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Dynamic responses of metal sandwich beams under high velocity impact considering time inhomogeneity of core deformation

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ABSTRACT

The objective of this paper is to establish a yielding criterion for a sandwich beam by considering the time inhomogeneity of foam core deformation, which results in the time-varied neutral surface and cross-sectional area. Taking into account of the bending and axial stretching, a unified dynamic yielding criterion for metallic sandwich beams considering the mass redistribution along with the core compression is established. A membrane factor is proposed and an analytical solution for the large deflection of the beam under high velocity impact is given. Different from the traditional yielding surface, when the core is partially densified, the yielding surface is asymmetric. Comparison of analytical solutions with numerical ones reveals that the present model improves the prediction accuracy of high-velocity impact responses of fully clamped sandwich beams. The present method can also be degenerated to predict the low velocity/energy impact responses of sandwich beams.

1. Introduction

As a structure with light weight and high specific stiffness, sandwich beams are widely used in various important equipment, and attract amounts of attention. Accurate prediction of the dynamic performance of sandwich beams remains a challenge, especially for sandwich beams with novel core materials.

Fleck and Deshpande [1] proposed to separate the responses of sandwich beams into three stages, and provided a frame to analyze the responses of sandwich beams under blasting loading. Ashby et al. [2] and Tan et al. [3] simulated the deformation of the foam structure by using ideal rigid-plastic locking model. Lopatnikov et al. [4,5] extended the work by considering ideal locking elastic-plastic model. Later, Radford et al. [6] gave the peak and average stresses of the foam under impact loading. In 2007, Tillbrook et al. [7] measured the stresses on both the front and rear faces of Y-frame cores by using a direct impact Kolsky bar. The experimental results showed that under higher impact velocities, plastic wave propagation within the core caused the stress in the front face to be increased along with the increase of the impact velocity; whilst stresses of the rear face remained approximately constant. Barnes et al. [8] and Gaitanaros and Kyriakides [9] presented the results of the crushing of Al open-cell foams. They also found the inhomogeneous stress distribution in the structures. The stress behind the shock front was found to be increased as square of the impact velocity. The stress in front of the shock front remained at a constant level that approximately corresponded to the initiation stress recorded in quasi-static crushing experiments.

Without considering the coupling responses of face sheets and foam core, Qin and Wang [10,11] derived a yielding criterion for geometrically symmetric metal sandwich structures incorporating the effect of core strength. Based on that criterion, Qin and Wang [12] and Qin et al. [13] investigated impulsive responses of fully clamped symmetric metal sandwich beams by using the membrane factor method, in which interaction of bending and stretching is considered. Then Qin et al. [14,15] analyzed the low-velocity impact responses of fully clamped geometrically asymmetric sandwich beams loaded by a heavy mass. The yielding criteria for asymmetric sandwich beams were presented, which provided acceptable predictions of fully clamped geometrically asymmetric sandwich beams under low-velocity impact.

These models well predict the behavior of sandwich beams under low-velocity impact or quasi-static loading. However, as aforementioned, under a high-velocity impact, the stress loaded on the face sheets and in the core due to core compression are velocity dependent. The foam core displays progressive collapse, which causes the mass reassigned in the space. Consequently, the neutral surface and the cross-sectional area are time-dependent. Unfortunately, this

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Nomenclature

I	blast impulse
L	span of the beam
b	width of the cross-section
h	face-sheet thickness
C	initial core thickness
C_1	uncompressed region
z	densification region
V_0	initial velocity of front face
V_c	propagation velocity of the collapse front relative to the front face sheet
z_p	plastic neutral surface
H	present plastic neutral surface
ε_c	average compression strain of the foam core
ε_D	core densification strain
t	time
t_D	time of core densification
t_{eq}	time that front and back face-sheet with same velocities at the mid-span
τ	response time of a plastic string
(x, y, z)	coordinates
σ_f	yield strength of face sheet
σ_c	yield strength of foam core
N	axial force
M	bending moment
N_p	fully plastic axial force
M_p	fully plastic bending moment
Ms	bending moment at the support
Mm	bending moment at the mid-span.
h_f	front face-sheet thickness
h_b	back face-sheet thickness
ρ_c	core density,
σ_t	transverse yield strength
σ_l	longitudinal yield strength
ρ_f	material density of face-sheets
σ_Y	tensile strength
σ_m	transverse compressive stress loading at the front face sheet
σ_t	transverse compressive stress loading at the back face sheet
e	longitudinal extension of the sandwich beam
κ	angular rotation of the sandwich beam
$\dot{e}, \dot{\kappa}$	the rates of extension and angular rotation of the sandwich beam
W_0	mid-span deflection
$\ddot{W}_0$	mid-span acceleration
f_n	membrane factor
v_f, w_f	front face sheet velocity and deflection at mid-span
v_b, w_b	back face sheet velocity and deflection at mid-span

time heterogeneity due to local deformation of foam core under high-velocity impact has not yet been fully considered in previous models.

