European Journal of Mechanics A/Solids 47 (2014) 14–22

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

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

Large deflection response of rectangular metal sandwich plates subjected to blast loading

Qinghua Qin*, Chao Yuan, Jianxun Zhang, T.J. Wang*

State Key Laboratory for Strength and Vibration of Mechanical Structures, Department of Engineering Mechanics, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 26 November 2013
Accepted 21 February 2014
Available online 5 March 2014

Keywords:
Metal sandwich plate
Blast loading
Large deflection

ABSTRACT

A theoretical study is conducted to predict the large deflection response of fully clamped rectangular sandwich plates subjected to blast loading. Using the energy dissipation rate balance theory and a new yield criterion including the effect of core strength, we obtained the solutions for the dynamic response of rectangular sandwich plate, in which the effect of finite deflection are incorporated and elastic effect is neglected. Also, we obtain the new so-called 'bounds' of dynamic response by using the inscribing and circumscribing squares of the exact yield locus. Further, we neglect the effect of bending moment and obtained analytical membrane mode solutions for large deflection of the sandwich plate. Finite element numerical calculations are also carried out to study the dynamic response of the sandwich plate subjected to blast loading. Comparisons of the present analytical predictions and the present numerical and the previous experimental results are given and good agreement is found.

1. Introduction

Sandwich structure has been paid more attention due to its advantages relative to monolithic solid structure of the same materials and equal mass subjected to extreme blast loading. However, the advantages of such a structural system depend on the innovative topological design and manufacture of cellular cores (Ashby et al., 2000; Evans et al., 1999, 2001; Gibson and Ashby, 1997). Then, the low density porous cores with the innovative structural characteristics, such as metal foams (Ashby et al., 2000; Banhart, 2001), hexagonal, triangular and square honeycombs (Hou et al., 2011; Hu and Yu, 2010; Wadley et al., 2007; Wadley, 2006), lattice materials of pyramidal and tetrahedral arrangements (Evans et al., 2010, 2001; Wadley, 2006), egg-box (Deshpande and Fleck, 2003), woven material (Sypeck and Wadley, 2001) and functionally graded (Brothers and Dunand, 2008; Liu et al., 2012; Wang et al., 2013) and hierarchical cores (Ajdari et al., 2012; Kooistra et al., 2007), are designed and manufactured to meet the functional requirements in engineering applications.

These sandwich structures have been considered as a promising alternative to the monolithic solid structures. The impact and explosion resistances of the sandwich structures have been investigated extensively. Fleck and Deshpande (2004) suggested that the dynamic response of sandwich beam may be split into a sequence of three stages: Stage I, fluid–structure interaction; Stage II, core compression; Stage III, plastic bending and stretching. The parallel numerous investigations demonstrated that the optimized sandwich structures outperform solid counterparts with the same mass subjected to air and water blast loadings (Ebrahimi and Vaziri, 2013; Liang et al., 2007; Mori et al., 2009; Vaziri et al., 2007; Wadley et al., 2008; Wei et al., 2008; Xue and Hutchinson, 2004). Using a shock simulation technique involving high-speed impact of aluminum foam projectiles (Radford et al., 2005), the dynamic responses of the metal sandwich beams and plates were investigated experimentally (McShane et al., 2006; Radford et al., 2006a, 2006b; Rathbun et al., 2006; Wang et al., 2011).

Fleck and Deshpande (2004) developed an analytical model for the dynamic response of the fully clamped sandwich beam subjected to uniform blast loading. Recently, Qin and Wang (2009a) derived a new yield criterion for the metal sandwich structures including the effect of core strength. Based on the new yield criterion, Qin and Wang (2009b, 2011, 2013) and Qin et al. (2009) obtained the analytical solutions for the impulsive response of fully clamped metal sandwich beams by using the membrane factor method (Yu and Stronge, 1990) and for the low-velocity impact response of fully clamped metal sandwich beams struck by heavy mass. Qiu et al. (2004) gave the analytical solutions for the so-called

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

http://dx.doi.org/10.1016/j.euromechsol.2014.02.016
0997-7538/

'bounds' of the maximum central deflection and the response time of fully clamped circular sandwich plates. Neglecting the effect of bending moment, Qin and Wang (2007) obtained the membrane mode solutions for the impulsive response of fully clamped circular sandwich plates. The dynamic response of metal sandwich plates with square honeycombs (Dharmasena et al., 2008), hexagonal honeycombs (Zhu et al., 2008) and pyramidal lattice core (Cui et al., 2012a; Dharmasena et al., 2011) subjected to air blast loading were experimentally investigated and deformation and failure of various cores were analyzed. However, it is difficult to establish an accurate analytical model to predict the dynamic response of sandwich plates subjected to blast loading. Employing the inscribing and circumscribing squares of the new yield criterion (Qin and Wang, 2009a), Zhu et al. (2010) adopted the Fleck-Deshpande three-stage framework (Fleck and Deshpande, 2004) and obtained the so-called 'bound' solutions for the dynamic response of square sandwich plates subjected to blast loading. Similarly, using the inscribing and circumscribing squares of the classical yield criterion (Martin, 1975), Cui et al. (2012b) obtained the so-called upper and lower 'bound' solutions for the dynamic response for square sandwich plates with a pyramidal lattice core subjected to blast loading based on the experiments (Cui et al., 2012a).

