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Recent advances in hybrid lattice-cored sandwiches for enhanced multifunctional performance

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ABSTRACT

Ultralight sandwich structures with either two-dimensional (2D) prismatic or three-dimensional (3D) lattice truss cores, such as honeycombs, folded panels (corrugations) and pyramidal trusses, are known to possess attractive mechanical stiffness/strength and impact resistance. These properties can be significantly improved further by inserting different materials into the interstices of the lattices to construct hybrid lattice-cored sandwiches, as summarized in this mini-review. Three different types of hybrid lattice-core for sandwich constructions are discussed, including ceramic- or concrete-filled lattice cores for superior penetration resistance, metallic or polymeric foam-filled lattice cores for simultaneous enhancement in load-bearing and energy absorption, and metallic honeycomb-corrugation cores for simultaneous load-bearing, energy absorption and broadband low-frequency sound absorption. Corresponding enhancement mechanisms are explored.

Contents

1. Introduction

As is well known, some desirable material properties are inaccessible for a single material, but could sometimes be achieved by making hybrids: combinations of two (or more) materials, or of material in space, in chosen configuration and scale [1–4]. The traditional method—developing new metal alloys, new polymer chemistries, and new compositions of glass and ceramics

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to access the desirable properties is usually an expensive and uncertain process. However, creating a hybrid is more economical and controllable. Particulate and fibrous composites, sandwich structures, foams, lattice structures, and segmented structures are successful examples of the hybrids [5–8].

Sandwich plates with periodic lattice cores such as pyramidal trusses [9,10], corrugated panels [11–14] and honeycombs [15–17] possess superior bending stiffness, strength and shock resistance relative to monolithic plates of equal mass, and present opportunities for additional functionality, such as active cooling and intelligent actuation. The lattice cores, usually with high porosity, possess enough interior interstices for exploring multifunctionalities, such as simultaneous load carrying and heat dissipation [18,19]. Recently, by inserting various materials into these interstices, it has been demonstrated that hybrid lattice-cored sandwiches can be created to satisfy more severe requirements of engineering applications, such as blast and ballistic resistance, simultaneous load carrying and energy absorption, and simultaneous load carrying, energy absorption and sound absorption. In this paper, we focus on recent progress in hybrid lattice-cored sandwiches. Firstly, ceramic/concrete-lattice cored sandwiches for enhanced ballistic resistance are summarized; secondly, advances in foam-filled lattices are discussed, with particular focus placed on strength and energy absorption; thirdly, hybrid honeycomb-corrugation lattices for simultaneously enhanced strength, energy absorption and sound absorption are presented; finally, we conclude by offering our perspective on future directions of this rapidly evolving field.

2. Ceramic/concrete-lattice cored sandwiches for superior penetration resistance

As monolithic systems typically offer limited penetration resistance, the ballistic performance is usually enhanced by combining materials systems to create the so-called hybrid materials or structures [20–22]. Recent researches have demonstrated that the concept of hybrid sandwich core by exploiting the interior void spaces in lattice structures offers significant potential for manipulating the ballistic properties of lattice-cored sandwich plates.

2.1. Hybrid pyramidal metallic lattice truss-cored sandwich plates

It has been demonstrated experimentally that all-metallic sandwich plates with 3D pyramidal lattice truss cores (made of 304 stainless steel; Fig. 1(a)) displayed almost the same ballistic resistance against spherical steel projectile penetration, relative to monolithic plates of equal mass [23]. Built upon this work, Yungwirth et al. [24,25] explored experimentally to enhance the ballistic resistance by filling the interior space of the truss core with combinations of polyurethane (elastomer), alumina prisms (ceramic), and aramid fiber textiles (fabric), as illustrated in Fig. 1(b)–(e). It was found from Fig. 2 that the addition of the polyurethane (Fig. 1(b)–(c)) did not enhance the ballistic limit compared with the equivalent monolithic steel plate; while the ceramic-filled lattice core (Fig. 1(d)–(e)) provided the greatest resistance to penetration, with a ballistic limit about twice that of the equivalent monolithic steel plate. This is because that the polymer was penetrated by a hole enlargement mechanism which did not result in significant projectile deformation or load spreading and engagement of the steel face sheets; however, the ceramic inserts comminuted and dilated while eroding the penetrating projectile, which resulted in the stretching of the steel face sheets and significant energy dissipation. The addition of a Kevlar fabric within the systems (Fig. 1(e)) did not significantly change the ballistic limit but helped to reduce the residual velocities of the penetrated projectile and panel debris.

Ni et al. [26] carried out numerical simulations to explore the mechanisms underlying the ballistic performance of sandwich plates with three different types of core: metallic pyramidal lattice trusses, metallic pyramidal lattice trusses with ceramic prism insertions, and metallic pyramidal lattice trusses with ceramic prism insertions and void-filling epoxy resin (Fig. 1(f)). For the pyramidal-ceramic-epoxy hybrid sandwich core, the presence of ceramic insertions caused serious erosion and mass loss of the projectile, similar to that reported by Yungwirth et al. [24,25]. On top of this, the infiltrated void-filling epoxy resin adhered all the sub-structures as an integrated whole, which led to a larger region of energy absorption by ceramic fracture. As a result, the ballistic resistance and energy absorption capability of sandwich plates with pyramidal-ceramic-epoxy hybrid cores were appreciably improved relative to those without ceramic inserted or epoxy infiltrated, as shown in Table 1 and Fig. 5.

Based upon the previous experimental and numerical work, Ni et al. [27,28] numerically studied the normal and oblique projectile impact performance of single and double-layered pyramidal-ceramic–epoxy hybrid sandwich cores, and found that the angle of obliquity affected significantly the ballistic trajectory and erosion of the projectile. The proposed double-layer sandwich plates outperformed both the single-layer sandwich plates and the homogeneous (monolithic) metallic plates having equal total mass, with the top layer (the ceramic insertions in particular) of the double-layer configuration playing a more dominant role in energy absorption.

2.2. Hybrid corrugated metallic sandwich plates

From Yungwirth's ballistic experiments [23], it was found that identical lattice structures made from a 6061T6 aluminum alloy performed better than the stainless steel, due to the higher value of strength to density ratio σ_Y/ρ of the aluminum. Subsequently, Wadley et al. [29] fabricated corrugated sandwich panels from a 6061-T6 aluminum alloy by an extrusion-based method, and found experimentally that the empty corrugated sandwich plates exhibited slightly inferior ballistic resistance to that of monolithic plates with equal mass, which was similar to that of 3D pyramidal truss lattice-cored sandwich plates. However, inserting ceramic prisms into the interstices of the 2D corrugated core (Fig. 3(a)), with epoxy adhesive bonding the ceramic to the interior metal walls, greatly improved the ballistic response, even surpassing that of a solid plate with slightly larger mass [29,31], as shown in Fig. 2.

