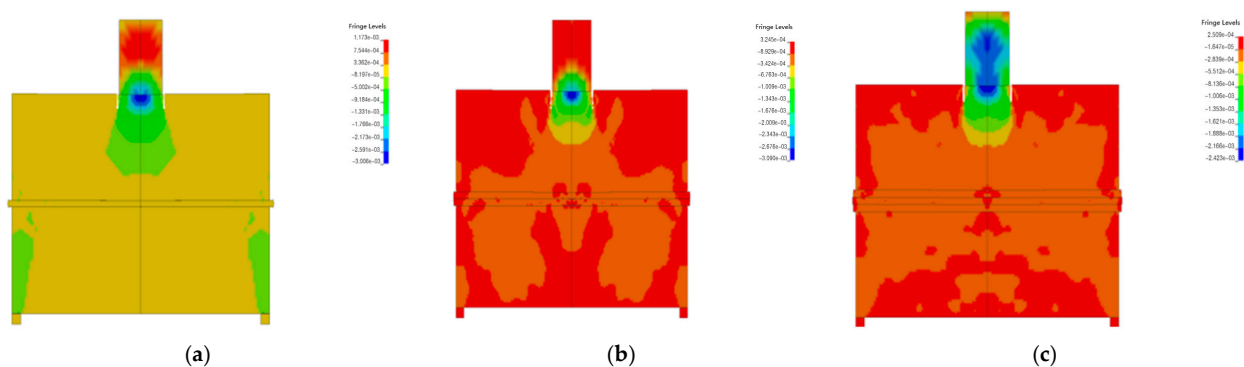


Figure 7. Stress cloud diagram of different polyurethane foam-aluminum energy-absorbing layers at the same time. (a) 8 mm, (b) 16 mm, and (c) 24 mm.

The observations indicate that as the thickness of the polyurethane foam-aluminum energy-absorbing layer increases, the area of stress variation on the front surface of the top concrete structure remains relatively constant. This aligns with the experimental analysis, suggesting that changes in the thickness of the energy-absorbing layer have minimal impact on the protection of the top plate's direct contact load surface. On the back surface, the stress decreases due to the diminished effect of reflected waves, which corresponds to experimental observations. Similarly, the internal stress of the bottom concrete plate decreases with an increase in the energy-absorbing layer's thickness, attributed to the layer's ability to weaken impact energy. This also concurs with experimental findings.

Figure 8 displays the numerical simulation curve derived from the Finite Element Method (FEM). The energy curve obtained from the numerical simulation data aligns closely with the experimental data, indicating a high degree of correspondence. Taking all

relevant factors into account, the numerical model constructed based on experimental data demonstrates considerable value in simulating experimental phenomena. Therefore, it can be utilized in subsequent analyses to conduct further research on impact tests, providing a reliable tool for understanding and predicting the behavior of composite structures under impact loads.

