

FINITE ELEMENT ANALYSIS AND OPTIMIZATION OF IMPACT HONEYCOMB UNDER MICROGRAVITY

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Abstract: This study presents a finite element analysis to simulate the damaging effects of a 20g copper-aluminum alloy bullet in a microgravity environment. We established equivalent finite element models of the satellite structure. The optimal cell thickness (t) and cell width (L) were determined to be 0.10 mm and 5 mm, respectively. Bullets with velocities ranging from 1000 m/s to 600 m/s maintain a speed greater than 300 m/s, which is lethal. Ballistic tests were conducted by firing 20g copper-aluminum alloy bullets from a ballistic gun at an initial velocity of 1000 m/s. We analyzed the damage results and compared them with the simulation outcomes to validate their accuracy. The design of anti-satellite weapons proves effective, showing that a velocity of 900 m/s can successfully cause secondary breakdown of an aluminum panel. These anti-satellite weapons are capable of targeting any structure, including space stations.

Keywords: Debris; Honeycomb sandwich; High-speed; Ballistic impact; Kinetic energy; Microgravity

1 HIGHLIGHT

Optimization of aluminum honeycomb: The optimal states of cell thickness t and cell width L are calculated, it shows $t=0.10\text{mm}$ and $L=5\text{mm}$.

Breakdown: No matter the speed of the attack, it consumes 300 m/s of kinematic energy. The remaining velocity of 667m/s is equal to 1000m/s, which is also equal to the object at 600m/s. Therefore, 1000m/s can undergo two breakdowns.

Efficiency of Anti-satellite weapon design concept: the velocity of 900m/s can decrease the mass of other structures during launch, such as the mass or thickness of the barrel.

2 INTRODUCTION

In 1969, NASA opted to use a sandwich structure made of aluminum for the Apollo spacecraft. This design utilized a honeycomb core and a steel panel, achieving a weight reduction of 70-90% while maintaining comparable bending stiffness to a solid structure of the same material and thickness [1-2]. This made it ideal for the lightweight requirements of aircraft structures.

A honeycomb sandwich structure is a type of porous material, consisting of a hexagonal honeycomb core with lower density, sandwiched between two layers of thin composite materials [3-4]. This configuration provides higher strength and stiffness through welding or bonding. Porous materials, such as honeycomb structures, are widely used in aerospace, transportation, and other industries due to their ability to absorb energy during impact loads, offering buffering and damping effects. However, honeycomb sandwich structures can face challenges related to impact resistance during use. As shown in Figure 1, the structure includes two surface layers and one honeycomb core, which together form this mechanism.

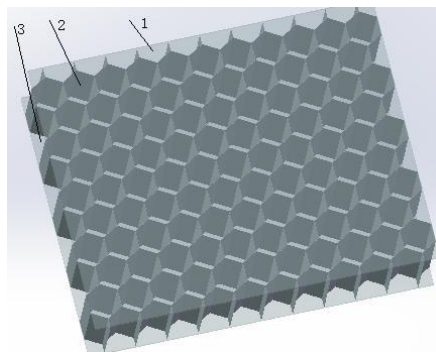


Figure 1 Schematic Diagram of Honeycomb Aluminum Structure (1-Panel; 2-Honeycomb; 3-Panel)

Honeycomb materials are widely used in the aerospace, machinery, and transportation industries due to their exceptional performance. Over the past few decades, researchers have focused on studying the structure and mechanical

properties of honeycomb materials [1]. Honeycomb boards are biomimetic structures that mimic the characteristics of bee nests [3]. The manufacturing process of aluminum honeycomb sandwich panels can be divided into two stages. First, the aluminum honeycomb core is produced, followed by bonding it with the outer skin to create a sandwich structure. Among the various types of honeycomb structures, the hexagonal shape is one of the most commonly studied and has received significant attention. For small deformations, the equivalent elastic parameters in the structural plane can be determined using classical beam theory, as described by the analytical formula proposed by Gibson [2]. The initial assessment of the mechanical properties of sandwich structures was documented by Allen [3]. Jiang [4] proposed a sandwich structure with a honeycomb core inspired by coconut trees, which enhances the impact mitigation performance of the structure [5].

