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Blast resistance of sandwich-walled hollow cylinders with graded metallic foam cores

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ABSTRACT

The dynamic responses and blast resistance of all-metallic sandwich-walled hollow cylinders with graded aluminum foam cores are investigated using finite element simulations, and compared with those of conventional ungraded ones. After validating the numerical approach and introducing the computational model, sandwich-walled hollow cylinders with various graded aluminum foam cores are analyzed under air blast loading. It is demonstrated that the radial deflection of graded cylinders is smaller than and the blast resistance superior to that of ungraded ones when subjected to identical air blast loading. This can be further improved by optimizing the foam core arrangement. Finally, the influence of face-sheet arrangements on the dynamic behavior of graded cylinders is explored.

1. Introduction

In recent years, the increasing threat of terrorism has stimulated much interest in novel blast resistant structures [1–9]. Although numerous blast protection devices have been developed to meet various blast resistance requirements, the weight of these devices is typically too large to be moved in the absence of mechanical means. Another issue restricting the wide application of traditional blast protection devices is the high cost. To address these issues, lightweight metallic sandwich structures consisting of two thin and strong face-sheets separated by thick and weak cellular core have emerged as promising candidates to mitigate high impulsive loading [1–9]. The face-sheets are usually made of high strength solid material whilst the cellular metallic cores are highly porous, such as metallic foams with random cell topologies and periodically arranged lattice structures (e.g., honeycomb, pyramidal truss and prismatic corrugation). When subjected to impulsive loading, the relatively weak cellular core enables large plastic deformation and hence absorbs a large amount of energy during the deformation, contributing to the high blast resistance of the sandwich structure relative to the equivalent monolithic counterpart under the same blast loading [10–21]. Broadly speaking, the dynamic responses of the sandwich structure subjected to air or underwater explosion may be split into three sequential stages: (1) fluid–structure interaction, (2) core compression, and (3) structure bending and stretching. To explore further the blast protection capability of light sandwich configurations, the focus of this study is placed upon sandwich-walled hollow cylinders with functionally graded aluminum foam cores.

The dynamic performance of sandwich structures having close-celled metallic foam cores has been investigated extensively, both experimentally and theoretically. For example, Zhu et al. [22] performed air blast experiment and finite element simulation on aluminum foam-cored sandwich panels. The simulation results well captured the deformation patterns of the sandwich panels observed in the tests, and agreed with the experimental measurements. They also carried out parametric studies on the energy absorption performance of the sandwich. However, most existing studies focused on plane sandwich beams or panels, and few concerned curved sandwich structures. Shen et al. [23] implemented blast loading tests on curved sandwich panels using a four-cable ballistic pendulum with corresponding sensors. It was demonstrated that the performance of sandwich shells is superior to that of equivalent mass solid counterparts and flat sandwich panels because of the initial curvature.

Further, since the material characteristics of layered materials can be controlled in a predetermined way, it is of interest to investigate how sandwich structures with graded aluminum foam cores perform under impulsive loading. Li et al. [24] found that the choice of layer gradation affects significantly the impulse response of layered and graded metal-ceramic composites. Focusing on the low velocity impact response of sandwich structures with functionally graded core, Apetre et al. [25] demonstrated that functionally graded core reduces the maximum strain and can be used effectively to mitigate or completely prevent impact damage. Utilizing three-dimensional (3D) finite element (FE) simulations, Etemadi et al. [26] demonstrated that sandwich beams with

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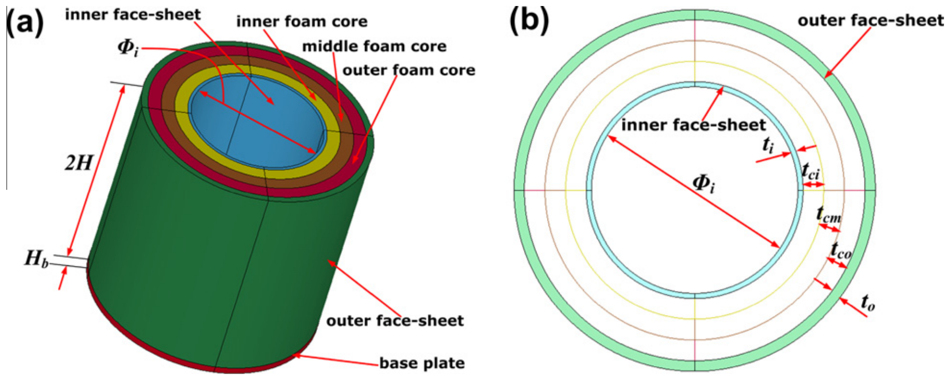

Fig. 1. Skematic of graded sandwich-walled hollow cylinder without cover: (a) overall view; (b) top view (base plate masked for better view).