In the present work, we theoretically study the dynamic response of fully clamped rectangular metal sandwich plates subjected to blast loading. Firstly, we derive the solutions and new so-called 'bounds' of the solutions for the dynamic response of the sandwich plate on the basis of the energy dissipation balance theory (Jones, 1971) and a new yield criterion including the effect of core strength (Qin and Wang, 2009a). Secondly, a simplified analytical solution is obtained by neglecting the effect of bending moment. We also carried out the finite element analysis to study the dynamic response of the sandwich plate. Comparisons of the present analytical solutions with the present numerical and the previous experimental (Cui et al., 2012a; Zhu et al., 2008) results are given.

2. Problem formulation

Consider a fully clamped rectangular sandwich plate of length $2L$ and width $2B$ with two identical face sheets of thickness h and a core of thickness c subjected to blast loading I per unit area, as shown in Fig. 1. It is assumed that the face sheets are made from rigid-perfectly plastic material with yield strength σ_f and density ρ_f, respectively, as shown in Fig. 2(a). The core is idealized as a rigid perfectly plastic locking (r-p-p-l) material, as shown in Fig. 2(b). The symbols ρ_c, σ_n, σ_l and ε_D are introduced to denote the density, normal compressive strength, longitudinal strength and densification strain of the core, respectively. Although no elastic deformations of the face sheets and the core occur, and material hardening in the plastic regime is neglected, the rigid-plastic approach can describe the real structural behaviors approximately.

Fleck and Deshpande (2004) decoupled the deformation of core compression and plastic bending and stretching. Qiu et al. (2004) and Qin and Wang (2007) extended this method to study the impulsive response of fully clamped circular sandwich plates. In the core compression stage, a one-dimensional slice through the thickness of the sandwich plate is considered and the reduction in momentum due to the impulse provided by the fully clamped supports is neglected. In the following analysis, these assumptions are adopted.

2.1. Core compression stage

It is assumed that the impulse I per unit area imparts to the upper face sheet with a velocity $V_0 = I/(\rho_f h)$. According to the momentum conservation, the final common velocity of the face sheets and the core of the sandwich plate is given by

$$V_f = \frac{I}{2\rho_f h + \rho_c c} \tag{1}$$

Neglecting the rate effect and considering the plastic energy dissipation in compressing the core at a stress σ_n, the average compressive strain ε_c over the entire thickness of the core can be expressed as (Fleck and Deshpande, 2004),

$$\varepsilon_c = \frac{\bar{I}^2\left(\bar{\rho}+\bar{h}\right)\left(\bar{\rho}+2\bar{h}\right)}{2\bar{\sigma}_n\bar{h}} \tag{2}$$

where $\bar{I} = I/[(2\rho_f h + \rho_c c)\sqrt{\sigma_f/\rho_f}]$, $\bar{h} = h/c$, $\bar{\rho} = \rho_c/\rho_f$ and $\bar{\sigma}_n = \sigma_n/\sigma_f$. However, if ε_c exceeds the densification strain ε_D, then ε_c is set to be ε_D.

2.2. Bending and stretching stage

At the end of the core compression stage, it is assumed that the rectangular sandwich plate will be brought to rest by plastic bending and stretching. Jones (1971) developed an approximate theoretical procedure to analyze the dynamic plastic behavior of monolithic rectangular plates considering influence of finite

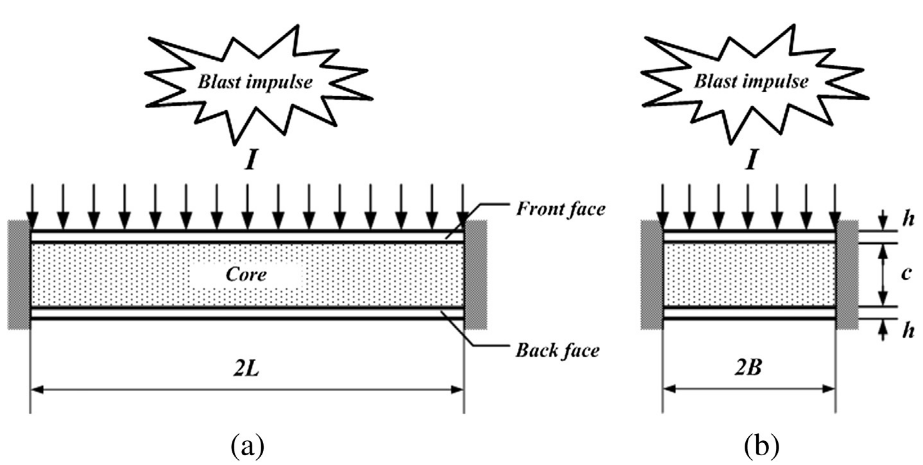

Fig. 1. Sketch of a fully clamped rectangular sandwich plate subjected to blast loading. (a) Front view and (b) side view.