As a continuous study, O'Masta et al. [30] repeated the experiment with a ceramic-corrugation hybrid core encased in a cross-ply ultrahigh molecular weight polyethylene (UHMWPE) fiber (which is one of the highest specific strength materials commercially available [32]) reinforced laminate (named Dyneema® laminate); the fabrication sequence of the test structure is shown in Fig. 3(b). As shown in Fig. 2, the encased hybrid sandwich possesses the best ballistic resistance with a ballistic limit at least 100% higher than that of an equal areal density, similarly encapsulated aluminum plate target (which is even superior to the un-encased hybrid sandwich plate in ballistic resistance). Fragmenting, spatially/temporally dispersing the momentum of the impact, and pre-accelerating the rear Dyneema® laminate prior to debris impact combined to suppress local fiber failure and greatly increased the penetration resistance of the self-gripping, Dyneema® encased hybrid sandwich construction. Especially, pre-acceleration of the rear laminate by bulging of the rear face of the intervening panel reduced the debris impact velocity upon the rear laminate by at least 40%, thus reducing the incident pressure upon the laminate and probability of local penetration.

Alternatively, Xia et al. [33] and Ni et al. [34] developed a novel hybrid steel corrugated sandwich plate with steel fiber-reinforced

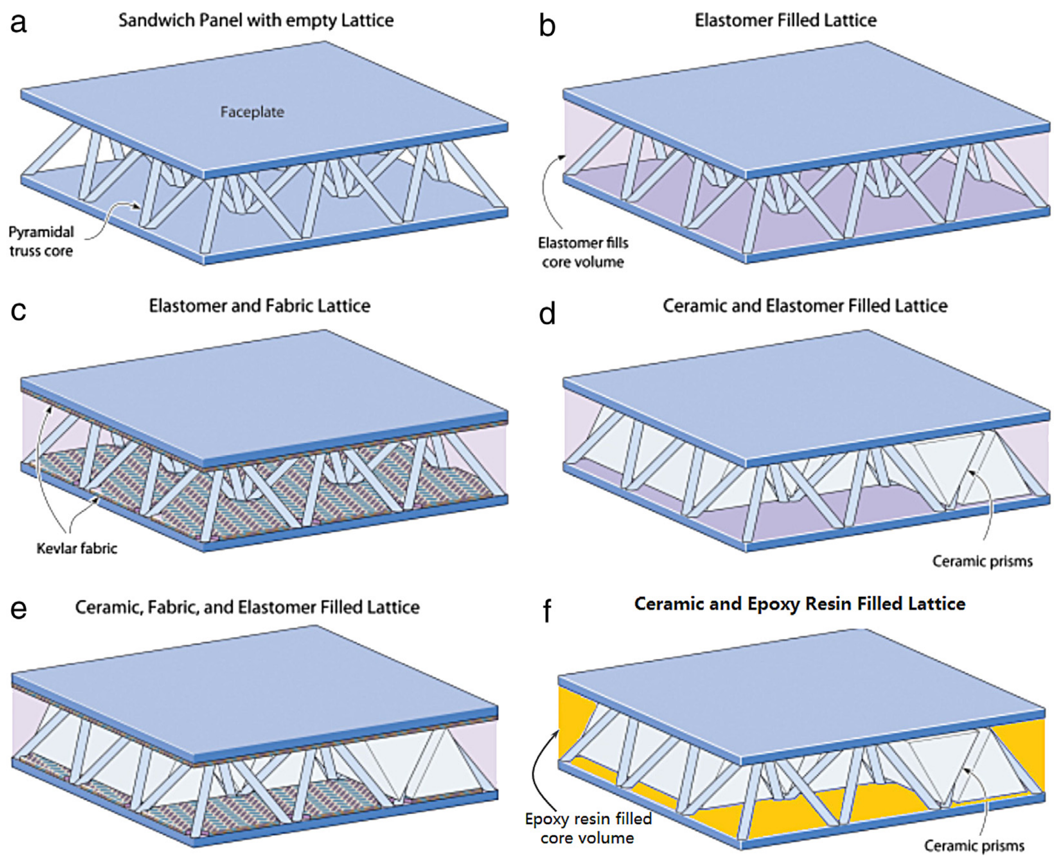


Fig. 1. (a) Empty pyramidal lattice core sandwich panel. Five hybrid variants of (a): polymer-filled lattice panel (b); hybrid polymer-filled lattice panel (c); ceramic-filled lattice panel (d); hybrid ceramic-filled lattice panel (e); and ceramic and epoxy resin filled lattice panel (f).
Source: Redrawn from Yungwirth et al. [25], and Ni et al. [26].

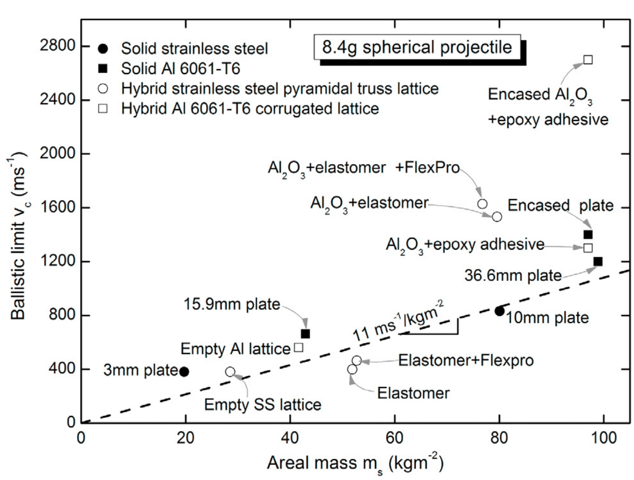


Fig. 2. A summary of ballistic limit for hybrid pyramidal truss-cored and corrugated sandwich plates, and monolithic plates (made of either 304 stainless-steel or Al 6061 T6) that span the areal density range of hybrid-cored sandwich plates.
Source: Redrawn from Yungwirth et al. [24,25], Wadley et al. [29], and O'Masta et al. [30].

high performance reactive power concrete (RPC) prism insertions and void-filling epoxy resin for ballistic application. Experimental measurements and numerical simulations revealed that plastic deformation and shear-off failure of the metallic plates as well as cracking and fracture of the RPC prisms combined to absorb the kinetic energy of the projectile (Fig. 4). As shown in Fig. 5, compared with monolithic RPC plate (Fig. 4(a)) and corrugation-RPC hybrid sandwich plate (Fig. 4(b)), the corrugation-RPC-epoxy hybrid sandwich plate (Fig. 4(c)) achieved the best ballistic performance with only a moderate increase in areal density, this was because filling the interstices with epoxy resin improved the structural integrity of the sandwich while confinement of the RPC was supplied by the corrugated plates. In contrast, the weak interface confinement between metallic panels (including face sheet and corrugated panel) and concrete was the main reason for the inferior ballistic performance of sandwich plates directly filled with RPC prisms (Fig. 4(d)–(f)). However, the ballistic performance of the corrugation-RPC-epoxy sandwich was inferior to that of the pyramidal-ceramic-epoxy sandwich (Fig. 5) for two main reasons. Firstly, the ceramic (AD 98 alumina) used by Ni et al. [26] has a compressive strength (∼4 GPa) much higher than that of the RPC (∼175 MPa). Secondly, the ceramic insertions in the pyramidal-ceramic-epoxy plate experience 3D network confinement supplied by the pyramidal trusses relative to the 2D confinement of RPC insertions by corrugated plates.

