Journal of Computational Applied Mechanics 2023, 54(4): 623-644

DOI: 10.22059/jcamech.2023.357536.821

REVIEW PAPER

A review on structural response and energy absorption of sandwich structures with 3D printed core

Masoud Babaie, Rouhollah Hosseini [*], Alireza Naddaf Oskouei

Mechanical Engineering Department, Engineering Faculty, Imam Hossein Comprehensive University, Tehran, Iran

Abstract

Sandwich structures are widely used in many industries such as marine& submarine, aerospace, automobiles and etc due to its lightweight nature, high bending stiffness, high fatigue resistance and ability to absorb energy. However, the investigations into sandwich structures with 3D printed core are limited in number. These structures can create a meta material behavior with the change of geometry which leads to negative poison ratio of core. Hence, in this article, investigations into sandwich structures with 3D printed core under various loading for comparing their structural responses have been reviewed in detail. Different shapes of 3D printed cores have been reviewed and their specifications are discussed.

Keywords: Sandwich structure; 3D printed core; Energy absorption; Structural response;

1. Introduction

Sandwich structures are widely used in many industries such as marine& submarine, aerospace, automobiles and etc. These structures are fabricated from two major part including face sheets and cores. The face sheets are located at the bottom and top of the core. The face sheets are usually stronger than core and protect the core from external forces and environmental condition such as temperature and humidity. In these structures the shapes, thickness and mechanical property of core plays an important role in behavior of them under static, dynamic loading. Therefore, a lot of investigations have been performed about the type of material, thickness and shapes of cores subjected to various loading. In most of researches, the shapes of sandwich structures are considered in cellular form and these structures are classified and named based on the shapes of core like honeycomb sandwich structures (See Fig.1). For instance, in honeycomb sandwich structure, the core is made of a lot of six side cells with equal length. These cells could be repeated in a certain or random pattern and can be created stochastic or with periodical cell structures, respectively (See Fig.1).

---

[*] Corresponding author. *E-mail address:* R.Hosseini.mech@gmail.com

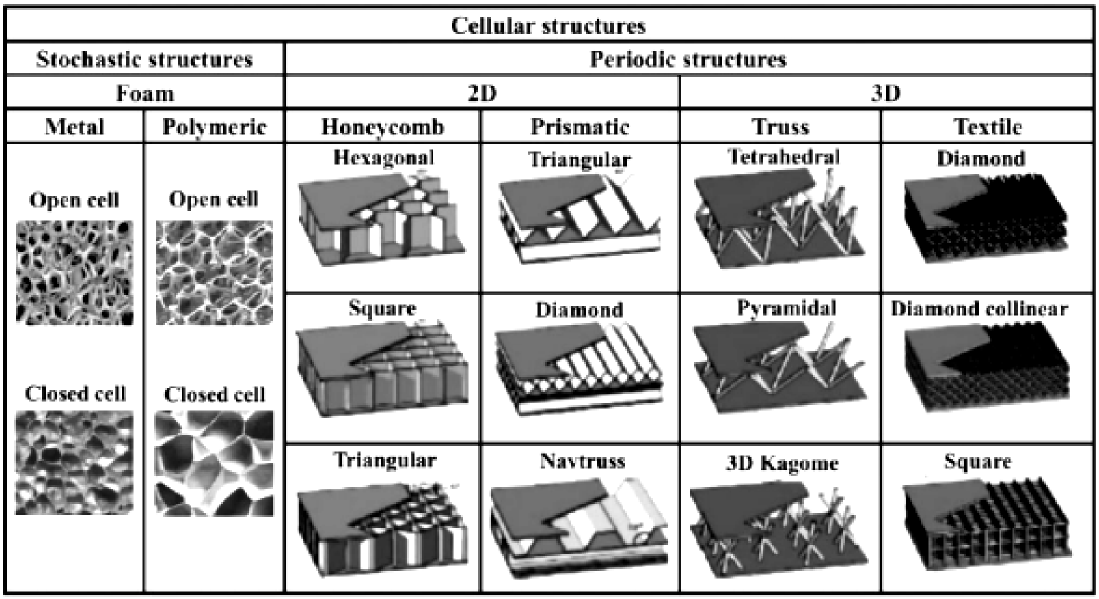


Figure 1: The most common various cellular shapes in sandwich structure

With the advancement of technology and appearance of 3D printers for fabricating of different parts, researches have studied the performances of sandwich structures with 3D printed core under various loading such as quasi static and dynamic loads to predict the response of these structures in practical application. Additive manufacturing is gaining popularity in both research and industrial applications. There are presently several commercially accessible additive manufacturing methods, with metal technology dominating what is utilized in industry [1]. The most often utilized filaments in 3D printing are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) [2]. The process of fabrication of sandwich structure is indicated in Fig 2. Many investigations have been made about structural performance of composite structures [3-9]. Among them researches into sandwich structures with 3D printed core is limited. This investigation help researches to know these structures are reliable and have sufficient performance to practical application or not due to the material of 3D printed core are plastics and polymers. Furthermore, they can create a metamaterial structure. These structures behave against the traditional structures which are available in nature and environment. This behavior could be from the constituent material of these structures or its geometry. On the other hand, metamaterial can be classified in two major group including materially and geometrically. For example, we can achieve the negative poison ratio with the change of geometry of core and can control the amount of poison ratio with topology optimization of core. The negative poison ratio, also known as auxetic materials or structures. In this article, these behaviors in sandwich structures with 3D printed core have been reviewed. In details, Li and Wang [10] accomplished numerical and experimental investigation about bending response of sandwich composite structures with tunable 3D-printed core materials. The type of core was from re-entrant honeycomb and the face sheets were made of carbon fiber reinforced polymer (Fig. 3). Acrylic-based photopolymer is considered for the constitutive material for the core structures. The numerical simulation is performed in ABAQUS software and plane stress is assumed for simulation. Therefore, the 6-node triangular elements are adopted for numerical modeling. Their results showed that truss, conventional honeycomb, and re-entrant honeycomb conventional honeycomb structures provide a non-auxetic behavior while the re-entrant honeycomb structure provides an auxetic behavior. Under bending, the re-entrant honeycomb sandwich structures showed an interesting global failure mode because of the relatively homogeneous stress distribution. Moreover, the re-entrant honeycomb sandwich structures exhibit sequential snap-through instabilities which significantly increase the energy absorption capacity. In contrast, the truss and conventional honeycomb sandwich structures showed catastrophic failure earlier due to the localized stress concentration.

