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The plastic behavior of sandwich beams with core gradation

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ABSTRACT

The objective of this paper is to establish yielding criteria for a slender sandwich beam with two-layer metal foam cores under transverse loading. A unified yielding criterion for this geometrical or physical asymmetry four-layer metallic sandwich beam is established. Based on the yield criteria, an analytical solution for large deformation of fully clamped multilayer sandwich beams under transverse loading is presented. Comparisons of present solutions with numerical results are given and good agreements are obtained. Finally, the effects of core strength and thickness ratios on the large deflection responses of the sandwich beams with core gradation are discussed in detail. It is demonstrated that the present analytical model can reasonably predict the behavior of the plastic deformation of four layer sandwich beams.

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1. Introduction

Due to the light weight and high specific stiffness, multilayer sandwich structures are commonly used in engineering equipment, such as aircrafts, spacecrafts, vehicles, high speed trains, and ships. Typical sandwich structure is constituted by two face sheets and a core which is made from metal foams, polymer foams, honeycombs, woven materials, lattice materials, or functionally graded materials [1–14]. With the continuous development of core materials, more and more possibilities and choices appear in the structural design of sandwich structures.

The analytical models of sandwich structures have been extensively investigated in past years. Fleck and Deshpande [7] studied dynamic responses of fully clamped sandwich beams subjected to uniform blast loading. Zhu et al. [15] obtained a theoretical solution to predict dynamic responses of peripherally clamped square metallic sandwich panels with either honeycomb core or aluminum foam core under blast loading, and gave the lower and upper' bounds' of the maximum central deflection and response times. Castanié et al. [16] investigated a specific theory which enables faster design loops. This theory was firstly validated by comparison to numerical models, and then used to correlate structural tests on asymmetric sandwich plate under combined compression/shear loadings. Recently Qin and Wang et al. [17–25] derived the yielding criterion for geometrically symmetric or hybrid (geometrically, physically) asymmetric metal sandwich structures incorporating the effect of core strength. Based on this criterion, considering the interaction of bending and stretching, they also obtained the impulsive response of fully clamped sandwich beams by using the membrane factor method. Meanwhile, to validate their analytical models, Zhu et al. [15], Qin et al. [18,20] and Wang et al. [26] conducted numerical simulations and experiments. The results showed that the analytical models coincided well with numerical simulations and experimental results, and the sandwich beams displayed a higher shock resistance than the monolithic ones.

In recent years, stepwise graded materials, where the material properties vary gradually or layer-by-layer within the material itself, were utilized as core materials in sandwich structures [27]. The numerical investigation by Apetre et al. [28] had shown that a reasonable graded core design can effectively reduce the shear forces and strains within the structures. Since the properties of multilayer cores could be designed and controlled, they show great potentials to be an effective core material for absorbing the blast energy, dispersing high-intensity impulses, reducing the transmitted pressures and improving the overall blast resistance of sandwich structures [14,25–31]. Due to the gradual or layer-by-layer variation of material properties, the sandwich beams would display geometrical or physical asymmetry. Although Qin et al. [18,22,25] considered the geometrical or physical asymmetry caused by the face sheet, the effects of layer thickness and strength, as well as core gradation, on the plastic yielding of multilayer sandwich beams are still unclear, especially for large-deflection of multilayer sandwich beams under transverse loading. The establishment of the yield criterion of sandwich beams with multilayer cores has become crucial, which,

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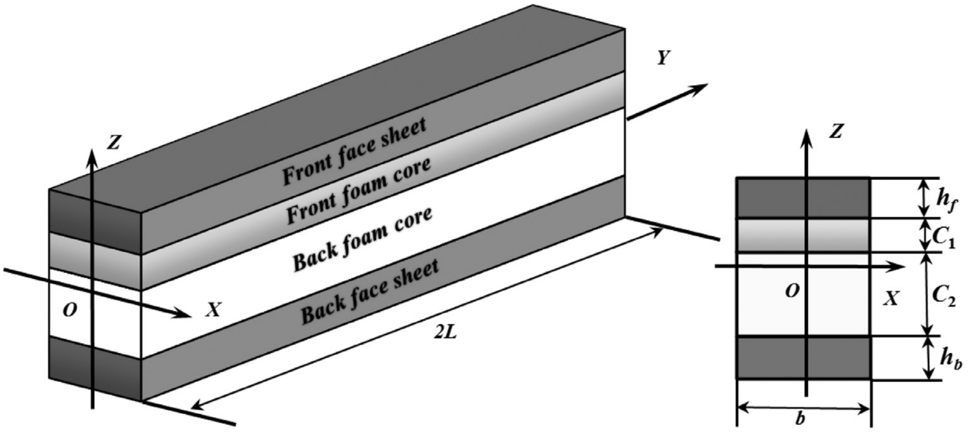

Fig. 1. Cross-section of four layers sandwich beam.

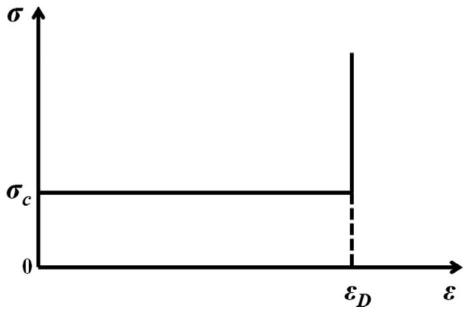

Fig. 2. Typical dynamic stress–strain curve for the metal foam.

unfortunately, has not yet been fully understood by now to best knowledge of per author's.

