Mechanical Performance of Spacecraft Protection Structure Under Hypervelocity

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Abstract. In order to improve the ability of the spacecraft protection system to resisted hypervelocity orbit debris, a composite double-layer honeycomb sandwich structure was proposed in the article. Four sets of models were established, through the method of controlling variables, and the SPH algorithm of the LS-DYNA finite element software was used to analysis the composite honeycomb sandwich structure. The diameter of the aluminum ball was 7mm and the velocity was 5818m/s. The results show that the residual velocity of debris cloud decreases with the increase of the cell diameter of the front-stage honeycomb, and the residual velocity of debris cloud increases with the decreases of the cell diameter of the back-stage honeycomb structure. The energy absorption effect of the composite structure was much higher than that of the traditional honeycomb structure, the remaining speed was reduced by about 64%, and the total energy absorption was increased by 77.6%.

1. Introduction
In recent years, the increasing threat of orbital debris to spacecraft has led National Space Science Center, CAS to improve the spacecraft’s ability to withstand hypervelocity collisions over its lifetime. The honeycomb structure has the characteristics of high specific strength, specific stiffness and specific energy absorption. In addition, it was a double-layer structure with good airtightness and adiabatic, large structural attenuation, local damage after shock, cracking was not easy to expand, so it has been widely used in aerospace and other fields [1-4].

Structural mechanical properties test to the application of honeycomb filled members, from optimization design to the use of new materials, with thorough research on honeycomb structure, many research results have been obtained [5-9]. The quasi-static compression, low velocity impact and explosive impact tests of composite honeycomb structures were carried out by Yi Meng et al. they were found that
the energy absorption and compressive strain decrease with the increase of slider thickness and scaling distance, and the empirical formula was in good agreement with the experimental results \cite{10}. Fatigue damage and failure of honeycomb structure with GFRP skin were studied by F. Alila et al. The results show that the failure mode of most specimens was based on the core shear failure of cell wall cracking \cite{11}. The impact resistance of expanded honeycomb core and traditional honeycomb core, as well as the equivalent sandwich plate composed of metal surface were analyzed by Gabriele Imbalzano et al. The results show that hybrid auxetic composite panels (HACPs) can dissipate and reduce energy more effectively than traditional honeycomb panels \cite{12}. In order to predict the local buckling load of a honeycomb structure and determine the material model of NomexTM honeycomb structure, tested and modeled the sandwich plate of NomexTM honeycomb core and bolt insert by R. Roy et al \cite{13}. In addition to the research on mechanical properties, there have been many researches on the propagation of waves in honeycomb structures. The propagation of Lime waves in honeycomb structures was numerically simulated by Seyed Mohammad Hossein et al. Through parameter research, the influence of the geometrical properties of honeycomb panels, the material properties of the skin and the loading frequency on the group velocity and energy transfer was revealed \cite{14}. With the continuous embodiment of the advantages of the honeycomb structure, it was widely used in aviation, aerospace, ships, radar and other fields \cite{15-18}. In this paper, the satellite protection structure was improved, and a compound honeycomb structure was proposed. The energy absorption characteristics of the compound honeycomb structure under the ultra-high speeds state were simulated by using LS-DYNA software, and the influence of different sibling element diameter combination on the energy absorption characteristics of the structure was discussed.

2. Structural design and material model

2.1. Structural design

In this paper, the cell of the compound double layer honeycomb structure is equal hexagon. The cell diameter was 2mm, 3mm and 4mm, and the cell wall thickness was 0.025mm. The protective structure was comprised of honeycomb core layers of different structure sizes. The upper and lower skin thickness was 0.7mm. The middle skin thickness was 0.2mm, and the structure height was 21.6mm. The diameter of impact aluminum ball was 7mm and the speed was 5818m/s. The finite element model of honeycomb sandwich structure was shown in Figure 1. The basic dimensions of the composite honeycomb structure were given in Table 1.

