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Low-velocity impact response of geometrically asymmetric slender sandwich beams with metal foam core

Zhengjin Wang, Qinghua Qin, 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

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ABSTRACT

The low-velocity impact response of fully clamped slender metal foam core sandwich beams with geometrically asymmetric cross-section struck by a heavy mass at midspan is investigated. The exact and approximate yield criteria for metal sandwich cross-section are presented considering the effect of core strength. Using the yield criteria, the analytical solutions for large deflection of the fully clamped slender sandwich beams, including dynamic and quasi-static solutions, are derived respectively. Also, finite element (FE) calculations are carried out to validate the analytical model. Moreover, the effects of material elasticity and strain hardening of face sheets are considered in FE analysis. Comparisons of the FE results and analytical solutions reveal that the present analytical model enables the acceptable predictions of the low-velocity impact response of fully clamped asymmetric slender sandwich beams. Material elasticity and strain hardening of face sheets have minor effects on dynamic response.

1. Introduction

Sandwich structures are widely used in many important engineering fields, such as aerospace, automobile and marine industries, due to their advantages over conventional structures. The sandwich structure is made of two thin and strong face sheets separated by a relatively low-density core to reduce the weight and improve the bending strength. Various cores, such as metal and polymer foams, honeycomb and lattice materials [1–5], have been selected according to their applications. The conventional sandwich structure is composed of two identical face sheets with the same thickness and material. In order to obtain the optimal performances and save the natural resources and energy, asymmetric sandwich structures are designed and used in some constructions [6–8].

As promising multi-functional structures, sandwich structures have excellent performances over the conventional monolithic structures with the same weight. However, they are more susceptible to impact damage caused by dropped tools, bird-strike, runway debris, hail stone, floating debris, etc. [9,10]. These impact events may reduce the strength and resistance of sandwich structures, sometimes are fatal to applications in-service. For these reasons, much attention has been devoted to the impact resistance of sandwich structures.

The low-velocity impact behavior of symmetric sandwich structure has been investigated extensively. Abrate [9] summarized dynamic failure modes of composite sandwich structures, such as core yield, core crack, debonding, beam crack and fiber crack in the face sheet. Gibson and Ashby [1] and McCormack et al. [11] concluded the quasi-static failure modes of sandwich beams with a metal foam core, i.e. face yielding, face wrinkling, core shear, core crack, debonding and indentation. Experiments on the low-velocity impact show that the impact failure modes are similar to those under quasi-static loadings [11–15]. Energy-balance [12,16] and spring-mass models [8,16–18] have been proposed to predict the low-velocity impact response of the sandwich structure. However, these models are based on elastic assumptions and are only valid for the elastic impact response. Foo et al. [19] extended the energy-balance model to predict the impact behavior of the sandwich structure beyond the elastic regime. Li et al. [20] proposed an elastic–plastic model to predict the impact response of simply supported composite sandwich beam. Qin and Wang [21] investigated the dynamic large deflection response of fully clamped metal sandwich beam with symmetric cross-section. The results confirmed that the quasi-static analytical scheme has enabled the acceptable predictions of the low-velocity impact response when the mass ratio of the striker to the beam is large enough.

Comparing to the classical symmetric sandwich structure, asymmetric sandwich structure may provide an alternative in engineering applications, such as marine industry, vehicle and hot pad system [22–24]. Frostig and Shenhar [6] theoretically investigated the bending behavior of sandwich beams with soft core and two asymmetrical composite face sheets. Castanié et al. [7] developed a geometrically non-linear theory of asymmetric sandwich structures, while the in-plane rigidities of the core are

* Corresponding author. Tel./fax: +86 29 82665168.
E-mail address: wangtj@mail.xjtu.edu.cn (T.J. Wang).

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neglected. Recently, Qin et al. [25] developed a quasi-static analytical model to predict the large deflections of geometrically asymmetric metal sandwich beams transversely loaded by a flat punch, in which the strength of the core is considered.

To the authors' knowledge, the dynamic response of large deflections of geometrically asymmetric sandwich structures has not been studied previously. The objective of this paper is to study the low-velocity impact response of fully clamped slender asymmetric sandwich beam struck by a heavy mass at midspan. The yield criteria for geometrically asymmetric sandwich structure are presented. Analytical solutions for the quasi-static and low-velocity dynamic responses of the asymmetric sandwich beam are derived. Also, the finite element results are obtained. The effects of asymmetry, elasticity and strain hardening of face sheets on the dynamic response of the asymmetric sandwich beams are discussed in details.