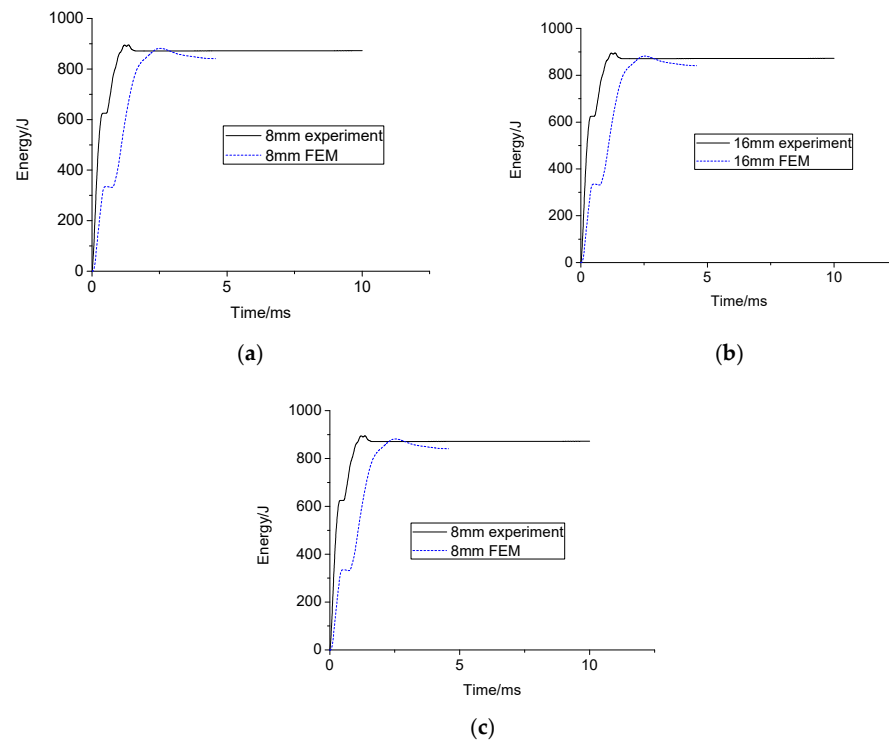


Figure 8. Polyurethane foam-aluminum sandwich structure energy comparison. (a) 8 mm, (b) 16 mm, and (c) 24 mm.

4. Discussion

4.1. Analysis of the Impact of Polyurethane Foam Aluminum Energy Absorption Layer Thickness on the Impact Resistance of Composite Structures

As the thickness of the energy absorption layer is augmented, it is observed that the internal structural damage sustained by the polyurethane foam-aluminum sandwich structure decreases. To achieve a more profound understanding of the precise influence of thickness on this phenomenon, a comparison group was established, with the detailed parameters outlined in Table 6.

Table 6. Energy absorption layer thickness.

Number	1	2	3	4	5	6	7
The thickness of the energy-absorbing layer/mm	1	2	4	8	16	24	100

Figure 9 depicts a line graph illustrating the penetration depth of the hammer head into the top concrete plate at the point of maximum damage for structures featuring various energy absorption layer thicknesses. Upon comparison, it is evident that as the energy absorption layer thickness is increased from 1 mm, 2 mm, and 4 mm, the penetration depth of the hammer head into the top plate steadily rises. However, when the energy absorption layer thickness reaches 8 mm, the penetration depth remains relatively stable, and ceases to exhibit significant changes with further increases in thickness. This observation aligns well with the experimental findings. Among the three structures, each with distinct energy absorption layer thicknesses, the degree of damage to the top plate remains compara-

ble, showing no notable differences associated with variations in the energy absorption layer thickness.

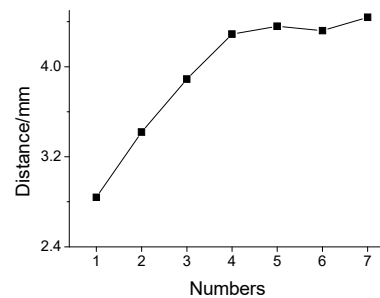


Figure 9. Line chart of penetration depth.

Figure 10 presents a line graph that illustrates the energy absorption of the top and bottom concrete plates following impact for the structures equipped with varying thicknesses of the polyurethane foam-aluminum energy absorption layer. Upon comparing the data, it becomes apparent that as the thickness of this energy absorption layer increases, the absorbed energy of the top concrete plate exhibits a slow upward trend. This increase corresponds to a shift in the damage mode of the top structure, transitioning from shear failure to penetration damage within the annular region of the concrete. Conversely, the bottom concrete plate exhibits a marked decrease in energy absorption, clearly demonstrating the protective efficacy of the polyurethane foam-aluminum layer in safeguarding the internal structure.

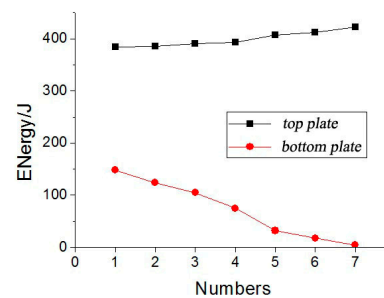


Figure 10. Energy absorption of different thicknesses of concrete slab structures.

