THEORETICAL & APPLIED MECHANICS LETTERS **4**, 021001 (2014)

Penetration of sandwich plates with hybrid-cores under oblique ballistic impact

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(Received 31 July 2013; revised 14 November 2013; accepted 10 December 2013)

Abstract The oblique penetration performance of lightweight hybrid-cored sandwich plates are investigated numerically. To compose the hybrid-core, ceramic prisms are inserted into pyramidal metal lattice trusses and fixed using epoxy resin. Three-dimensional finite element simulations are carried out for the hybrid-cored sandwich impacted at 15°, 30°, 45°, and 60°obliquity by a hemispherical projectile. The ballistic limit, the energy absorbed by the constituting elements, and the critical oblique angle are quantified. The physical mechanisms underlying the failure and the influence of fundamental system parameters are explored. The angle of obliquity is found to have significant influence on the ballistic trajectory and erosion of the projectile, thus it is important for the impact response and penetration resistance of the sandwich. For oblique angles equal to or larger than 45°, the projectile moves mainly horizontally and can not effectively penetrate across the sandwich.

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Keywords sandwich, oblique impact, pyramidal lattice

Two- and three-dimensional periodic metallic lattice trusses have been widely used to construct lightweight sandwich structures for a wide range of civil and military applications. In the past decade, in addition to specific stiffness/strength, increasing studies have focused on the energy absorption capability and shock resistance of lightweight structures.[1–5] For typical instance, making use of the open pore (fluid through) topology of pyramidal lattice trusses, Ni et al.[6] recently studied both experimentally and numerically the penetration performance of sandwich plates with hybrid-cores. To compose the hybrid-core, ceramic prisms are inserted into pyramidal metal lattice trusses and fixed using epoxy resin, as shown schematically in Fig. 1(a).

With the oblique angle of the impact projectile fixed at 0° (Fig. 1(b)), Ni et al.[6] demonstrated that the kinetic energy of the projectile was absorbed mainly via plastic deformation and shear expansion of the face sheets, the damage and fracture of the solidified epoxy resin and ceramic prisms, as well as the macroscopically bending deformation of the whole structure. The ceramic insertions significantly enhanced the penetration performance of the structure, due to their erosion effects on the impact projectile, reducing significantly its total mass. Further, by adhering the hybrid-cored sandwich structures as an integrated whole, the infiltrated epoxy resin was also found to contribute appreciably to ballistic energy absorption. Built upon the work of Ni et al.,[6] the aim

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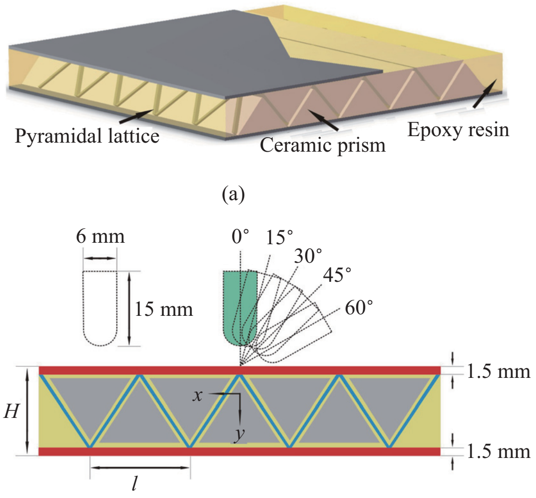


(b)

Fig. 1. (a) Schematic of lightweight hybrid-cored sandwich plate; (b) oblique impact at plate center by a hemispherical projectile (bullet).

of this study is to characterize the impact response and penetration performance of sandwich plates with hybrid-cores under oblique projectile impact (as shown in Fig. 1(b)).

