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Effect of honeycomb core under hypervelocity impact: numerical simulation and engineering model

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Abstract

Honeycomb sandwich panels (HC/SP) are the most common used structures for space vehicle. Under the threat of meteoroid and space debris, the distribution of the fragments produced in a hypervelocity impact event on HC/SP is critical to the vulnerability assessment of space vehicle. CISAS developed an engineering model to describe fragments clouds propagating inside spacecraft in consequence of space debris impact on HC/SP. In this model, the effect of the honeycomb core was modeled by an empirical corrective factor, which was not related to the physical of the impact. To improve this model, a new model to describe the effect of the honeycomb core was developed. In the new model, the honeycomb core was equaled to multi-parallel thin plates, which can represent the discontinuity of honeycomb core without complex boundary. Based on the knowledge of hypervelocity impact on a simple thin plate and approximation supported by numerical simulation results, the model was deduced. The coefficient of the model was fitted by the numerical simulation results.

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Keywords: Honeycomb core; Hypervelocity impact; Numerical simulation; Engineering model;

1. Introduction

As the population of orbital debris grows, the risk of space vehicle being hit by orbital debris becomes higher, which makes vulnerability assessment one of the most important steps in space vehicle design. Honeycomb

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sandwich panel (HC/SP) is a common structural component in space vehicle, and its debris cloud under hypervelocity impact is critical to the vulnerability assessment of space vehicle. There are three ways to obtain the characteristics of debris cloud, which are test [1-4], numerical simulation [5, 6] and using engineering model [7]. In early design stage of space vehicle, since detailed numerical simulation and test are too much expensive, using engineering model becomes the best choice. As a discontinuous structure, the properties of debris cloud of HC/SP are affected by the impact point, the orientation of honeycomb cell, the cell size, the height of honeycomb, the impact angle, and so on. All these factors make it too complicated to model the debris cloud of HC/SP. Existing vulnerability assessment tools usually treat HC/SP as a plate or a triple wall system [8] with additional adjustable parameters, which only predict the ballistic limit, without any information of the largest fragment.

To describe the characteristics of the debris cloud of HC/SP under hypervelocity impact, Alessandro and his team developed an engineering model [7] by using method of equal effect. In this model, the impact process was divided down into three steps: a first impact on the front face, which produces a debris cloud; an interaction with the honeycomb core, which filters out the dust jet and makes the largest fragment smaller and slower; a second impact on the rear face, which takes the output of previous step as input. The honeycomb core is treated as a "filter", the effect of which is expressed by a corrective factor for both the mass loss and velocity loss after impact with honeycomb. The ballistic limit of HC/SP was obtained based on this engineering model, and the result agrees well with test data. However, the model has defects in two ways. First, the corrective factor for the mass loss and velocity loss could be different. Second, the corrective factor was obtained by reverse fitting the SRL ballistic limit equation, in which the honeycomb core was treated as plate.

To improve the honeycomb model, numerical simulation of projectile hypervelocity impact honeycomb core was carried out, and the mass loss and velocity loss of the projectile were studied. According to the discontinuous impact process of honeycomb core, a model for the honeycomb effect was developed by applying a simplified equivalence of honeycomb core. Based on the knowledge of hypervelocity impact on a simple thin plate and approximation supported by numerical simulation results, the model was deduced. The coefficient of the model was fitted by the numerical simulation results.

Nomenclature

h	Height of honeycomb core, height of thin plates
q	Equivalent diameter of honeycomb cell
t	Thickness of the honeycomb core foil, thickness of the thin plate
θ	Impact angle
d	Projectile diameter
ρ_{hc}	Density of honeycomb core material
ρ_p	Density of projectile material
m_p	Mass of projectile
v_i	Impact velocity
m_i	Mass of the projectile
v_{LF}	Velocity of the largest fragment
d_{LF}	Diameter of the largest fragment
m_{LF}	Mass of the largest fragment
m_t	Silhouette mass of the thin plate.
m_t*	The effective mass of silhouette mass of the thin plate
s	Space between two neighbour parallel thin plates
a, b, $k1$, $k2$	Correction coefficient of the engineering model