Table 7 presents the impact duration of polyurethane foam-aluminum structures, featuring various thicknesses of the energy absorption layer. Through comparative analysis, it is evident that as the thickness of the energy absorption layer increases, the impact duration experiences a notable improvement. Polyurethane foam aluminum, recognized for its exceptional cushioning and energy absorption capabilities, effectively reduces the overall stiffness of the composite structure. This reduction leads to an increase in the contact time between the impact load and the structure, thereby prolonging the impact duration.

Table 7. Impact over schedule of different thickness of energy absorption layer.

	1 mm	2 mm	4 mm	8 mm	16 mm	24 mm	100 mm
Impact end time/ms	0.812	0.928	1.27	1.53	1.92	2.33	5.18

4.2. Variation of Response to Different Impact Energies for the Same Structure

To conduct a detailed analysis of the structural response of polyurethane foam-aluminum-concrete composite structures with a consistent configuration to varying impact energies, a polyurethane foam-aluminum sandwich structure with a 16 mm thick energy absorption layer is selected. This structure features upper and lower concrete plates, each with a thickness of 100 mm. The specific details of this analysis scheme are outlined in Table 8.

Table 8. Comparison of different impact energies.

Number	Number of Concrete Structure Layers	Concrete Structure Thickness/mm	Polyurethane Foam Aluminum Sandwich Thickness/mm	Impact Energy/J	Impact Speed/ms ⁻¹
1	2	100	16	450	4.2
2	2	100	16	600	4.9
3	2	100	16	750	5.5
4	2	100	16	900	6
5	2	100	16	1050	6.5

Table 9 provides a comprehensive breakdown of the energy absorption by each layer within different structures following impact.

Table 9. Energy absorption table for three-Layer Structure (unit: J).

Number	The Remaining Energy of the Hammer Head	One-Layer Concrete	Two-Layer Concrete	Energy-Absorbing Layer
1	31	103	16	262
2	72	162	16	305
3	14.3	335	30	320
4	10.5	407	33	350
5	0	479	36	378

Figure 11 illustrates the energy absorption of the top concrete layer. It is noticeable that in Groups 1 and 2, where the top structures did not undergo penetration failure, they absorbed a comparatively smaller fraction of energy. Conversely, in Groups 3, 4, and 5, where penetration failure occurred in the top concrete panels, the absorbed energy surged significantly.

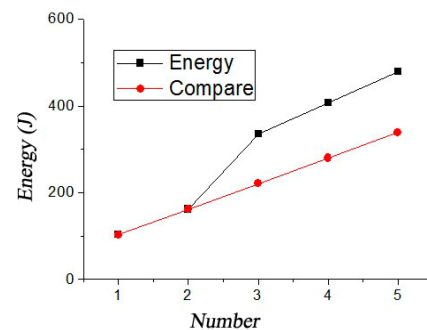
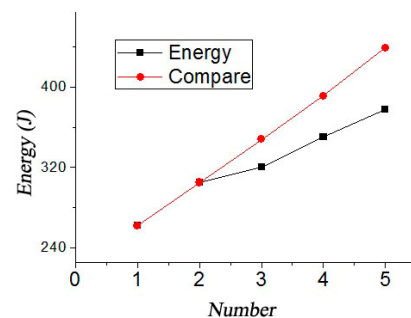
**Figure 11.** Top concrete energy absorption.

Figure 12 displays the energy absorption of the polyurethane foam-aluminum layer under varying impact loads. When compared to Groups 1 and 2, where penetration failure of the top concrete did not occur, the energy absorption trend of the energy absorption layer in Groups 3, 4, and 5 flattened out progressively as the impact energy escalated.