When objects collide with satellites in orbit, the high kinetic energy can alter the satellite's position and trajectory, damage its surface and internal control systems, and potentially lead to the satellite's complete destruction. The object is propelled by gunpowder from a 12.7mm ballistic gun at a speed of 1000m/s, with a maximum speed tolerance of 5m/s. Aluminum honeycomb sandwich structures are extensively used in various industries, including spaceflight, aviation, and shipping, due to their excellent material properties. The positive hexagon aluminum honeycomb core is the most commonly used form of this core. Research into the mechanical functions of these products is essential for improving quality and ensuring safe and reliable use. Currently, widely used and authorized finite element method software lacks standard honeycomb sandwich elements. As illustrated in Figure 2, if an object accurately impacts the honeycomb sandwich board, it can cause damage to the internal structure of the components [6].

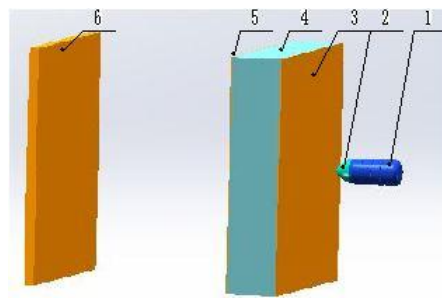


Figure 2 Object Attacks Honeycomb Aluminum on Satellites (1-Aluminum Core; 2-Copper Jacket; 3, 5-Aluminum Jacket; 4-Honeycomb Aluminum; 6-Target Aluminum)

Honeycomb sandwiches can be classified into three categories based on the speed of collisions: low-speed collisions [6-10], high-speed collisions [11-14], and ultra-high-speed collisions, also known as blast impacts [15-19].

Satellite equipment often incorporates a honeycomb aluminum sandwich layer as a vital component of its outer structure. Penetration of this material is essential for affecting the internal mechanisms of the satellite. Therefore, accurately calculating the composition of the sandwich is very important.

However, the addition of armor to the spacecraft significantly increases its weight, which can adversely affect maneuverability and flexibility.

3 HONEYCOMB CALCULATION

For hexagonal honeycomb materials with equal wall thickness, the cell wall can be modeled as a beam, as shown in Figure 3 [5].

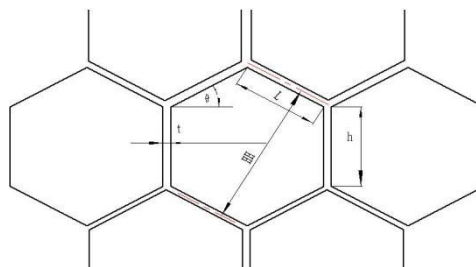


Figure 3 Honeycomb with Uniform Thickness

Cell height HH, cell width L, and cell thickness t are shown in Figure 1 [1, 2, 6]. The results are summarized in Table 1.

Table 1 Different Cell Properties Per Millimeter

Cell Properties	1	2	3	4	5
Cell height HH	10.39	8.66	3.46	8.66	6.93
Cell width L	6	5	2	5	4
Cell thickness t	0.04	0.04	0.03	0.10	0.10

Different hexagonal units can be seen on a scale.

$$E^* = \frac{4E_s t^3}{\sqrt{3} L^3} \frac{1}{1+(5.4+1.5\mu_s)(\frac{t}{L})^2} \quad (1)$$

Where: E_s is the Young's modulus of the matrix material, μ_s is the Poisson's ratio of the matrix material, t represents the cell wall thickness, and L represents the cell wall length.

Let's assign specific values to t and L , which can be found in the standards [5]. We'll set $t/L = 0.04/6 \ 0.04/5 \ 0.03/2 \ 0.10/5 \ 0.10/4$. The elastic modulus is shown as Figure 4.

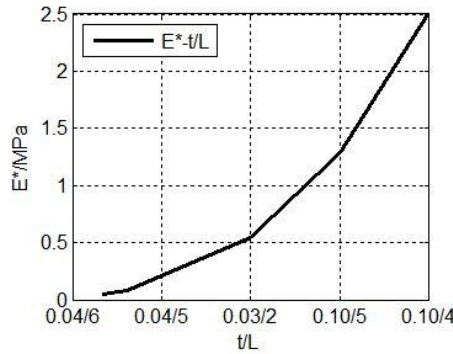


Figure 4 E^* to t/L

Relative density is a measure of the density of a substance compared to the density of another substance.

$$\frac{\rho^*}{\rho_s} = \frac{2}{\sqrt{3}} \frac{t}{L} \quad (2)$$

Let $t/L = 0.04/6 \ 0.04/5 \ 0.03/2 \ 0.10/5 \ 0.10/4$. As shown in Figure 5, the specific gravity of the material is relatively light, giving it a weight advantage.

