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Crush dynamics and transient deformations of elastic-plastic Miura-ori core sandwich plates

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A B S T R A C T

The response of elastic-plastic Miura-ori core sandwich plates to high-intensity dynamic loads is numerically studied using the commercial finite element software ABAQUS/ Explicit. Crushing simulations conducted on the Miura-ori core over a range of loading rates clearly illustrate the dynamic strengthening of the core by inertial effects, particularly at loading rates relevant to blast experiments. Exploratory design studies have been conducted to determine the influence of the unit cell parameters of the Miura-ori pattern on the energy dissipated by the core through plastic deformations, and to compare its performance with that of square honeycomb cores of equal areal density. Material strain rate effects, a material failure criterion and debonding between the core and the facesheets have not been considered. It is found that for low to moderate load intensities, the Miura-ori core consistently outperforms the corresponding honeycomb core in terms of plastic dissipation (by as much as 68%) and facesheet centroidal deflections, and offers a rich design space to tailor its mechanical performance. However, the plastic energy dissipated in the core as a fraction of the total plastic energy dissipated in the structure is nearly the same for the Miura-ori and the honeycomb core sandwich plates of equal core areal density.

1. Introduction

Sandwich panels are efficient modular structures with high stiffness-to-weight ratios and can be tailored to meet various design requirements. The sandwich core, which may be either continuous in the form of a metallic or low strength foam, or discrete in the form of a corrugated sheet or square or hexagonal cell honeycombs can dissipate large amounts of energy through plastic compression, transverse shear deformations and bending [1]. Thus, sandwich panels have found prolific use as blast-mitigation structures.

Numerous studies have been conducted on the mechanical response of foam core sandwich beams and plates subjected to either air or underwater blast loads [2–5]. These investigations have detailed the sequential stages in the response of the sandwich structure namely, the fluid-structure interaction during the blast which imparts a uniform velocity to the outer facesheet, followed by core compression and densification and finally, panel stretching and plastic bending. Various regimes of core deformations have been postulated based on the relative velocities of the facesheets. It has been found that sandwich structures have higher shock resistance (in terms of energy dissipation) than corresponding solid plates of equal mass. For cellular core sandwich structures, both homogenized [6,7] and discrete core models [8–13] have been used to study the blast response of a variety of core geometries. These have indicated the superiority of the honeycomb architecture over other core geometries. By comparing the finite element simulation results with experimental findings, it was determined that the finite element based software ABAQUS/ Explicit accurately simulates the response of sandwich structures to blast loads [14].

The blast effectiveness of honeycomb cores is well established, however, these cores are known to suffer from a moisture accumulation problem wherein the sealed honeycomb cells trap condensed moisture which can severely deteriorate their mechanical performance over time. This has led designers to conduct physical and virtual tests [15,16] on new core architectures [17–20] which also improve the multi-functional capabilities of sandwich structures. The tessellated Miura-ori fold pattern, which is designed using rigid origami principles and exhibits interesting properties such as a wide range of Poisson's ratios and remarkable buckling and load bearing capabilities [21–23] shows tremendous promise to be employed as an alternative to the honeycomb core. However, most current research studies on the mechanics of the Miura-ori pattern derive its material properties under the assumption of *isometric or rigid folding* [24,25] wherein the Miura-ori patterned sheet is permitted to fold freely without any constraints.

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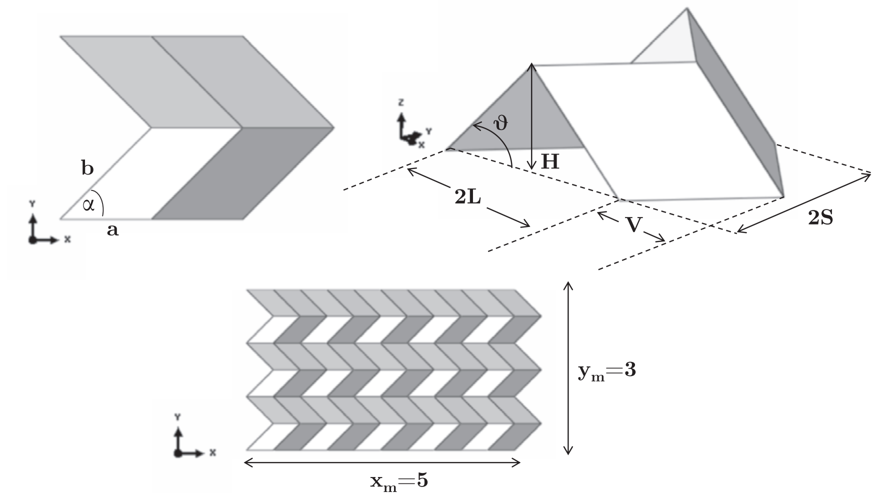

Fig. 1. Geometric parameters of a Miura-ori unit cell.