**Figure 12.** Polyurethane foam aluminum energy absorption.

Through a thorough analysis of various factors, it is evident that for an identical polyurethane foam-aluminum-concrete composite structure, when the structural integrity of the top plate is maintained, the polyurethane foam-aluminum layer demonstrates higher energy absorption efficiency, and the composite structure exhibits superior impact resistance. However, as the impact energy intensifies, and the damage to the top plate worsens, the energy absorption efficiency of the polyurethane foam-aluminum layer decreases markedly.

4.3. Analysis of the Impact of Structural Combination on Impact Performance

To delve deeper into the impact of structural combinations on the energy absorption efficiency of composite structures, a series of configurations was selected, featuring a concrete layer with a uniform thickness of 200 mm, and a polyurethane foam-aluminum layer with a collective thickness of 16 mm. These configurations encompass single-layer, double-layer, triple-layer, and quadruple-layer polyurethane foam-aluminum sandwich structures. The comprehensive structural parameters for these comparative analyses are detailed in Table 10.

Table 10. Structure combination parameter.

Number	Number of Concrete Structure Layers	Concrete Structure Thickness/mm	Number of Polyurethane Foam Aluminum Sandwich	Polyurethane Foam Aluminum Sandwich Thickness/mm	The Height of the Hammer/m	Impact Energy/J	Impact Speed/ms ^{−1}
1	2	100	1	8	1.8 m	900	6
2	3	66	2	8	1.8 m	900	6
3	4	50	3	5.3	1.8 m	900	6
4	5	40	4	4	1.8	900	6

Table 11 provides a timeline of when the peak load and maximum displacement occur. It reveals a consistent pattern where the maximum load precedes the maximum displacement, aligning with the experimental findings. Table 12 offers a detailed description of the final damage state of the structure.

Table 11. Peak load and displacement of the timetable (unit: ms).

	Peak Stress Time	Peak Displacement Time
Single mezzanine	1.36	1.52
Double mezzanine	1.15	1.34
Three mezzanine	1.35	1.52
Four mezzanine	1.48	1.6

Table 12. Structure damage form.

	Damage Form of Specimen	Displacement Difference (mm)
Single mezzanine	The hammer head penetrated into the top concrete plate, causing penetration damage with an approximate penetration depth of 0.42 cm. The top plate exhibited clear circular cracks with a depth of about 1.8 cm.	0.29
Double mezzanine	The top plate developed circular cracks with a depth of approximately 1.4 cm, and the hammer head did not cause any penetration damage to the concrete plate.	0.1
Three mezzanine	The hammer head penetrated into the top concrete plate, causing penetration damage with an approximate depth of 0.2 cm. The top plate exhibited clear circular cracks with a depth of approximately 3.2 cm.	1.2
Four mezzanine	The hammer head penetrated into the top concrete plate, causing penetration damage with a depth of 4 mm, and the top plate exhibited obvious through-and-through circular cracks.	2.3

Figure 13 illustrates the displacement contour of the composite structure at the point when the hammer head attains its maximum displacement. This critical moment corresponds to the final structural damage, which is comprehensively outlined in Table 12.