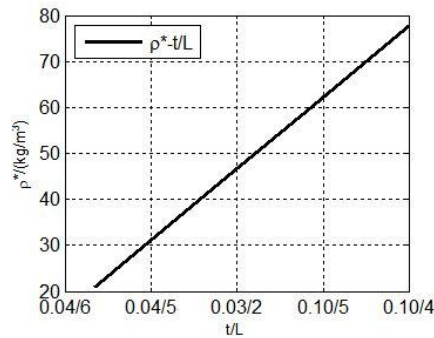


Figure 5 ρ^* to t/L

The Poisson's ratio [1, 2] is displayed in:

$$\mu^* = \frac{\cos^2 \theta}{(\beta + \sin \theta) \sin \theta} \quad (3)$$

Let $t/L = 0.04/6 \ 0.04/5 \ 0.03/2 \ 0.10/5 \ 0.10/4$, and the result is shown as Figure 6.

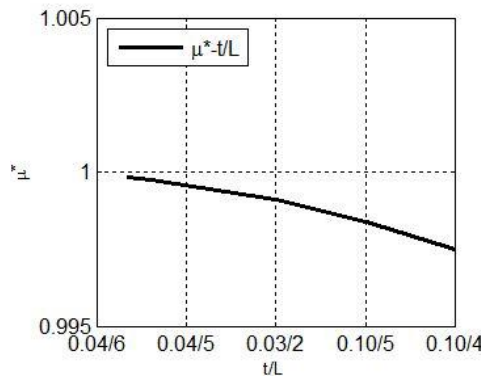


Figure 6 μ^* to t/L

The total length of the honeycomb decreases as the size of L increases. If the cell thickness is too large, it becomes difficult to strike. By comparing the calculation results and the energy impact score, the selection rules for honeycomb materials can be determined.

4 FINITE ELEMENT MODEL

4.1 Geometric Modeling and Mesh Generation

In microgravity, objects penetrate the honeycomb aluminum sandwich panel at various positions, requiring the creation of a comprehensive model of the target plate. The dimensions of both the honeycomb aluminum sandwich panels and aluminum plates are $102\text{ mm} \times 104\text{ mm}$.

To enhance efficiency and streamline calculations, the distance between the target plates is reduced to 30mm. The objects have a diameter of 12.7 mm. The honeycomb aluminum sandwich panel consists of three layers: upper, middle, and lower. Each layer measures 104mm in length and 102mm in width.

First, a single hexagon is drawn. Next, it is arranged along the x and y axes according to the desired overall size. Finally, the hexagon is stretched along the z-axis by 25 mm to create the honeycomb aluminum sandwich panel, accurately representing the geometric structure, as shown in Figure 7.

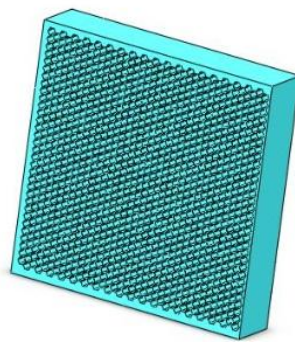


Figure 7 The Structure of Honeycomb Sandwich Aluminum Core Layer

The honeycomb core layer comprises six walls in each honeycomb cell, constructed from shell cells with a uniform grid size of 0.5 mm, as illustrated in Figure 8.

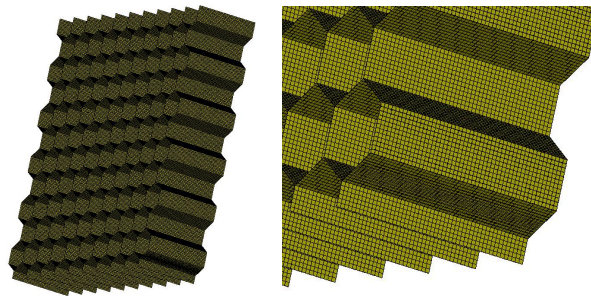


Figure 8 Local Finite Element Model of Honeycomb Aluminum Core Layer

The target plates utilize a hexahedral grid with a size of 0.5 mm, while the bullet employs a tetrahedral grid with a size of 0.4 mm, as shown in Figure 9.