In the present discussion, a yielding criterion for a slender sandwich beam with two-layer metal foam cores is firstly established. Then, based on the proposed dynamic yielding criteria, the analytical solutions for the large deflections of fully clamped sandwich beams under transverse loading are predicted and comparisons with numerical simulations are made. The effects of strength and thickness of each layer, as well as the gradation profile, on the large deflection responses of multilayer sandwich beams are discussed in detail. Finally, the conclusions are given.

2. Yielding criterion for general sandwich beams with two-layer metal foam cores

As shown in Fig. 1, we consider a rectangular slender sandwich beam with two-layer foam cores and axial constraints. The beam length is $2L$, b is the width of the cross-section, which is taken as unit length in the present discussion. It is assumed that the front and back face sheets are perfectly bonded to the foam core with thickness h_f and h_b, respectively. Here plastic yielding of metal sandwich beams are considered, and beam failure, such as debonding, local buckling, or failure at the interfaces, is not included. We also ignore the transverse shear effect of the beam, and assume that the front and back face sheets obey the rigid-perfectly plastic law with the yield strength σ_f and σ_b, respectively. The thicknesses of metal foam cores are C_1 and C_2 with total thickness $C = C_1 + C_2$ (Fig. 1). Here we define a core thickness ratio $\alpha = C_1/C_2$. If $\alpha = 1$ the front and back cores have the equal thickness.

The metal foam cores are molded as rigid-perfectly-plastic-locking (*RPPL*) material (Fig. 2) with the yield strength σ_1 and σ_2, respectively. Compared with three-layer symmetric sandwich structures, the four-layer structures, geometrical or physical asymmetry or symmetry, have a variety of combinations and will provide much more functions. The case of $h_f/h_b = 1$, $\sigma_f/\sigma_b = 1$, $\sigma_1/\sigma_2 = 1$ corresponds to a typical symmetric sandwich structure [18], which is adopted to study large deflections of lightweight metallic foam core sandwich beams under transverse loading by a flat punch, in which interaction of bending and stretching induced by large deflections is considered. The case of $h_f/h_b \neq 1$, and $\sigma_1/\sigma_2 = 1$ corresponds to a geometrically asymmetric sandwich beam [22], which is applied to study the low-velocity impact response of fully clamped slender asymmetric sandwich beam struck by a heavy mass at midspan. The case of $h_f/h_b = 1$, $\sigma_f/\sigma_b \neq 1$, $\sigma_1/\sigma_2 = 1$ corresponds to a physically asymmetric sandwich beam [23,25], which is used to develop a yield criterion for physically asymmetric sandwich structure. The case of $h_f/h_b = 1$, $\sigma_f/\sigma_b = 1$, $\sigma_1/\sigma_2 \neq 1$ corresponds to a sandwich beam with two-layer foam cores, which is the focus of the present discussion.

For an ordinary symmetric multilayer sandwich beam ($h_f/h_b = 1$, $\sigma_f/\sigma_b = 1$ and $\sigma_1/\sigma_2 = 1$), the plastic neutral surface is coincident with the geometric neutral surface. However, the plastic neutral surface may derivate from geometric neutral surface for (geometrically or physically) asymmetric sandwich beams. Herein, we define z_p as the initial plastic neutral surface, which is marked out by dash dot line in Fig. 3. Then we have

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

where $\sigma(z)$ is the yielding strength of the materials. So we have

$$z_p = \begin{cases} \dfrac{(\sigma_f h_f - \sigma_b h_b) + \sigma_1 C_1 + \sigma_2 C_2 - \sigma_b C}{2\sigma_b}, & -\dfrac{C+2h_b}{2} \le z_p \le -\dfrac{C}{2} \\ \dfrac{(\sigma_f h_f - \sigma_b h_b) + (\sigma_1 - \sigma_2) C_1}{2\sigma_2}, & -\dfrac{C}{2} \le z_p \le -\dfrac{C}{2} + C_2 \\ \dfrac{(\sigma_f h_f - \sigma_b h_b) + (\sigma_1 - \sigma_2) C_2}{2\sigma_1}, & -\dfrac{C}{2} + C_2 \le z_p \le \dfrac{C}{2} \\ \dfrac{(\sigma_f h_f - \sigma_b h_b) - \sigma_1 C_1 - \sigma_2 C_2 + \sigma_f C}{2\sigma_f}. & \dfrac{C}{2} \le z_p \le \dfrac{C+2h_f}{2} \end{cases} \tag{2}$$

We assume that the metal face sheets and foam cores are all in the plastic state with the initial physical neutral surface at z_p. Due to the combination effects of the plastic bending and stretching, the resulting strain and stress distributions along cross-section of the sandwich beam are shown in Fig. 3. Now the plastic neutral surface no longer coincides with the initial plastic neutral surface. The plastic neutral surface may shift due to combined plastic stretching and bending and locate in different layers. The update neutral surface is measured from the bottom of the back face sheet, which is denoted by $H = \eta(h_f + h_b + C)$, with the value of η lying between 0 and 1.

We define that the value is positive when the moment turns clockwise. The sandwich beam is in fully plastic state resulting from a combination of an axial force and a bending moment. The resultants of the

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