Existing studies concerning the penetration resistance of a structure or material focused mainly on the most dangerous impact condition, namely, the normal impact case where the angle between the velocity vector of the projectile and the normal vector of the target plate is zero. However, the oblique angle of the impact projectile was also found to have important influence not only on the penetration resistance of the target but also on its deformation/failure mode.[7–11] In general, increasing the impact oblique angle led to increased penetration resistance of the target. Recently, Børvik et al.[12] carried out a combined experimental and numerical impact study of small arms bullets on 20 mm thick AA6082-T4 aluminum plates. It was demonstrated that, at high oblique angles, the velocity drop during perforation was considerable and the critical oblique angle was less than 60° for two different bullet types: the 7.62 mm×63 mm NATO Ball (with a soft lead core) and the 7.62 mm×63 mm APM2 (with a hard steel core). Thus far, no study (either experimental or theoretical) concerning the oblique projectile impact of hybrid-cored sandwich plates exists in the open literature.

As illustrated in Fig. 1(b), consider a hybrid-cored (metallic pyramidal lattice-ceramic insertions-epoxy filling) sandwich plate fully clamped along its edges and subjected to ballistic projectile impact at its center. As the oblique angle φ varies from 15°, 30°, 45°, to 60°, the method of finite elements (FE) is employed to determine the variation trend of the penetration resistance and the critical oblique angle at which the penetration process is changed from perforation to embedment. In addition to exploring the underlying deformation/failure mechanisms, the variation of energy absorbed by each sub-component and ballistic trajectory of the projectile with varying oblique angle is also calculated. The commercial FE code ANSYS LS-DYNA[13] is employed to perform all the numerical simulations.

The plate dimensions and the size of the projectile shown in Fig. 1(b) are selected according to the experimental work of Ni et al.,[6] as the numerical approach employed in the present study has been validated against the normal impact results measured experimentally by Ni et al.[6] Changing these geometrical dimensions will certainly lead to changed plate responses, but this will be left for future study due to space constraints of the present paper. Further, for simplicity, this study considers only the special case of projectile impact at the central apex of the pyramidal lattice trusses, see Fig. 1(b). Again, whilst the selection of this special impact location is consistent with the experimental set-up of Ni et al.,[6] other situations when the projectile impacts the sandwich at points off the plate center will be investigated in a separate study. Consequently, with the geometrical dimensions of both the sandwich plate and the projectile as well as the location of projectile impact all fixed, the focal question the present study aims to answer is how the hybrid-cored sandwich plate would respond when it is subjected to oblique projectile impact.

Following Ni et al.,[6] an FE model for the hybrid-cored sandwich of Fig. 1 is constructed using three-dimensional solid elements, with Euler elements adopted to simulate the void-filling epoxy and Lagrange elements adopted to simulate the remaining sub-structures. Whilst all the numerical simulations are carried out using the arbitrary Lagrangian–Eulerian method, the selection of mesh size and allocation of fine and dense elements are carefully considered, eventually reaching a compromise between numerical accuracy and computational cost.

To model the face sheets, the pyramidal lattice trusses and the projectile (all made of AISI 304 stainless steel), the Johnson–Cook (J–C) constitutive relation and fracture criterion[14] in conjunction with the Mie–Gruneisen equation of state model[13] are employed. For the ceramic (AD 98 alumina) prisms under high velocity penetration, the Johnson–Holmquist–Ceramics (JH-2) constitutive relation and fracture criterion[14,15] are adopted. Following Lopez–Puente et al.,[16] the elastic–plastic–hydro constitutive relation is employed to model the epoxy as a kind of hydrodynamic material. Relevant material constants used for the present FE simulations can be found in Ref. 6.

For the case of normal impact (oblique angle equal to 0°, as shown in Fig. 1(b)), the constitutive relations, fracture criteria, and FE simulation procedures as outlined above have been validated against experimental measurement,[6] with good agreement between experimental measurements and simulation results achieved. Details of the validation procedures are hence omitted here for brevity.

Figure 2 plots the predicted residual velocity of the impact projectile as a function of its initial velocity (i.e., entry velocity) for varying oblique angles. For the case of oblique angle equal to 15° (i.e., $\varphi = 15^\circ$), obtained results suggest that when the projectile has an entry velocity of about 1.8 km/s, it can just penetrate across the hybrid-cored sandwich (i.e., residual velocity equal to zero). This velocity is thence considered the ballistic limit velocity for the case of $\varphi = 15^\circ$. The corresponding deformation and failure modes of the sandwich at different stages of projectile penetration are presented in Fig. 3.