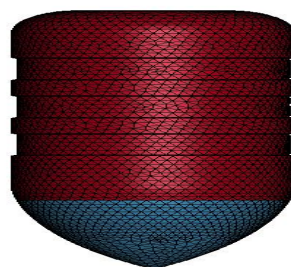


Figure 9 Finite Element Model of the Object

The finite element model of the entire structure under various fire angles is shown in Figure 10. Different shooting angles can provide a basis for design; if all angles can be accounted for, the design can be adjusted accordingly. The complete model consists of 1,138,131 nodes and 882,659 elements.

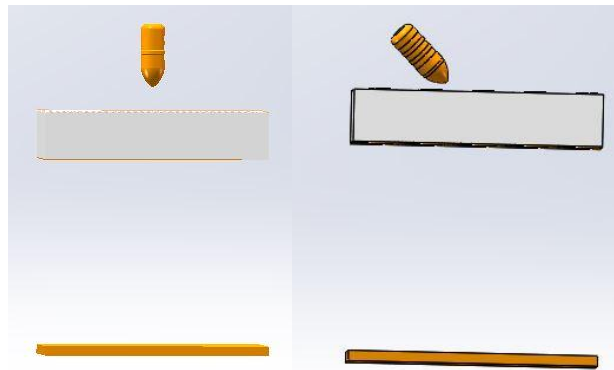


Figure 10 Finite Element Models at Various Angles ((a) 0° Shooting Angle; (b) 45° Shooting Angle)

4.2 Material Model

The object consists of titanium alloy, aluminum, and copper using the *MAT_PLASTIC_KINEMATIC model. The parameters values for the material model are listed in Table 2.

Table 2 Partial Material Parameters

Materials	ρ	E	ν	σ_0	$E_{\tan}$	f_s
H90	8900	110	0.37	195	137	0.8
7A04	2780	70	0.3	337	700	0.5
Titanium	4650	110	0.31	1006	1592	0.7

The honeycomb aluminum sandwich panel and the aluminum target panel are both constructed from the 2A12-T4 aluminum alloy. The Johnson-Cook constitutive model is employed to describe the material's behavior.

This model is widely used in numerical simulations for metal materials because it allows for easy acquisition of material parameters, possesses a clear physical interpretation, and provides accurate predictions of mechanical changes in the material. The Johnson-Cook model is represented by Equation (4).

$$\sigma_{eq} = (A + B\epsilon_{eq}^n)(1 + C \ln \dot{\epsilon}_{eq}^*) (1 - T^{*m}) \quad (4)$$

Where: A - the yield strength;

B, n - the strain hardening coefficients;

C - the strain rate sensitivity coefficient;

m - the temperature softening coefficient;

T - dimensionless temperature.

The J-C model is a fracture criterion used in strength modeling.

$$\epsilon_f = [D_1 + D_2 \exp(D_3 \sigma^*)] (1 + \dot{\epsilon}_{eq}^*) D_4 (1 + D_5 T^*) \quad (5)$$

Where: D_1 – D_3 is the material parameter that reflects the influence of stress triaxiality on fracture; D_4 is the material parameter that reflects the influence of strain rate on fracture; D_5 is the material parameter of the influence of reaction temperature on fracture.

The material parameters of the 2A12-T419 aluminum alloy according to the modified J-C model are presented in Table 3.

Table 3 Material Parameters of 2A12-T4

E/GPa	ν	ρ /(kg/m ³)	Cp/(J·kg ⁻¹ ·K ⁻¹)
71.7	0.33	2770	921
A/MPa	σ_u /MPa	ϵ_u	C_1
400.0	635.0	0.1255	0.0713
D1	D2	D3	D4
0.116	0.211	-2.172	0.012
Tr/K	Tm/K	m	χ
293	863	1.426	0.9
C_2 /MPa	ω	$\dot{\epsilon}_0$ /s ⁻¹	C
288.0	0.0	1.11×10^{-3}	0.001
D5	D6		
-0.01256	13.04		

4.3 Contact Mode

The contact and material models for each component of the system are defined using ANSYS software [20]. The failure strain is set at 0.8. When the plastic strain reaches this threshold, the element fails, leading to the automatic removal of the error source.

