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Blast loading of bumper shielded hybrid two-core Miura-ori/honeycomb core sandwich plates

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ABSTRACT

We analyze transient elasto-plastic deformations of two-core sandwich plates with and without a bumper and subjected to blast loads with the objective of ascertaining the energy dissipated due to plastic deformations. The facesheets and the core are assumed to be made of a high strength steel modeled as an isotropic material that obeys the von Mises yield criterion with linear strain hardening. It is first shown that considering a material failure criterion and deleting failed elements does not noticeably affect the energy dissipated in a sandwich plate. Subsequent analyses of two-core structures with and without a blast shield ignore the material failure and assume facesheets to be perfectly bonded to the core. The nonlinear transient problems have been numerically analyzed with the commercial finite element software, ABAQUS/ Explicit. Four different two-core sandwich plates obtained by varying locations of the Miura-ori and honeycomb cores are considered. Results without a shield indicate that using a Miura-ori core beneath the topmost facesheet dissipates more energy for moderate blast loads, while a combination of a honeycomb and a Miura-ori core has the least facesheet deflections. The effects of using a blast shield or a bumper, at a fixed standoff distance from a honeycomb-Miura sandwich panel, is studied by ensuring that the shield and the sandwich structure combination has the same areal density as the sandwich panel without the shield. It is found that for a given blast load, using the shield significantly reduces the energy dissipated in the sandwich panel, the bottom facesheet maximum centroidal deflection and the maximum plastic strain in the cores when compared with equal-weight panels without a shield. For the same energy dissipation, the structure with a blast shield has approximately 42% less weight than that without the shield.

1. Introduction

Sandwich panels are widely used as primary load bearing members in high-performance aerospace, naval and automobile industries because of their multi-functionality, high stiffness-to-weight ratios and their capability to be tailored to meet design requirements. Discrete or cellular sandwich cores, constructed as a corrugated sheet or square/hexagonal cell honeycombs, dissipate a significant amount of incident energy through a combination of their plastic compression, and bending and transverse shear deformations of the core [1], making them ideally suited for blast-mitigating applications.

The mechanical response of *single* cellular-core sandwich structures subjected to air or underwater blast loads has been investigated using both, homogenized [2–5] and discrete core models [6–16]. These studies have established that sandwich structures have higher specific energy dissipation than solid plates of the same areal density, and have indicated the superiority of the honeycomb core architecture over other core geometries [17]. However, moisture accumulation in sealed honeycomb cells can severely compromise their mechanical performance. Novel core architectures [18–22], including origami-based designs, can help mitigate this problem and further improve the performance of sandwich structures.

Investigations on quasi-static deformations of single Miura-ori sandwich cores [23,24] and on transient deformations of blast-loaded stacked Miura-ori core sandwich beams [25] have shown the effectiveness of the Miura-ori core architecture. Design studies on single-core Miura-ori and honeycomb core sandwich plates subjected to high-intensity dynamic loads [26] have found that the Miura-ori core consistently outperforms the honeycomb core of equal areal density in terms of the energy dissipated through plastic deformations, particularly for moderate blast intensities.

Dual-core or multi-core sandwich panels consisting of two or more cores separated by metallic or composite facesheets have been shown to be superior to equal areal density single-core structures in terms of their impact resistance [27,28], energy absorption [29] and sound-absorbing capabilities [30]. Infinitesimal elastic deformations of multilayered

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foldcore sandwich panels have been analytically studied [31], however, the mechanics of transient deformations of the elasto-plastic core under dynamic loads [25,26] is quite involved due to inertia effects. For single core elasto-plastic sandwich plates with the Miura-ori and the honeycomb cores [26] of equal areal density with material failure not considered, we found that while the bottom facesheet of the Miura-ori core sandwich plate had lesser maximum deflection the honeycomb core considerably reduced the top facesheet maximum deflection. Furthermore, for moderate blast intensities, the Miura-ori cores dissipated a greater fraction of the incident energy through plastic deformations than the honeycomb cores.

In terms of structural reliability, an ideal sandwich panel should dissipate large quantities of energy without sacrificing its integrity. This has motivated us to study two-core sandwich plates with the Miura-ori and the honeycomb core located in either the top or the bottom layer, which gives four combinations - Miura-honeycomb, honeycomb-Miura, Miura-Miura and honeycomb-honeycomb, wherein the first term refers to the top core that first interacts with the blast load.

For space structures, a thin shield placed at a distance above the primary structure, known as a Whipple bumper [32], efficiently reduces the penetration due to hypervelocity meteoric impact and offers considerable weight savings [33–39]. For aircrafts, a Hardened Unit Load Device (HULD) [40] and an overhead bin blast composite shield [41] provide on-board countermeasures against small explosions. There is a clear need for research on shielding aircraft, automobile and naval structures from high-intensity dynamic loads caused by explosive blasts or crashes.

Thus, objectives of this paper are to:

1. Examine effects of a Whipple shield, i.e., a thin metallic plate located above the primary structure and interacting first with the blast load.
2. Delineate effects of considering material failure and deleting failed elements from the analysis.
3. Investigate the blast performance of hybrid two-core sandwich structures designed as a combination of Miura-ori and square honeycomb core layers perfectly bonded to facesheets.