2. Yield criteria for geometrically asymmetric sandwich structures

Consider a fully clamped geometrically asymmetric slender sandwich beam with rectangular cross-section struck by a heavy mass G_s with initial velocity V_I at midspan, as shown in Fig. 1. The length of the beam is $2L$, and the width of the cross-section is b. It is assumed that the top and bottom face sheets with thickness h_t and h_b are assumed to be perfectly bonded to the metal foam core with thickness c. Moreover, it is supposed that the face-sheet metal has strong stiffness and is rigid-perfectly plastic with yield strength σ_f, as shown in Fig. 2a, while there is no elastic deformation occurring. The metal foam core is modeled as a rigid-perfectly-plastic-locking $(r-p-p-l)$ material with plateau-stress σ_c and critical densification strain ε_D, while elasticity of foam core is neglected in analysis, as shown in Fig. 2b.

The classical yield criterion for sandwich structure [26] is highly accurate for symmetric sandwich beam with thin and strong face sheets, thick and weak core. While it becomes less accurate as the sandwich cross-section approaches the monolithic limit [5]. Qin and Wang [27] developed a yield criterion for the symmetric sandwich structure considering the effect of core strength, which is not only accurate for symmetric sandwich structure with a weak core, but also for that with a strong core. Subsequently, Qin et al. [25] developed the yield criteria for geometrically asymmetric sandwich structure considering the effect of core strength. For the sake of completeness, we directly give the expressions of the yield criteria for the asymmetric sandwich structures including

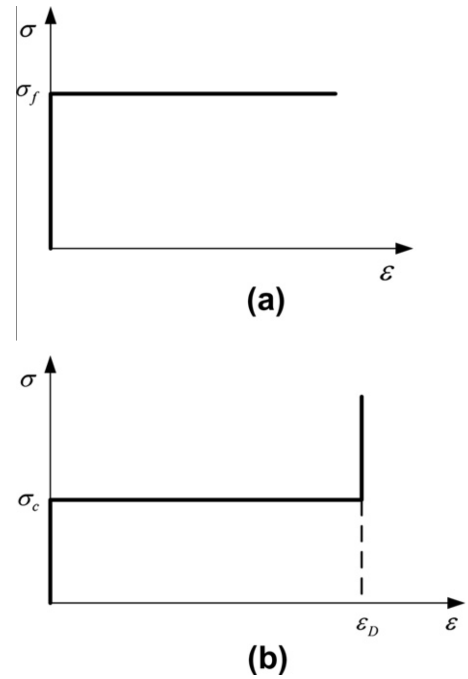

Fig. 2. Material properties of (a) the face-sheet and (b) the metal foam core.

the circumscribing and inscribing squares herein, see Ref. [25] and Appendix A for more details.

2.1. Yield criteria

The geometric and plastic neutral surfaces of the symmetric sandwich structure are coincident, while the plastic neutral surface of the asymmetric sandwich structure deviates from the geometric neutral surface. We then define z_p as the deviation of the plastic neutral surface from the geometric center O of the core in z direction, as shown in Table 1. It then follows that

$$\int_{-\frac{c}{2}-h_b}^{z_p} \sigma(z)dz = \int_{z_p}^{\frac{c}{2}+h_t} \sigma(z)dz \tag{1}$$

where $\sigma(z)$ is the yield strength of the material. From Eq. (1), we obtain

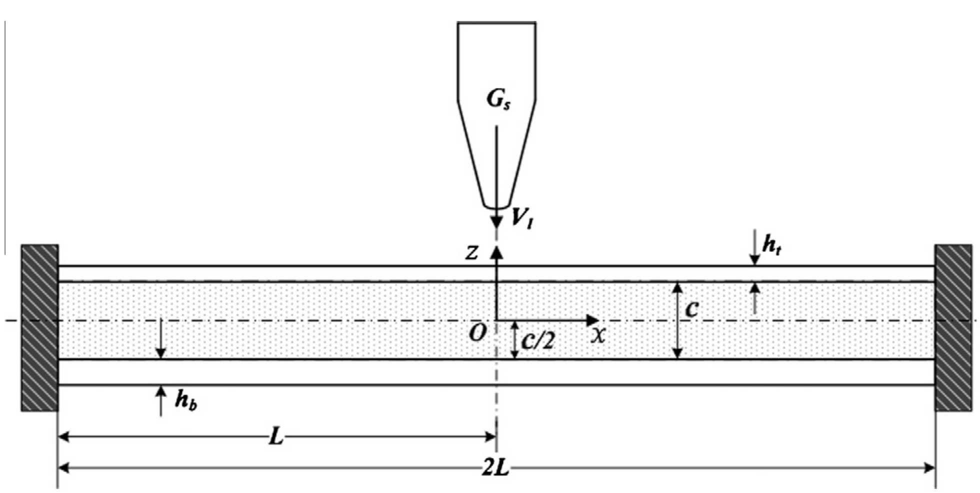

Fig. 1. Sketch of a fully clamped asymmetric slender sandwich beam struck by a heavy mass G_s with an initial velocity V_I.