The contact mechanism is configured according to the settings detailed in Table 4.

Table 4 Contact Mode

Part to Part	Contact type/(CONTACT)
Copper jacket and aluminum	TIED_SURFACE_TO_SURFACE
Object to honeycomb	ERODING_SURFACE_TO_SURFACE
Aluminum to honeycomb	ERODING_SURFACE_TO_SURFACE
Honeycomb to aluminum	AUTOMATIC_SURFACE_TO_SURFACE

The bullet speed is determined using the keyword *INITIAL_VELOCITY_GENERATION. The bullet travels at a speed of 1000 m/s along its axis.

Normal stiffness [21]:

- (1) When the normal stiffness is set as a factor, only non-zero positive values are supported, with a range of 0.01-10;
- (2) Small stiffness factor, easy convergence, more penetration, and low accuracy; High stiffness factor, difficult convergence, small penetration, and high accuracy;
- (3) If bending deformation is the main deformation, use a smaller value of 0.01-0.1;
- (4) For large deformation problems, it is better to choose 1;

After trial calculations, the normal stiffness factor is 0.1. For refined meshes, with a reduced finite element size, the penetration limit factor will lead to a lower level of penetration [21].

4.4 Numerical Simulation for t and L at 0 Degrees

Different honeycomb aluminum sandwich panels demonstrate varying properties when subjected to impact, exhibiting distinct deformation behaviors and residual velocities of the object. The final results of the impacts on various honeycomb panels are illustrated in Figure 11.

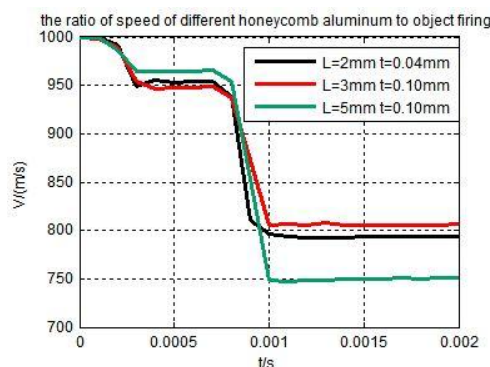


Figure 11 Honeycomb Sandwich Structure Subjected to Velocity

The thickness of the cells between the frames continues to play a significant role. An object can pass through the honeycomb sandwich if it has a red line with a thickness of 2 mm and a width of 0.04 mm; in this case, the decrease in speed is minimal, only 100 m/s. However, for the blue and black lines, the speed reduction is significant, reaching 200 m/s and 250 m/s, respectively.

4.5 The Effects of Objects Moving at Different Speeds

The results of the data comparison after bullet penetration at different initial velocities are presented in Table 5 and Figure 12, with L=5mm and t=0.10mm.

Table 5 Comparison of Bullet Storage Velocity at Different Muzzle Velocities (m/s)

Initial velocity	Penetration velocity	Penetration velocity	ΔV
1000	987	667	333
900	887	601	299
800	788	488	312
700	688	402	298
600	589	292	308

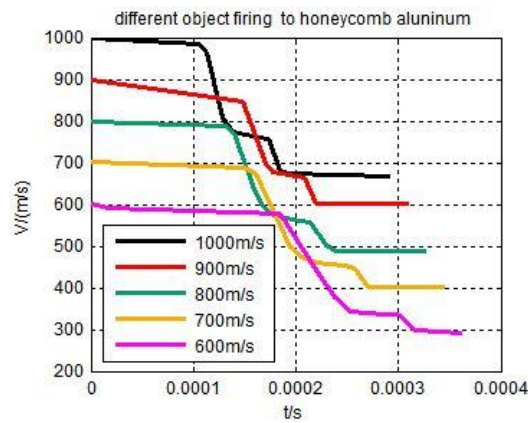


Figure 12 Attenuation of Object Velocity at Different Muzzle Velocities

According to Table 5 and Figure 12, initial velocities between 1000 m/s and 600 m/s can penetrate the satellite's protective structure and cause significant damage. The attenuation chart shows that as the initial velocity decreases, the time spent penetrating the target plate gradually increases, while the velocity attenuation pattern remains consistent.