![Finite element model of honeycomb sandwich structure](image)

Figure 1. Finite element model of honeycomb sandwich structure

| Table 1. Structural dimensions |
|--------------------------------|
| (a) 1# top d=2mm bottom d= 4mm |
| (b) 3# top d=4mm bottom d=2mm  |
2.2. material model

MAT_JOHNSON_COOK model and EOS_GRUNEISEN state equation were selected for the material model coupled with SPH and Lagrange algorithm, and the flow stress of the material was expressed as the product of strain function, strain rate function and temperature function. The material of honeycomb core and skin in the composite double honeycomb sandwich structure was 2024 aluminum. The material parameters were shown in Table 2.

| Material | $P$ (g/cm$^3$) | $G$ (Mbar) | $A$ (Mbar) | $B$ (Mbar) | $n$ | $c$ | $m$ | $T_m$ (K) | $T_r$ (K) |
|----------|----------------|-----------|------------|------------|-----|----|-----|-----------|-----------|
| 2024 Aluminum | 2.785 | 0.286 | 0.00265 | 0.0426 | 0.34 | 0.015 | 1.00 | 775 | 300 |

3. Analysis of superhigh speed impact composite honeycomb structure

J.M. Sibeaud$^{[19]}$ studied a honeycomb protective structure with a cell diameter of 4mm, a wall thickness of 0.025mm and a height of 21.6mm. was verified the accuracy of finite element software operation of ANSYS18.2, the experimental structure of J.M. Sibeaud was simulated and analyzed. Data results of 20 points were taken from the debris cloud generated by the aluminum ball, and the average value was obtained as the remaining velocity of the aluminum ball. The results show that the numerical simulation results are consistent with the experimental and simulation results of J.M. Sibeaud, as showed in Figure 2, 3, 4 and 5.

Figure 2. Numerical simulation and J.M. Sibeaud$^{[19]}$ experiment results
3.1. Influence of cell diameter and compound mode on energy absorption characteristics of the structure

In order to analyze the effect of cell diameter on the mechanical properties of the composite honeycomb structure, the cell diameter of the upper honeycomb structure was changed by controlling the size of the
lower honeycomb structure unchanged. The process of aluminum ball impacting composite honeycomb structure at super high speed was shown in Figure. 6.

![Figure 6. Section of damage process of composite honeycomb structure](image)

The lower cortex of the composite structure was destroyed at about 5μs and completely destroyed at 8μs. The average velocity of 10 points of the debris cloud was randomly selected as the remaining velocity to analyze the energy absorption characteristics of the structure. The remaining velocity curves of structure 1# and 2# are shown in Figure 7.
As can be seen in figure 7, the contact speed of the aluminum sphere with the skin showed a sharp decrease, and the stable speed of the 1# structure with the diameter of the anterior cell D=2mm was around 3300m/s. The structure of # 2 with a diameter of D=3mm tended to stabilize at a speed of 3170m/s and a minimum speed of 2940m/s. The residual velocity was relatively low, indicating that the overall energy absorption effect increases with the increase of the diameter of the front stage honeycomb. The remaining velocity curves of structure 3# and 4# are shown in Figure 8.

It can be clearly seen from (a) and (b) in figure 8 that, when the structure of remaining velocity tends to be stable, the velocity was relatively lower than that of structure 1# and 2#, among which, the energy absorption curve of structure 4 had little fluctuation, and the lowest velocity was close to that of structure when it was stable, which was 2796m/s, and the total energy absorption was 2.33J. The damaged section diagram of the honeycomb structure is shown in Figure 9.
According to the damage of the four structures, the expansion trend of the debris cloud was similar, and the damage of #3 structure was very serious due to the size relationship.

4. Conclusion

This paper used LS-DYNA software to study the mechanical properties of the composite honeycomb structure, analyzes the energy absorption characteristics of the structure through the residual velocity of the debris cloud and the damage of the honeycomb structure, and draws the following conclusions.

As the cell diameters of the front and rear stages were different, the energy absorption characteristics of the composite honeycomb structure are enhanced with the increase of the cell diameter of the front stage and the debris cloud velocity is relatively low while the cell size of the rear stage remains unchanged.

The size of the honeycomb structure of the rear stage is changed when the diameter of the front stage cell remains the same. With the increase of the diameter of the afterstage cell, the residual velocity of the debris cloud is relatively low.

The composite structure with the cell diameter of 4mm in front and 3mm in rear had the best energy absorption effect, which was 77.6% higher than the results of J.M. Sibeaud study.

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