Composite Structures 169 (2017) 21–28

Contents lists available at ScienceDirect

Composite Structures

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

Clamped sandwich beams with thick weak cores from central impact: A theoretical study

Hua Liu *, Hu Liu, Jialing Yang

Institute of Solid Mechanics, Beihang University, 100191 Beijing, PR China

ARTICLE INFO

Article history:
Received 26 October 2016
Revised 20 December 2016
Accepted 3 February 2017
Available online 6 February 2017

Keywords:
Sandwich beam
Impact
Dynamic response

ABSTRACT

A theoretical model is obtained to predict the dynamic response of a clamped sandwich beam with thick weak core impacted centrally by a projectile. The core is weak and thick enough that only part or all of the front face sheet and the core undergo permanent plastic deformations, while the back face sheet undergoes an elastic vibration. The core is taken to be rigid-plastic and the front face sheet is treated as an individual rigid-plastic beam resting on a foundation. The back face sheet is modeled as an Euler–Bernoulli beam. Based on the rigid-perfectly theory and Galerkin method, two types of the sandwich beam response are given, i.e., intermediate strength and low strength core type responses. The critical kinetic energy of the projectile as the back face sheet reaches its elastic limit is studied. The localized indentation and response history of the sandwich beam are presented. It is found that the dynamic response of the sandwich beam is sensitive to the core strength, mass ratio, breadth and impact velocity of the projectile. The finite element (FE) simulation is also carried out to verify the analytical predictions and a good agreement is achieved.

1. Introduction

Sandwich structures, consisting of two relatively stiff and strong face-sheets and a thick low density core, have been successfully and commonly used in many lightweight engineering applications. Over the last decade, sandwich structures with various cores have been devised and analyzed. Examples are the commonly used honeycomb and foam-core sandwich panels. Honeycomb and foam cores are artificial cellular solids, whose topologies can be designed. In recent years, new core topologies with super structure characteristics have emerged. For example, new focus on lattice materials has been motivated recently. The structural properties rely on the deterministic periodic unit cells of the cellular solids.

The sandwich structures are often subjected to a wide range of dynamic loadings, it is quite necessary to investigate the dynamic characteristics of structures. There are many outstanding works devoted to modeling and analyzing the sandwich structures subjected to intense blast loads. For example, Fleck and Deshpande [1] proposed a rigid perfectly-plastic analytical model and identified three phases of the whole dynamic response for a clamped sandwich beam. Phase I is a one-dimensional fluid-structure interaction problem, the blast impulse is transmitted to the front face sheet of the sandwich beam and results in a uniform velocity of the front face sheet. In phase II, the front face sheet is decelerated by the core, the core and the back face sheet of the sandwich beam are accelerated. The final common velocity of the face sheets and the core is dictated by momentum sharing. In phase III, the beam is brought to rest by plastic bending and stretching. The splitting of the analysis into three distinctive three stages agreed well with finite element results [2]. Later, based on the three-phase model, Qiu et al. [3] analyzed the dynamic response of clamped beams subjected to impulsive loading over a central patch. Hutchinson and Xue [4] sought the optimal performance for the square honeycomb-cored sandwich panel under uniform impulsive pressure loading. Zhu et al. [5] predicted the dynamic response of square metallic sandwich panels with honeycomb core and aluminum foam core. In their studies, the two face sheets and the core were assumed to acquire a uniform velocity at the end of phase II and underwent plastic bending and stretching just like a monolithic structure in phase III.

Apart from the three-phase theory, recently, Qin and Wang [6,7] proposed a theoretical model based on the rigid plastic beam-on-foundation theory to predict the low-velocity impact response of foam core sandwich beams struck by a heavy mass. Subsequently, this theoretical model was extended to analyze the impact response of geometrically asymmetric [8] and multi-layered sandwich beams [9]. Jiang et al. [10] presented a beam-spring

---

* Corresponding author.
E-mail address: liuhuarui@buaa.edu.cn (H. Liu).

http://dx.doi.org/10.1016/j.compstruct.2017.02.028
0263-8223/

model to simulate the dynamic deformation process of sandwich beams with foam core, in which the transverse compression and bending effect of the foam core were considered. In their analyses, the front and the back face sheets were both treated as rigid-perfectly plastic materials, and they would both suffer plastic deformation during the dynamic process.

However, in many practical applications, the front and the back face sheets may undergo different deformation modes. For instance, sandwich structures are often preferred as protective structures for blast loading in engineering. A large amount of energy is often input to the sandwich structure. The sandwich structure must have enough energy absorption capacity and ensure that the forces transmitted to the protected structure are under accepted levels, otherwise the protected structure may undergo plastic deformation and even be destroyed [11]. Actually, in the design of the energy absorbers, considerable energy should be dissipated by the plastic deformations of portion or all of the front face sheet and the core, thus that the stresses in the back face sheet and the protected structure are within their elastic limits. For this case, the dynamic response of the sandwich structure is rather complicated. Obviously, the analytical model mentioned above cannot be employed to the complicated response due to the fact that the front face sheet and the back face sheet experience different deformation modes, and no overall plastic bending and stretching phase appears in the sandwich structure. To date, no detailed analytical investigations have been devoted for this kind of problem because of the involved complexity.