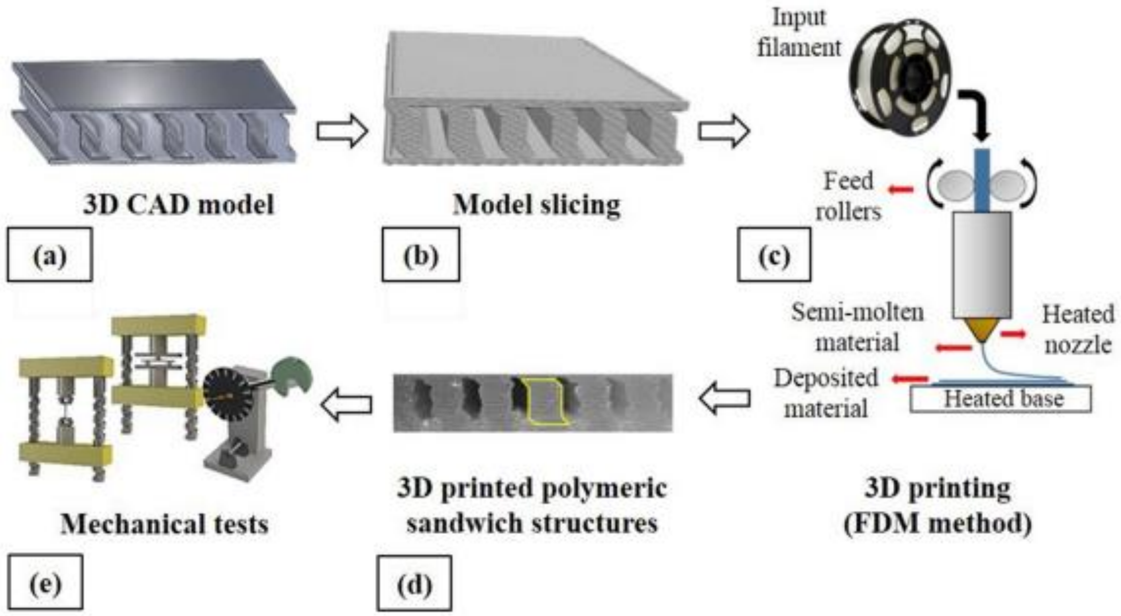


Figure 2: Development and mechanical characterization of the panels: (a) CAD model in STL format, (b) 3D printer-software interface, with model slicing and G-code file generation, (c) 3D printing using FDM method, (d) 3D-printed polymeric sandwich structures with cellular cores and (e) mechanical tests

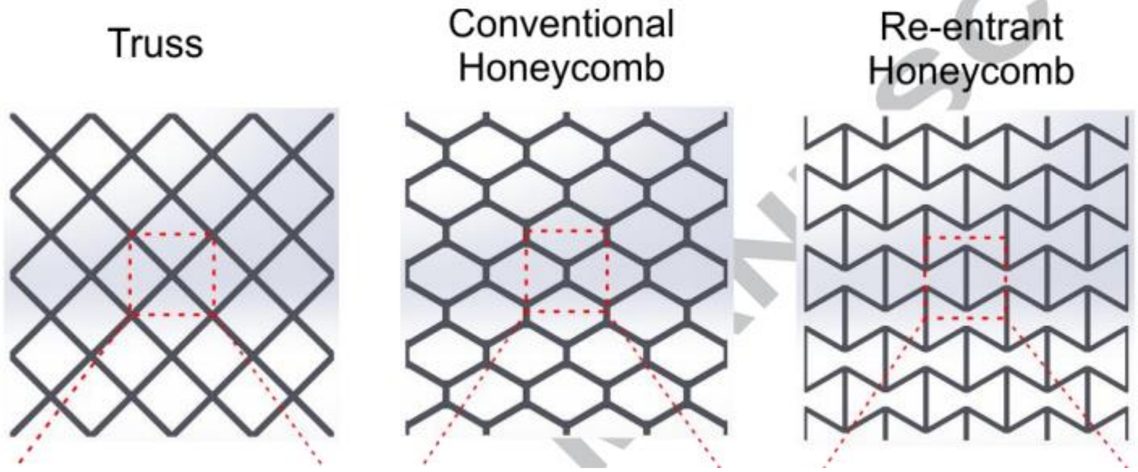


Figure 3: Different types of unit cell of the truss, conventional honeycomb, and re-entrant honeycomb [10].

Peng et al. [11] studied bending behavior of 3D printed sandwich beams with bioinspired cores numerically and experimentally. For numerical analysis, ABAQUS/Explicit with S4R element was applied. The shape of core was triply periodic minimal surface (TPMS) and three different patterns such as Primitive, Neovius and IWP were considered for the core of structure (Figure 4). Also, the materials of core and face sheets were from one material. On the other hand, the face sheets and core were integrally printed. By this way, the delamination between the face sheets and core are removed. Their results showed that the geometrical parameters and the relative density of the core have a significant influence on their bending stiffness, maximum load and energy absorption capacity, while the core topology has limited effects on the bending stiffness but affects the maximum load and energy absorption remarkably. Also, the bending stiffness is similar for sandwich structures with different core topologies at a core density of 0.35, while the Neovius core can provide marginally higher strength. At a core density of 0.5, sandwich structures with a Neovius core have higher bending stiffness and strength than other core topologies. The dominant failure mechanism is found to be core shear, followed by bottom face-panel failure. In addition, with an increase in relative density of the TPMS core, the bending stiffness, strength, and energy absorption capacity of sandwich structures increase for designs with both thick and thin face-panels, while the core topology has limited effect on these properties for designs with thick face-panels. For sandwich structures with thin face-panels, higher bending strength and energy absorption capacity are observed for the Neovius core.

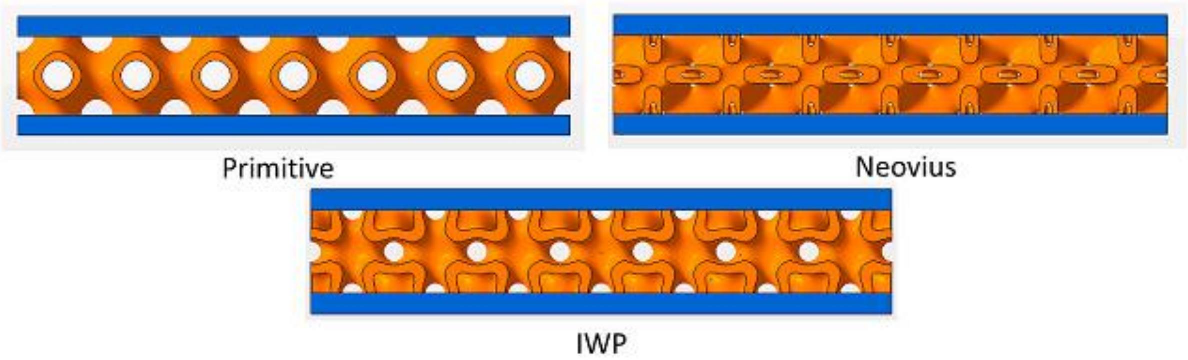
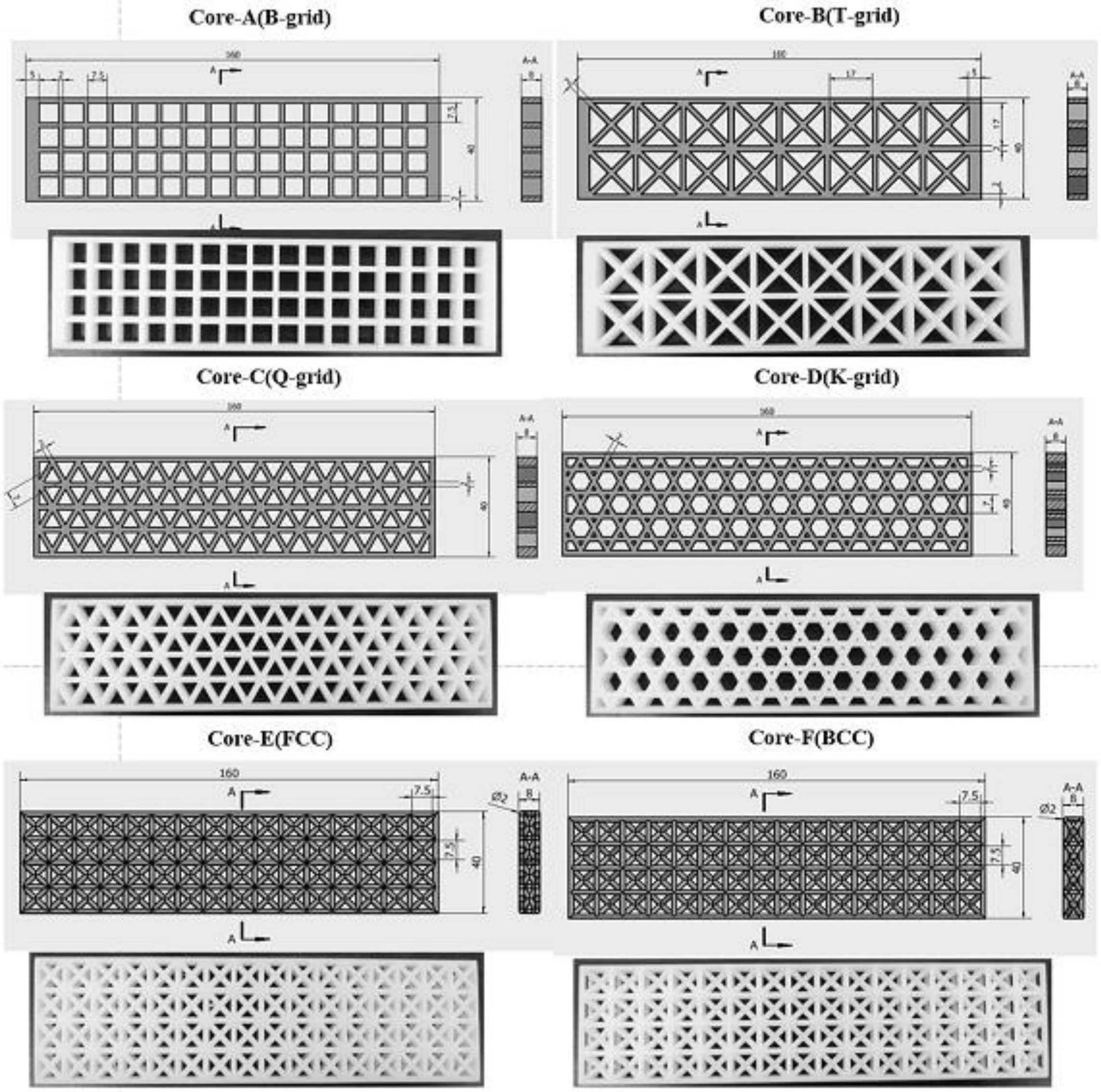