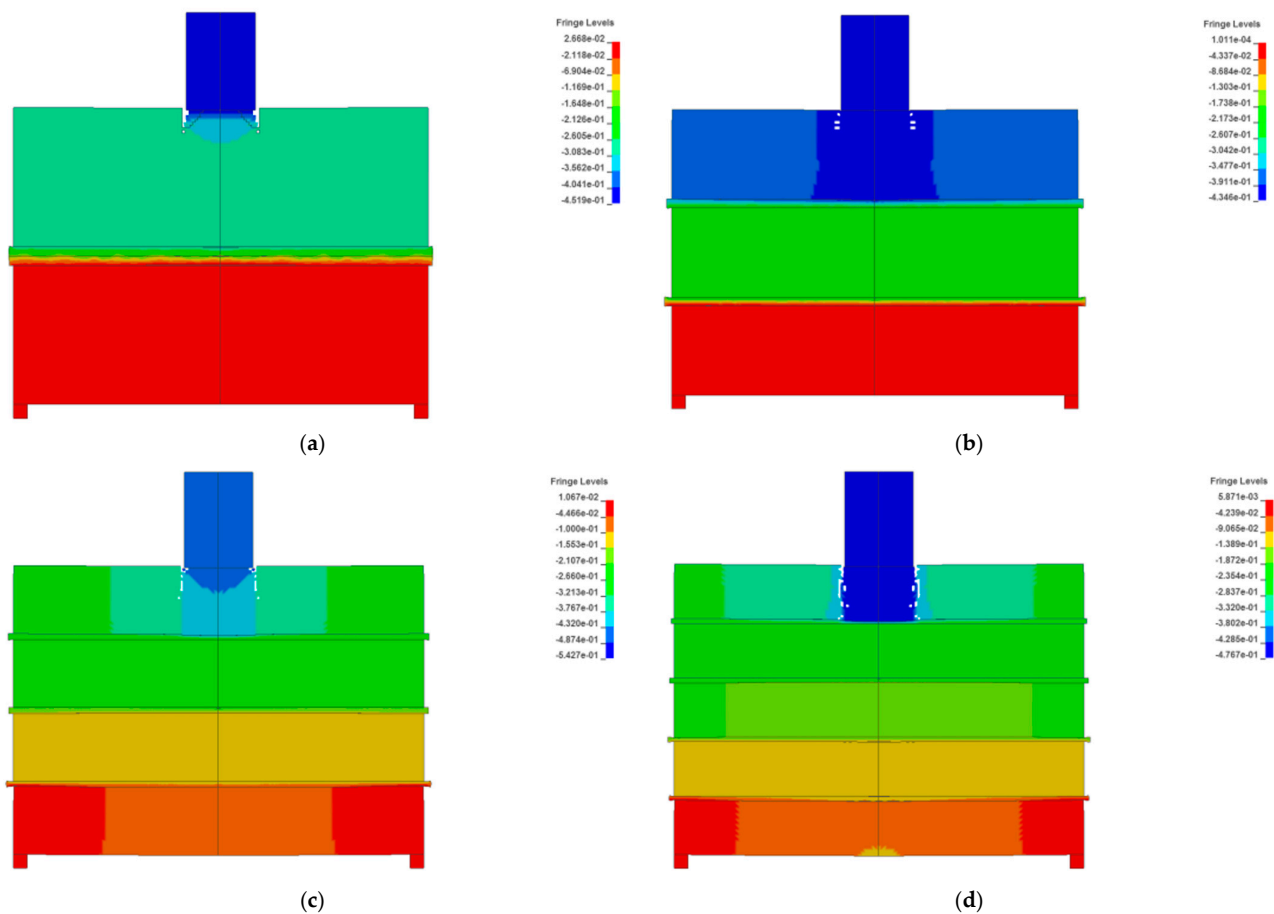


Figure 13. Structural displacement cloud diagram. (a) Single mezzanine, (b) double mezzanine, (c) three mezzanine, and (d) four mezzanine.

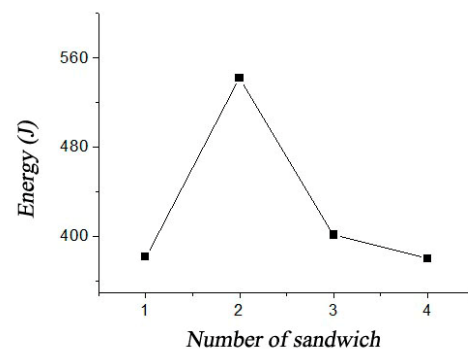
Upon examining the displacements of the base concrete plates, it becomes apparent that in both single-layer and double-layer sandwich configurations, the bottom plates exhibit a consistent coloration, suggesting an absence of bending deformation. However, in triple-layer and quadruple-layer sandwich structures, the bottom plates display marked color differences, indicative of varying degrees of bending deformation. Notably, in the quadruple-layer structure, the central segment of the bottom plate experiences concrete failure, due to excessive bending deformation.