For an object traveling at an initial velocity of 1000 m/s, the speed decreases to 667 m/s after penetrating the target plate, resulting in a velocity attenuation of 333 m/s. Similarly, when the object starts at 900 m/s, it slows to 601 m/s upon penetrating the target plate, leading to an attenuation of 299 m/s.

When the initial velocity is 800 m/s, the speed after penetrating the target plate drops to 488 m/s, resulting in a decay of 312 m/s. If the initial velocity is 700 m/s, it decreases to 402 m/s after penetrating the target plate, with a decay of 299 m/s. At an initial velocity of 600 m/s, the object's speed decreases to 292 m/s upon penetrating the target plate, leading to a velocity decay of 308 m/s.

To penetrate honeycomb aluminum, the object's kinetic energy is reduced by 300 m/s. This leaves a remaining velocity of 667 m/s, which is consistent with the initial velocity of 1000 m/s, effectively allowing for two breakdowns.

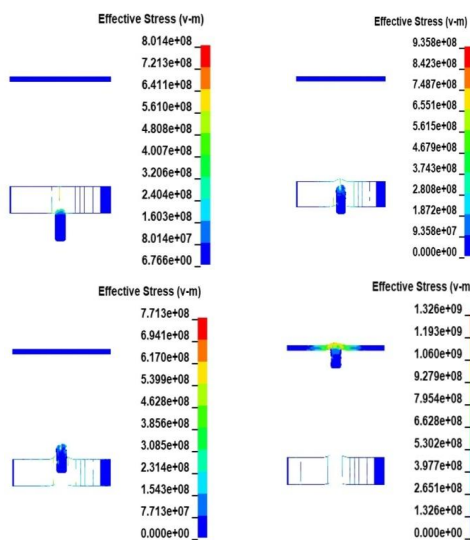
Thus, an object with an initial velocity of 1000 m/s can still cause significant damage to internal structures after penetrating the target due to its high kinetic energy.

5 VARIOUS LANDING ANGLES

The aluminum honeycomb had a thickness of 0.10 mm and a length of 5 mm.

5.1 Under a 0-Degree Attack

The LS-DYNA software simulated the stress of a three-layer target plate before and after being penetrated by a projectile at a 0-degree angle and a velocity of 1000 m/s, as shown in Figure 13:



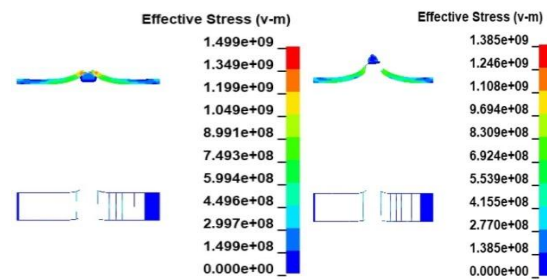


Figure 13 The Intrusion Process and Stress Cloud at a 0° Angle ((a) $2e-5$ s; (b) $3.9e-5$; (c) $6e-5$; (d) $1.6e-4$; (e) $1.8e-4$; (f) $2e-4$)

The back of the honeycomb aluminum sandwich plate exhibits petal-shaped damage as the penetration process continues. The most significant wear failure occurs in the object head during the penetration of a 4 mm aluminum panel, which causes the warhead to tilt. In the scenario illustrated in Figure 14, a sandwich with a thickness of 0.10 mm and a length of 5 mm strikes the honeycomb aluminum at a speed of 1000 m/s.

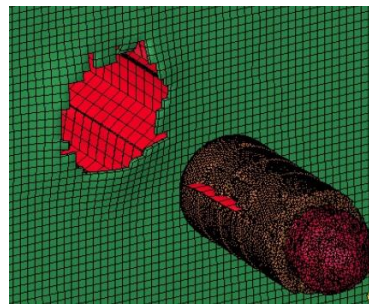


Figure 14 The Object Penetrates Honeycomb Aluminum

Once it passes through the aluminum plate, it shifts to the situation illustrated in Figure 15.

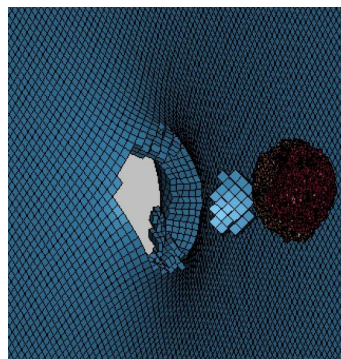


Figure 15 The Object Pierces the Aluminum Plate

The object in Figure 14 displayed some honeycomb aluminum debris. The object in Figure 15 changed shape and was compressed into a ball. The partial kinetic energy is illustrated in Figure 16.