Figure 4: Sandwich structures based on Primitive, Neovius and IWP unit cells [11].

Experimental and numerical performances of metal-polymer sandwich structures with 3D-printed lattice cores subjected to bending load was presented by Liu et al. [12]. The face sheets were made of aluminum core with 2D (Bi-grid, Tri-grid, Quadri-grid and Kagome-grid) and 3D (face-centered cubic-like and body-centered cubic-like) topologies (Figure 5). The lattice cores were discretized using 8-node linear brick element with reduced integration (C3D8R) or 4-node linear tetrahedron element (C3D4) depending on the complexity of core geometry. Face sheets were modeled using a second-order 10-node modified tetrahedron element (C3D10M) with single-layer structure to avoid the stiff behavior induced by using a linear brick element and thus improve computation accuracy. In this case, the delamination was observed in the bottom layer of face sheet and core in experimental tests while the authors assumed the delamination will not be occurred in numerical analysis. Their results denote that in the elastic deformation region, sandwich structure with FCC lattice core has the best damage-tolerant capability followed by that with BCC lattice core, while sandwich structure with Q-grid lattice core has the worst damage-tolerant performance. Also, BCC lattice core and its sandwich structure have the largest defection corresponding to the maximum load, which illustrates that BCC lattice core and its sandwich structure have excellent load-bearing capacity. Furthermore, sandwich structure with BCC lattice core has the best level of energy absorption performance followed by the one with FCC lattice core.



Core-A(B-grid) **Core-B(T-grid)**

Core-C(Q-grid) **Core-D(K-grid)**

Core-E(FCC) **Core-F(BCC)**

Figure 5: Lattice core topologies [12].

Dong Goh et al. [13] employed experimental approach to investigate Quasi-static indentation and sound-absorbing properties of 3D printed sandwich core panels. Various sandwich core including (a) Double Ellipse Core, (b) Corrugated Triangle with Horizontal Beam Core, (c) Hybrid Honeycomb Core were supposed for this study (Figure 6). They found that the bidirectional face sheet layup exhibited the best indentation energy absorption recording 4.2 J, which is 37% more than the 45-degree layout and 66% more than the quasi-isotropic layup. The specific energy absorption of the hybrid honeycomb core is the best among the three core designs recording 404 J/kg, which is 56% higher than the corrugated triangle with horizontal beam core (359 J/kg) and 20% higher than double ellipse core (335 J/kg). It was found that the bidirectional layup exhibited a different failure mode as compared to the 45-degree and quasi-isotropic layup. In terms of the acoustic properties, the face sheets with various layup patterns have a low acoustic absorption coefficient with minimal differences from each other at low frequencies (500 Hz–3000 Hz) and have higher absorption coefficients with greater differences from each other at frequencies between 3000 Hz–6500 Hz. The hybrid honeycomb sandwich structure was the optimal structure among the three designs for balanced indentation resistance and acoustic insulation.

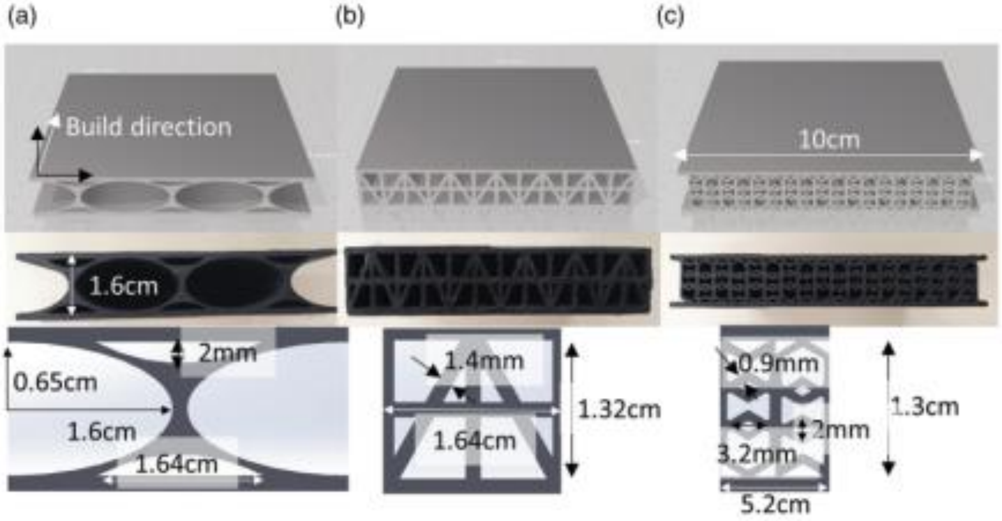


Figure 6: Various sandwich core designs with the dimensions. (a) Double Ellipse Core, (b) Corrugated Triangle with Horizontal Beam Core, (c) Hybrid Honeycomb Core [13].