At the velocity of 1.8 km/s (ballistic limit), the projectile with $\varphi = 15^\circ$ quickly perforates the top face sheet and starts to penetrate across the hybrid-core. The metallic pyramidal lattice trusses in the core then absorb the impact energy by strut bending and fracturing, whilst the central ceramic insertion directly under the projectile impact as well as those nearby contribute

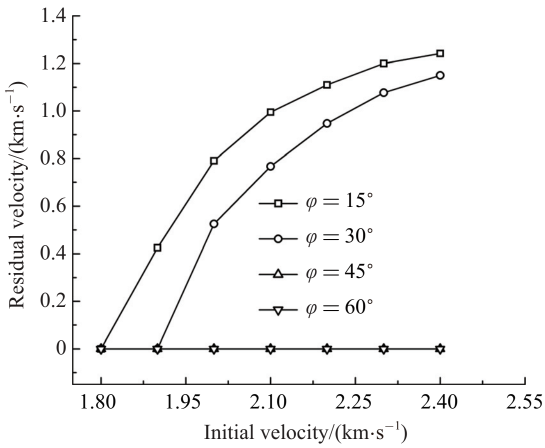
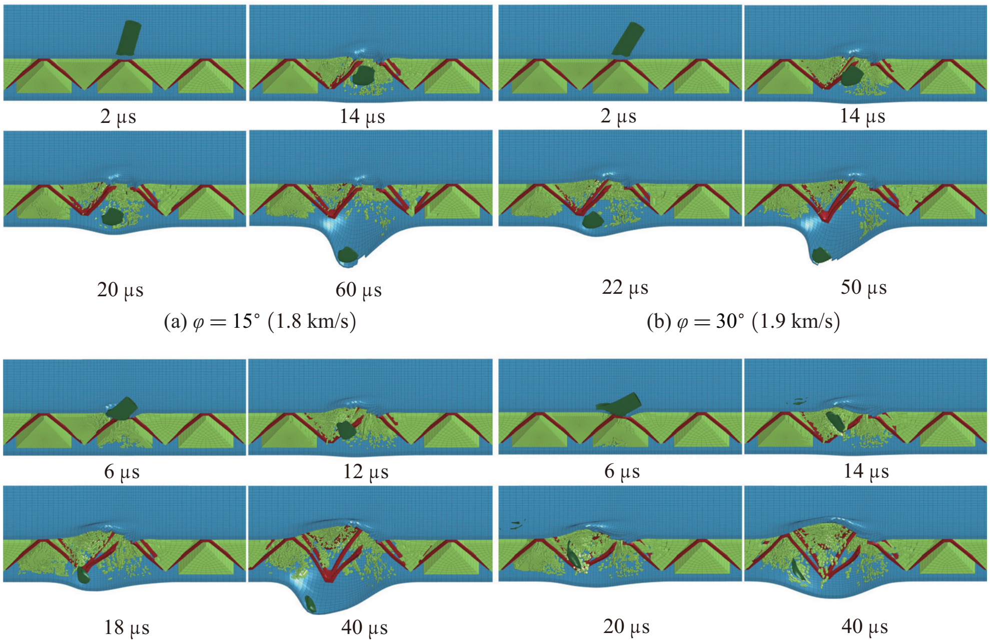


Fig. 2. Residual velocity versus initial impact velocity for selected oblique angles.

to the energy absorption mainly by fragment fracture, as shown in Fig. 3(a). In addition, the ceramic fragments continuously erode the projectile, causing asymmetric failure of its tip as well as significant loss of its total mass. At about 20 μs after initial impact, the considerably eroded and decelerated projectile reaches the bottom face sheet at an angle larger than the initial obliquity. The bottom face sheet responds by humping outward, absorbing remained impact energy via large bending deformation. Eventually, the bottom face is perforated, during which more ceramic insertions (especially those located on the left side of the impact, as shown in Fig. 3(a)) experience fragment fracture.