Thus, the parallelogram facets between the creases remain rigid and deformation is confined only to the fold lines. In such a scenario, the Miura-ori sheet behaves as a mechanism with one degree of freedom. On the other hand, when the Miura-ori pattern is used as a sandwich fold core, it must be suitably bonded to the facesheets which restricts its free-folding kinematics and rigid motion. Quasi-static studies have been conducted on Miura-ori sheets sandwiched between rigid plates [26,27] and have helped provide an insight into the mechanical properties of these folded cores. Recently, a stacked folded core concept was introduced [28] for sandwich beams wherein Miura-ori patterned sheets were stacked to produce cores whose collapse kinematics were governed by a distinctive folding mechanism instead of buckling of core facets. This made the core less sensitive to imperfections whilst offering the versatility to alter the collapse mechanics by changing the core geometry.

In applications where the sandwich core is subjected to blast loads and must absorb large quantities of incident energy, dynamic effects are expected to play a significant role. In particular, the mechanics of deformation of the core under dynamic loads may be significantly different and more complicated than the corresponding quasi-static modes of deformation due to the effects of the inertial resistance of the core as has been shown for honeycomb sandwich plates [7]. Hence, using results from quasi-static studies may underestimate the performance of Miura-ori cores under high-intensity dynamic loads, particularly when sandwiched between deformable facesheets. Clearly, in order to employ the Miura-ori geometry as a blast mitigating core, it is imperative to characterize its dynamic collapse kinematics, and compare its performance with that of the ubiquitous honeycomb core. Using detailed numerical calculations with the commercial finite element software ABAQUS/ Explicit ver. 6.14, this paper seeks to:

1. Investigate the contribution of the inertial resistance of the Miura-ori core to its dynamic strengthening by simulating crushing tests on the core. Material strain rate effects, a failure criterion and debonding between the facesheets and the core have not been considered in these computations.
2. Conduct exploratory design studies to ascertain the influence of unit cell parameters of the Miura-ori pattern on the energy dissipated due to plastic deformations of the core as well as on the facesheet centroidal deflections.
3. Compare the blast performance of the Miura-ori cores with that of square honeycomb cores of equal areal density.

Results of the crushing simulations on the Miura-ori core indicate that the loading strain rate plays an important role in the dynamic strengthening of the core, particularly for high-intensity impulses relevant to blast loaded sandwich plates. Using the centroidal transient deflections and transverse velocities of the facesheets to characterize the response of the Miura-ori core sandwich plates, the design studies show that the Miura-ori core consistently outperforms corresponding honeycomb cores while offering a rich and versatile design space to tailor its mechanical performance.

The layout of the paper is as follows. The geometry of the Miura-ori core sandwich plate and details of its finite element modeling with ABAQUS/ Explicit are described in Section 2. The effects of inertial hardening on the Miura-ori core during dynamic crushing are investigated in Section 3. The collapse kinematics and the response of the Miura-ori core sandwich plate with deformable facesheets under the action of high-intensity dynamic loads are explained in Section 4. Results from design studies on the influence of unit cell parameters on the response of the Miura-ori core are presented in Section 5, with particular emphasis on plastic dissipation in the core. In Section 6 we have compared the performance of the Miura-ori core with that of honeycomb cores of equal areal density. Conclusions of the work are summarized in Section 7.

2. Geometry and modeling of the Miura-ori core sandwich plate

A single Miura-ori unit cell consists of four identical parallelograms and can be characterized by four parameters in its unfolded state: side lengths a and b, acute angle α and the thickness of the sheet material t_s (Fig. 1). In a particular folded configuration, the Miura-ori unit cell can be completely characterized with one additional parameter: the dihedral fold angle θ between the facets and the horizontal base. The unit cell can also be described by its outer dimensions, height H, width $2S$, length $2L$ and amplitude V given by ([21])

$$H = a\ \sin\ \theta \sin\alpha$$

$$S = b\frac{\cos\theta\tan\alpha}{\sqrt{1+\cos^2\theta\ \ \tan^2\alpha}}$$

$$L = a\sqrt{1-\sin^2\theta\ \ \sin^2\alpha}$$

and

$$V = b\frac{1}{\sqrt{1+\cos^2\theta\ \tan^2\alpha}} \tag{1}$$

With the outer dimensions specified, the unit cell parameters can be easily determined ([21]). A planar Miura-ori core consists of x_m and y_m unit cells tessellated along and across the corrugation, respectively. The mass density of the Miura-ori core is given by