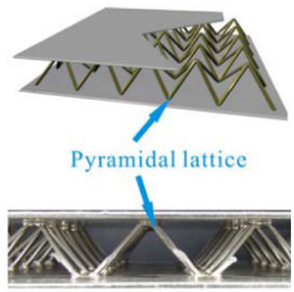
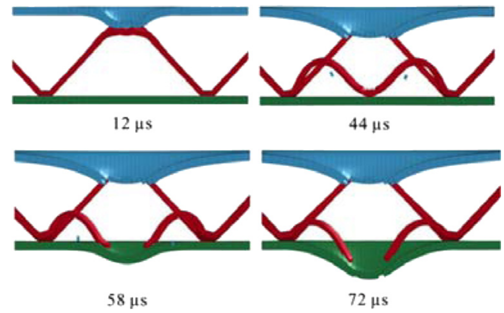
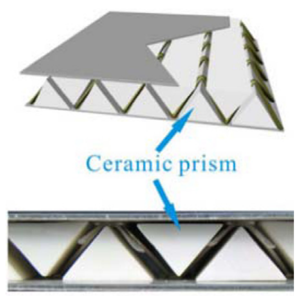
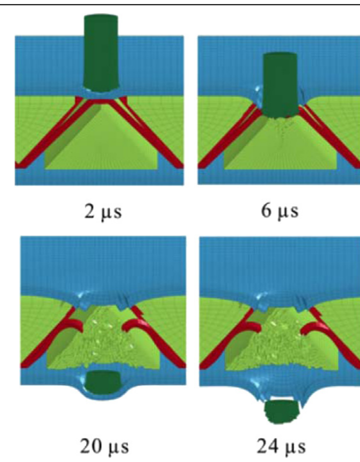
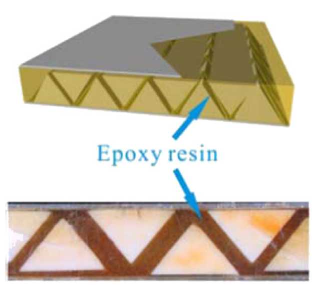
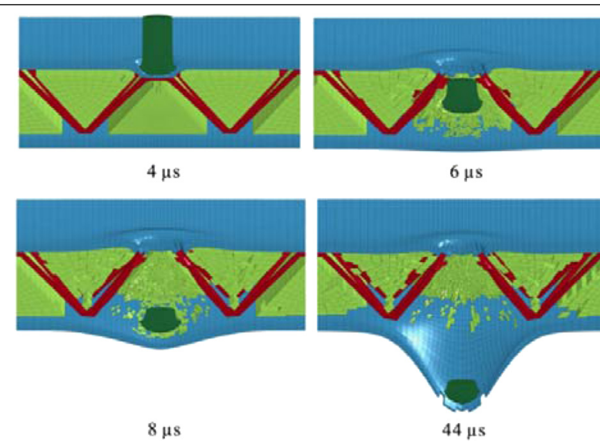
3. Foam-filled sandwiches with lattice cores for simultaneous load carrying and energy absorption

In recent years, there was a growing interest in exploiting stochastic foams as a filling material to enhance, simultaneously, the load-bearing and energy absorption capabilities of traditional lightweight structures, such as hollow tubes and sandwich plates having flow-through, periodic lattice cores (e.g., 2D corrugations, honeycombs, and 3D pyramidal trusses).

3.1. Foam-filled corrugations

By inserting polymeric foams (Divinycell) into the interstices of metallic sandwich panels with corrugated cores, Vaziri et al. [35]

Table 1
Deformation evolution and failure of three different sandwich plates during the penetration process of hemisphereical projectile.
Source: Redrawn from Ni et al. [26].

Sandwich plate	Evolution of deformation and failure
	
	
	

found rather limited enhancement in compressive strength and impact resistance, which was attributed to the insufficient lateral support provided by the somewhat weak filling foam to metallic core members against buckling. Through hybridization of glass and carbon fibers as well as foam filling, Zhang et al. [36] attempted to improve the bending strength and energy absorption of corrugated sandwich composite structures. Due to better support of core webs by the filling foam, the peak load was increased, delaying debonding of the core and face sheets, and thus core failure. However, the improvement in crashworthiness was not significant as the foam used was relatively weak (low density).

Instead of polymeric foams, Yan et al. [37] and Han et al. [38] inserted closed-cell aluminum foams into the interstices of corrugated sandwich panels made of stainless steel (Fig. 6(a)). They demonstrated, both theoretically and experimentally, that the out-of-plane compressive strength and energy absorption of the hybrid-cored sandwich were much greater than the sum of those of an empty corrugated sandwich panel and the aluminum foam alone (Fig. 7(a)). This was because foam filling stabilized buckling and reduced the amount of post-buckling softening, leading to synergistic benefits in strength and energy absorption. Moreover, different from the traditional buckling modes of empty corrugations, four new buckling modes were identified for foam-filled corrugations, as shown in Fig. 7(b). Similar enhancement effect and deformation modes were also found in the out-of-plane compressive behaviors of aluminum foam-filled diamond lattice sandwich cores (Fig. 6(b)–(c)) [39].

Besides out-of-plane uniform compression, Yan et al. [40] investigated experimentally the transverse three-point bending (i.e., bending plane normal to corrugation axis) performance of aluminum foam-filled metallic corrugated sandwich beams. While the filling of aluminum foam led to dramatically increased bending stiffness and strength of the sandwich, its mass also increased considerably. To explore whether the filling of a corrugated core

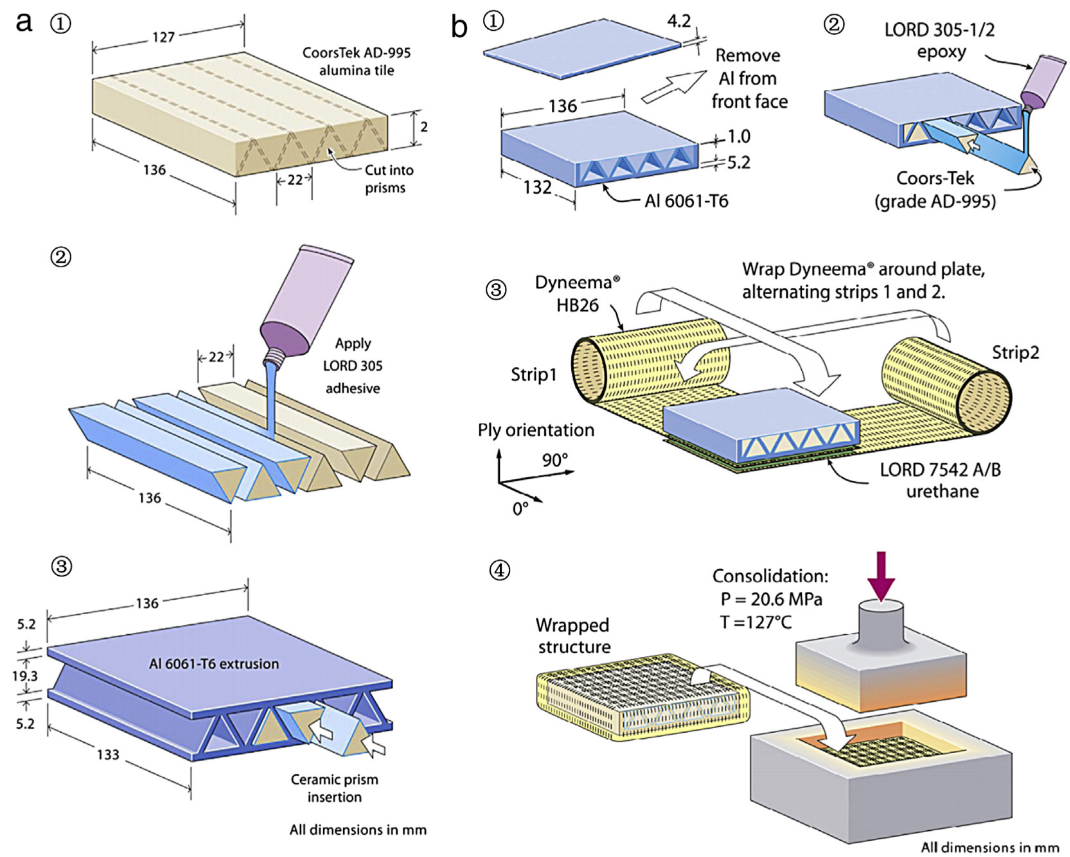


Fig. 3. The fabrication sequence for making (a) ceramic-corrugation hybrid-cored sandwich panel and (b) Dyneema® encased ceramic-corrugation hybrid-cored sandwich panel.
Source: Redrawn from Wadley et al. [29] and O'Masta et al. [30].

