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Low-velocity impact of sandwich beams with fibre-metal laminate face-sheets

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ABSTRACT

Low-velocity impact of fully clamped sandwich beams with fibre-metal laminate face-sheets and metal foam core struck by a heavy mass is investigated. Analytical solutions are developed for the dynamic response of sandwich beams with fibre-metal laminate face-sheets considering the interaction of bending and stretching induced by large deflections. According to the rigid-plastic material approximation with modifications, simple formulae are obtained for the large deflection of sandwich beams with fibre-metal laminate face-sheets. Numerical calculations are carried out, and analytical solutions capture numerical results reasonably. The effects of the composite volume fraction, the ratio of metal layer strength to composite layer strength, and core strength on the structural response are discussed. Using the analytical formulae, optimal design charts are constructed to minimize the mass of sandwich beams. It is demonstrated that the present analytical model can predict the post-yield behaviour of sandwich beams with fibre-metal laminate face-sheets reasonably.

1. Introduction

Sandwich structures comprising two stiff and strong face-sheets separated by a lightweight core are typical lightweight structures because of various advantages. Several kinds of lightweight cores have been developed to meet the needs in engineering, for example, metal foam, lattice material, woven material, honeycomb, and pyramidal truss [1–12]. Lightweight structures have been widely used in engineering, such as aerospace, aircraft, high speed trains, ships, etc. Also, fiber-metal laminates with combined metal and composite materials can enhance energy absorption and increase the impact resistance by designing the layer angle, layer arrangement and layer thickness [13–15]. Combining the fiber-metal laminates face-sheets and sandwich structures can form the sandwich structures with fibre-metal laminate face-sheets, which can posses the better advantages to resist the impact.

Over the past decades, low-velocity impacts of sandwich structures with metal/composite face-sheets and foam core have been investigated extensively. For example, Qin and Wang [16] and Foo et al. [17] analytically investigated the dynamic response of sandwich beams and plates subjected to low-velocity impact, respectively. Crupi et al. [18] and Yu et al. [19] experimentally studied the low-velocity impact response of sandwich structures with metal foam core, and failure modes were observed. Also, Wang et al. [20] and Hwang et al. [21] numerically studied the low-velocity impact of sandwich structures.

With the needs of the sandwich structures with good impact resistance and load-carrying capacities, attention has been paid to the investigations on quasi-static behaviors and impact response of sandwich beams with fiber-metal laminate face-sheets and foam core. Dariushi et al. [22] conducted three-point bending tests to study sandwich beams with fiber metal laminate (FML) face-sheets and foams, and show that FML faces have good resistance against transverse local loads. Reyes [23] evaluated the low-velocity impact behaviors of the sandwich panels with thermoplastic fiber-metal laminates skins and aluminum foam core using an instrumented dropping weight impact tower, modeled the dynamic response using an energy balance approach, and revealed that the systems offer excellent residual flexural strength. Kiratisaevee and Cantwell [24] investigated the low-velocity impact response of the sandwich structures with glass fiber-reinforced polypropylene-based fiber-metal laminates and aluminum foam cores using an instrumented drop-weight impact tower, and results for tensile tests of the damaged sandwich structures show that systems offer promising residual load-bearing properties. Liu et al. [25] carried out the drop weight impact test to study low-velocity impact response of sandwich panels with aluminium foam core and fibre metal laminate skins, and numerical results prove the effectiveness and accuracy of experimental results. Liu et al. [26] carried out gas gun impact tests to

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investigate the high velocity impact response of the sandwich panels with aluminium foam core and fibre-metal laminate skins. Baştürk et al. [27] predicted the blast response of fiber-metal laminate/aluminum foam sandwich plates were by combining the compression test results and user-defined blast data, and found that core shear and core crushing were the main failure mechanisms.

To the authors' knowledge, there is little work on the theoretical investigations of low-velocity impact response of sandwich structures with fiber-metal laminate face-sheets and metal foam core. The objective of this work is to investigate the low-velocity impact response of slender sandwich beams with fiber-metal laminate face-sheets and metal foam core. The paper is organized as follows. In Section 2, the statement of the problem is presented. In Section 3, an analytical solution is developed to predict the plastic behaviour of a sandwich beam subjected to low-velocity impact at midspan. In Section 4, finite element analysis is performed. In Section 5, comparisons between numerical results and analytical predictions are presented. Moreover, the effects of the composite volume fraction, the ratio of metal layer strength and composite layer strength, and core strength on structural response are discussed. In Section 6, minimum mass design is conducted on the basis of the analytical solutions. Finally, the concluding remarks are presented.

