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Blast resistance and parametric study of sandwich structure consisting of honeycomb core filled with circular metallic tubes

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ABSTRACT

Hierarchical sandwich structures have been popularly investigated due to its promotion in structural stress and stiffness. A composite Honeycomb structure Filled with Circular Tubes (short as HFCT) was proposed in the previous study. In this paper, the blast resistance performances of sandwich plate filled with HFCT core (short as SP-HFCT) are investigated numerically by considering plastic dissipation energy, deflection of back face-sheet and deformation modes. The comparisons of performance between the general honeycomb sandwich plate (short as GHP) and the SP-HFCT illustrate that the composited filling mode can effectively improve blast resistant capacity by reducing the maximum deflection of the back plate and improving the ratio of plastic energy dissipated by cellular core to the total plastic energy dissipated by sandwich plate. Parametric analyses are performed to evaluate the influence of matching effect between container and filler, filling mode and blast loading on the resistance performance of SP-HFCT. The results show that a stronger honeycomb container filled with weaker circular tubes is a more favorable configuration of HFCT core. Meanwhile, by filling circular tubes into a buckling area, a considerable mass efficiency improvement with respect to deflection resistance can be obtained. With the increasing of stand-off distance, the effectiveness of SP-HFCT against blast loads will be boosted.

1. Introduction

Honeycomb, as a cellular structure [1–6], attracts wide attention in the past twenty years for its excellent performance on energy absorption and outstanding impact resistance, particularly due to its outstanding weight to cost ratio. Numerous studies have been conducted to deeply understand the mechanical behaviors of honeycomb subjected to compression and impact loadings [7–15].

New structures with new geometric configuration based on the hexagonal honeycomb structures have been proposed. The filling configurations, such as honeycomb-filled structures [16,17], foam-filled structures [18,19] and other patterns [20–22], have been put forward in recent years for its advantage in simplexes, economy, and reliability. The mechanical properties of filling cellular structure under uni-axial compression have been studied comprehensively, the remarkable improvements of load carrying and energy absorption ability caused by filling configuration have been testified by numerous researches, such as thin-walled aluminum tubes filled with honeycomb [23] and natural flax fabric reinforced epoxy composite tubes filled with polyurethane-foam [24].

Different from axial compression properties, with the increasing requirements of light armor for vehicles and structures subjected to explosion impulse, it is inevitable to carry out a series of study about the blast and impact resistance performance of the sandwich plate consist of cellular core [25–28], particularly in some novel functional structures as originally developed by Wei and Pei [29–31]. To date, most of the existing researches are focused on the conventional hexagonal honeycomb sandwich plate [32,33], composites sandwich plate [34], novel sandwich plate made of negative Possion's ratio (NPR) cellular core [35] and lattice sandwich plate [36–38]. The above novel structures all displayed some attractive mechanical properties, like an advance energy absorption capability of the honeycomb and the lattice sandwich plate [39,40]; a material concentration effect of NPR cellular core [35]. However, in terms of another key factor as the deflection resistance, although a certain degree of improvement has been achieved base on these structures, it is still not good enough. A filling configuration can be a potential choice to solve this which has been discussed in previous study [41].

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In our previous study, a strong dependence of mechanical properties of the honeycomb filling into thin-walled square tube (HFST) structure on the matching effect between the inside honeycomb core and the outside tube container has been observed. To reduce the turbulence of mechanical properties induced by matching effect while to maximize use the empty space of each cell of conventional honeycomb, even in deformation progress, a novel filling configuration, micro-cell honeycomb filled with ultra-micro circular tubes (HFCT) structure, has been put forward [42]. The uniaxial compression tests have been carried out experimentally; obvious filling effect and matching effect were extensively discussed around several kinds of filling patterns. Not only has an excellent energy absorption capability been obtained, but also a controllable deformation pattern was observed. Besides, the complex interaction between the honeycomb cell and tube provides potential preponderance in the shear strength of the sandwich plate without significantly increasing weight which is a superior character for impact protection structure.

Considering the research on the blast resistance of sandwich plate with filling configuration core is very limited [43,44], hence the objective of the present work is to investigate the dynamic response and energy absorption performance of the square metallic HFCT sandwich plate (SP-HFCT in the following text). An effective full-scale 3D numerical model to simulate the SP-HFCT subjected to blast loadings will be developed with ABAQUS software. Detailed numerical and material model will be illustrated in section 2. Two key parameters related to blast resistance of sandwich plate [7,13], the back face-sheet maximum deflection and the ratio of the cellular core energy dissipation to the total energy dissipation of sandwich plate, will be adopted to evaluate the blast resistance performance of sandwich plate, see section 3. Various parametric studies on the influence of the matching effect, filling mode and blast loading will be presented in section 4. In detail, different sets of configuration of the cell thickness of honeycomb container and inside circular tube will be used to analyse the strength matching effect. For filling mode, three kinds of partially filling modes of HFCT core will be studied to find a more effective filling mode and explain the interaction of which part of the cellular core is the most vital to the blast resistance. Relationship between detonation position and blast resistance efficiency of SP-HFCT will also be extensively discussed. Some major conclusions will be drawn in section 5.

