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Improved shielding structure with double honeycomb cores for hyper-velocity impact ☆

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ABSTRACT

Aluminum sandwich panel made from double honeycomb cores can serve as a cost-effective shielding structure against hyper-velocity impact of space debris. The double honeycomb sandwich panel is improved and investigated in detail in this paper. Different from the original structure, the transverse position of the intermediate facesheet is varied instead of at the right middle of the panel. The influence of the transverse position is investigated numerically with point-based internal-structure model and material point method. Much better shielding performance can be obtained when the distance between the intermediate facesheet and the front facesheet is around the equivalent shielding distance. The equivalent shielding distance is defined as the maximum distance the debris fragments can travel in transverse direction before they interact with honeycomb cell walls. The morphologies of the facesheets and the residual energy are also discussed. A new shielding structure with multiple intermediate facesheets is suggested based on simulation results, and substantially improved shielding capability is achieved.

1. Introduction

Honeycomb sandwich panels are widely used in many engineering disciplines [1–4]. Though different forms of sandwich cores, such as aluminum foam [5,6] and Nomex honeycomb [7], have shown more attractive properties, common aluminum honeycomb sandwich panels still play an important role in engineering applications especially on unmanned spacecraft as major load-bearing components [8]. Shielding structures can also be built based on honeycomb panel to protect inside functional elements from hyper-velocity impact of orbital debris [9]. One drawback of honeycomb sandwich shielding structures is that the debris fragments are confined in a small region due to the existence of honeycomb cell walls, which is named channeling effect. Channeling effect implies concentrated impact energy flux and sequentially decreased shielding performance.

Turner et al. [9] proposed a cost-effective shielding structure, called double honeycomb panel, by simply inserting one intermediate facesheet between the front and the rear facesheets. A significant performance increase can be observed for the new shielding structure. It was reported that the ballistic limit, defined as the projectile diameter when the hole diameter of the rear facesheet equals 1 mm, increased from 0.58 mm to 0.91 mm at the cost of mass increase 1.2 kg/m^2 [9].

The shielding capability of honeycomb sandwich panel has been investigated experimentally [9] and numerically [10,11]. The ballistic limit equations were obtained based on a series of experimental results [8,12]. Different simulation techniques, such as SPH method [10] and material point method (MPM) [11], were used to investigate behaviors of honeycomb sandwich panel under hyper-velocity impact, especially for the velocity range the experiments cannot cover. Channeling effect was clearly observed from numerical results.

As a meshfree particle method, MPM is very competitive for problems of large deformation and fragmentation. No mesh distortion exists in MPM. Numerous contacts and self-contacts can be dealt with easily in MPM. Another important advantage is the high efficiency in large deformation phase, which is attributed to no decrease in critical time step size and no neighbor particle search. Ma et al. [13] compared MPM with widely-used meshfree SPH method, and they found that the computational cost of MPM can be several times lower than that of SPH. MPM has been successfully applied for high- and hyper-velocity impact problems [6,11,14–16]. One important advantage for high- and hyper-velocity impact simulation is that MPM can describe fragmentation and debris cloud

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without erosion schemes, which is quite different from traditional finite element method. Such an advantage ensures mass conservation throughout the impact process. The performance of shielding structures with aluminum foam was investigated with MPM model reconstructed from CT-scanned images [6]. MPM internal-structure model was built and used for direct simulation of high-velocity impact on single honeycomb panel [11]. Particle feature made model construction simple and straightforward. The influences of internal-structure form and parameters can be studied directly with point-based internal-structure model.

The shielding capability of improved double honeycomb structure is investigated in this paper based on MPM and internal-structure model. Material point method, material models and the double honeycomb structure are introduced briefly in Section 2. An improvement technique of moving intermediate facesheet is also proposed. Then the simulation results are given and discussed in Section 3. A much improved multilayer honeycomb structure is proposed based on simulation results. The paper is concluded in Section 4.

2. Simulation method and models

A set of Lagrangian points and an Eulerian background mesh are used in MPM. Lagrangian points trace history variables such as stress and plastic strain. The background mesh is used to solve momentum equations and to calculate spatial derivatives. MPM usually utilizes explicit time stepping scheme. At the beginning of each MPM step, a regular background mesh is established, and history variables are mapped to background mesh nodes. The momentum equations are solved on background mesh nodes. Then the variables on Lagrangian points are updated based on the increments on background mesh nodes. The above process means that Lagrangian points are bound to and deform with background mesh inside each step. At the end of the step, the deformed background mesh is abandoned. Regular background mesh is reused for the next step. Lagrangian points can overcome the challenge of interface tracking problems and convection term in pure Eulerian method. While Eulerian mesh can guarantee valid element deformation and feasible time step size which may have difficulties when large deformation is encountered in traditional Lagrangian mesh-based method. For a more detailed introduction to MPM, see e.g. Ref. [13,17].

