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Large deflections of metallic sandwich and monolithic beams under locally impulsive loading

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A rigid-perfectly plastic model is adopted to predict the dynamic response of fully clamped sandwich and monolithic beams subjected to localized impulse. Large deflection effect is incorporated in analysis by considering interaction between plastic bending and stretching. Based on the principle of energy equilibrium, a membrane factor for metallic sandwich beams with *nonuniform* cross-section thickness is derived to consider the effect of axial force induced by large deflection. Then, the dynamic response solution is obtained for the large deflection of metallic sandwich beams subjected to localized impulse. In addition, tighter 'bounds' of the solutions for sandwich beams are derived by using the inscribed and circumscribed squares of a new yield criterion including the core effect. As a degenerated limit case, solution for the large deflection response of solid monolithic beams is also obtained. The present solutions are in good agreement with finite element (FE) results and lie in the 'bounds' of the solutions. It is demonstrated that the axial (membrane) force associated with stretching plays an important role in the dynamic response of large deflections; in comparison with small deflection solutions, the axial (membrane) forces substantially stiffen the metallic sandwich and monolithic beams.

1. Introduction

Blast-resistance structures are used in chemical, oil, nuclear, automobile and aircraft industries, etc. As a new member in the family of blast-resistance structures, metallic sandwich beam, plate and shell with various lightweight cores have been paid great attentions [1–3]. Several kinds of metallic cores are developed, such as metallic foams [3–5], lattice materials of pyramidal and tetrahedral arrangements [6–8], egg-box [9] and woven material [10]. Due to the excellent resistance to blast loading compared with solid monolithic structures with equal mass, sandwich structures possess potential engineering applications, e.g. ship hulls, aircrafts and automotive vehicles.

Over the past decades, extensive studies have been devoted to the dynamic response of solid monolithic structures. Symonds [11] carried out the small deflection analysis of dynamic response of fully clamped solid monolithic beam subjected to blast loading. Martin and Symonds [12] examined the dynamic response of fully clamped solid monolithic beam subjected to impulsive loading over a central patch in small deflection. These phases are incorporated in the motions of the fully clamped solid monolithic beam and depend on whether the ratio of the length of the length of impulsive loading patch to the solid monolithic beam span is greater than or less than 0.5. Neglecting the elastic effects, Jones [13] extended the previous work [11] and obtained an approximate solution for the dynamic response of large deflection of fully clamped solid monolithic beam. Next, using the approximately inscribed and circumscribed squares of the exact yield criterion, Symonds and Jones [14] obtained the so-called 'upper' and 'lower' bounds of the dynamic response of large deflection of fully clamped solid monolithic beam under blast loading. Schubak et al. [15] developed an analytical procedure to predict the dynamic response of solid monolithic beams with axial restraints to pulse loadings including rectangular and I-type beams, in which the moment–axial force interaction is decoupled into an initial bending-only phase and a plastic string phases. On the main progress in the dynamic response of solid monolithic structure, see Jones [16] for more details. Thereafter, Yu and Stronge [17] proposed a membrane factor method on the basis of energy equilibrium to study the dynamic response of large deflection of a rigid-perfectly plastic solid monolithic beam-on-foundation, in which the effect of the axial (membrane) force induced by large deflection is considered in analytical model. Qiu et al. [18] applied the analytical method of Symonds and Jones [14] to the dynamic response of fully clamped solid monolithic beam impulsively loaded over a central patch and also gave the 'upper' and 'lower' bounds of large deflection.

Recently, some investigations have been carried out to analyze the dynamic response of metallic sandwich structures with various types of core. Fleck and Deshpande [19] examined the resistance of fully clamped sandwich beams subjected to uniformly transverse blast loading. The finite element calculations to investigate the dynamic response of fully clamped metal sandwich beams and plates under impulsive loading were carried

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out by Qiu et al. [20] and Xue and Hutchinson [21], respectively. Subsequently, Qiu et al. [18] developed an analytical model for the dynamic response of fully clamped sandwich beams subjected to blast loading over a central patch. Tilbrook et al. [22] proposed an analytical lumped mass model based on the relative time-scales of compression and the combination of plastic bending and longitudinal stretching, and conducted finite element simulations to classify the impulsive response of sandwich beams. Moreover, four distinct regimes of behavior are defined and marked on maps. Employing a shock simulation technique involving high-speed impact of aluminium foam projectiles, the dynamic response of the fully clamped sandwich beams was experimentally investigated, see Refs. [23–25]. The dynamic response of metallic sandwich structures subjected to underwater blast loading and air blast loading with different types of cores were reported elsewhere [26–33]. Karagiozova et al. [34] and Tekalur et al. [35] investigated the dynamic response of flexible sandwich panels with polystyrene and aluminium honeycomb cores and 3-D woven E-glass composite skins and stitched foam core subjected to blast loading, respectively. Employing a yield criterion comprising the effect of core strength, Qin and Wang studied the dynamic response for the fully clamped circular sandwich plates with a metallic foam core subjected to impulsive loading [36] and obtained an analytical solution for the large deflection of a slender metallic foam core sandwich beam with axial restraints under transverse loading by a flat punch [37].