Results shown in Fig. 3 indicate that the use of epoxy resin to fill the interstices between ceramic insertions and lattice trusses to adhere the hybrid-cored sandwich as a whole. Consequently, there is significantly more stress wave spreading in the structure in comparison with the case without using the epoxy resin.[6] Correspondingly, on account of projectile penetration, fragment fracture occurs not only in the central ceramic prism but also in the neighboring ones. In addition, the epoxy resin constrains small ceramic fragments to further resist the projectile penetration. Although the results are not shown here for brevity, the lattice trusses under the impact zone are found to deflect much less compared with those in sandwiches without using void-filling epoxy.

Consider next the evolution of deformation and failure in the hybrid-cored sandwich for the case of $\varphi = 30°$. The calculated ballistic limit velocity is about 1.9 km/s, as shown in Fig. 2. At this entry velocity, the projectile perforates the top face sheet with ease, causing the central portion of the top face to hump towards the left, and then moves forward along the interstice between two neighboring ceramic insertions, as shown in Fig. 3(b). As the diameter of the projectile is much larger than the interstitial gap, the two ceramic insertions break into numerous small fragments to absorb the impact energy. At about 22 μs after initial impact, the seriously eroded projectile starts to perforate the bottom face. However, during the perforation, instead of keep moving towards the left side of the impact zone, the projectile is increasingly deflected back towards the central ceramic prism, as shown in Fig. 3(b). The perforation of the bottom face is complete at about 50 μs.



(a) $\varphi = 15^\circ$ (1.8 km/s) (b) $\varphi = 30^\circ$ (1.9 km/s)

(c) $\varphi = 45^\circ$ (2.4 km/s) (d) $\varphi = 60^\circ$ (2.4 km/s)

Fig. 3. Hybrid-cored sandwich plate under projectile impact at ballistic limit velocity for different angles of obliquity. The Euler elements for epoxy resin are marked for clarity.

Similar to the case of $\varphi = 30^\circ$, at the oblique angle of $\varphi = 45^\circ$, the projectile with entry velocity of 2.4 km/s also tends to move along the interstice between two neighboring ceramic insertions, forcing the central ceramic insertion to break up, as shown in Fig. 3(c). As the projectile moves further within the hybrid-core, the ceramic insertion located at the left of the central one falls to pieces whilst that located at the right side remains intact. By the time (approximately 18 μs) when the projectile reaches the bottom face, it is considerably more eroded relative to the case of $\varphi = 15^\circ$ or $\varphi = 30^\circ$, with only a tiny mass left. Subsequently, the bottom face goes through large bending-dominated deformation whilst the second left ceramic insertion is fragmentized (Fig. 3(c)). However, at $\varphi = 45^\circ$, the projectile can not complete the perforation process across the bottom face and the penetration process is changed from perforation to embedment. This is due to the fact that the projectile reaching the bottom face is seriously eroded and decelerated, thus its remained impact energy is not enough to fully perforate the bottom face. Further, the obliquity effect enhances the transverse (x-direction) movement of the projectile, reducing significantly its penetration capability in the vertical direction (z-direction), as shown in Fig. 3(c).

The case of $\varphi = 60^\circ$ is similar to that of $\varphi = 45^\circ$. An projectile with initial velocity of 2.4 km/s or higher can not fully penetrate across the sandwich (Fig. 2) and the penetration process is changed from perforation to embedment (Fig. 3(d)). However, relative to the case of $\varphi = 45^\circ$, the projectile with $\varphi = 60^\circ$ moves farther in the transverse direction, its erosion and mass loss are accelerated, and the region within which the ceramic insertions experience fragment fracture is enlarged.

In summary, under the present simulation conditions, 45° may be taken as the critical oblique angle at which the penetration process is changed from perforation to embedment. In comparison with a homogeneous steel plate of equal mass, the relatively thin top face of the hybrid-cored sandwich enables the projectile to perforate with ease and hence ricochet is rarely observed. Also, embedment is more likely to occur in the sandwich in comparison with the homogeneous plate.