2. Numerical simulation

2.1. Numerical simulation set-up

The numerical simulation was carried out by using AUTODYN software. To simulate the projectile breakup during impact and to reduce the simulation time, a SPH-FE coupled method was used, in which the projectile is simulated by the SPH processor, and the honeycomb core is simulated by the shell processor. The material of the projectile and honeycomb core is aluminum alloy. For the projectile, shock EOS and Steinberg-Guinan strength model were used. For the honeycomb core, linear EOS and Johnson-Cook strength model were used. The default values in the AUTODYN material library are adopted for the material parameters.

In the numerical simulation, the equivalent diameter (as shown in Fig. 1) of the honeycomb cell is 4.763mm, and the thickness of the foil is 0.025mm. The impact velocity, projectile diameter, honeycomb cell orientation (as show in Fig. 1), and honeycomb core height were varied in the numerical simulation, and the detailed parameters are shown in Table 1.

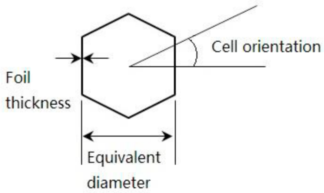


Fig. 1. Parameters of honeycomb cells

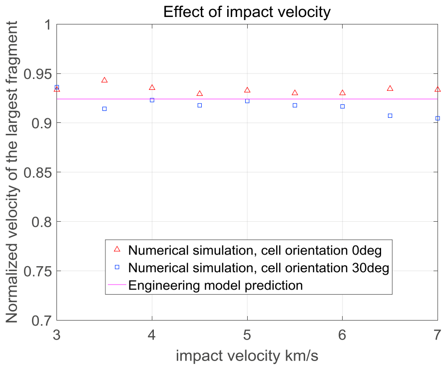
Table 1. Numerical simulation parameters.

Case No.	Projectile diameter (mm)	Impact velocity (km/s)	Impact angle (degree)	Cell orientation (degree)	Honeycomb core height (mm)
1	5	3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7	45	0, 30	25
2	5	6	15, 20, 25, 30, 35, 40, 45, 50, 55, 60	0, 30	25
3	3, 4, 5, 6, 7, 9, 11	6	45	0, 30	25
4	5	6	45	0, 30	15, 20, 25, 30, 35

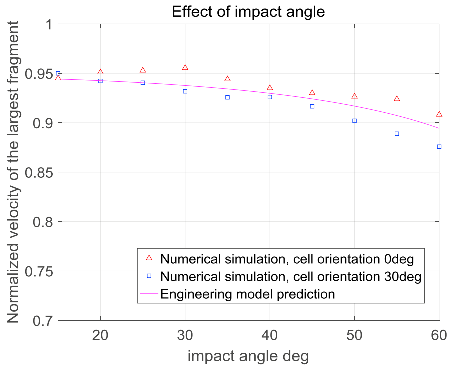
2.2. Numerical simulation results

Defining the normalized velocity as the ratio of fragment velocity to the impact velocity, and defining the normalized mass as the ratio of fragment mass to the projectile mass, the result of normalized velocity of the largest fragment is shown in Fig. 2. Under the same impact velocity, projectile diameter, impact angle and honeycomb height, the normalized velocity of the largest fragment is higher at 0 degree cell orientation than that at 30 degree. In case 1, the normalized velocity of the largest fragment keeps in the range of 0.9 to 0.95, as shown in Fig. 2a; In case 2, the normalized velocity of the largest fragment decreases as the impact angle increases, as shown in Fig. 2b; In case 3, the normalized velocity of the largest fragment increases as the projectile diameter increases, as shown in Fig. 2c; In case 4, the normalized velocity of the largest fragment decreases as the honeycomb height increases, as shown in Fig. 2d.