Based on experimental and numerical methodology, bending behavior of 3D-printing plastic sandwich structure was presented by Lu et al. [14]. The face sheets and core were made of carbon-fiber/epoxy composite and PLA, respectively. The core was fabricated based on Bi-Grid, Tri-Grid, Quadri-Grid and Kagome-Grid honeycombs patterns (Figure 7). Numerical analysis was performed in ABAQUS software with S8R element. The authors observed an excellent agreement between numerical and experimental results. They showed that the bending capacity of the Quadri-Grid sandwich structure is the best, and the Tri-Grid sandwich structure has the lowest loading capacity. The failure behavior of the four structures is analyzed, and the results indicate that the failure modes of Bi-Grid sandwich structure is the interfacial de-bonding between the core and face sheet. While the failure modes of the Tri-Grid, Quadri-Grid and Kagome-Grid are core shear.

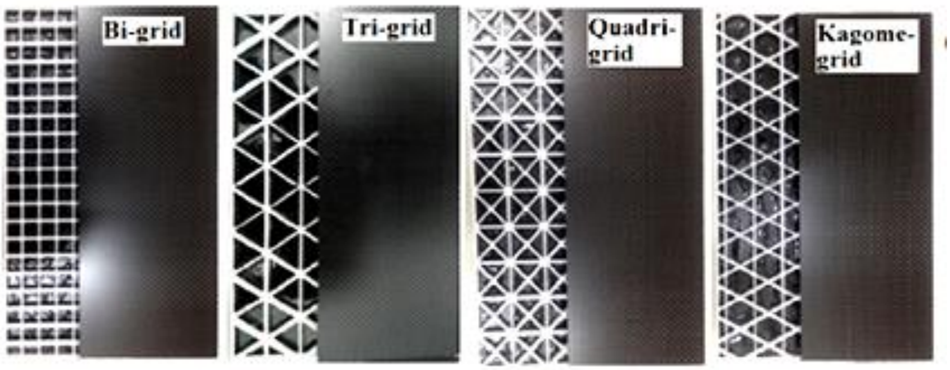


Figure 7: Lattice grid sandwich structures [14].

Ghanadpour *et al.* [15] investigated structural behavior of 3D-printed sandwich beams with strut-based lattice core by employing experimental and numerical solution. 10 various types of core were considered for this investigation (Figure 8). The bending and energy absorption behavior of these structured were studied. Bending/compressive models and pins meshed with nonlinear quadratic tetrahedral elements C3D10 (six degrees of freedom per node) and rigid element (R3D4), respectively. The constituent material of face sheets and core were exactly from one material. According to their experimental data, Star and Diamond topologies had maximum flexural and compression strength, as well as Grid and Re-entrant Honeycomb structures had minimum flexural and compression strength. Also, their results showed that some structures, such as Grid had a better response under compressive load while having the weakest response to three-point bending. Furthermore, the Octet-truss structure resisted much greater deflection. Their results indicated that Star and Diamond structures have higher stiffness and they are the best choice in the sandwiches under compressive and bending.

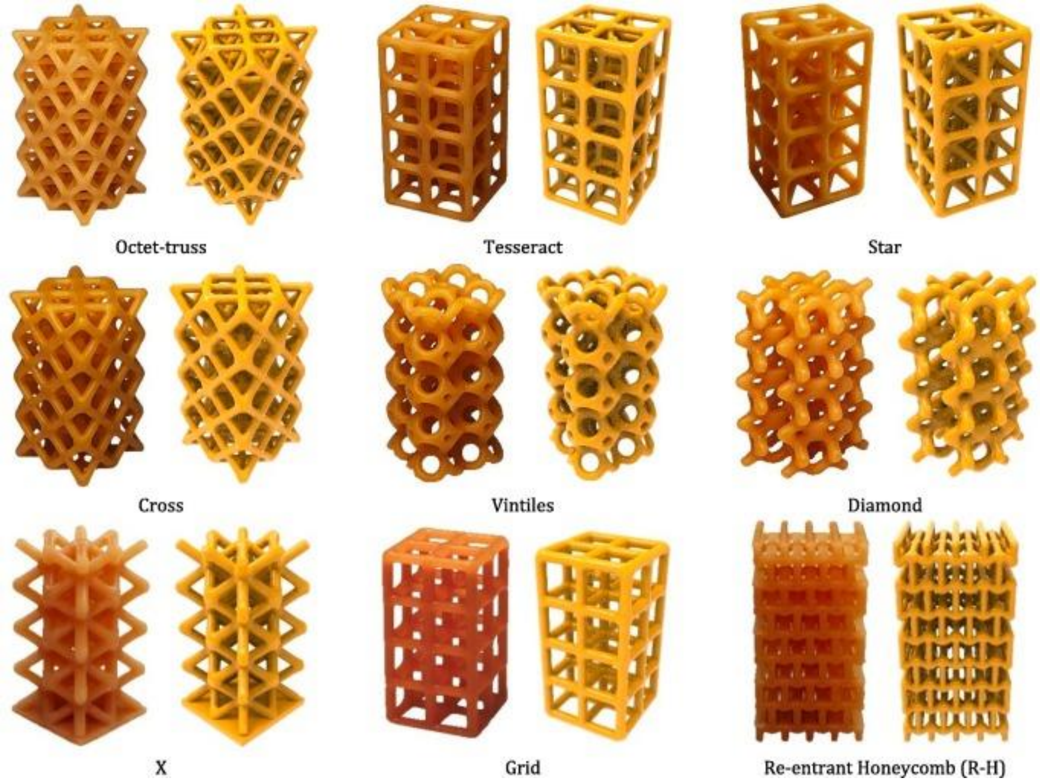


Figure 8: Various types of core [15].

Türkoğlu *et al*. [16] examined a research about experimental investigation of 3D-printed auxetic core sandwich structures under quasi-static and dynamic compression and. bending loads. Four different patterns were assumed for the core like sinusoidal corrugated, honeycomb, Double arrowhead and tetrachiral (Figure 9). They found that except for the re-entrant (RE) type core, the auxetic core foam sandwich structures demonstrate higher rigidity and load-carrying capacity than classical sinusoidal corrugated (SC) core and honeycomb (HC) core sandwich structures under both quasi-static and impact-loaded compression and three-point bending experiments. Double arrowhead (DAH) and tetrachiral (TC) auxetic cores outperformed honeycomb core in terms of specific quasi-static and impact load-bearing performance under compression by 1.5 ± 0.25 times. In three-point bending experiments under both quasi-static and impact loading conditions, the load-carrying capacity of the double arrowhead and tetrachiral auxetic cores was found to be more than 1,86 ± 0.38 times that of the honeycomb core sandwich panels.

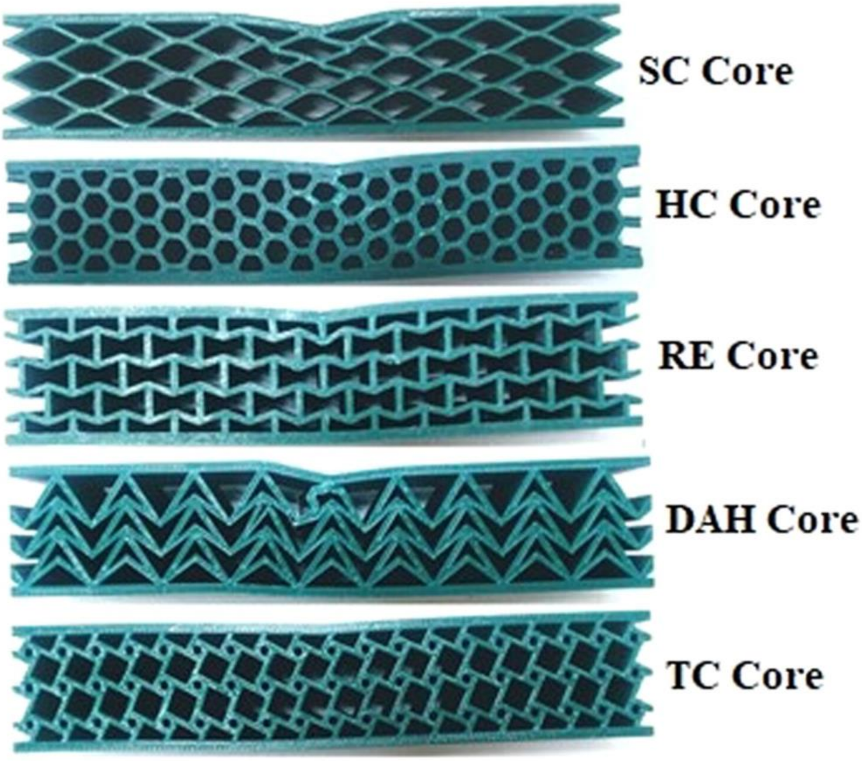


Figure 9: Different pattern of core [16].