To explore further the mechanisms underlying the penetration process of the hybrid-cored sandwich, Fig. 4(a) plots the ratio of the residual mass to initial mass (m/M) of the projectile as a function of its x-direction movement trajectory for selected oblique angles, with the initial impact velocity fixed at 2.4 km/s. Correspondingly, Fig. 4(b) plots m/M as a function of the z-direction movement trajectory. Here, x and z denote the transverse and vertical coordinates of the projectile tip, l is the width of the pyramidal unit cell, and H is the total height of the sandwich (Fig. 1).

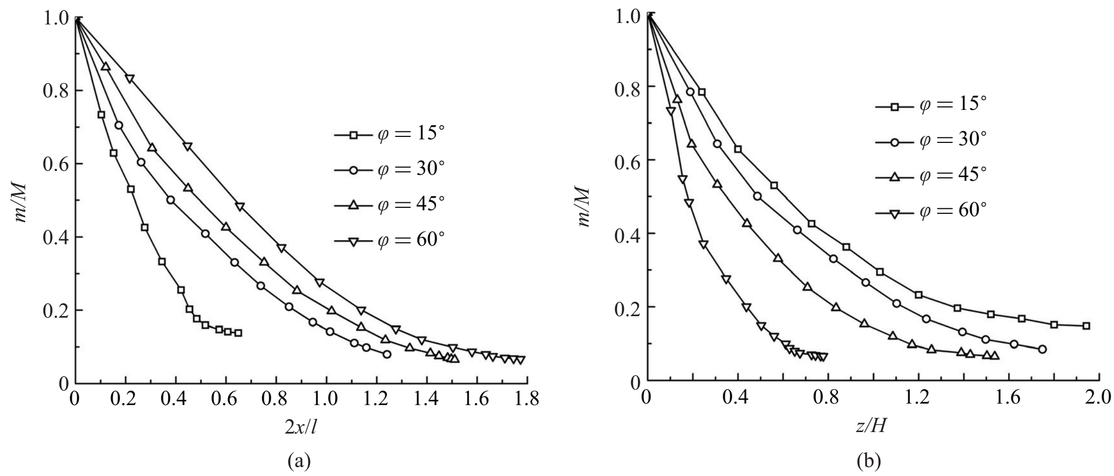


Fig. 4. Ratio of projectile residual mass to initial mass, m/M, plotted as a function of (a) x-direction movement trajectory ($l = 29$ mm being the width of pyramidal unit cell in Fig. 1) and (b) z-direction movement trajectory ($H = 17.5$ mm being total sandwich height in Fig. 1) for selected oblique angles, with initial impact velocity fixed at 2.4 km/s.

It is seen from Fig. 4(a) that, for a given transverse position, the projectile acquires the largest mass loss when its oblique angle is 15°. This is because at this transverse position the projectile advances farthest along the z-direction in comparison with other oblique angles, and hence its interaction with the constituting elements of the hybrid-core is most intensive (as shown in Fig. 4(b) where a trend opposite to that of Fig. 4(a) is observed).

In general, the loss of projectile mass increases with increasing oblique angle, suggesting that the penetration resistance of the sandwich is enhanced as the oblique angle is increased. However, the final mass loss of the projectile is more or less the same once the oblique angle is raised to 30° or above. This indicates that when the oblique angle exceeds 30°, the penetration capability of the projectile is seriously weakened due to the large mass loss associated mainly with the erosion effects of the ceramic insertions.

At the oblique angle of $\varphi = 15°$, it is seen from Fig. 4(b) that the z-direction movement of the projectile is farthermost, reaching $z/H = 1.97$ and accomplishing full perforation of the sandwich. In comparison, at $\varphi = 60°$, the x-direction movement of the projectile is the farthest, achieving $2x/l = 1.8$. In this case, the projectile tip reaches the second insertion at the left side of the central insertion, initiating fragment fracture in the insertion located further to the left, a feat not achieved by a projectile impacting at smaller oblique angles.