functionally graded cores exhibited maximum contact force increasing and maximum strain decreasing in comparison with those having homogenous cores subjected to the same blast loading. Using a shock tube facility, Wang et al. [27] experimentally demonstrated that different core configurations led to considerably different dynamic responses of sandwich panels with multilayered graded foam cores, due mainly to different degrees of deformation and failure. Chittineni and Woldesenbet [28] experimentally investigated the quasi-static compression performance of four-layer functionally graded composites fabricated from four different hollow particles, and found that the arrangement of layers affected significantly the compressive strength and energy absorption of the composite. Gunes and Aydin [29] numerically studied the shock behavior of functionally graded circular plates with peripherally clamped boundaries under a drop-weight. It was shown that the compositional gradient exponent, impact velocity and plate radius significantly influenced the impact response of the plate, whilst the layer number through the plate thickness had a minor effect. At present there is not yet a report on the air blast loading responses of curved sandwich configurations with graded metallic foam cores.

The objective of the present work is to investigate the air blast response of sandwich-walled hollow cylinders with multilayered graded aluminum foam cores using 3D FE simulations. For comparison, conventional sandwich-walled hollow cylinders with homogeneous aluminum foam cores are also simulated. Fig. 1 displays the geometric model of the graded sandwich-walled hollow cylinder with cover removed. The hollow cylinder is consisted of two face-sheets made of steel, a three-layered aluminum foam core, and a base plate also made of steel. The three close-celled aluminum foam layers differ in relative density (or, equivalently, porosity). The case of covered cylinder is separately simulated, the cover having identical shape and size as the base plate. The explosive (TNT) used in the simulation has a spherical shape and is positioned at the center of the sandwich-walled hollow cylinder (see Fig. 5b).

The article is organized in the following manner. The numerical approach is validated by comparing with experimental measurements carried out for sandwich panels with homogeneous aluminum foam cores [22], as presented in Section 2. Thereafter, Section 3 introduces the computational models for both graded and conventional sandwich-walled hollow cylinders, whilst Section 4 presents and analyzes the numerical results, with focus placed upon the influence of core layer arrangement on blast resistance. At last, the influence of face-sheet arrangement is discussed in Section 5.

2. Validation of numerical approach

Numerical simulations are performed using commercially available FE code LS-DYNA 971. To validate the numerical approach, aluminum foam-cored sandwich panels tested by Zhu et al. [22] under air blast loading are simulated. The specimens consist of two identical aluminum alloy (2024-T3) face-sheets and an aluminum foam core with 6% relative density. The peripherally fully clamped sandwich panels have in-plane dimensions of 250 mm $\times$ 250 mm, whilst the face-sheet thickness and foam core height are varied according to that specified in Table 1. The TNT explosive is located in front of the center of the sandwich panel, with a constant stand-off distance of 200 mm (Fig. 2a). The blast resistance of each sandwich is quantified by the permanent normal deflection at the center of the back face-sheet, which is experimentally measured (Table 1) [22].

For FE simulation, only a quarter of the sandwich panel is analyzed due to symmetry, with symmetrical boundary conditions imposed (Fig. 2b). Both the sandwich panel and the surrounding air domain are modeled using eight-node linear solid elements with reduced integration as shown in Fig. 2a. The explosive has a cylindrical shape and is detonated at the center of its top surface. The sandwich panel is meshed using Lagrange elements whilst the air domain is meshed utilizing Euler elements. Lagrange elements and Euler elements are coupled through ALE (Arbitrary Lagrange Euler) approach, which combines the best features of the Lagrange and Euler methods and is suitable to analyze high speed deformation under explosion. To ensure numerical convergence, the number of elements selected for the sandwich panel is 10,800 while that for the air domain is 94,192.

The mechanical behavior of explosive is governed by a high explosive material model (MAT_HIGH_EXPLOSIVE_BURN in LS-DYNA) incorporating the JWL equation of state (EOS_JWL). Its mass density is 1630 kg/m^3, detonation velocity is 6700 m/s and Chapman-Jouget pressure is 19 GPa. The mechanical behavior of air (mass density 1.29 kg/m^3) is governed by a null material model (MAT_NULL) comprising the linear polynomial equation of state (EOS_LINEAR_POLYNOMIAL).

The mechanical behavior of aluminum alloy 2024-T3 (mass density 2680 kg/m^3, Young's modulus 72 GPa, Poisson ratio 0.33, yield stress 318 MPa and tangent modulus 737 MPa) is governed by material model MAT_PLASTIC_KINEMATIC, which is a bi-linear

Table 1
Specifications of foam-cored sandwich panels and experimental results [22].

No. of specimen	Face-sheets thickness (mm)	Core thickness (mm)	Mass of TNT explosive (g)	Central deflection of back face-sheet (mm)
1	1.0	20	20	4.9
2	1.0	20	30	6.1
3	0.8	30	30	6.2
4	0.8	30	40	6.3
5	1.0	30	30	5.6
6	1.0	30	40	7.0