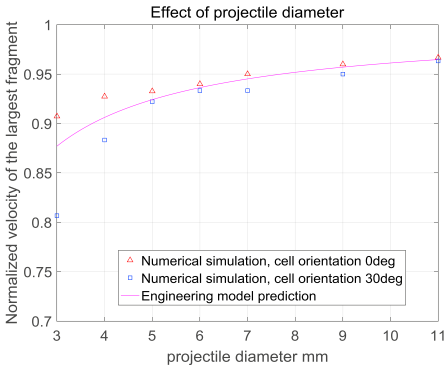
The result of the normalized mass of the largest fragment is shown in Fig. 3. Under the same impact velocity, projectile diameter, impact angle and honeycomb height, the normalized mass of the largest fragment is higher at 0 degree cell orientation than that at 30 degree. In case 1, the normalized mass of the largest fragment decreases as the impact velocity increases, as shown in Fig. 3a; In case 2, there are no obvious relations between the normalized



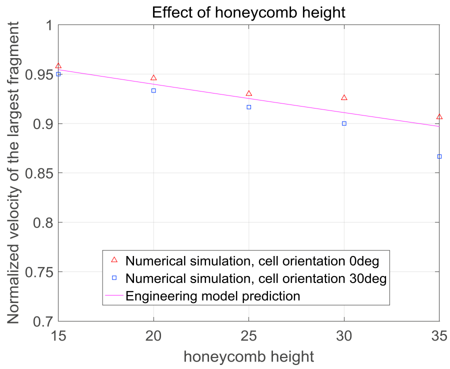
a) $\theta = 45$ degree, $d = 5$mm, $h = 25$mm.



b) $v = 6$km/s, $d = 5$mm, $h = 25$mm



c) $v = 6$km/s, $\theta = 45$ degree, $h = 25$mm.



d) $v = 6$km/s, $\theta = 45$ degree, $d = 5$mm

Fig. 2. Normalized velocity of the largest fragment

mass of the largest fragment and the impact angle, as shown in Fig. 3b; In case 3, the normalized mass of the largest fragment increases as the projectile diameter increases, as shown in Fig. 3c; In case 4, the normalized mass of the largest fragment decreases as the honeycomb height increases, as shown in Fig. 3d.

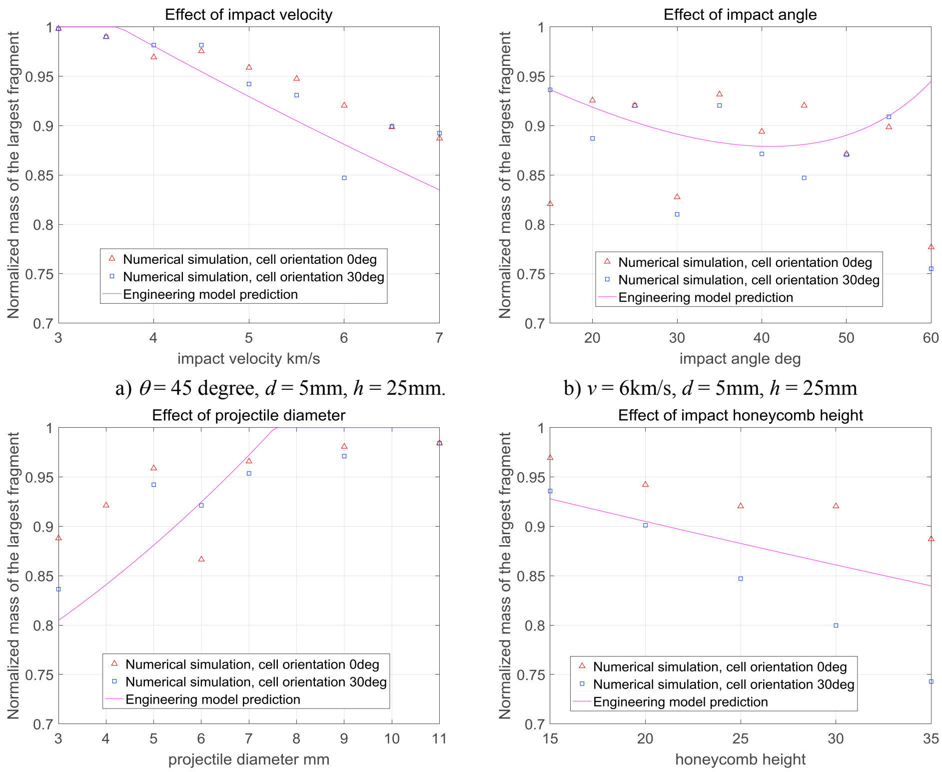
In all the simulation cases, the deviation angle of the largest fragment is less than 1 degree. Under the same condition, the deviation angle at the cell orientation of 0 degree is less than that of 30 degree.