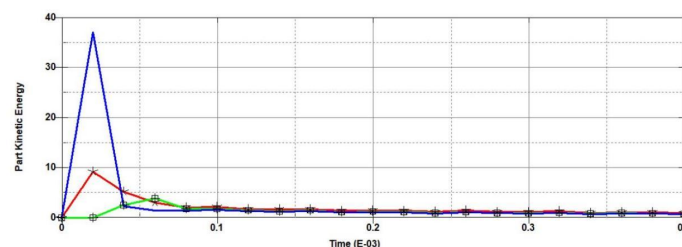


Figure 16 Honeycomb Sandwich and Its Kinematic Energy

When sandwich panels are subjected to ballistic impact, energy absorption occurs primarily through the plastic deformation of both the front and rear panels. The front panel is represented by the red line and rice-shaped curve, while the rear panel is shown by the purple line.

Notably, the energy absorbed by the rear panel is greater than that absorbed by the front panel, while the honeycomb material contributes very little to energy absorption.

Additionally, there is a clearly observable transition from a cylindrical shape to a spherical shape. If the honeycomb aluminum is replaced with solid aluminum of the same thickness, the results will resemble those shown in Figure 17:

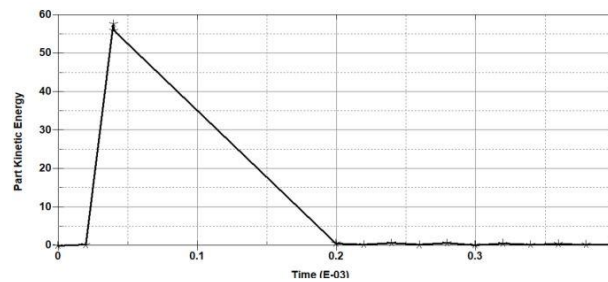


Figure 17 Solid Aluminum and Kinetic Energy

Comparing Figure 16 and Figure 17, it is clear that the time required for energy consumption has decreased, and this reduction will not significantly impact the mechanism. In Figure 16, the time is 0.05 milliseconds, while in Figure 17, the time is approximately 0.2 milliseconds. Given the difference between the two options, I preferred the state illustrated in Figure 16, as it also offers a quality advantage.

5.2 Under a 45-Degree Attack

Before and after the object penetrates the three-layer target panel at a 45-degree angle with a velocity of 1000 m/s, the stresses are measured as shown in Figure 18. The object traveled directly into the panel but also veered to one side.

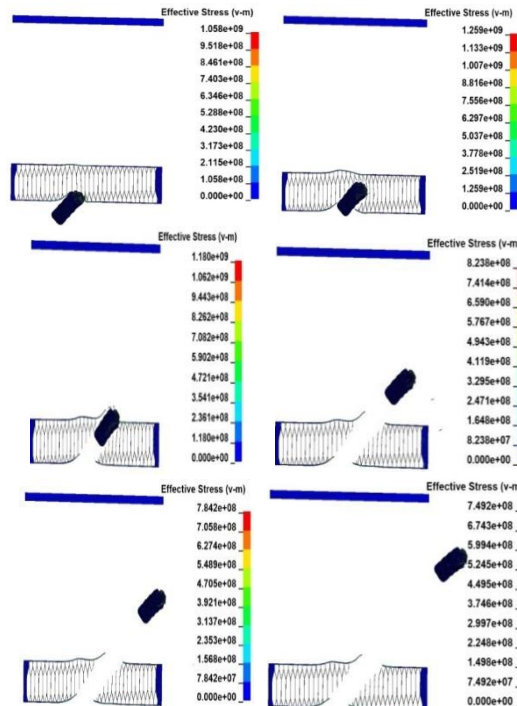


Figure 18 Intrusion Process and Stress Cloud at 45 Degrees ((a) 2e-5; (b) 4e-5; (c) 6e-5; (d) 1e-4; (e) 1.2e-4; (f) 1.6e-4)

5.3 The Velocity of an Object

The angle of the object changes from 0 degrees to 45 degrees, as shown in Figure 19, which displays the object's velocity.