Figure 5 plots the energy absorption percentage of each constituting element of the hybrid-cored sandwich as a function of the oblique angle, with the initial impact velocity fixed at 2.4 km/s. Due to low mass (high porosity), the stainless steel pyramidal lattice trusses absorb the least amount of impact energy. As the oblique angle increases, the humping (asymmetric bending deformation) of the top face sheet is intensified, enhancing significantly its energy absorption capacity.

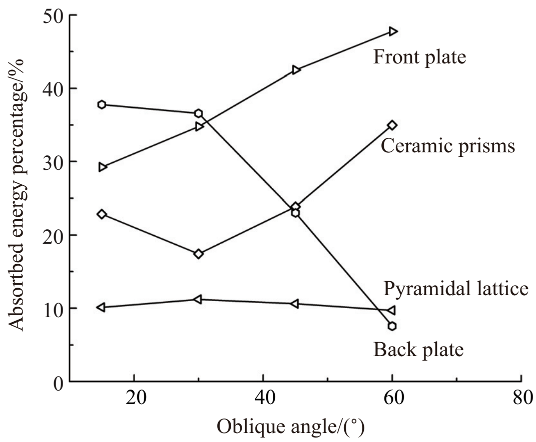


Fig. 5. Energy absorption percentage of each sub-structure of hybrid-cored sandwich plate plotted as a function of oblique angle, with initial impact velocity fixed at 2.4 km/s.

The energy absorbed by the ceramic insertions is lowest at $\varphi = 30°$, because at this oblique angle the projectile tends to advance along the interstices between two neighboring ceramic insertions, as shown in Fig. 3(b). As the oblique angle increases to 45° or even 60°, the percentage of impact energy absorbed by the ceramic insertions increases because increasingly more insertions experience fragment fracture.

As the oblique angle increases, the interaction of the projectile with the bottom face sheet decreases. In particular, at $\varphi = 60°$, the projectile moves mainly in the transverse direction (x-direction) and hence the energy absorbed by the bottom face is lowest comparing to the other three oblique angles.

Results shown in Fig. 5 suggest that, for relatively small oblique angles ($\varphi \leqslant 30°$), the percentage of impact energy absorbed by the bottom face sheet is highest, followed by the top face sheet, due mainly to their large deformation. As the oblique angle increases to 45°, projectile embedment rather than perforation occurs, reducing significantly the amount of energy absorbed by the bottom face. In contrast, as previously mentioned, the humping of the top face is now intensified due to bending deformation and hence the amount of energy it absorbs is the largest. Correspondingly, at relatively high oblique angles, the ceramic insertions also absorb more energy, accompanied by the broadening of the fragment zone.

Built upon our previous experimental and numerical work[6] concerning the normal impact of hybrid-cored sandwich plate by a hemispherical projectile, this study employs the FE method to investigate the variation trend of the impact response and penetration resistance of the same sandwich with varying oblique angles and explore the underlying mechanisms. As the oblique angle systematically increases, the variation of energy absorbed by each constituting element of the sandwich and the movement trajectory of the projectile are also calculated. Research results suggest that the oblique angle has important influence not only on the penetration resistance of the target plate but also on its deformation/failure modes. The ballistic limit velocity of the hybrid-cored sandwich increases with increasing oblique angle and the critical oblique angle at which the penetration process is changed from perforation to embedment is about 45°. These results are consistent with the existing work concerning oblique projectile impact of homogeneous plates.[7–12] However, in comparison with a homogeneous steel plate of equal mass, ricochet is rarely observed and embedment is more likely to occur in the hybrid-cored sandwich plate. Relative to a hybrid-cored sandwich subjected to normal impact, increasing the angle of obliquity leads to increasing erosion (mass loss) as well as increasing transverse movement of the projectile. Further, the front face sheet dominates the absorption of impact energy at large oblique angles, whilst the back face sheet plays the dominant role at small oblique angles.

This work was supported by the National Basic Research Program of China (2011CB610305).

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