3. Engineering model

Based on numerical simulation results, using multi-parallel thin plate equivalent method, an engineering model to describe the effect of honeycomb under hypervelocity impact was developed. The model gives the normalized velocity and normalized mass of the largest fragment in this form:

$$\frac{v_{LF}}{v_i} = \left(\frac{1}{1 + a \cdot \dfrac{t\rho_{hc}}{d\rho_p \sin(\theta)}}\right)^{\frac{2h}{q}\tan(\theta)} \tag{1}$$

$$\frac{m_{LF}}{m_i} = (\min(1, \max(0, 1 - b(v_i \cos(\theta) - k1(\frac{\rho_{hc} t}{\rho_p d})^{k2}))))^{\frac{6h}{q}\tan(\theta)} \tag{2}$$



a) $\theta = 45$ degree, $d = 5$mm, $h = 25$mm. b) $v = 6$km/s, $d = 5$mm, $h = 25$mm

c) $v = 6$km/s, $\theta = 45$ degree, $h = 25$mm. d) $v = 6$km/s, $\theta = 45$ degree, $d = 5$mm

Fig. 3. Normalized mass of the largest fragment

3.1. Multi-parallel thin plates equivalent

During the process of a projectile impacting a honeycomb core, the projectile impacts the honeycomb foils several times. If there's an engineering model, which predicts the mass and velocity of the largest fragment, omitting the accumulative effect, the final velocity and mass of the largest fragment can be calculated by an iteration method. However, the impact position, impact angle and boundary conditions are different at each impact making this method too hard to be applied. To make the problem simpler, the honeycomb core was equalled to multi-parallel thin plates. The thickness and height of the plate are equal to that of the honeycomb core, and the average density of the multi-parallel thin plates is equal to that of the honeycomb core, as shown in Fig. 4. The equivalence is adopted for the following reasons:

- Make the boundary simple, and the foil can be treated as a semi-infinite plate;
- The impact process is discontinuous;
- No cell orientation problems.

Using the equivalence, with the following assumption, the multi-parallel thin plates problem becomes a single thin plate problem:

- After one of the thin plate is impacted, the largest fragment flies along the impact direction;
- After one of the thin plate is impacted, there's no accumulate damage in the largest fragment.

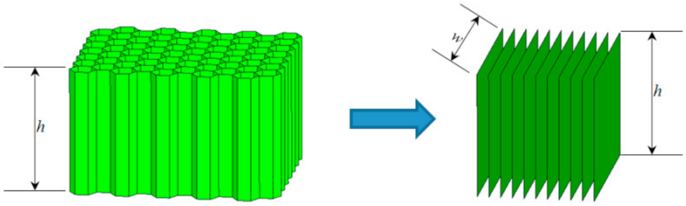


Fig. 4. Multi-parallel plates equivalent for honeycomb core.