On the other hand, Qiu et al. [18] only obtained the 'upper' and 'lower' bounds of the dynamic response of fully clamped metallic sandwich and monolithic beams impulsively loaded over a central patch on the basis of classical inscribed and circumscribed squares of the yield criteria for the sandwich and solid monolithic cross-sections. However, the classical yield criterion for sandwich cross-section with the core effect neglected may be highly accurate for the metallic sandwich structure with thin, strong face-sheets and a thick, weak core. It becomes less accurate as the sandwich cross-section approaches the solid monolithic limit. Thus, this analytical investigation provides the motivation to current study on the exactly dynamic response of impulsively loaded sandwich and monolithic beams, in which the core effect and interaction between plastic bending and stretching in deforming regions are considered in analysis of sandwich beam.

The objective of present work is to develop the membrane factor method to characterize the dynamic response of fully clamped metallic sandwich and monolithic beams subjected to localized impulse. The outline of this paper is as follows. The dynamic response of fully clamped sandwich beam impulsively loaded over a central patch in small deflection is presented in Section 2, in which it is assumed that the dynamic response may be separated into three distinct motion phases. Then, yield criteria for uncompressed and compressed sandwich structures are presented in Section 3. Moreover, based on the principle of energy equilibrium and the yield criterion considering core effect, bounds of the solutions are obtained and membrane factor for the fully clamped sandwich beam with a *nonuniform* cross-section thickness is derived in Section 4. Subsequently, the membrane factor is introduced into the governing equations for small deflection to account for the effect of axial (membrane) force induced by large deflection, and then governing equations for large deflection of the dynamic response of fully clamped sandwich beam are obtained. As a degenerated limit case, the expressions for dynamic response of large deflection of solid monolithic beam are also presented. Comparisons of the present results and finite element results are carried out to validate the present theoretical solutions. In Section 5, concluding remarks are presented.

2. Dynamic response in small deflection

Consider a fully clamped metallic sandwich beam of span $2L$ with identical face-sheets of thickness h and core thickness c subjected to blast loading I per unit length over a central patch of length $2a$, as shown in Fig. 1. It is assumed that the face-sheets are made from a rigid-perfectly plastic material of yield strength σ_f and density ρ_f. The core with density ρ_c posses a compressive strength σ_n in the transverse direction of the beam with a densification strain ε_D; beyond densification, the core is taken to be rigid, as shown in Figs. 2(a) and (b), respectively. The axial tensile strength of the core is taken to be σ_l.

The dynamic response of fully clamped metallic sandwich beams subjected to impulsive loading over the entire span and a central patch have been studied in Refs. [18,19], the 'upper' and 'lower' bounds of the dynamic response were only obtained. The coupling between the core compression and beam bending and stretching are decoupled because the time period of the core compression is much smaller than the overall response time of the sandwich structure. Moreover, in the core compression stage, they assumed that a one-dimensional slice through the thickness of the

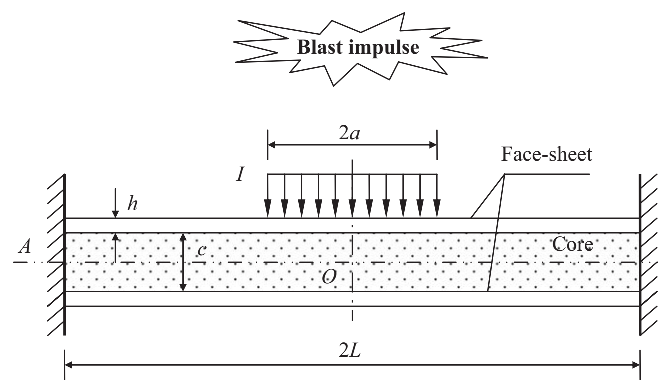

Fig. 1. Sketch of a fully clamped sandwich beam under impulsive loading over a central patch.

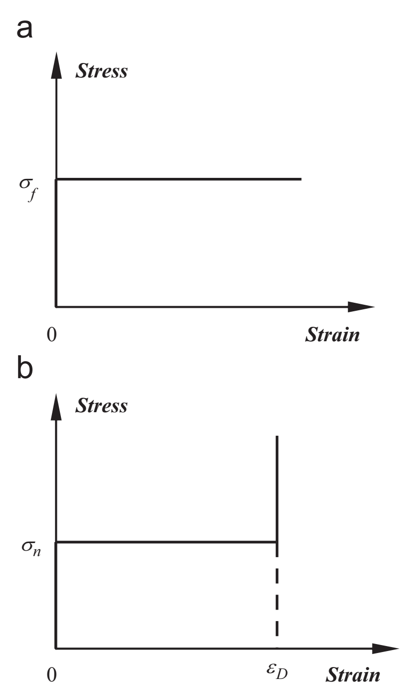

Fig. 2. Material characteristics of a metallic sandwich beam: (a) face-sheets and (b) metallic foam core.