In the basis of experimental and numerical methods, the bending behavior of hybrid sandwich composite structures containing 3D printed PLA lattice cores and magnesium alloy face sheets were presented by Zhou et al. [17]. An explicit finite element analysis using ABAQUS/Explicit with a self-written VUMAT user subroutine was conducted. Four different patterns (Figure 10) for core were assumed such as body-centered cubic (BCC), BCC with gradient distribution of struts (BCCG), BCC with vertical struts connecting all nodes (BCCV), and face and body centered cubic unit cell with vertical struts (F2BCCZ). The authors figured out the bending resistance of the hybrid PLA core/Mg alloy composite sandwich panel is better than that of the integrated PLA sandwich panel.

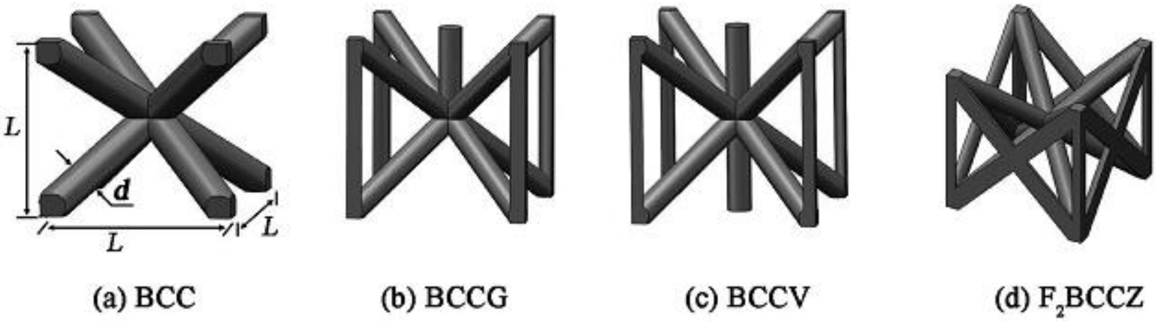


Figure 10: Body-centered cubic and its derived lattice cells [17].

Choudhry *et al.* [18] analyzed the bending behavior of 3D printed modified auxetic sandwich structures experimentally and numerically. The core made of modified re-entrant, conventional re- entrant, rotated modified reentrant and rotated conventional re-entrant (Figure 11). Linear hex-dominated 8- node bricked (C38DR) elements have been used for meshing the structure in ABAQUS software. It was found that the structures with modified re-entrant core outperformed with greater energy absorption due to its flat pleatue area under the force–displacement curve with highest displacement (among all cases) before the failure, while the rotated version of the conventional re-entrant structure showed the maximum load-bearing capacity.

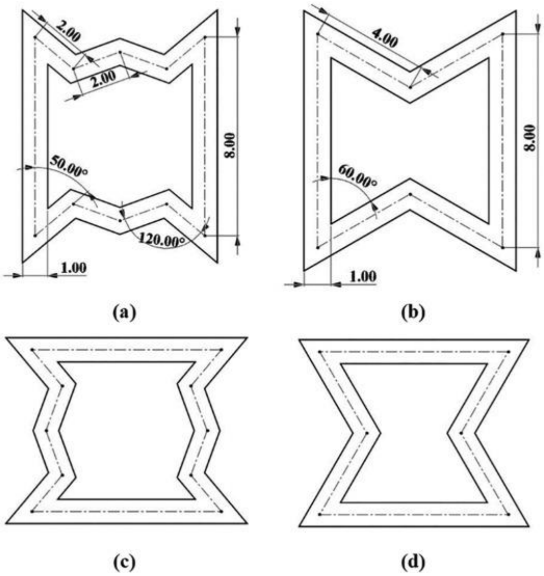


Figure 11: Various types of cells [18].

Ali and Batai [19] performed an experimental investigation about the bending response of sandwich composite structures of 3D-printed materials. The type of core was honeycomb pattern and the honeycomb core was made of polylactic acid and the face sheets were built of ABS. According to their experimental results based on Von-Mises stress distribution and deformation rule under the bending loads, a sandwich structure with honeycomb core indicates better mechanical performances in terms of deformation and stress than the bending loads for the same weight. Gunasegeran and Sudhagar [20] applied the numerical and experimental procedure to study natural frequencies and forced vibration analysis of 3D printed bioinspired sandwich beam using HSDT. Four different patterns were assumed for the core such as: SBIM01 to BIM04 (Figure 12).

Their results indicated that among various bioinspired composite sandwich beam configurations, BIM02 produces the highest stiffness, followed by BIM01, BIM04, and BIM03 because of the strain energy distribution.

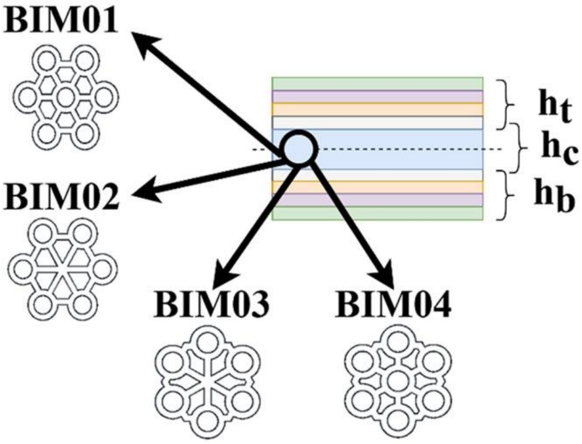


Figure 12: Four different patterns for the core [20].

Hou *et al.* [21] employed an experimental methodology to investigate the low velocity impact of sandwich composites with 3D-printed auxetic and non-auxetic lattice cores. Three different core topologies including diamond lattice including (truss), conventional honeycomb (hexagon) and re-entrant honeycomb (re-entrant) were assumed in this investigation. The faces sheets were made of carbon fiber reinforced composite (CFRP) and core was made of PLA. Their results showed that for sustaining impact load, the re-entrant core folds cell walls, producing interlaced pattern globally, whereas both truss and hexagon buckle core ligaments, yielding localized hinge-rotation and snap-through phenomenon, respectively. This interlaced pattern is not good at absorbing energy compared with the other two but grants the re-entrant structure superior robustness and durability. Therefore, the re-entrant panel shows both low peak reaction force and high energy loss coefficient, provided that the impact energy is appropriate. However, as the energy increases, fully densified re-entrant core shall bend with two face sheets and raises the reaction force drastically. It not only lowers energy dissipation, but also yields large deflection and hence ruptures the face sheet earlier. Nevertheless, the robust re-entrant design stabilizes the penetration occurrence regardless of the impact energy, making the panel performance more predictable. Furthermore, the re-entrant core remains intact and performs remarkably consistent under cyclic impact. In contrast, both truss and honeycomb panel show progressively damaged core structures due to the stress concentration, which perturbs the peak force value and degrades the energy loss coefficient significantly. Aside from that, the durable core structure also brings the re-entrant panel better performance after penetration occurs while other two designs scatter immediately when the front face sheet ruptures.