The finite element (FE) software ABAQUS/ Explicit ver. 6.14 [42] is used to numerically solve the pertinent nonlinear initial-boundary-value elastic-plastic problems by using the FE mesh that gave converged results for a prototype one-core sandwich structure. It is found that considering a damage model and deleting failed elements has a minimal effect on the energy absorbed and the maximum deflection of the structure. Material strain rate effects, thermal softening, debonding between the core and the facesheets and imperfections, if any, in the cores have not been considered.

Design studies conducted to investigate the influence of the unit cell parameters of the Miura-ori and the honeycomb pattern on the sandwich panel deformations indicate that design trade-offs need to be considered. The Miura-ori core in the top layer dissipates more energy through plastic deformations, and the honeycomb-Miura combination minimizes the facesheet deflections. Using a panel with a Whipple shield reduces the back facesheet maximum deflection and decreases the maximum equivalent plastic strain in the cores when compared with an equal areal density panel without the shield. For the same energy dissipation under a given blast load, the structure with a blast shield has approximately 42% less weight than that without the shield.

The layout of the remainder of the paper is as follows. The geometry of the two-core Miura-ori and honeycomb sandwich plate, the constitutive relations for the material and the FE modeling in ABAQUS/ Explicit are described in Section 2. Results for (i) a single-layer sandwich plate under blast loads with and without considering material failure, and (ii) a single fold with and without accounting for pre-damage induced in its crease during the fabrication process are also discussed in Section 2. The collapse kinematics and the response of the

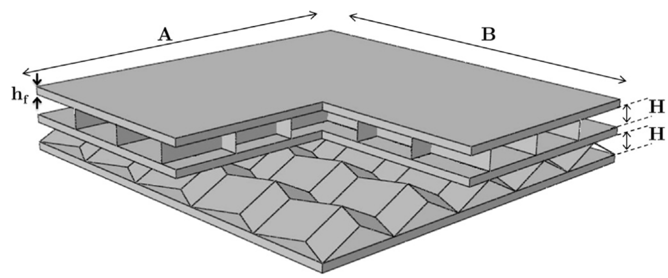

Fig. 1. “Honeycomb-Miura” hybrid sandwich plate.

four two-core sandwich plates under blast loads are described in Section 3. The influence of unit cell parameters on the energy dissipated due to plastic deformations in the cores and on the facesheet deflections of the two-core sandwich plates are presented in Section 4. The influence of a blast shield on deformations of a honeycomb-Miura sandwich plate is examined in Section 5. In Section 6 we comment upon experimental work needed to verify results of simulations. Conclusions of the work are summarized in Section 7.

2. Geometry and modeling of the hybrid two-core sandwich plate

The hybrid two-core sandwich plate consists of a top, a middle, and a bottom facesheet with two cores (of either a Miura-ori or a honeycomb-type architecture) between a pair of facesheets (see, for example, Fig. 1, for the “honeycomb-Miura” combination). The three facesheets, assumed here to be identical for simplicity, have dimensions $A \times B \times h_f$ and the core thickness equals H. The edges of the facesheets are rigidly clamped and a high-intensity dynamic load given by

$$p(r,t) = \begin{cases} 0 & t < t_a \\ p(t)\mathrm{e}^{-(r/r_0)^2} & t \geq t_a \end{cases} \tag{1}$$

where

$$p(t) = P_0\left[1 - \frac{t - t_a}{t_d}\right]\mathrm{e}^{-(t-t_a)/t_\theta} \tag{2}$$

is applied to the outer surface of the top facesheet. The blast pressure is adapted from the numerical studies of Dharmasena et al. [9], and exponentially decreases with distance r from the facesheet centroid according to Eq. (1). The peak overpressure P_0 occurs at $r = 0$ and time $t = t_a$ and decreases exponentially with time $t > t_a$ (see Fig. 2). We set, $r_0 = 50$ mm, $t_a = 20$ µs, $t_d = 180$ µs and $t_\theta = 189.8$ µs. Batra and Hassan [43] considered p to be a polynomial of degree 4 in r and exponentially decaying in time with various parameters given by Cole's [44] empirical formulae.

The Miura-ori core consists of x_m and y_m “unit cells” tessellated along and across the corrugation, respectively. A single unit cell is constructed from four identical parallelograms which can be characterized by four parameters in its unfolded state: side lengths a and b,

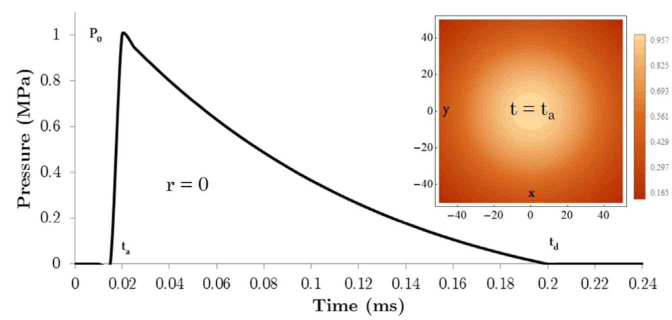

Fig. 2. Time and spatial (inset) variation of the high-intensity dynamic load (Eq. (2)).