with metal foams would lead to a larger failure load than that of an empty core with equal mass, Han et al. [41] carried out a combined analytical and numerical study of the structural stiffness, collapse strength and minimum mass optimization of foam-filled metallic corrugated sandwich beams under transverse three-point bending. On the basis of equal mass, the structural efficiency of metallic corrugated sandwiches filled with aluminum foams was found to be inferior to that of the empty ones, while those filled with polymer foams (Rohacell) were structurally more efficient than the empty ones especially at relatively low load levels. The enhancement was attributed to the increased buckling resistance of face sheets and corrugated members due to lateral support of the polymer foam matrix. The final structural efficiency was a trade-off between mass addition and enhanced buckling resistance of constituent members, both attributed to foam filling. As shown in Fig. 7(c), for buckling failures (i.e. elastic buckling of corrugated panel or elastic wrinkling of face sheet), a larger structural efficiency was achieved with a denser foam due to larger strengthening effect of buckling resistance. For material yielding failures (i.e. yielding of corrugated panel or face sheet), the structural efficiency decreased with increasing foam density, as no further strengthening was gained by increasing the foam density.

The poor transverse shear strength [11] of corrugated sandwich core could also be radically improved by filling a proper polymer foam [42], which even surpassed the best known cellular sandwich cores such as square honeycombs [16] and hollow pyramidal lattices [43]. Again, the enhancement was attributed to the support of foam matrix against strut buckling, especially at relatively low load levels.

3.2. Foam-filled hollow pyramidal lattices

Cellular materials with hollow pyramidal (HP) lattice truss topologies exhibited higher compressive and shear strengths than equivalent structures with solid trusses due to their greater resistance to elastic or plastic buckling, resulting from their higher radius of gyration [43,45,46]. The structural performance and energy absorption of stainless steel hollow pyramidal lattice trusses significantly exceeded those of competing lattice, prismatic and honeycomb topologies.

Inspired by the concept of foam filling, Han et al. [47] inserted PMI polymer foams into the interior interstice of HP truss tubes to create foam-filled hollow pyramidal (FHP) lattice, and measured its quasi-static out-of-plane compressive behavior, as shown in Fig. 8(a). The foam-filled hybrid structure possessed much greater peak strength and energy absorption than the sum of the HP structure and sole PMI foam, with the foam insertion stabilizing the multi-lobe diamond buckling and post-buckling of hollow tube (Fig. 8(b)). Compared with competing cellular materials, FHP appeared to be the best structural topology in terms of both compressive strength and energy absorption, as shown in Fig. 9.

3.3. Other foam-filled lattice materials

Other studies have also revealed performance benefits associated with foam filling.

The structural performance of a hierarchical all-composite corrugated sandwich core filled with PMI-foam (Rohacell) was investigated analytically and experimentally by Kazemahvazi et al. [50,51]. It was found that the weight specific strength of a well-designed hierarchical structure could be 7 times higher than

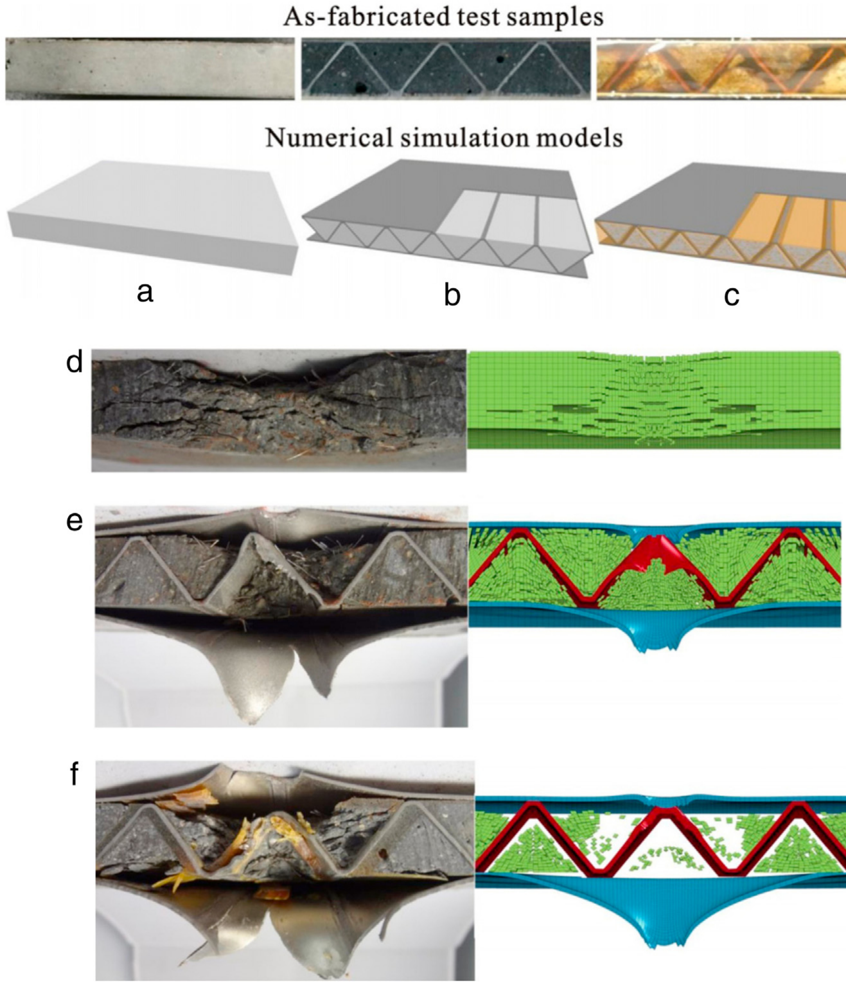


Fig. 4. Comparison between numerical (finite element) model and as-fabricated test sample for protective application: (a) monolithic RPC plate, (b) corrugated metallic sandwich plates directly filled with RPC, and (c) corrugated metallic sandwich plates with RPC prism insertions and void-filling epoxy resin. (d)–(f) successively display the experimental observed and numerically predicted local damage of each target plate (cross-sectional view at plate center) after projectile penetration.
Source: Redraw from Xia et al. [33] and Ni et al. [34].

