International Journal of Mechanical Sciences 84 (2014) 61–72

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Sandwich plates with functionally graded metallic foam cores subjected to air blast loading

X.R. Liu [a], X.G. Tian [a,*], T.J. Lu [a,*], B. Liang [b]

[a] State Key Laboratory for Mechanical Structural Strength and Vibration, Xi'an Jiaotong University, Xi'an 710049, China
[b] Xuhai College, China University of Mining & Technology, Xuzhou 221008, China

A R T I C L E I N F O

Article history:
Received 16 January 2013
Received in revised form
9 July 2013
Accepted 20 March 2014
Available online 29 March 2014

Keywords:
Sandwich plate
Functionally graded material
Aluminum foam
Air blast
Finite element

A B S T R A C T

The dynamic responses and blast resistance of all-metallic sandwich plates with functionally graded close-celled aluminum foam cores are investigated using finite element simulations, and compared with those of ungraded single-layer sandwich plates. Upon validating the numerical approach using existing experimental data and introducing the present computational model, different graded sandwich plates under air blast loading are analyzed in terms of deformation and blast resistance. The effects of face-sheet arrangements and interfacial adhesion strength between different foam layers are quantified. The results demonstrate that relative to conventional ungraded plates subjected to identical air blast loading, the graded plates possess smaller central transverse deflection and superior blast resistance, with further improvement achievable by optimizing the foam core arrangement. The blast resistance of both graded and ungraded sandwich plates subjected to the constraint of equivalent mass is also explored.

1. Introduction

Lightweight all-metallic sandwich plates consisting of two thin and strong face-sheets separated by thick and weak cellular cores have been increasingly exploited as blast resistant structures [1–9]. The face-sheets are typically 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., honeycombs, pyramidal trusses and prismatic corrugations). When subjected to impulsive loading, it has been established that the cellular core enables large plastic deformation and hence absorbs a large amount of impact energy, contributing to the superior blast resistance of the sandwich structure relative to monolithic counterpart with equivalent mass [10–16].

Radford et al. [17] utilized the metallic foam projectile to successfully simulate the high intensity pressure impulse exposed on sandwich structures, with the applied pressure versus time impulse having a peak pressure on the order of 100 MPa and loading time of approximate 100 μs. This experimental technique was subsequently employed by Radford et al. [18,19], McShane et al. [20] and Tagarielli et al. [21] to investigate the shock resistance of clamped sandwich beams/plates having lattice truss or metallic foam cores, revealing that the sandwich structures have superior shock resistance compared to monolithic counterparts. Bahei-El-Din et al. [22] proposed a modified sandwich plate design, with a thin polyurea interlayer inserted between the outer face-sheet (loaded side) and the foam core. The simulation results showed that, under blast loading, the modified sandwich plate reduced foam core crushing, face-sheet strain and overall deformation relative to conventional sandwich design, absorbing however also less energy. Zhu et al. [23–25] performed air blast experiment and finite element (FE) 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 experimental measurements. Nurick et al. [26], Karagiozova et al. [27] and Theobald et al. [28] investigated the responses of sandwich panels subjected to intense air blast loading both experimentally and numerically, and found that the face-sheet thickness affects significantly the blast resistance of sandwich panels; the compromise between improved energy absorption and loading transfer through the core to the bottom face-sheet was also explored. Shen et al. [29] implemented blast loading tests on curved sandwich panels using a four-cable ballistic pendulum with corresponding sensors. It was demonstrated that, due to the initial curvature, the performance of sandwich shells is superior to that of equivalent mass solid counterparts and flat sandwich panels. Existing theoretical and experimental studies also demonstrate that, broadly speaking, the

* Corresponding authors. Tel./fax: +86 29 8266 8751.
E-mail addresses: tiansu@mail.xjtu.edu.cn (X.G. Tian), tjlu@mail.xjtu.edu.cn (T.J. Lu).

http://dx.doi.org/10.1016/j.ijmecsci.2014.03.021
0020-7403/

dynamic responses of sandwich structures 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.

