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Blast response of geometrically asymmetric metal honeycomb sandwich plate: Experimental and theoretical investigations

Tao Wang[a,b], Qinghua Qin[a,*], Mingshi Wang[a], Wenli Yu[b], Jintao Wang[b], Jianxun Zhang[a], T.J. Wang[a,*]

[a] State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China
[b] Department of Engineering Physics, Xi'an Research Institute of High-Tech, Xi'an 710025, China

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ABSTRACT

Dynamic response of geometrically asymmetric sandwich plates with aluminum hexagonal honeycomb core subjected to blast loading is investigated experimentally and theoretically. Specimens of various face sheet thicknesses are tested for three blast intensities which are varied by changing the weights of cyclotrimethylene trinitramine (RDX) explosive charges at a constant standoff distance. Four edges of sandwich plates are fully clamped. The deformation and damage modes of sandwich plates are obtained. The influences of the blast loading and the core density on the dynamic response of sandwich plates are analyzed. The analytical model is developed to predict the blast response of the geometrically asymmetric sandwich plate subjected to blast loading. It is shown that the theoretical predictions of the deflection of the center point at the rear face sheet is in good agreement with the experimental results. The geometrical asymmetry due to the thicknesses of the face sheets has a significant effect on the deformation and damage of sandwich plates.

1. Introduction

Sandwich structures have many excellent characteristics, such as lightweight, high strength and stiffness to weight ratios, energy absorption and multifunctionality over the conventional monolithic structures. They have been used widely to resist the explosive and impact loadings as attenuation layers. The sandwich cores play important roles in the energy absorption of explosive and impact loadings. A lot of new core topologies for sandwich structures have been designed and manufactured, such as metal foam, folded plate, pyramidal truss, diamond celled and honeycomb [1–5].

Over the past decade, much attention has been paid on the investigations on dynamic response of sandwich structures. Fleck and Deshpande [6] theoretically studied the structural response of fully clamped metal sandwich beams subjected to uniform transverse blast loading and obtained the so-called upper and lower bounds of large deflections by using the approximate yield criterion neglecting the core strength. Based on the yield criterion considering the effect of core strength, Qin and Wang [7–9] obtained the analytical solutions for the impulsive response of fully clamped metal sandwich beams and rectangular sandwich plates, in which interaction of bending and stretching was considered. The optimization design and comparative study on metal sandwich plates were also conducted by theoretical analysis, experiment and numerical simulation [3,4, 8, 10–12].

Sandwich structure with a honeycomb core has bee widely used in the fields of aerospace, transportation, package and defense engineering. Many researchers focused on the dynamic behavior of symmetric sandwich structure with honeycomb core subjected to blast loading. In a parallel study, Nurick and co-authors [13,14] experimentally studied the dynamic behavior of sandwich panels with aluminum honeycomb core subjected to intense air blast and discussed the failure modes and the effects of core height and face sheet thickness on the dynamic response. Dharmasena et al. [15] experimentally and numerically investigated the dynamic response of fully clamped metal square honeycomb sandwich panels subjected to blast loading and found some new failure modes. It is demonstrated that the honeycomb sandwich panels suffered significantly smaller back face deflections than solid plates of identical mass. Zhu et al. [16–18] studied the dynamic response of sandwich plates with a hexagonal honeycomb core and proposed an analytical model to predict the dynamic response.

The current investigations related to blast resistance of the honeycomb core sandwich structure consider with an identical face sheets. However, the application of sandwich structures in critical structures requires consideration of other possible design scenarios. Examples of such design scenarios are: (i) the different thicknesses of front and rear face sheets, and (ii) the different thicknesses and materials of front and rear face sheets. Here, we focus on the first scenario mentioned above. Bella et al. [19] experimentally

* Corresponding authors.
E-mail address: qhqin@mail.xjtu.edu.cn (Q. Qin), wangtj@mail.xjtu.edu.cn (T.J. Wang).

