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Blast resistance and design of sandwich cylinder with graded foam cores based on the Voronoi algorithm

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ABSTRACT

Blast resistance and design of sandwich cylinder with graded foam cores are investigated using numerical simulations. The finite element (FE) model is constructed based on the random Voronoi algorithm, and validated by experimental results. The deformation process of sandwich cylinder subjected to blast loading is simulated using the ABAQUS/Explicit software. Subsequently, parametric studies are carried out to analyze the effects of explosive charge, thicknesses of face-sheet and core, and core gradient on deformation pattern, plastic dissipation of the core, and maximum radial deflection (MRD) of the outer face-sheet. The cylinder structure with high plastic dissipation and low MRD is a good choice for protecting persons and objects located on the outside of the cylinder from the internal blast. The results show that the blast resistance increases with the foam core thickness increasing. However, the plastic dissipation of core and the MRD of outer face-sheet are two conflicting objectives to evaluate blast resistance for other parameters.

1. Introduction

Foam is considered as a new class of ultra-light material with the ability to undergo large deformation at a nearly constant plateau stress, and thus can absorb more energy duo to its excellent specific stiffness and strength properties [1]. Sandwich structures with foam cores have been extensively used in various important fields, such as aerospace, marine and other military applications [2–4]. The foam core can reduce the outer face-sheet deflection and mitigate the damage caused by the impact and blast.

The sandwich structure with graded core configurations has been recently receiving an increasing attention to achieve a better blast resistance [5–7]. The graded core shows great potential to be effective for absorbing energy and improving the overall blast resistance [8–10]. The dynamic response of graded foams under blast loading has been well studied [11,12]. Shen et al. [13] proposed that single shock wave and double shock wave appeared in the density-graded cellular when gradient are positive and negative, respectively. Karagiozova and Alves [14,15] considered that the density distribution for the boundaries of a rod with finite thickness played a significant role in the stresses and strains in the crushing process. Liu et al. [16] proposed analytical solutions for graded cellular rods with linear, quadratic and square root density distributions. Zheng et al. [17] examined impact response of density-graded cellular rods with various distributions, and found three shock fronts exist in the middle-low one.

With increasing of terrorism, improved blast resistant structures become a tendency due to the low efficiency and high cost of traditional blast protection devices. The sandwich cylinder has been proposed as a novel design to enhance the blast resistance of explosion containment vessels to contain explosive materials, protecting persons or equipment from the shock waves and detonation products. Shen et al. [18] found that sandwich cylinders appeared a better blast resistance than a monolithic cylinder with the same mass. Liu et al. [19] demonstrated that the radial deflection of the sandwich cylinder with graded core was smaller than that of ungraded ones subjected to internal blast loading. More recently, Karagiozova et al. [20] proposed a theoretical model for the deformation of a sandwich cylinder with polystyrene foam core to study the process of foam crushing and radial deflection of outer face-sheet. Although several investigations have been proposed for the blast response of sandwich cylinder, the underlying mechanism is not thoroughly understood and further investigation is necessary.

Most available mechanical models are usually based on idealized unit foam structures, and are not able to account for the natural variations in microstructure that are typical for most foam structures [21]. The random Voronoi algorithm is a smart tool to simulate the deformation process and dynamic response of foam material and structure. Zhu et al. [22,23] constructed the random Voronoi structures to determine the effect of cell irregularity on foam materials. Zheng et al. [24] simulated the dynamic crushing process of foams using 2D and 3D Voronoi structures. Ajdari et al. [25] introduced the Voronoi

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algorithm to investigate the energy absorption of honeycombs with constant and functionally graded density. Liao et al. [26] used a method to obtain the local strain field of foam materials using the Voronoi algorithm. In this paper, the Voronoi algorithm is used to investigate blast resistance and design of sandwich cylinder with graded foam cores. Firstly, the Voronoi algorithm is employed to create the FE model, and then the FE model is validated by the experimental result. Subsequently, the deformation process of the sandwich cylinder under blast loading is studied using ABAQUS/Explicit software. Finally, parametric studies are carried out to analyze the effects of explosive charge, the thicknesses of face-sheet and core, and core gradient on deformation pattern, plastic dissipation, and the MRD of outer face-sheet.

2. Voronoi algorithm

The 2D random Voronoi algorithm is applied to generate closed-cell foams with a uniform cell-wall thickness using the Matlab software. The foam structure is formed by the nucleation and growth of cells, which nucleate simultaneously in areas and grow at an isotropic rate. Firstly, N nuclei (points) are randomly generated in a given area A based on the principle that the minimum distance between any two nuclei is constrained to be larger than a given distance δ_{min}:

$$\delta_{\min} = (1 - k)\delta_0, \tag{1}$$

where k is the degree of cell irregularity, and $k=1$ for a fully random Voronoi structure. $k=0.2$ is used in this study. δ_0 is the distance between any two adjacent nuclei which is given by

$$\delta_0 = \sqrt{2A/\sqrt{3}N}. \tag{2}$$

Secondly, each nucleus is copied to the surrounding 8 neighboring regions by maintaining periodic boundary conditions. The process is repeated before N nuclei have been specified. Thirdly, the Delaunay triangulation and the Voronoi diagram are constructed (Fig. 1). The Voronoi cell contains all points that are closer to its data point than any other data points in the set. Finally, the periodic Voronoi structure is constructed after the given area A is deleted. The relative density of the Voronoi foam is given by

$$\rho = t\sum_{i=1}^{N} l_i/A, \tag{3}$$

where t and l_i are the thickness and length of cell wall, respectively. For a given area and a relative density, the thickness of cell wall can be obtained.