Since the material characteristics of layered materials can be controlled in a predetermined way, a growing number of theoretical and experimental studies focused on how sandwich structures with graded cores perform under impulsive loading. For typical instance, Li et al. [30] found that the choice of layer gradation significantly affects the impulse response of layered and graded metal–ceramic composites. Regarding low velocity impact responses of sandwich structures having functionally graded cores, Apetre et al. [31] demonstrated that the 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. [32] demonstrated that sandwich beams with functionally graded cores exhibited increasing maximum contact force and decreasing maximum strain in comparison with those having homogenous cores. For sandwich plates with multilayered graded foam cores, Wang et al. [33] demonstrated experimentally with a shock tube facility that different core configurations led to considerably different dynamic responses, due mainly to different degrees of deformation and failure. Chittineni and Woldesenbet [34] 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. The shock behavior of functionally graded circular plates with peripherally clamped boundaries under a drop-weight was numerically simulated by Gunes and Aydin [35]. Whilst compositional gradient exponent, impact velocity and plate radius were found to influence significantly the impact response of the plate, the layer number through the plate thickness had a minor effect. Ajdari et al. [36] investigated using finite element models the dynamic crushing and energy absorption of two-dimensional (2D) honeycombs with functionally graded density. It was shown that decreasing the relative density in the direction of crushing can enhance the energy absorption capability of the honeycomb at early stages of crushing. Employing the same experimental device of Wang et al. [33], Gardner et al. [37] investigated the performance of functionally graded sandwich composite beams. It was found that increasing the layer number of monotonically graded foam core helped to maintain the structural integrity and enhanced the blast resistance of the sandwich composite, because acoustic wave impedance mismatch between successive layers was decreased.

Despite extensive theoretical and experimental investigations as discussed above on sandwich structures subjected to air blast loading, at present there is yet a systematic study focusing on the dynamic responses and blast resistance of sandwich configurations with graded metallic foam cores. With 3D FE simulations, this deficiency is addressed in the present work by studying the air blast behavior of sandwich plates with multilayered graded aluminum foam cores. The influences of simulated pressure history (rectangular versus exponential type), foam core layer number and interfacial connection strength are considered. For comparison, conventional single-layer sandwich plates with homogeneous aluminum foam cores are also computed. The paper is organized in the following manner. In Section 2, the numerical approach is validated by comparing with existing experimental measurements for both circular and square plates [19,23]. Computational models for both conventional and graded sandwich plates are introduced in Section 3. Section 4 presents and analyzes the simulation results considering two different joint connection types, with particular focus placed upon the influence of core layer number and core layer arrangement on blast resistance. Section 5 examines the influence of face-sheet arrangements on the dynamic responses of sandwich plates, whilst Section 6 illustrates the blast resistance of sandwich plates with equivalent mass and compares with the case of equivalent volume. At last, the conclusions are drawn in Section 7.

2. Validation of numerical approach

2.1. Validation with circular plates

Numerical simulations are performed using the commercially available FE code LS-DYNA 971. For validation, the responses of circular metallic aluminum foam-cored sandwich plates tested by Radford et al. [19] to simulated blast loading are numerically predicted. The sandwich plates (denoted here as S) consist of two identical AISI 304 stainless steel face-sheets (1.18 mm in thickness) and close-celled aluminum foam (Alporas) core having 15.9% relative density and 10 mm core height. Circular monolithic stainless steel plates (denoted here as M) having the same mass as the sandwich plates are also simulated. Both the sandwich and monolithic plates have an in-plane radius of 80 mm and are peripherally fully clamped. The blast loading is generated by cylindrical aluminum foam projectiles of diameter 28.5 mm, impacting at the central circular area of the top face. As previously mentioned, it has been established that metallic foam projectiles can be used to create pressure impulses exposed on sandwich structures, with peak pressure on the order of 100 MPa and loading time of approximately 100 μs [17]. The performance of each plate is quantified by permanent transverse deflection at the center of the bottom face, which is experimentally measured [19]. For each type of plate, Table 1 summarizes the impulse/area exerted on the plate by aluminum foam projectile and the corresponding central deflection of the bottom face measured experimentally [19]. Accordingly, in the present study, $\sim 10\ \mathrm{kN\,s\,m^{-2}}$ is selected as the impulse/area for all FE simulations, mimicking a pressure magnitude of about 100 MPa.

For numerical simulations, the air blast loading is modeled as pressure versus time history and is applied to the top face of the plate over a central circular region of diameter 28.5 mm. Two different pressure histories, rectangular and exponential, are adopted. For the rectangular case, the pressure versus time history has a time duration of 100 μs, and the plateau pressure is derived from the impulse/area (as listed in Table 1) based on impulse conservation. For example, the impulse/area exerted on sandwich plate S2 is $13.31\ \mathrm{kN\,s\,m^{-2}}$, while the corresponding pressure is 133.1 MPa, as shown in Fig. 1a. For the exponential case, the applied pressure is described by exponentially decaying time-dependent history, as

$$p(t) = p_0 e^{-t/t_0} \quad (1)$$

where p_0 is the peak pressure and t_0 is the time taken by the shock wave to decay to $1/e$ of the peak pressure. In this case, the

Table 1
Impulse/area and the corresponding central deflection of bottom face for both sandwich plates (S) and monolithic plates (M) [19].

Specimen	Impulse/area ($\mathrm{kN\,s\,m^{-2}}$)	Central deflection of bottom face (mm)
S1	9.93	8.1
S2	13.31	12.8
M1	10.51	10.6
M2	11.75	12.2
M3	13.07	14.2