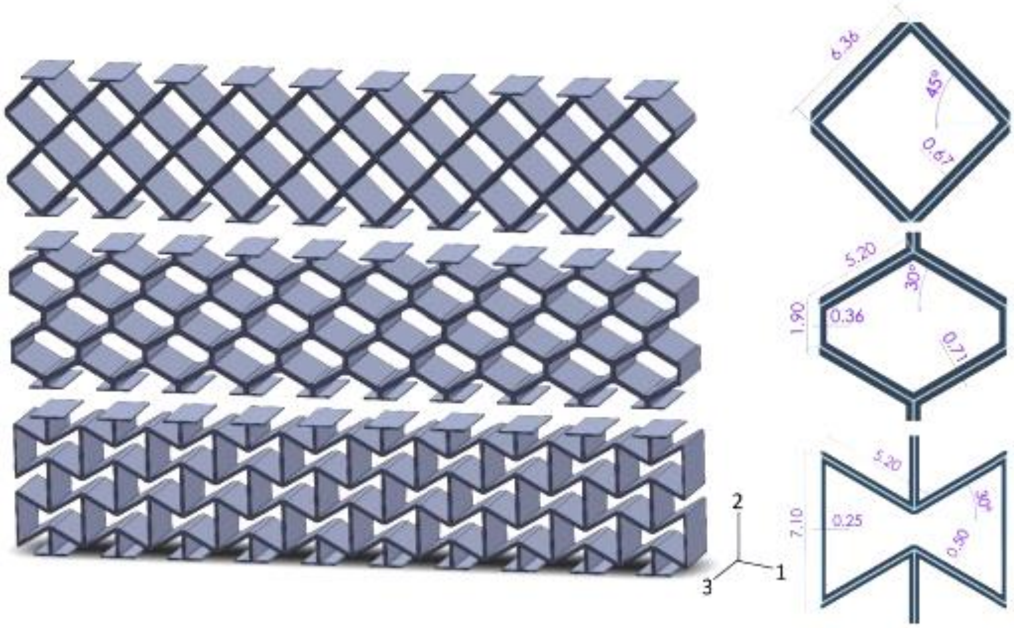


Figure 13: Designed sandwich core and unit cell for diamond lattice (truss), conventional honeycomb (hexagon) and re-entrant honeycomb (re-entrant) [21].

Hedayati *et al.* [22] surveyed the bending behavior and energy absorption of sandwich structures with repairable cores based on truncated cube cells numerically, experimentally and analytically. Linear hexahedron (C3D8R) elements were employed for discretizing both the upper and lowermost plates, and linear tetrahedron C3D4 elements were used for the unit cell. The material of face sheets was made of Aluminum and core was made of PLA. Results indicated that bulk material Poisson's ratio has an insignificant impact (less than 1.5%) on the relative stiffness, yield stress, and Poisson's ratio of a truncated cube structure. Seven sandwich panels with identical aluminum face sheets but with different cores (three core types (Figure 14) consisted of unit cells with uniform strut radii and four core types consisted of graded unit cells) were considered as application cases of the truncated cube unit cells. The functionally graded sandwich panel presented the best performance while considering both energy absorption capacity and mass. Functionally graded sandwich panels (Type 4) increased specific energy absorption by almost 21% and decreased the maximum displacement by 2.5% with respect to the second-ranking best option.

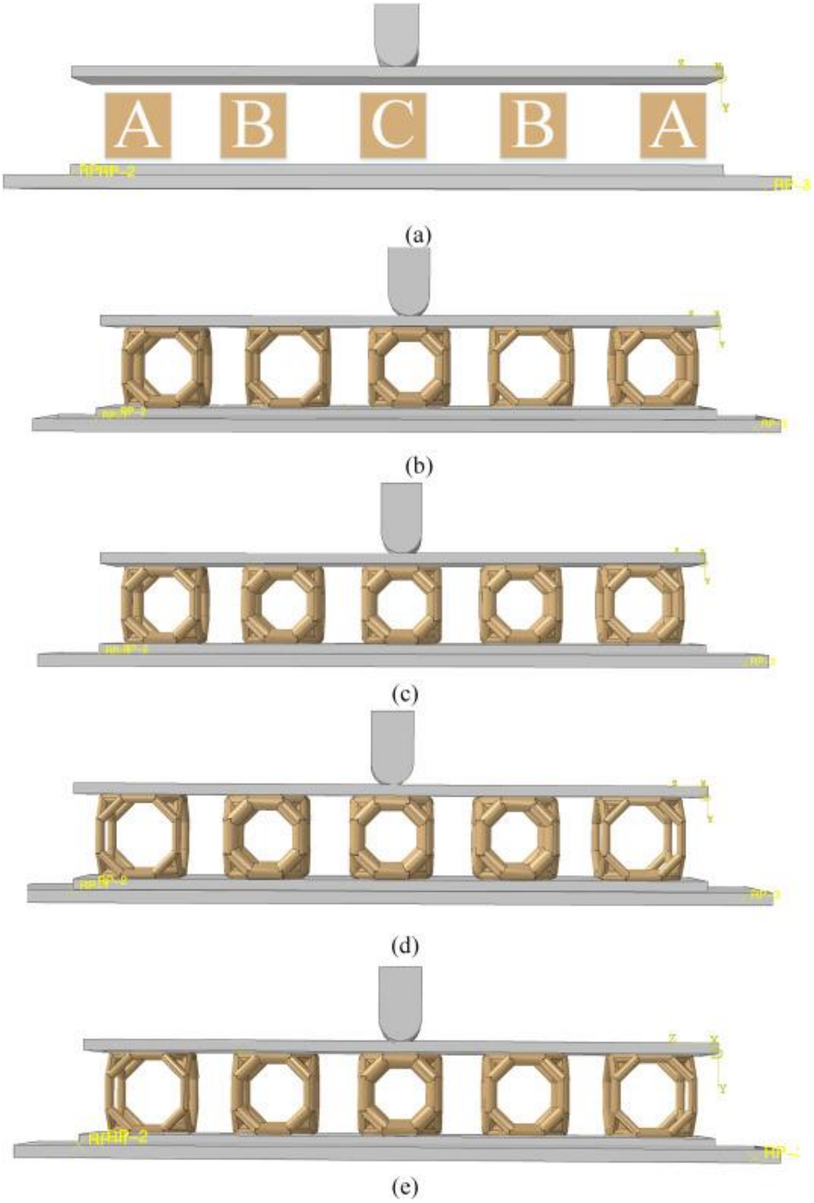


Figure 14: Definition of different positions in the sandwich panel. Different types of sandwich structures studied: (b) Type 1, (c) Type 2, (d) Type 3, and (e) Type 4 [22].