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Nomenclature

A	total area of sandwich plate
B	semi-width of the rectangular sandwich plate
$c, \bar{c}$	thickness of honeycomb core and its non-dimensional form
D_R	diameter of the cylindrical RDX explosive charge
E	Young's modulus of the face sheets
h_f	thickness of the front face sheet
h_r	thickness of the rear face sheet
$\bar{h}$	non-dimensional thickness of the face sheets
h_w	wall thickness of honeycomb core
$I, \bar{I}$	impulse per unit area and its non-dimensional form
k	non-dimensional decay coefficient of pressure
L	semi-length of the rectangular sandwich plate
L_R	length of the cylindrical RDX explosive charge
l	length of the unit cell of the honeycomb
l_m	length of the m th hinge line
M, m	bending moment per unit length and its non-dimensional form
M_p	fully plastic bending moment
N, n	membrane force per unit length and its non-dimensional form
N_p	fully plastic membrane force
p	external uniform pressure on the sandwich plate
$p(t)$, p_{so},	pressure at time t, peak incident pressure
R	standoff distance
r	number of plastic hinge line
$T, \bar{T}$	structural response time and its non-dimensional form
t, t_0, t_a	time, positive phase duration, arrival time of incident wave
V_1	initial velocity of the front face sheet
V_2	common velocity of both face sheets and the core at the end of the core compression phase
W_0	deflection at the centre of the plate
W_{0m}, $\overline{W}_{0m}$	maximum deflection at the centre of plate and its non-dimensional form
$w, \dot{w}, \ddot{w}$	transverse deflection, velocity and acceleration of the plate
x, x', y	coordinates defined in Fig. 22
α	thickness ratio of the front face sheet to the rear face sheet h_f/h_r
δ	non-dimensional parameter to distinguish the position of plastic neutral surface
ε_c, ε_D	average compressive strain and critical densification strain of the honeycomb
ϕ	angle defined in Fig. 22
μ	mass per unit area of the plate
$\dot{\theta}_m$	relative angular velocity across the m th straight hinge line
ϑ	inscribing coefficient for yield locus
ρ_f	density of the face sheet
ρ_c, $\overline{\rho}_c$	density of the core and its non-dimensional form
σ_b, σ_Y	tensile strength and 0.2% offset yield stress of the face sheet
σ_n	quasi-static out-of-plane compressive strength of the core
σ_{Dn}, $\overline{\sigma}_{Dn}$	dynamic out-of-plane compressive strength and its non-dimensional form of the core
σ_l, $\overline{\sigma}_l$	longitudinal strength of the honeycomb and its non-dimensional form of the core
ς	ratio of the semi-width to the semi-length of the plate B/L

investigated the static mechanical behavior of asymmetric structures and analyzed the effect of manufacturing procedure on asymmetric sandwich structures under static load conditions. Castanié et al. [20] developed a geometrically non-linear theory of asymmetric sandwich structures based upon classic displacement assumptions and compared with the numerical calculations and experimental results. Kim and Swanson [21] investigated the effect of unequal thickness face sheets on load-resistance of sandwich beams with fiber composite face sheets and polymeric foam. Qin et al. [22] derived the yield criteria for geometrically asymmetric metal sandwich structures, and gave the analytical solutions for large deflection of the asymmetric metal sandwich beams under transverse loading by a flat punch. Wang et al. [23] numerically studied the deformation modes and energy absorption of geometrically asymmetric sandwich plates subjected to blast loading.

The objective of the present work is to investigate the dynamic response of geometrically asymmetric sandwich plates with aluminum hexagonal honeycomb core subjected to blast loading and give an insight into the effect of geometrical asymmetry of the face sheets on the deformation and damage. The outline of this paper is as follows. Firstly, specimens for the geometrically asymmetric metal sandwich plates as well as the experimental set-up are designed and manufactured. Next, experimental results of the dynamic response of the sandwich plates subjected to blast loadings are presented and the influences of the thickness of face sheets and the core density on the deformation and damage modes are considered. Thirdly, an analytical model is proposed to predict the dynamic response of geometrically asymmetric metal sandwich plates and is compared with experimental results. Finally, conclusions are provided.

2. Experiment

2.1. Specimens

In the present tests, both face sheets of the sandwich plate specimens are made of 3003H24 aluminum alloy with the density of $\rho_f = 2.73 \times 10^3\,\mathrm{kg/m^3}$. The stress-strain curves of the face sheets are shown in Fig. 1. The mechanical properties are as follows: Young's modulus $E = 71.8$ GPa, the 0.2% offset yield stress $\sigma_Y = 194$ MPa, and tensile ultimate strength $\sigma_b = 213$ MPa. An expanded hexagonal honeycomb of 3003H18 aluminum alloy, which is provided by Xi'an Weixin Technology Co., Ltd, China, is selected as the sandwich cores with height $c = 30$ mm and wall thickness $h_w = 0.05$ mm, as shown in Fig. 2. The side lengths l of the unit cell of the honeycombs are

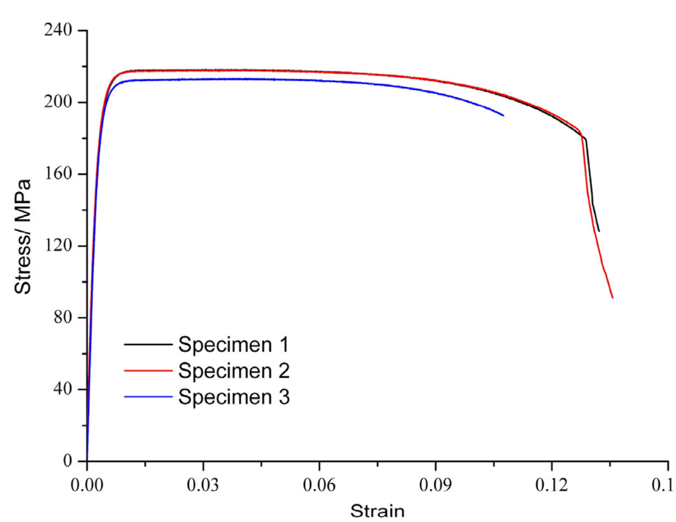

Fig. 1. Stress-strain curves of the face sheets.