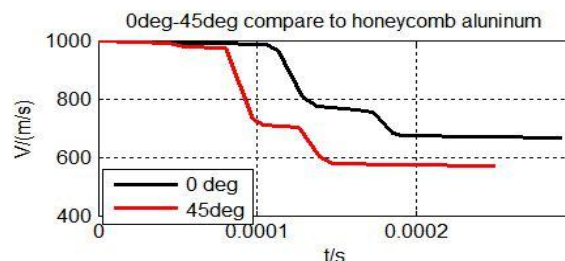


Figure 19 The Object's Velocity Ranges from 0 Degrees to 45 Degrees

The 45-degree curve is currently only simulated because the object has already passed the side distance. This suggests that any angle between 0 and 45 degrees can penetrate honeycomb aluminum and aluminum panels.

6 TESTING AND EXPERIMENTATION

After completing the experiment, observe the macroscopic morphology of the target plate and analyze the collision process between the object and the target panel. This analysis will serve as a reference for the next experimental simulation, as illustrated in Figure 20.



Figure 20 The Appearance of a Target Board (Columns from Left to Right: Honeycomb Aluminum Front Panel; Honeycomb Aluminum Rear Panel; Target of Aluminum Front Panel; Honeycomb Sandwich. Rows from Top to Bottom: Round 1 to Round 5)

Due to the close placement of the second and third layers of the 4 mm aluminum board on the same shelf during the experiment, it was not possible to photograph the back of the aluminum board after each shot. The damage on the back of the second layer can only be observed after disassembling the target board once the experiment is complete (Figure 21).



Figure 21 Damage Visible on the Rear of the Aluminum Honeycomb Plate

Figure 22 accurately depicts a fixed board instead of two flying satellites, and there are no speed or angle issues between them.



Figure 22 The Actual Situation of the Honeycomb Sandwich

7 EFFICIENCY OF ANTI-SATELLITE WEAPON DESIGN CONCEPT

The honeycomb sandwich panel deforms when external forces are applied. As the force impacts the panel, the work done by these external forces is converted into the total energy absorbed by the honeycomb panel. This total energy can be divided into two main components: kinetic energy and internal energy.

When considering launch costs and vulnerability to enemy strikes, a specific design should adhere to the following formula:

$$F = \max(A_1, A_2) \quad (6)$$

$$W = A_1 \times I + A_2 \times C \quad (7)$$

$$g = \max\left(\frac{\partial F}{\partial W}\right) \quad (8)$$

Where: F: Best Launch and Strike Effects

W: effect of current emissions

A1: launch cost proportion is an important factor to consider.

A2: The text discusses the impact of enemy strikes, which can result in both elastic strain and plastic deformation.

$$A_1 + A_2 = 1$$

I: launch cost per kilogram required (¥/kg);

C: enemy strike (1/kg).

g: maximum F to A1, A2

Each time it is launched, the object is measured in kilograms and is targeted by the enemy. The impact on an area will depend on whether it is affected or not, indicating a relationship between the two factors.

Based on my interpretation of the readings, I should strive to maximize its impact while minimizing its size. To improve component C independently, I conclude that, according to the equation $A_1 + A_2 = 1$, A2 must be greater than 50%.

Referring to Table 4 and Figure 12, the optimal speeds among the five listed are 1000 m/s and 900 m/s. Choosing a speed of 900 m/s can achieve the goal of causing a secondary breakdown in the aluminum panel. Additionally, using a speed of 900 m/s can reduce the mass of other components involved in launch costs, such as the barrel mass or barrel thickness.

8 CONCLUSION

The object impacts the aluminum honeycomb sandwich at high velocity in a microgravity environment. After discussions, the following results were obtained:

- 1) An optimal aluminum honeycomb sandwich configuration has been identified, featuring a cell thickness of 0.10 mm and a cell width of 5 mm.
- 2) This finding indicates that any impact angle between 0 and 45 degrees can effectively penetrate both the aluminum honeycomb and aluminum panels.
- 3) The efficiency of anti-satellite weapon designs shows that selecting a velocity of 900 m/s can successfully cause a secondary breakdown of the aluminum panel.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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AUTHOR CONTRIBUTIONS

Jian Xu wrote the manuscript and discussed it, Professor Yang provided suggestions, Professor Li provided funding support, and Xuefang Chang conducted experiments and recorded them.

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