Table 12 illustrates the displacement discrepancy between the centroid of the bottom concrete plate and the specimen boundary post-impact. Specifically, in the double-layer sandwich structure, the displacement discrepancy measures 0.1 mm, which is notably less than the 0.29 mm observed in the single-layer sandwich structure. As the number of structural layers escalates, so does the displacement discrepancy, reaching 1.2 mm in the triple-layer structure, and 2.3 mm in the quadruple-layer structure. A greater displacement discrepancy serves as an indicator of more pronounced bending deformation and subsequent structural damage. Additionally, Table 13 presents the energy absorption capabilities of each layer across various structures following the impact.

Table 13. Energy absorption table for five-Layer Structure (unit: J).

	Hammer Head Energy	One-Layer Concrete	Two-Layer Concrete	Three-Layer Concrete	Four-Layer Concrete	Five-Layer Concrete	One-Layer Energy Absorption Layer	Two-Layer Energy Absorption Layer	Three-Layer Energy Absorption Layer	Four-Layer Energy Absorption Layer
Single mezzanine	14.3	407	17	—	—	—	381.99		—	—
Double mezzanine	41.8	178	83	30	—	—	248	294	—	—
Three mezzanine	43	204	66	41	124	—	151	80.8	169.7	—
Four mezzanine	30.85	195	42	30.85	37	100	110.4	67.253	116.61	86

As depicted in Figure 14, the polyurethane foam aluminum in the double-layer sandwich structure demonstrates the peak energy absorption capacity. However, as the number of structural layers augments, the proportion of energy absorption by the polyurethane foam aluminum exhibits a declining trend. This phenomenon is primarily attributed to factors such as interlayer friction and voids resulting from excessive layering, which adversely impact energy absorption by reflecting energy waves.

**Figure 14.** Energy absorption of different structures absorbing energy layers.

Owing to constraints posed by testing equipment, the maximum cross-sectional dimension of the test specimens is confined to 300 mm × 300 mm, with the length and width being comparable to the structural thickness. Consequently, due to this small thickness-to-diameter ratio, a comparative analysis of parameters such as structural deflection is infeasible. To conduct a comprehensive investigation into the impact resistance of polyurethane foam-aluminum-concrete composite structures, it is imperative to augment the cross-sectional dimensions of the plates in future experiments, thereby enabling the exploration of a broader range of research variables.

A comprehensive analysis of the four structures reveals that the double-layer polyurethane foam-aluminum structure exhibits optimal energy absorption performance. As the number of structural layers escalates, and the top plate thickness diminishes, the ultimate bearing capacity decreases, leading to a decline in energy absorption efficiency under identical impact loads. Furthermore, an increase in structural layers significantly heightens the construction complexity, impacting the practical production and application feasibility of polyurethane foam-aluminum-concrete composite structures. Therefore, it is advisable to utilize an appropriate thickness of the energy absorption layer based on specific requirements in practical engineering, while avoiding excessive layering to uphold energy absorption performance and construction feasibility.

5. Conclusions

The specific conclusions are outlined below:

- (1) Analysis of structures with varying thicknesses of the energy absorption layer indicates that as the thickness of this layer increases, the energy absorption of the bottom

concrete plate decreases markedly. This reduction is attributed to the energy absorption capabilities of polyurethane foam aluminum, which also tends to decrease the overall stiffness of the composite structure.

- (2) An examination of composite structures with a consistent thickness of the energy absorption layer, but differing impact energy, reveals that while maintaining the structural integrity of the top plate, the energy absorption efficiency of the polyurethane foam-aluminum layer is directly proportional to the impact energy. However, as the impact energy rises and the top plate damage intensifies, the energy absorption efficiency of polyurethane foam aluminum decreases substantially.
- (3) The number of composite structural layers does not significantly enhance the impact resistance of polyurethane foam-aluminum-concrete composite structures. Specifically, the double-layer polyurethane foam-aluminum structure demonstrates the highest energy absorption performance. Nevertheless, as the number of structural layers increases, so does the complexity of construction, significantly impacting the practical production and application feasibility of these composite structures.

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