Indreș *et al.* [23] studied bending behavior of 3D printed sandwich beams with different core topologies. Various different patterns (Figure 15) including conventional honeycomb, re-entrant auxetic honeycomb with two positions of the cells, and chiral were assumed. The sandwich beams were manufactured from polylactic acid polymer for both face sheets and core. Three-point bending testing of the sandwich beams revealed that the honeycomb core had the stiffest behavior and can withstand the maximum force. Chiral core topology follows in this respect. As relative density increased the response of the honeycomb beam was more brittle and the lower part ruptured completely. The chiral core had lower strength than the honeycomb as ligaments failed successively. These two topologies are good candidates for various applications where high stiffness is required. Sandwich beams with a re-entrant auxetic core are more compliant and show a surprisingly good recovery. Thus these types of sandwich structures have a strong potential of reusable abilities. When relative density was higher, and re-entrant cell positioned at 90 degrees, the specific absorbed energy was 38.5% greater than for the honeycomb core. This core topology is expected to be promising for low velocity impact applications.

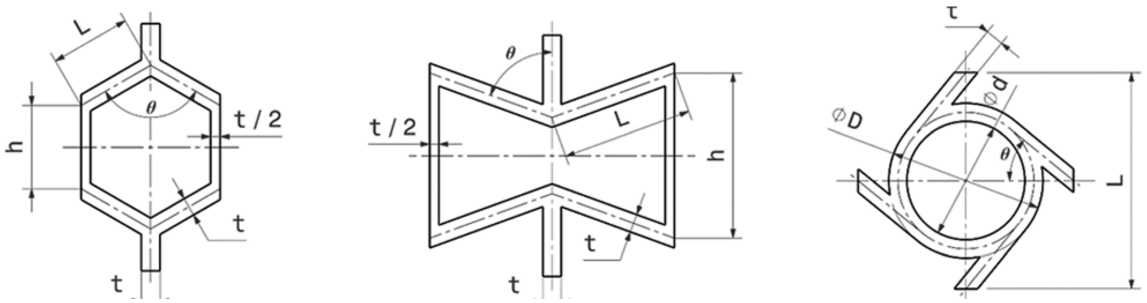


Figure 15: Honeycomb cell, re-entrant cell, and tetra-chiral cell [23].

Experimental, theoretical and numerical investigation on the buckling loads of 3D printed sandwich structure with lattice core was presented by Cao *et al*. [24]. Two different patterns (Figure 16) including body centered cubic (BCC) and rhombic dodecahedron (DOD) were considered for the core. The face sheets and core were integrally printed from PLA. Their comparative results show that DOD lattice sandwich panel not only has higher bearing capacity, but also shows stronger toughness in the post-buckling stage than BCC type panel, even they have the same characteristic size. The buckling mode depends on the topology of the unit cell. For BCC and DOD type panels, the main buckling modes are local buckling and global buckling respectively.

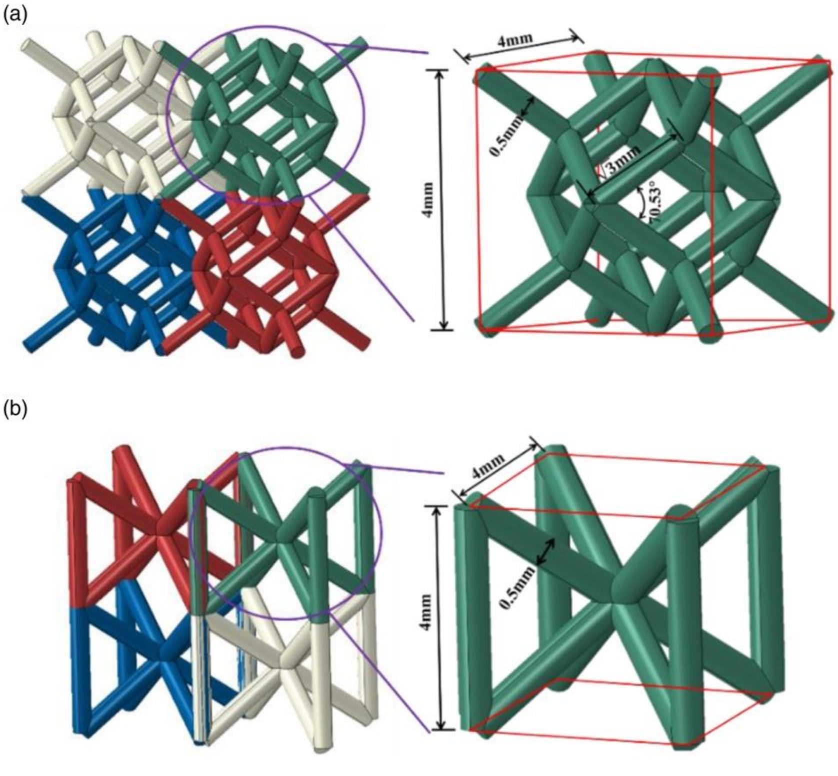


Figure 16: Two different patterns of the core [24].

Yu Jhou [25] conducted numerical and experimental investigations to study the dynamic impact response of 3D-Printed polymeric sandwich structures with lattice cores. The lattice cores of sandwich structures were based on two unit cells, a body-centred cubic (BCC) and an edge-centred cubic (ECC). ANSYS LD-DYNA with the explicit solver was employed to simulate their dynamic impact response. Tetrahedron elements were applied for meshing the sandwich structure. The thermoplastic polyurethane (TPU 95A) was used for printing the sandwich structure. The findings suggested that with the stiffer cell shape design, ECC, a thinner strut diameter structure showed better absorption capability. In contrast, with the softer cell shape design, BCC, a thinner strut diameter structure had poor absorption capability due to the structure collapse effect. The collapse of structure can be improved by increasing the Young's modulus of its apparent material.

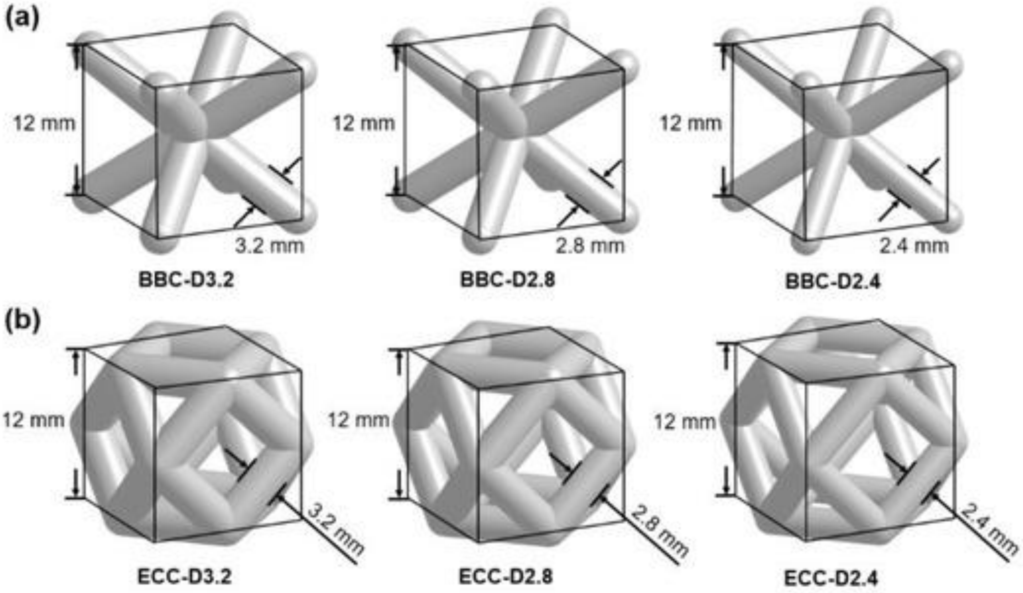


Figure 17: Geometry definition for two individual strut-based unit cells: (**a**) body-centered cubic (BCC) unit cell, and (**b**) edge-centered cubic (ECC) unit cell [25].