This paper presents an analytical model for the dynamic response of a clamped sandwich beam with thick weak core under central impact. The sandwich beam has enough large absorption capacity that only portion or all of the front face sheet and the core experience plastic deformations while the back face sheet undergoes an elastic vibration. Based on the rigid-plastic beam-on-foundation model proposed by Yu and Stronge for analyzing the localized indentation of thin cylindrical shell struck by projectile [12,13] and Galerkin method, the dynamic response of the protective clamped sandwich beam with thick weak core subjected to central impact is investigated. The sandwich beam response is classified as three types. The intermediate strength and low strength core type responses are elucidated in the current study.

2. Analytical model

Consider a clamped sandwich beam of length $2L$ with a thick weak core of thickness h_c and front and back face sheets of thicknesses h_f and h_b, respectively, as shown in Fig. 1. The sandwich beam has uniform rectangular cross section of width b_f, struck by a rigid projectile of mass G with an initial velocity V_0. The projectile with breadth $2b$ dynamically loads the sandwich beam at its center. The back face sheet is made from the same material as the front face sheet with yield strength Y_f and density m_f. The core is modeled as a rigid-perfectly plastic continuum with yield strength Y_c and density m_c.

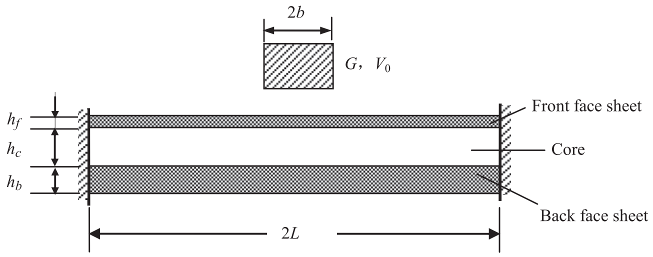

Fig. 1. Sandwich beam under impact.

It is assumed that the core is thick enough that full densification of the core will not occur; only the front face sheet and the core undergo permanent plastic deformations, while the back face sheet experiences an elastic vibration. In the following analysis, small transverse deflections are considered and stretching of the sandwich beam is neglected. For simplicity, we assume that the traveling speed of the plastic hinges in the front face sheet is unaffected by the soft core and the reaction per unit length of the face sheets is

$$\begin{cases} q_c = Y_c b_f, & \text{if } W_f > 0 \\ q_c < Y_c b_f, & \text{if } W_f = 0 \end{cases} \tag{1}$$

where W_f is the transverse displacement of a point in the front face sheet, the fully plastic bending moment of the front face sheet is $M_0 = Y_f b_f h_f^2/4$. The reaction force becomes zero as the plastic hinges in the central section of the front face sheet ceases.

Following McMeeking et al. [14] and Tilbrook et al. [15], a lumped mass approximation with the mass of the core uniformly and equally tied to the front and back face sheets. The mass per unit length of the front and back face sheets are

$$\rho_f = m_f b_f h_f + m_c b_f h_c/2 \tag{2a}$$

and

$$\rho_b = m_f b_f h_b + m_c b_f h_c/2 \tag{2b}$$

respectively.

The distinction of the dynamic responses of the sandwich beam is contingent upon the core strength, geometry of the sandwich beam and the input energy. Three types of response may be classified as low strength core, intermediate strength core and high strength core responses. For low strength core response, all of the core and the front face sheet undergo plastic deformations. When the core is stronger, intermediate core behavior appears. For intermediate core response, the permanent deformed region of the front face sheet and the core is less than the length of the sandwich beam. If the core is sufficiently strong, high strength core response occurs. For high strength core response, shear sliding may develop at the edges of the projectile. Since this paper is concerned with the dynamic response of the sandwich beams with weak cores, the solutions are not obtained for the high strength core behavior. The analytic formulas for soft and intermediate core responses are given as follows.

2.1. Front face sheet

2.1.1. Intermediate strength core

For this case, there is only a transient phase of dynamic response in the front face sheet. The traveling plastic hinges can't reach the supports of the sandwich beam due to the reaction from the intermediate strength core. A typical velocity diagram of the front face sheet at time t is as shown in Fig. 2. Two traveling plastic hinges that move from the edges of the projectile appear symmetrically at points A and D. Due to symmetry, only half of the sandwich beam is considered. The position of the traveling plastic

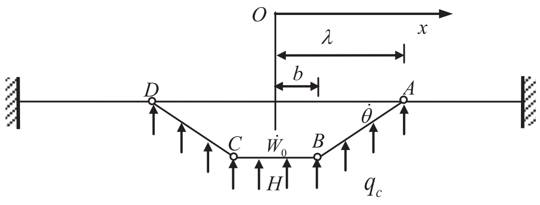

Fig. 2. Velocity diagram of front face sheet in transient phase.