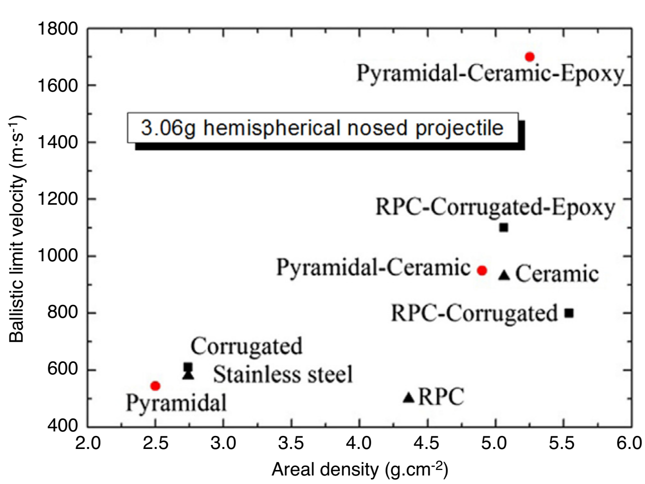


Fig. 5. Ballistic limit velocity plotted as a function of areal density: comparison among pyramidal-ceramic sandwich plates, corrugated-RPC sandwich plates, and solid plates made of either stainless steel or ceramic.
Source: Redrawn from Ni et al. [26,34].

that of its monolithic counterpart. The enhancement in strength was attributed mainly to the increased buckling resistance of hierarchical core members due to foam support, especially for core configurations with low overall density.

For sandwich plates with foam-filled aluminum hexagonal honeycomb cores subjected to uniform out-of-plane compression [52–55], foam filling increased both the mean crushing strength and energy absorption due to increased number and regularity of folds of honeycomb cell walls. Foam filling could also reduce the local modes of vibrations and stiffen the honeycomb structure, increasing particularly its overall flexural rigidity.

Yoo et al. [56] tested foam-filled composite egg-box sandwich panels under compression and found that this construction showed good energy absorption capacity with stable collapse response. Further, filling with low density foams led to the best energy absorption performance. Li et al. [57] investigated an integrated orthogrid stiffened syntactic foam core with both low velocity impact tests and compression after impact (CAI) tests. The integrated core exhibited enhanced impact energy absorption and positive composite action with higher CAI strength.

Recently, Ostos et al. [58] inserted polyurethane foams with submillimeter pores into the centimeter-scale interstices of low-density polymer lattices and assessed the concept in terms of quasistatic compressive response. It was demonstrated that the filling of even a weak foam could double the crushing strength of the lattice, as the lateral support of foam caused a transition from bend-dominated to stretch-dominated behavior in the lattice trusses [59].

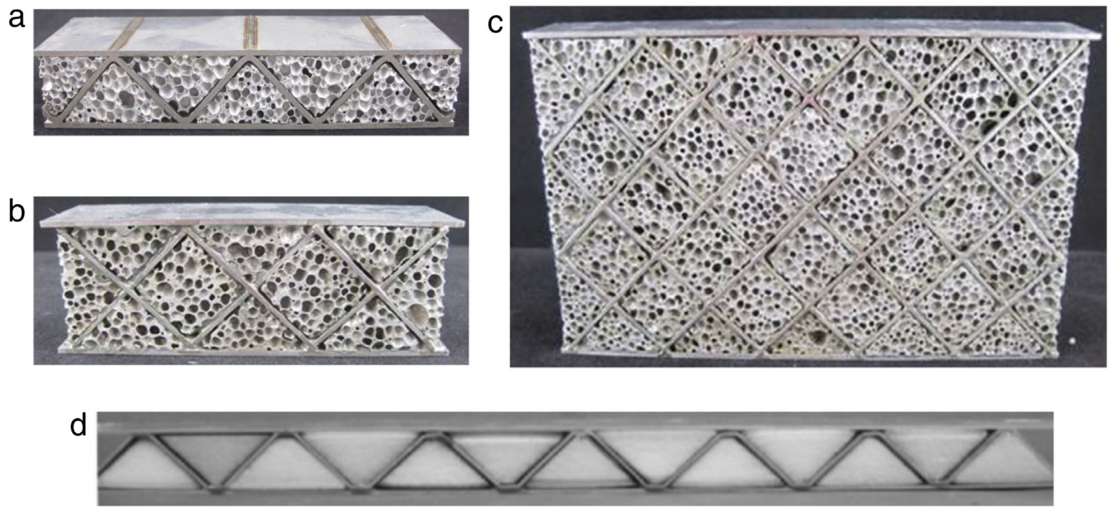


Fig. 6. (a) Aluminum foam-filled corrugated sandwich, (b) aluminum foam-filled single-layer diamond-cored sandwich; (c) aluminum foam-filled multi-layer diamond-cored sandwich; (d) polymer foam-filled corrugated sandwich.
Source: Redrawn from Yan et al. [37] and Han et al. [39,44].

4. Honeycomb-corrugation hybrid-cored sandwiches for simultaneous load carrying, energy absorption and low-frequency sound absorption

4.1. Honeycomb-corrugation hybrid-cored sandwiches

Built upon the concept of foam filling, Han et al. [48,49] proposed to fill the interstices of aluminum corrugations with precision-cut trapezoidal aluminum honeycomb blocks to construct a novel hybrid sandwich core, as shown in Fig. 10(a). The compressive and shear strengths as well as energy absorption of the sandwich were all dramatically enhanced, compared to those of a sandwich with either empty corrugation or honeycomb core (Fig. 10(b)–(c)). The enhancement was induced by the beneficial interaction effects of honeycomb blocks and folded panels on improved buckling resistance as well as altered crushing modes at large plastic deformation. The mutual deformation constraints of corrugation and honeycomb stabilized the corrugated panels and honeycomb cell walls against elastic buckling, and hence greatly increased the critical stresses of both constituent components. In addition, complex deformation mechanisms at large compressive strains, *e.g.*, compression-induced plastic deformation including twisted folding of honeycomb cell walls, rotation of multi-plastic hinges on corrugated plate, and their interaction in region II of Fig. 10(b), contributed to the enhanced energy absorption, in contrast to that of the conventional progressive folding of honeycomb cell walls (region I of Fig. 10(b)) [60,61]; for transverse shear (Fig. 10(c)), multi-plastic hinges formed in the initially compressed corrugated member, and the multiple shear bands approximately uniformly distributed in a much wider region of honeycomb blocks (rather than a quite localized and narrow region for the individual honeycomb), caused the hybrid core to dissipate much more plastic deformation energy in shear. The proposed approach provided an effective method to further improve the mechanical properties of conventional honeycomb-cored sandwich constructions with low relative densities.

4.2. Perforated honeycomb-corrugation hybrid-cored sandwiches

Introducing small perforations with submillimeter diameters to both top face sheet and corrugated panel of a honeycomb-corrugation lattice-cored sandwich did not affect much its mechanical performance but led to a new class of subwavelength acoustic metamaterial, named perforated honeycomb-corrugation hybrid-core sandwich (PHBC; Fig. 11(a)–(b)) [62]. Inspired by the acoustic theory of micro-perforated panel [63], the design of this novel topology brought in series of different acoustic Helmholtz resonators comprised of narrow perforations and the cavity behind, with viscous energy dissipation at perforation regions dominating the total energy consumed in the propagating process of a plane acoustic wave normally incident on top face sheet. As illustrated in Fig. 11(c), the unit cell of PHCH composed of six sections can be visualized as a combination of series of Helmholtz resonators, including one typical single-layer micro-perforated panel (SLMPP) and five simplified double-layer micro-perforated panels (DLMPPs). It is implied from Fig. 11(c) that thermal dissipation distributed mainly on the inner wall surfaces in PHCH is almost negligible, accounting for only 0.04% of total energy dissipation; while the viscous dissipation due to the friction between the air and the inner wall of perforation concentrates mainly in narrow regions and contributes most of the total energy dissipation, especially when the frequency of sound approaches the resonant frequency. Compared with either honeycomb-cored or honeycomb-corrugation hybrid-cored sandwiches with only top perforated face sheet, PHBC gained superior broadband sound absorption in low-and-intermediate frequency range, as shown in Fig. 11(d). With extraordinary low-frequency sound absorption, excellent stiffness/strength and impact energy absorption, the proposed new acoustic metamaterial shows promising multifunctional applications.