Aiming to this problem, in this paper, the dynamic yielding criterion for a sandwich beam with time inhomogeneity of core deformation is established. A membrane factor for the dynamic responses of a metallic sandwich beam under the blasting loading is also proposed to incorporate the large deformation effect. Based on the proposed dynamic yielding criterion and the membrane factor, the dynamic deformation of a fully clamped sandwich beam under blasting loading is predicted and corresponding comparison with previous theoretical results are made. At last, the conclusion is given.

2. Dynamic yielding criterion for sandwich beams with time inhomogeneity of cores

Due to the light weight and high stiffness, cellular solids are widely used as the core of sandwich structures. There are two deformation modes for cellular solids under crushing: (a) homogeneous deformation, and (b) progressive collapse. For homogeneous deformation, the cellular solid deforms homogeneously over the entire volume of the sample [16]. However, as a material with inner microstructure, the cellular solid displays localized deformation under the high velocity impact. Fig. 1 gives the deformation process of a triangle honeycomb under high velocity impact [17]. It is seen that from the impact end to the distal end, the material displays a progressive collapse deformation. The material near the impact end is densified and propagates to the distal end with a certain velocity; whilst the material near the distal end remains intact. When the cellular solid is used as the core of a sandwich beam and subjected to a high velocity impact, the core will deform progressively. This localized deformation mode will cause the mass redistribution in the space and change the position of neutral surface, as well as the sectional area. Although some works have been carried out to obtain the yielding criteria of sandwich beam under impact loading, the deformation of the cellular core is usually assumed to be homogeneous [12,13]. The progressive collapse modes of cellular materials, as well as the resultant variation of neutral surface, have rarely been considered.

2.1. Time-depended neutral surface of the sandwich beam

In order to reflect this time inhomogeneity under a high velocity impact, a sandwich beam model is shown in Fig. 2. Here we consider a metallic foam core sandwich beam with a rectangular cross-section and axial constraints. The beam length is $2L$, the width of the cross-section is b, and assuming that b is unit length. The face-sheet thickness is h, and the initial core thickness is C (Fig. 2(a)). When the front face sheet of the sandwich beam is subjected to the blasting impulse, the core begins to be compressed and progressively collapsed from the front face sheet to the back face sheet. The uncompressed region is C_1 and the densification region is $z = V_c t$ $(0 \le z \le (1-\varepsilon_D)C)$, which is linearly varied with respect to the time, with V_c the propagation velocity of the collapse front relative to the front face sheet. The corresponding plastic neutral surface z_p is marked out by a dash line in Fig. 2(b). If V is the current velocity of the front face sheet, we have $V_c = (1-\varepsilon_D)\, V/\varepsilon_D$ [18], where ε_D is the core densification strain. As the time t increases, z is increased, and the neutral surface becomes closer to the front face sheet as shown in Fig. 2(c). When the foam core is fully densified, the neutral surface is coincided with the geometrical symmetry axis X again (Fig. 2(d)). Usually, the shear force is negligible compared with the bending moment and the axial force [19]. As a result, in the present discussion, we ignore the transverse shear force of the sandwich beam. We consider the interaction of plastic bending and stretching, and assume that the front and back face sheets obey the rigid-perfectly plastic law with the yield strength σ_f. The foam core is modeled as rigid-perfectly-plastic-locking (RPPL) material with the yield strength σ_c (Fig. 3) and perfectly bonded with the face sheets. Fleck and Deshpande [1] assumed that the longitudinal plastic membrane force was insensitive to the degree of core compression. So we assume that the average yield strength is $\sigma_c\,/\,(1-\varepsilon_D)$ in the densification region.

It is known that the plastic neutral surface of the symmetric sandwich beam is coincident with the geometric neutral surface. However, due to the progressive collapse deformation of the core, the sandwich beam becomes asymmetrical and the plastic neutral surface deviates from the geometric neutral surface. In Fig. 2, we

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