With these assumptions, for a projectile impacting a single thin plate, the velocity and mass of the largest fragment are:

$$v_{LF} = F(v_i, \theta, d, t) \tag{3}$$

$$d_{LF} = G(v_i, \theta, d, t) \tag{4}$$

Then, for a projectile impacting N parallel plates, the velocity and mass of the largest fragment are:

$$v_{LF_N} = F(v_{LF_{N-1}}, \theta, d_{LF_{N-1}}, t) \tag{5}$$

$$d_{LF_N} = G(v_{LF_{N-1}}, \theta, d_{LF_{N-1}}, t) \tag{6}$$

As the average density of the multi-parallel plates and the honeycomb core is equal, the distance between two neighbor parallel plates is:

$$s = \frac{q}{2} \tag{7}$$

Given the impact angle, the number of the layers of the thin plates the projectile would impact is:

$$N = \frac{h\tan(\theta)}{s} = \frac{2h\tan(\theta)}{q} \tag{8}$$

3.2. The equation of the normalized velocity of the largest fragment

For a projectile impact a thin plate, since the diameter of the projectile is much larger than the plate thickness, it's assumed that the velocity of the center of gravity of the debris cloud is the same as the velocity of the largest fragment, according to the momentum conservation law [9]:

$$m_p v_i = (m_p + m_t^*) v_{LF} \tag{9}$$

Where m_t* is the effective fragment mass of silhouette mass of the thin plate. It is assumed that only the normal component of the projectile surface element's velocity provides the momentum to the ring element [9]. For oblique impact of a sphere projectile and a thin plate as shown in Fig. 5, m_t* is:

$$\frac{m_t^*}{m_t} = \frac{1}{A}\int^{A} (\hat{n}\cdot\hat{a})^2\, da = \frac{1}{\pi R^2}\int_0^R \cos^2\phi \cdot 2\pi r dr = \frac{1}{2} \qquad (10)$$

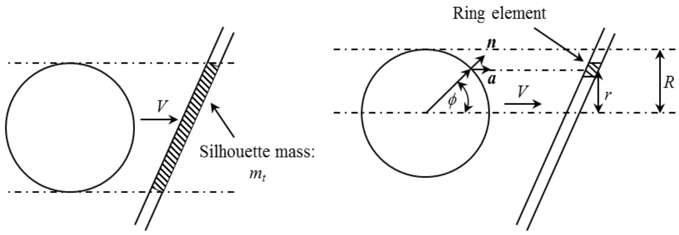


Fig. 5. Oblique impact of a sphere projectile and thin plate [9]

With equation (9) and equation (10), there is

$$\frac{v_{LF}}{v_i} = \frac{m_p}{m_p + m_t^*} = \frac{1}{1+\frac{m_t^*}{m_p}} = \frac{1}{1+\frac{0.5m_t}{m_p}} = \frac{1}{1+0.75\frac{t\rho_{hc}}{d\rho_p \sin\theta}} \qquad (11)$$

In a single impact, since the projectile diameter is much larger than the plate thickness, the diameter of the largest fragment is not much less than the projectile diameter,

$$\frac{d_{LF}}{d} \approx 1 \qquad (12)$$

Thus, the normalized velocity of the largest fragment after impacting multi-parallel thin plates is:

$$\frac{v_{LF}}{v_i} \approx \left(\frac{1}{1+0.75\frac{t\rho_{hc}}{d\rho_p \sin(\theta)}} \right)^{\frac{2h\tan(\theta)}{q}} \qquad (13)$$

During the impact process, the shape of the largest fragment is not exact sphere, and the diameter changes after each impact. These will cause the change of the effective mass m_t*. Thus a coefficient *a* is used, and the equation becomes equation (1). The coefficient *a* can be fitted from the numerical simulation results.

3.3. The equation of the normalized mass of the largest fragment

The breakup process of the projectile is related to the material properties, and during the impact, the accumulated effect exists. To make the engineering model simple, the accumulated effect is divided to each impact. In a single impact, the normalized mass of the largest fragment is [7]:

$$\frac{m_{LF}}{m_i} = \min(1, \max(0, 1 - b(v_i \cos(\theta) - k1(\frac{\rho_{hc} t}{\rho_p d})^{k2})))^3 \quad (14)$$

Since the projectile diameter is larger enough, the velocity and diameter of the largest fragment is almost the same as the impact projectile.

$$\frac{v_{LF}}{v_i} \approx 1 \quad (15)$$

$$\frac{d_{LF}}{d} \approx 1 \quad (16)$$

Equation (2) can be deduced with the above approximation, where *b*, *k1*, *k2* are the coefficient.