5. Conclusions

By inserting various materials into the interstices of lattice cores, hybrid lattice-cored sandwiches could be created to satisfy multifunctional requirements, e.g., ceramic/concrete-filled lattices for enhanced ballistic resistance, foam-filled lattices for simultaneously enhanced strength and energy absorption, and honeycomb-corrugation hybrid cores for simultaneously enhanced strength, energy absorption and low frequency sound absorption. Relevant enhancement mechanisms were summarized as follows:

1. For enhanced ballistic resistance, the plastic deformation and shear-off failure of metallic plates as well as cracking and fracture of inserted ceramic/RPC prisms combined to

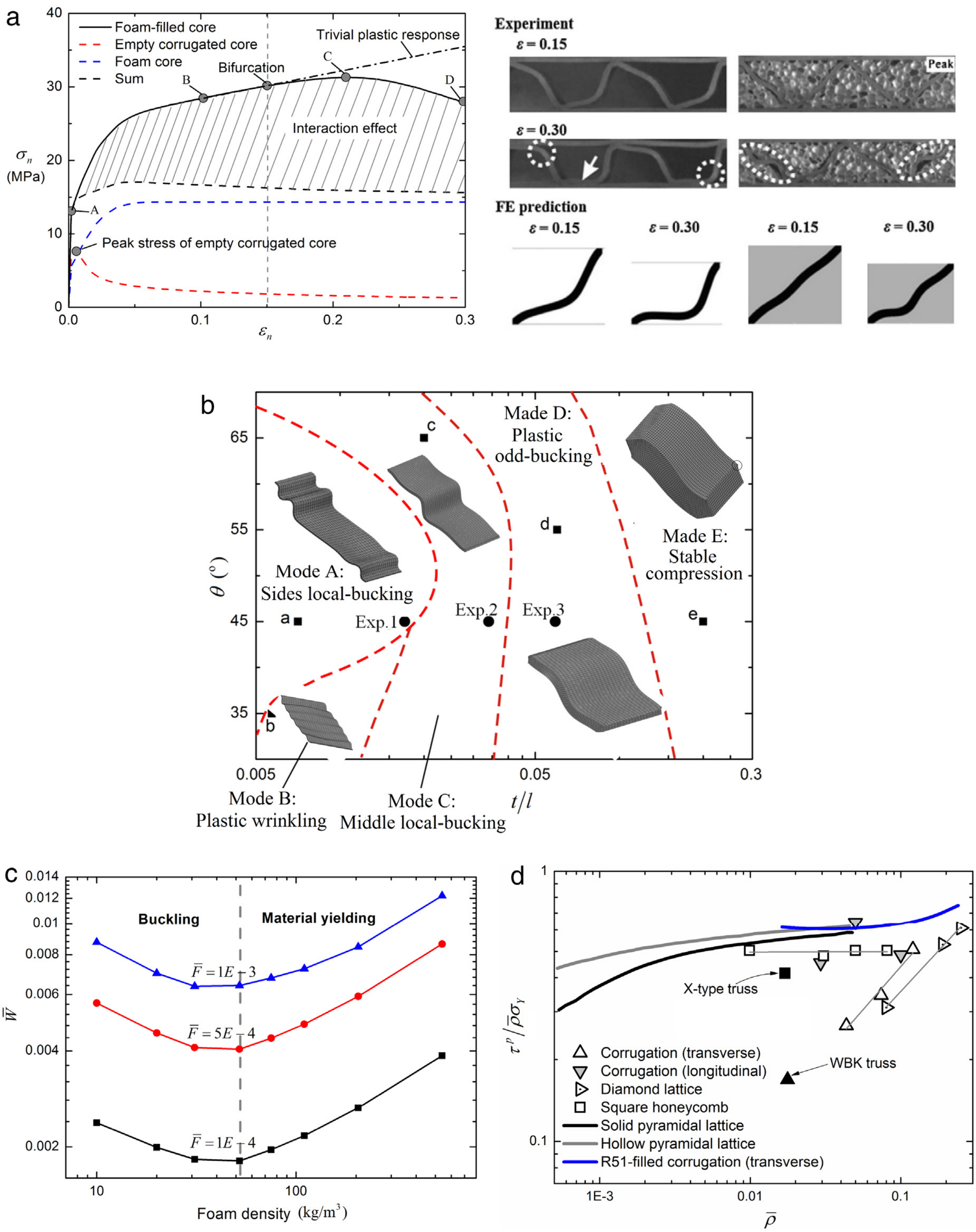


Fig. 7. (a) Out-of-plane compressive behavior and (b) collapse mechanism map for foam-filled corrugated sandwich core; (c) optimal minimum mass of foam-filled corrugated sandwich beams plotted as a function of foam density for three specific bending structural loads; (d) comparison of shear strength of polymer foam-filled corrugation with other cellular topologies.
Source: Redrawn from Yan et al. [37], and Han et al. [38,39,41,42].

absorb the kinetic energy of the penetrating projectile. In addition, the infiltrated void-filling epoxy resin adhered all the sub-structures as an integrated whole, resulting in a larger region of energy absorption by ceramic/RPC fracture. Further, Dyneema® laminate, which was used to encase the whole plate, contributed to reduce the debris impact velocity and the probability of local penetration, greatly increasing the penetration resistance. Therefore, Dyneema® encased metallic corrugated or pyramidal truss-cored sandwiches with ceramic insertions and void-filling epoxy resin would display quite fascinating ballistic resistance on the basis of equal mass.

2. Foam filling dramatically enhanced the (compressive) strength and energy absorption of lattice-cored sandwiches, which was attributed to the support of foam matrix against buckling and