The inherent contact algorithm in standard MPM is a non-slip contact constraint as single-valued velocity field is ensured automatically [18]. The same hyper-velocity impact example was computed by standard MPM and MPM with contact algorithms and different friction coefficients [16], and the friction coefficient was found to play a negligible role in the final morphology in hyper-velocity impact range and all the results were very close.

Detailed establishing process of internal-structure model of honeycomb core is given in Ref. [11]. The transition between facesheets and honeycomb core is straightforward and no special discretization treatment is needed. It is also convenient for MPM to refine the model to improve the accuracy and to show the details of the impact process. MPM internal-structure model for single honeycomb panel was validated in [11]. Comparisons of hole diameters and hole shapes between numerical results and experimental results or empirical formulas showed good agreements.

Double honeycomb sandwich panel is made of three facesheets and two honeycomb cores. They are the front facesheet, the

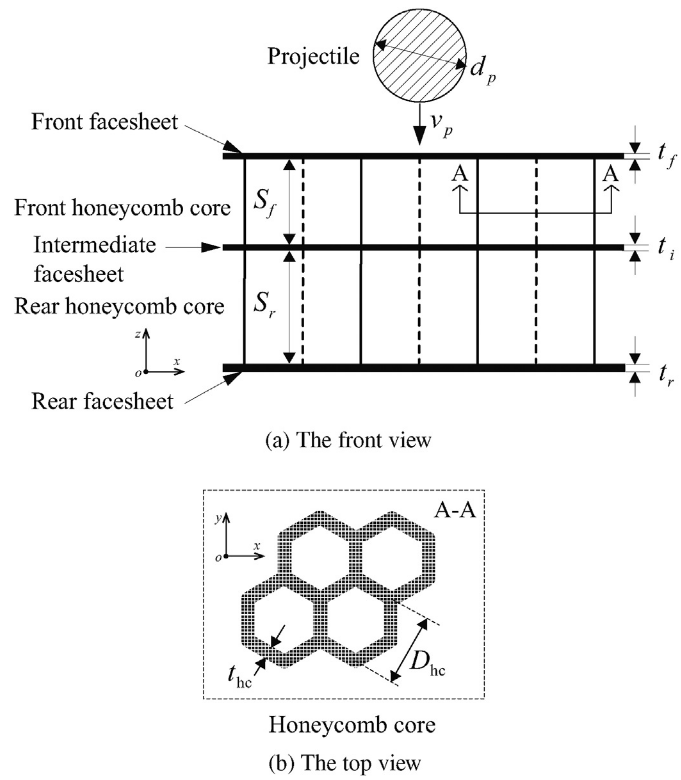

Fig. 1. Schematic diagram of double honeycomb panel.

intermediate facesheet, the rear facesheet, the front honeycomb core and the rear honeycomb core, as shown in Fig. 1. t_f, t_i and t_r are the thicknesses of the front facesheet, the intermediate facesheet and the rear facesheet, respectively. D_{hc} is the incircle diameter of the honeycomb cell. t_{hc} is the thickness of cell wall. S_f and S_r are distances between facesheets. d_p is the projectile diameter. Parameter values are listed in Table 1.

Both the sandwich plate and the projectile are made of aluminum alloy. The facesheets are made of Al2024-T81, the honeycomb cores are made of Al5052, and the projectile is made of Al2017. All of these materials are the same as used in the experiments of Ref. [9]. Johnson-Cook strength model and Mie–Grüneisen equation of state (EOS) are adopted to simulate the metal behavior under high pressure and high temperature. The material models used in this paper are identical to those adopted in Ref. [11], where material parameter values were listed in detail. The validity of using Johnson-Cook model and Mie–Grüneisen EOS was also discussed [11].

The intermediate facesheet is moved in the transverse direction (out-of-plane direction) with an interval of 2.125 mm to investigate influences of S_f and S_r on shielding performance. The summation of S_f and S_r, that is the total height of honeycomb core, is kept at 34 mm. Hyper-velocity impacts on seventeen configurations of double honeycomb structures, including the two extreme cases where the intermediate facesheet merges with the front facesheet (S_r = 34 mm) or the rear facesheet (S_r = 0), are simulated. S_r = 17 mm corresponds to the original double honeycomb panel. As shown in Ref. [9], there is a critical impact velocity at about 6–7 km/s where the shielding performance of double honeycomb

Table 1
Geometric parameters.

D_{hc} (mm)	t_{hc} (mm)	t_r (mm)	t_i (mm)	t_f (mm)	$S_f + S_r$ (mm)	d_p (mm)
4.76	0.178	0.4	0.4	0.4	34.0	2.0