2. Problem formulation

Consider a fully clamped slender sandwich beam with fiber-metal laminate face-sheets and metal foams, in which the mass of the beam is G_b per unit length and length of the beam is 2L, as shown in Fig. 1. The sandwich beam is struck by a heavy mass G_s and initial low-velocity of striker V_I, and the striker is assumed to be rigid. The identical fiber-metal laminate face-sheets of total thickness h are assumed to be perfectly bonded to the core of thickness c. The section of a fibre-metal laminate has n metal layers with thickness h_m and a flow stress σ_m separated by n-1 layers of composite material with thickness h_c and flow stress σ_c, as shown in Fig. 1, so that

$$h = nh_m + (n-1)h_f \tag{1}$$

The density of face-sheets is ρ_f, and the density of the metal foam core is ρ_c. The composite layers of face-sheets have the yield strength σ_f and Young's modulus E_f, and the metal layers of face-sheets have yield strength σ_m and Young's modulus E_m, respectively. The isotropic metal foam has the compressive strength σ_c, and Young's modulus E_c. To describe the ratio of the composite layer strength to the metal layer strength, we define a composite-metal layer factor

$$p = \frac{\sigma_m}{\sigma_f} \tag{2}$$

For $0 < p < 1$, the strength of composite layer is higher than that of metal face-sheet layers. The face-sheets of sandwich beam have the higher strengths of composite layer than those of the metal layer for $p > 1$, while for $p = 1$ both the strengths of composite and metal layers are identical.

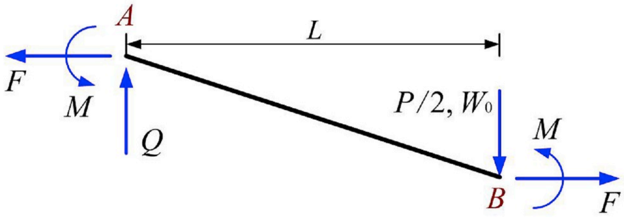

Fig. 2. Overall bending deformation pattern for the neutral surface of the left-hand portion in the fully clamped slender sandwich beam with fibre-metal laminate face-sheets and metal foam core. (Points A and B denote clamped ends and the point adjacent to the central striker, respectively.)

3. Analytical solutions

If the plastic behaviour dominates the plate response, then theoretical rigid plastic solutions can be used to predict the dynamic behaviour of fibre-metal laminates [28]. Here, the method is extended to predict the low-velocity impact of the sandwich structures with fiber-metal laminate face-sheets and metal foam core struck by a heavy mass.

Qin and Wang [16] developed an analytical model for the low-velocity impact of slender sandwich beams with metal foam core struck by a striker. For the sake of completeness, the solutions of structural response of slender sandwich beams under the low-velocity impact are briefly presented here. The metal sandwich beams contains identical top and bottom metal face-sheets with thickness h and the metal foam core with thickness c, in which the mass of the beam is G_b per unit length and length of the beam is 2L. The sandwich beam is struck by a heavy mass G_s. The sandwich cross-sections keep the original shape and the global deflection profile is the same as that of the fully clamped solid monolithic beam under loading. The face-sheets obey the rigid-perfectly plastic (*r-p-p*) law with σ_{fa}, and the meal foam core is assumed to be made of the rigid-perfectly plastic locking (*r-p-p-l*) material with yield strength σ_c and densification strain ε_D.

It is assumed that the sandwich beam deforms in a global manner without local denting beneath the striker when the ratio of the depth to the span of sandwich beam is small enough. Thus, the sandwich cross-sections keep the original shape, and the global deflection profile is the same as that of the fully clamped solid monolithic beam under low-impact impact. The equilibrium equation for the mass-beam system of the sandwich beam loaded at midspan is

$$2M + NW_0 - \left(G_s\frac{L}{2} + G_b\frac{L^2}{3}\right)\ddot{W}_0 = 0 \tag{3}$$

where M and N are the plastic bending moment and axial force of the sandwich beam; $F \approx N$ for moderate deflection; W_0 and $\ddot{W}_0$ are the deflection and acceleration at impact point; P is the external load at impact location, as shown Fig. 2.

Using the yield condition [29], the associated flow rules for the metal sandwich structures at fully clamped ends and the points adjacent to the central striker, and expressions of elongation and the angular rotation of the neutral surface, the analytical solutions were obtained

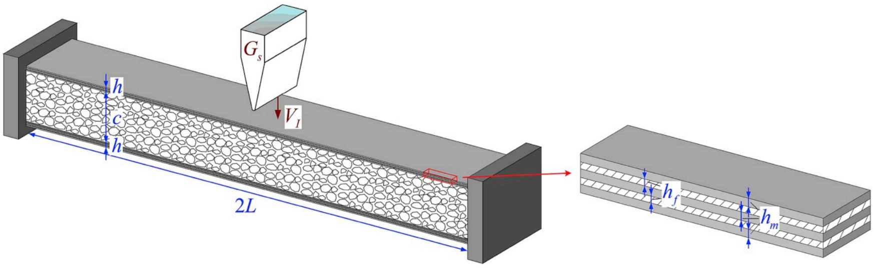

Fig. 1. Sketch of a fully clamped sandwich beam with fibre-metal laminate face-sheets and metal foam core struck by a heavy mass with initial low-velocity at midspan.

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