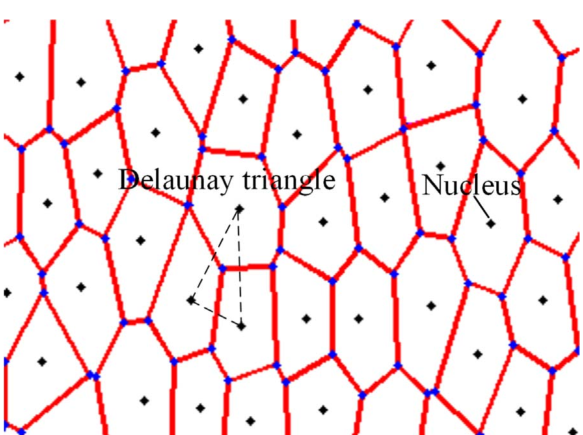

Fig. 1. Delaunay triangulation and the Voronoi diagram.

3. Numerical simulation

3.1. FE model

Numerical simulations are performed using the ABAQUS/Explicit FE analysis software. As illustrated in Fig. 2(a), the Delaunay triangulation and the Voronoi diagram are constructed in an area of a cylinder. The cylindrical foam core is constructed after the given area is deleted (Fig. 2(b)). As shown in Fig. 3, three kinds of cores (uniform, positive gradient, and negative gradient) are constructed by the Voronoi algorithm in an area of a hollow cylinder. The foam is sandwiched between two face-sheets. The diameter and thickness of outer face-sheet (d_i and t_i) are 64 and 1.5 mm, respectively. The diameter and thickness of inner face-sheet (d_o and t_o) are 104 mm and 1.5 mm, respectively. Each layer of the core has the same thickness for graded core. The details of specimens and explosive charges are listed in Table 1. The materials of foam and face-sheets are aluminum alloy and steel. The elastic-perfectly plastic models are used for foam cells. The material properties are shown in Table 2. Due to nonlinearity in the dependence of flow stress on plastic strain, an accurate value of the flow stress requires iteration for the increment in plastic strain. The Johnson-Cook (J-C) model is applied to account for the strain-rate effects of the face-sheets. The J-C model is given as

$$\sigma = [A + B\varepsilon^n][1 + c\,\ln(\dot{\varepsilon}^*)][1 - (T^*)^m], \tag{4}$$

where ε is the plastic strain of the material, $\dot{\varepsilon}$ is the dimensionless strain rate of the material, T^* is the homologous temperature defined as $(T\text{-}T_{room})/(T_{melt}\text{-}T_{room})$ where T_{room} and T_{melt} are the room and melting temperature, respectively. A is the quasi-static yield stress of the metal, B and n are the strain hardening coefficients, c is the strain rate hardening coefficient, and m is the thermal softening coefficient. The J-C parameters are listed in Table 3.

The JHL explosive charge to be detonated is held in place at the central of internal face-sheet. The Jones-Wilkins-Lee (JWL) equation of state is used to describe the detonation products of the explosive. The detonation pressure is given as the following:

$$p = A_e\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B_e\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E_{e0}}{V}, \tag{5}$$

where p is the detonation pressure, V is the relative volume, E_{eO} is the detonation energy density, and A_e, B_e, R_1, R_2 and ω are material constants. The JWL parameters for the JHL explosive are listed in Table 4. The core and face-sheets are modeled using a type of shell element (S4R). Self-contact is applied to all the cell surfaces. The general contact is considered between the core and the face-sheets with a friction coefficient of 0.02 [24].

3.2. Model validation with experiments

A schematic of experimental setup is shown in Fig. 4. Experiments were conducted using cylindrical explosive located in the central of the cylinder. The explosive charges have the same ratio of length to radius with the inner face-sheet. Two group poles were erected with two ropes. The test specimen was placed on the ropes, and the ropes were replaced after each testing. The purpose of this setup is to minimize the end effects influence on the specimen. The properties and dimensions of the specimen in tests were coincided with the corresponding simulation. The cylinder specimen was cut along the cross section of the maximum deflection by electro-discharge machine after testing. The face-sheet deflection results are listed in Table 5. The deflection results from the experiment and simulation are compared, and the errors are acceptable. As shown in Fig. 5, the deformation pattern from the simulation is compared with the experimental result. A good agreement is achieved between numerical and experimental results.