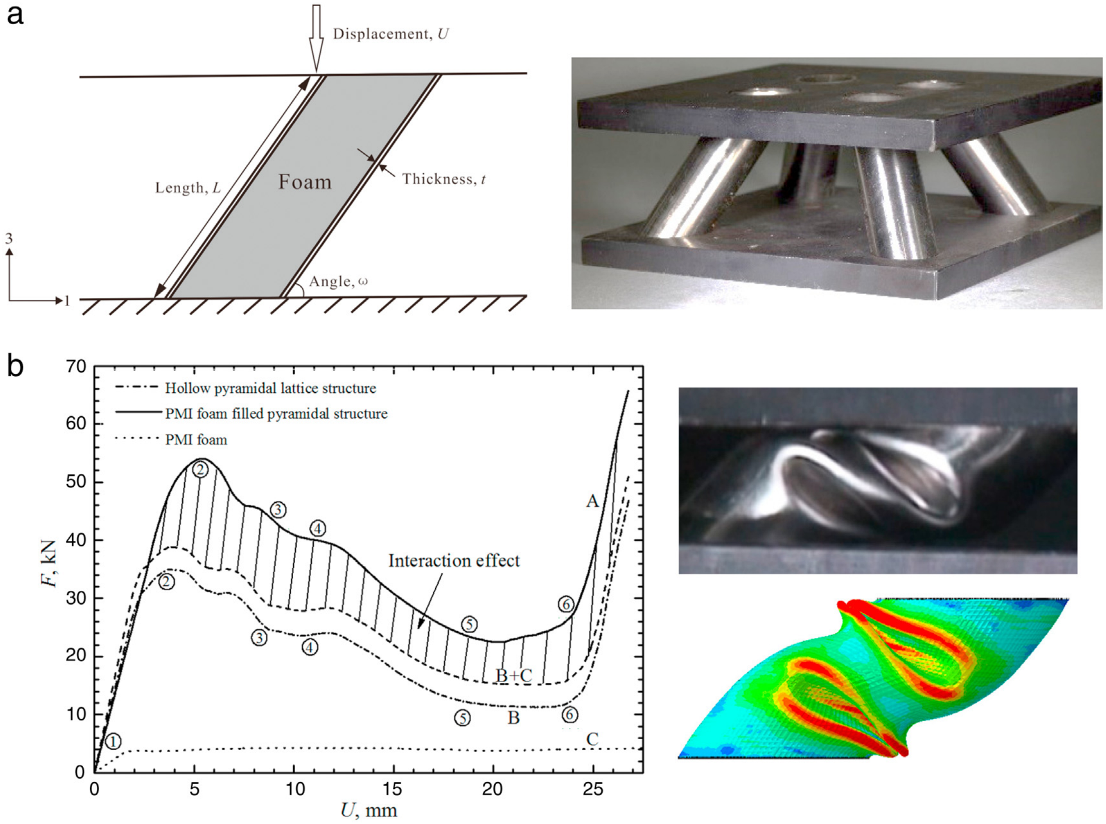


Fig. 8. (a) Schematic of foam-filled hollow pyramidal lattice; (b) experimentally measured compressive force–displacement curve of PMI foam-filled pyramidal lattice, with experimentally measured and numerically simulated deformation of the foam-filled core at $\varepsilon_n = 0.50$ displayed.
Source: Redrawn from Han et al. [47].

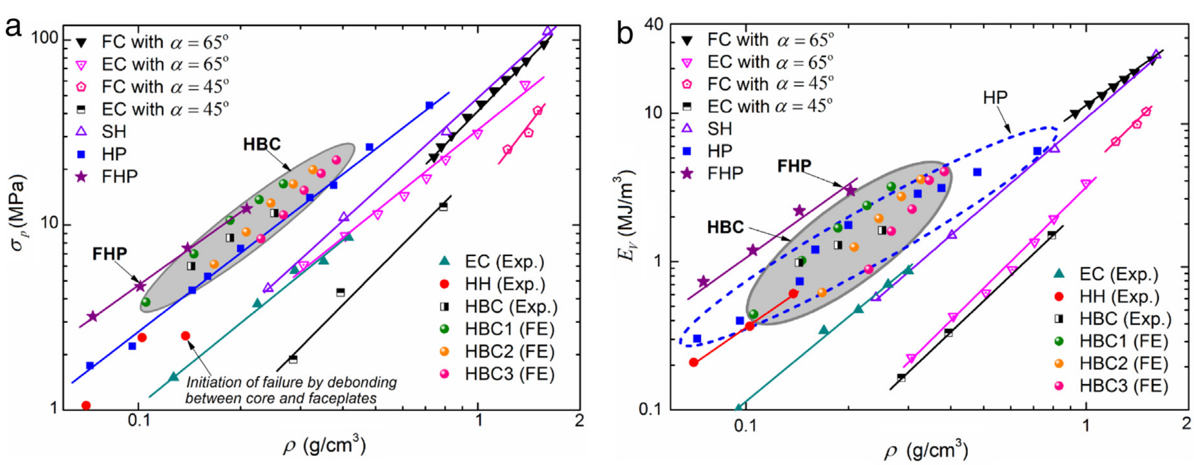


Fig. 9. (a) Compressive strength versus core density and (b) energy absorption per unit volume (up to $\varepsilon_n = 0.30$) plotted as a function of core density of various sandwich cores. HBC: honeycomb-corrugation hybrid; FC: foam-filled corrugation; EC: empty corrugation; SH: square honeycomb; HP: hollow pyramidal truss lattice; FHP: foam-filled hollow pyramidal truss lattice.
Source: Redrawn from Han et al. [47–49].

post-buckling softening of the panels, trusses or hollow tubes in the lattice core. However, due to different collapse modes of the lattice core, not every hybrid combination of the foam and lattice could lead to the beneficial enhancement. The best performance was usually achieved by filling the lattice core with a foam of matching density and/or material make.

3. By inserting honeycomb blocks into a corrugated sandwich core, both the compressive/shear strength and energy absorption could be greatly enhanced. This was mainly attributed to the beneficial interaction effects of honeycomb blocks and folded panels on buckling resistance as well as the altered crushing modes at large plastic deformation. With submillimeter perforations introduced to both top face sheet and corrugated panels, the honeycomb-corrugation sandwich became a novel multifunctional structure with extraordinary low-frequency sound absorption, excellent strength and impact energy absorption.

This paper only gave a brief summary of recent advances in representative hybrid lattice-cored sandwich constructions. New hybrid sandwich structures could be created to meet new requirements of multifunctionality. Moreover, through further