2. Numerical simulation

2.1. Geometric configuration of SP-HFCT

A typical configuration of the sandwich plate is composited by three parts: two face-sheets and a core made from cellular structure (here is HFCT). As shown in Fig. 1, the overall dimension can be characterized by L, W and T, while this paper considers $L = W$. The height T includes the cellular core height H, face-sheets height s and adhesive layer (ignored in simulation). The overall dimension of the sandwich plate are characterized as $L = W = 300$ mm and $T = 22$ mm, where the HFCT core's height is 20 mm and the face-sheet thickness is 1 mm for both the front and rear face-sheets to avoid the influence of thickness ratio. The geometrics of sandwich plate stay constant in all adopted models.

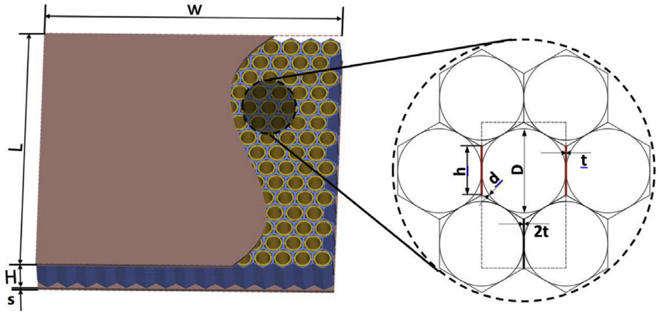

Fig. 1. Schematic diagram of the typical sandwich structure and the HFCT core with the geometrical parameters and the area to calculate the relative density ρ^* (within the rectangular dotted area, highlighted red lines mean single thickness, highlighted black line means double thickness). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The HFCT core can be described as filling a tiny circular metallic tube into each cell of hexagonal honeycomb. Each basic element is consisting of two components: one is the outside honeycomb cell, the other is the inside circular tube. The sketches of HFCT configuration are presented in the Fig. 1, with the key geometrical parameters as outside honeycomb foil thickness t (for the adhesive manufacture process, two of six edges are $2t$ thick), cell edge length h (here, each hexagonal cells are considered as regular) and inside tube outer diameter D, wall thickness d. The outer diameter D equals to the honeycomb across flat distance to make sure the tangential effect between the honeycomb cell and circular tube. Hence D can be described as $D = \sqrt{3}h$. No adhesive is need between these two components due to the geometrical constraints induced by tangential effect. For hexagonal honeycomb core, the relative density ρ^* can be given as [1]:

$$\rho^* = \frac{2t/h}{(1+\sin\theta)\cos\theta}\rho^s \tag{1}$$

where the ρ^s is the density of the bulk material and θ is the expanding angle of the honeycomb cell which remains constant as 30° here. However, in terms of the HFCT core which according to the schematic Fig. 1, considering the dotted rectangular area, the highlight black solid line means double thickness cell wall and oppositely the highlight red solid line means the 1/2 thickness counted double thickness cell wall, the rest solid lines in the area are single thickness, so equation (1) can be redefined as:

$$\rho^* = \frac{4th + \pi Dd}{(1+\sin\theta)2\mathrm{h}^2\cos\theta}\rho^s \tag{2}$$

2.2. Elements model and boundary conditions for SP-HFCT

With the ABAQUS/Explicit, the fully scaled FE model is established. In particular, the thin-walled foils and inner circular tube are meshed with 4-node doubly curved thin or thick shell (S4R) with enhanced hourglass control, the front and back face-sheets are also meshed with S4R elements. Under impact load, both the sandwich core and face-sheets could undergo large deformations, such as plastic bending, stretching and buckling, which could induce extreme distortion of coarse elements, so a rationally refined mesh must be applied (the mesh convergence will be discussed in the following section). A tie connection between the face-sheet and HFCT core is applied to replace the original adhesive layer. The detonation point is set at the stand-off distance of R (mm) from the center point of the plate with the charge weight Q (kg).

Due to the symmetrical boundary condition (X-Y and Z-Y plane), only a quadrant of the sandwich structure ($150\,mm \times 150\,mm \times 22\,mm$) needs to be modelled to reduce the numerical analysis cost as shown in Fig. 2, the cross section indicated by the red lines are equipped with the XSYMM and ZSYMM boundary conditions individually, fix boundary conditions are imposed on the perimeter of the sandwich plate. Furthermore, automatic general contact with friction coefficient 0.3 and hard contact behavior is set up between the face-sheets and the cellular core to avoid self-penetration.

2.3. Modeling blast load

In engineering application, a sandwich plate is generally utilized as a shield for the building and vehicle subjected to air blast loading. As well known that the air blast loading (Fig. 2) can be quantified based on