3.4. Results

The coefficient of the equation (1) and (2) are fitted by numerical simulation results. In equation (1), the correction coefficient $a = 1.05$. There is high correlation between the model and numerical simulation results, as shown in Fig. 2. In equation (2), $b = 0.002361$, $k1 = 0.00402$, and $k2 = -1.2192$. The model predication and numerical simulation results are shown in Fig. 3. The model predication shows consistence with numerical simulation results in case 1, case 3 and case 4. In case 2, the model predication fails to agree with numerical simulation results.

4. Discussion

The model is developed based on oblique impact on parallel thin plates equivalent, which is a statistical average model for different impact point and honeycomb cell orientations. When a projectile penetrating through a honeycomb core, if the flight direction of the projectile is parallel to one of the foil planes, the projectile will be cut by some of the foils. As the diameter of the projectile is much larger than the foil thickness, the foil is not able to cut the projectile into pieces, instead, a shockwave will be generated at the cutting point. Therefore, in the parallel thin plates equivalent, the shockwave generated by cutting is averaged into the shock of oblique impacts. The mass of the foils that encountered by the projectile in its flight path, which is defined as impact channel mass, is the key factor to the mass and velocity of the largest fragment. Assuming the projectile flights along a straight line, if the projectile diameter is larger than the equivalent diameter of the honeycomb cell, the impact channel mass varies little as the impact point and honeycomb cell orientation changes, and the velocity and mass of the largest fragment will be close to the model prediction. Due to the asymmetry of the shock on the projectile during the impact process, the projectile will have some deviation in its path, which means larger impact channel mass and results in lower velocity and mass of the largest fragment than the model prediction. If the projectile diameter is smaller than the equivalent diameter of the honeycomb cell, the difference of impact channel mass at different impact position and honeycomb cell orientation can’t be omitted, and the deviation can’t be omitted too. Thus, the effect from different impact point and honeycomb core orientation should be studied in further research. In the numerical simulation, the impact point was set at the center of a honeycomb cell to avoid asymmetry shock on the projectile. Given the impact point, the impact channel mass reaches it’s minimum at honeycomb cell orientation at 0 degree and reaches its maximum at 30 degrees.

Another limitation of this model is the impact angle. As this model is based on oblique impact equivalence, the impact angle can’t be 0 degree. If the impact angle is too small, the projectile could pass through the honeycomb cell without impact. If the impact angle is too big, the number of the equivalent parallel plates will be too large, then the accumulated error of the approximation in equation (12), (15) and (16) can't be omitted. If the largest number of the parallel plates allowed in the approximation is N_t, then the applicable range of the impact angle should be:

$$\arctan(\frac{q}{h}) < \theta < \arctan(\frac{N_t q}{2h}) \tag{17}$$

5. Conclusion

Numerical simulation of projectile hypervelocity impacting honeycomb core was carried out, and the mass loss and velocity loss of the largest fragment under different impact conditions were studied. An engineering model to describe the effect of honeycomb core under hypervelocity impact was developed. The honeycomb core was equaled to multi-parallel thin plates in the model. With this equivalence, the complex boundary and cell orientation problem are avoided, and the discontinuous impact process is also represented. Based on the knowledge of hypervelocity impact on a simple thin plate and approximation supported by numerical simulation results, the model was deduced. The momentum conservation is applied in the model, making it physically reasonable. The coefficient of the model was fitted by the numerical simulation results, and the model showed high consistence with numerical simulation results. In the future work, hypervelocity impact tests on honeycomb core could be performed to validate the model.

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