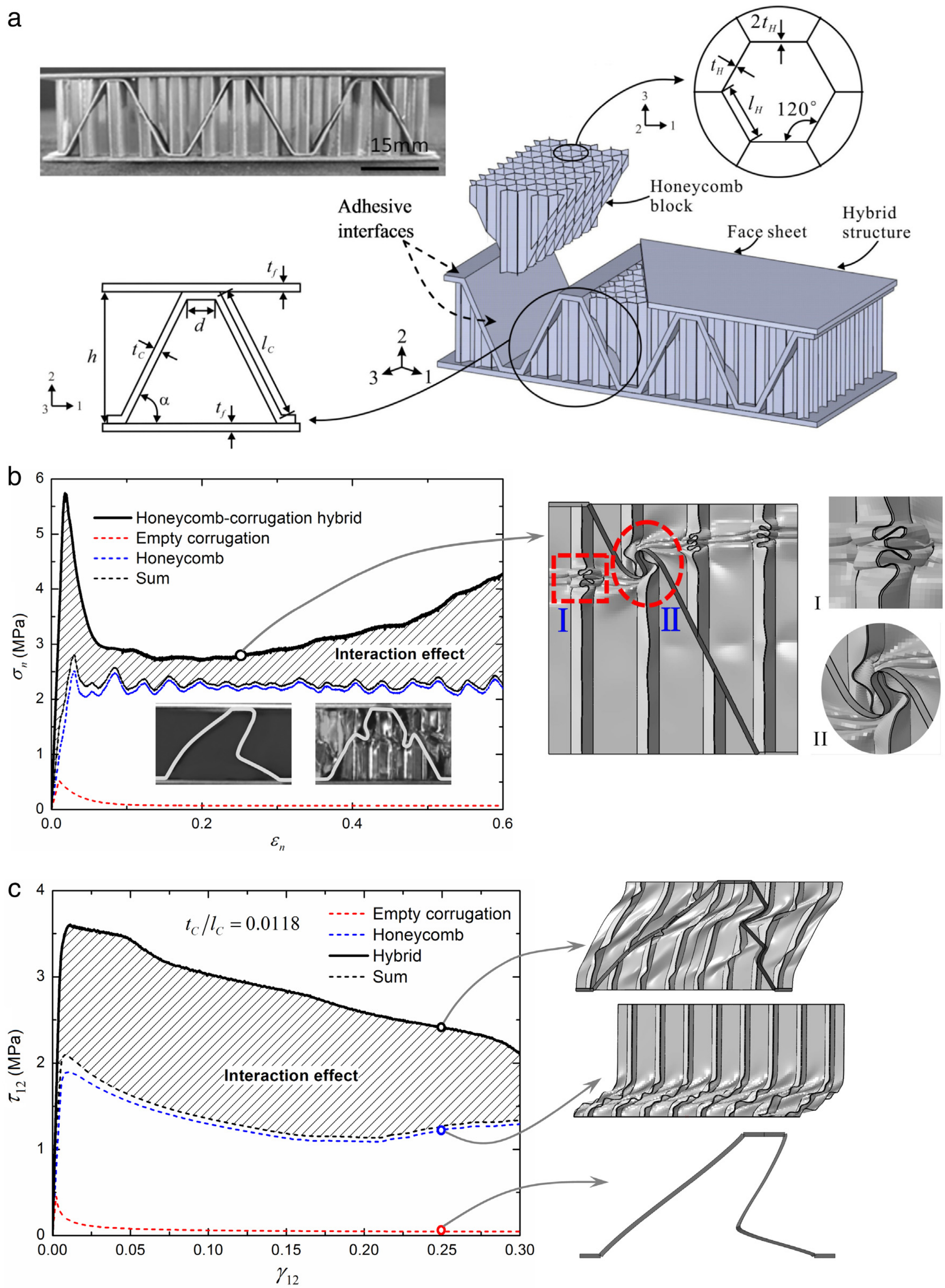


Fig. 10. (a) Schematic of honeycomb-corrugation hybrid sandwich; (b) experimentally measured compressive stress versus strain curves of honeycomb, empty corrugation, and honeycomb-corrugation sandwiches, with typical deformation images of empty corrugation and hybrid cores captured at $\varepsilon_n = 0.25$ included, and two different deformation mechanisms of the hybrid core presented; (c) comparison of the numerical results for honeycomb, empty corrugation, and honeycomb-corrugation hybrid sandwiches subjected to transverse shear, with shear deformations at shear strain of 0.25 for the three sandwich cores given.
Source: Redrawn from Han et al. [48,49].

collaborative optimization of lattice topology and component combination as well as multi-lattice sandwich plate layout, more efficient functionality and lightweight requirements may be achieved. Nonetheless, the potentially high fabrication costs of hybrid sandwich structures require more research efforts devoted to efficient mass manufacturing and cost deduction, e.g. developing in situ foaming technique to fabricate directly polymer or metallic foams in lattice cores.

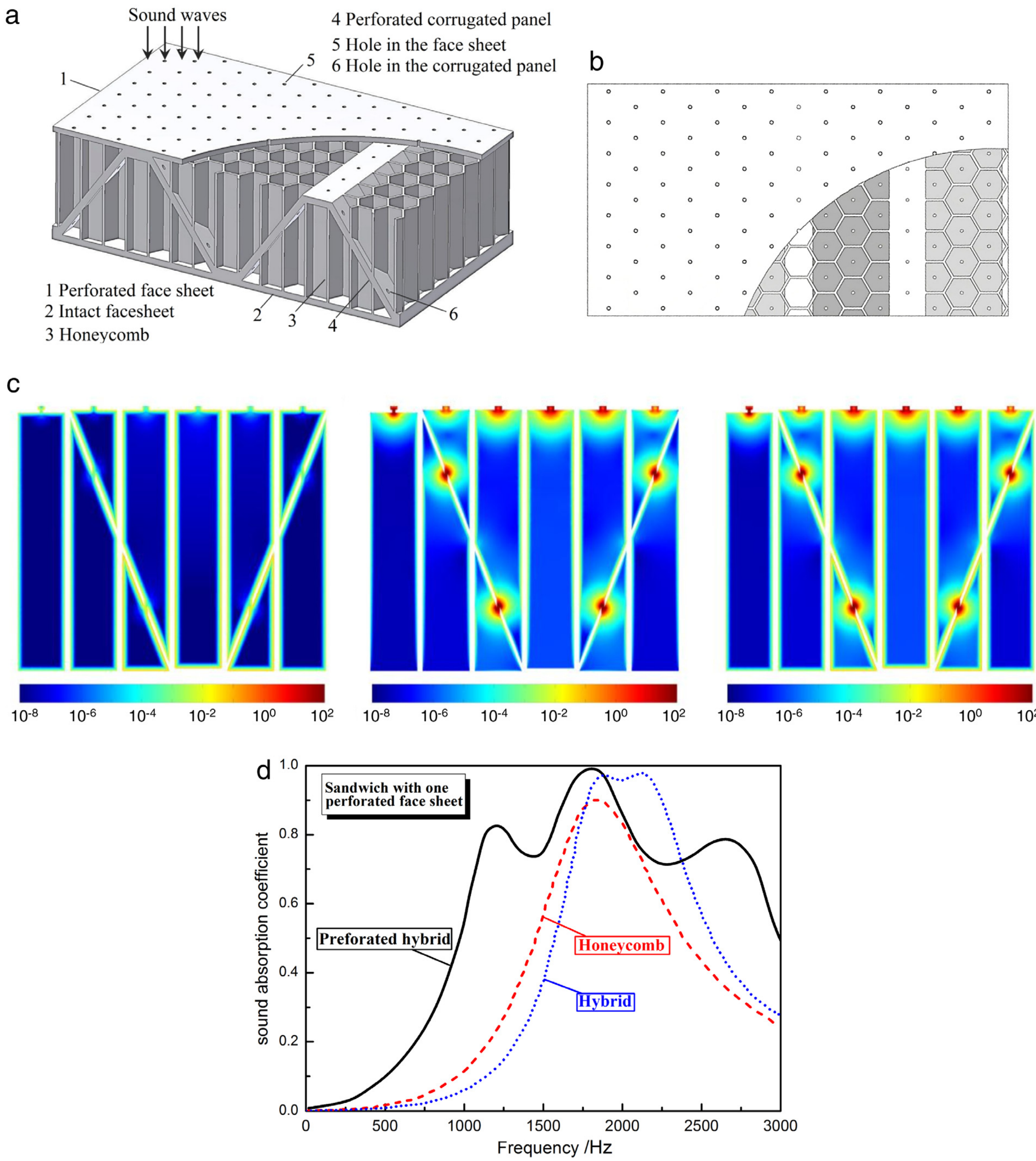


Fig. 11. (a) Schematic of perforated honeycomb-corrugation hybrid-cored sandwich (PHBC); (b) vertical view; (c) front views of the contour of acoustic energy dissipation (W/m^3) in one unit cell of the typical PHBC at 1750 Hz for thermal energy dissipation (left), viscous energy dissipation (middle) and total viscous-thermal dissipation (right); (d) predicted sound absorption coefficient of PHBC compared with competing structures.
Source: Redrawn from Tang et al. [62].

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