Theoretical and experimental study of the vibration dynamics of a 3D-printed sandwich beam with an hourglass lattice truss core was reported by Guo *et al.* [26]. The governing equation of the beam is established by using a homogenized model and the Hamilton's principle. The face sheets and core were integrally printed from PLA. The lattice truss core was modeled with the 1-dimensional 3-Node BEAM189 element and the face sheets were modeled with the 2-dimensional 4-Node SHELL181 element. Solyaev *et al.* [27] analyzed the static and dynamic response of sandwich beams with lattice and pantographic cores. The face sheets and core were integrally printed from PLA material. The pantographic-type lattices formed by the two families of inclined beams placed with small offset and connected by stiff joints (variant 1), by hinges (variant 2) and made without joints (variant 3). The fourth type of the core has the standard plane geometry formed by the intersected beams lying in the same plane (variant 4). From the experiments it is found that the plane geometry of variant 4 has the highest rigidity and the highest load bearing capacity in the static tests. However, other three variants of the pantographic-type cores (1–3) demonstrate the better performance under the impact loading. The impact strength of such structures are in 3.5–5 times higher than those one of variant 4 with almost the same mass per unit length.

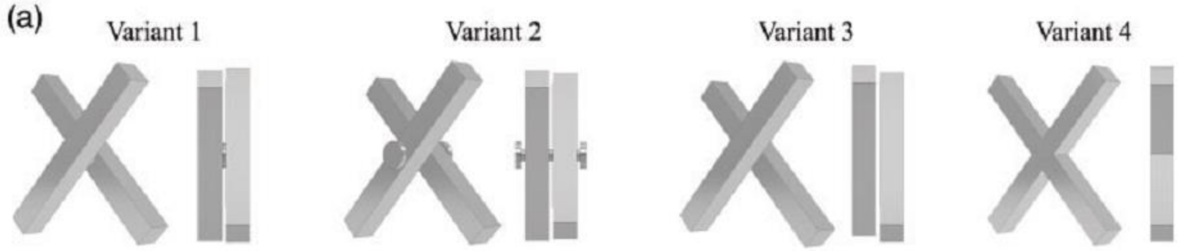


Figure 18: Variants of connections between the beams in the lattice cores used in the experiments (1 – stiff connection, 2 – hinges with pivots, 3 – absence of connection, 4 – single-layer lattice core)

Based on experimental and numerical methodology, the quasi-static and dynamic compressive properties and deformation mechanisms of 3D printed polymeric cellular structures with Kelvin cells was presented by Yu *et al*. [28]. The ABAQUS software with S4R element was applied for numerical simulation. Experimental results show that the elastic modulus and plateau stress increase with increasing relative density, which obeys the Gibson-Ashby polynomial scaling law. Numerical results indicate the presence of a critical relative density, below which the Kelvin foams deform primarily by cell edges bending, and beyond which the cell membranes stretching dominates. Ye *et al*. [29] applied numerical and experimental methodology to study compression and energy absorption performances of 3D printed lattice core sandwich structures (Figure 19). The core and face sheets were integrally made of PLA. Solid element C3D4 in ABAQUS software was used to simulate the lattice structure. Their results denoted that the diameter has the greatest influence on the specific energy absorption and mean crushing force.

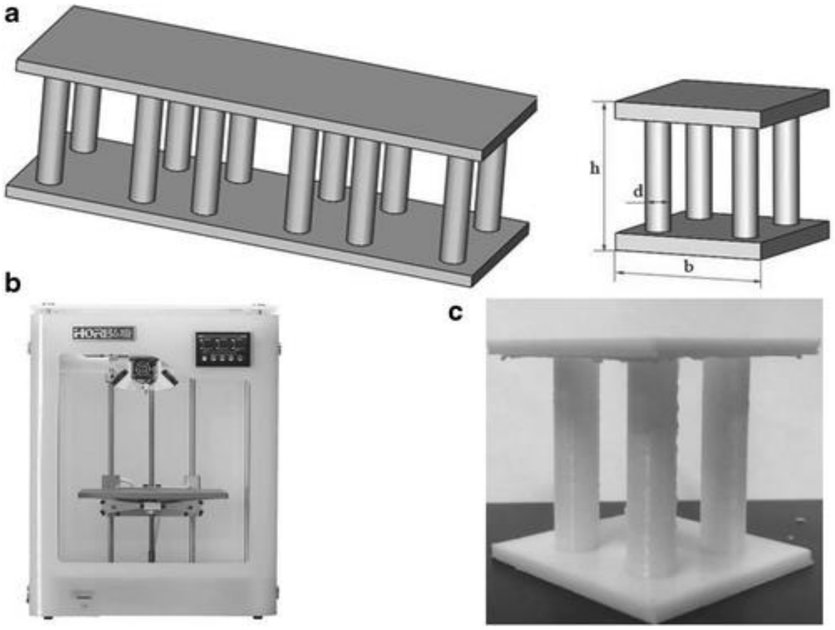


Figure 19: Designed lattice core sandwich panel, **(b)** printer, and **(c)** 3D printed unit cell of a lattice score sandwich panel [29].

Chahardoli *et al*. [30] studied flexural behavior of sandwich panels with 3D printed cellular cores and aluminum face sheets under quasi-static loading experimentally and numerically. Face sheets and core were made of aluminum 3105 alloy and PLA, respectively. LS-DYNA commercial software was employed for numerical simulation. Dynamic impact resistance of composite sandwich panels with 3-D printed polymer syntactic foam cores was presented by Tewani *et al*. [31]. 3-D printed syntactic foams have been developed using rasters of High-Density Polyethylene (HDPE) and Glass MicroBalloon (GMB) fillers by adopting the Fused Raster Fabrication (FFF) technique. Observations suggest that an increase in GMB % in HDPE matrix improves the impact performance in terms of the peak load of the material, but the failure behavior becomes brittle to an extent. It is noticed that core materials with higher GMB content are prone to individual raster breakage and delamination at the back face, in addition to debonding between individual rasters. Specimens printed along the longer dimension impart more warping in the final sandwich structures than that of specimens printed along the shorter dimension. Therefore, they are more susceptible to delamination at the back face. Also, addition of GMB fillers mitigate the tendency of the sandwich panels to warp. Castro *et al*. [32] accomplished numerical analysis of damage mechanisms for 3D-printed sandwich structures using a meshless method. The face sheets and core were made of PLA. Three cell core patterns were numerically evaluated under tensile and three-point bending tests: out-of-plane hexagonal honeycomb, S-shape corrugated, and in-plane hexagonal honeycomb cores. Their results showed that the nucleation and propagation of cracks had more heterogeneous profiles for in-plane hexagonal honeycomb cores, showing greater unpredictability in the susceptible areas to failure. Yazdani Sarvestani *et al*. [33] carried out an investigation about failure mechanism, energy absorption and multi-hit capability of 3D printed meta-sandwich structures by utilizing numerical and experimental approach. The face sheets and core were integrally printed with PLA. Six different patterns were considered for the core (Figure 20). The face-sheets and the core were discretized with tetrahedral and hexahedral elements. It is found that the core topology and geometrical parameters of the meta-sandwich structures play significant roles on their failure mechanism and energy absorption capability. For dynamic energy absorption, Isomax, octet and cubic meta-sandwich plates had almost the same ability, all higher than the auxetic core for low impact energy. For higher impact energy, octet meta-sandwich plates show higher energy absorption performance.

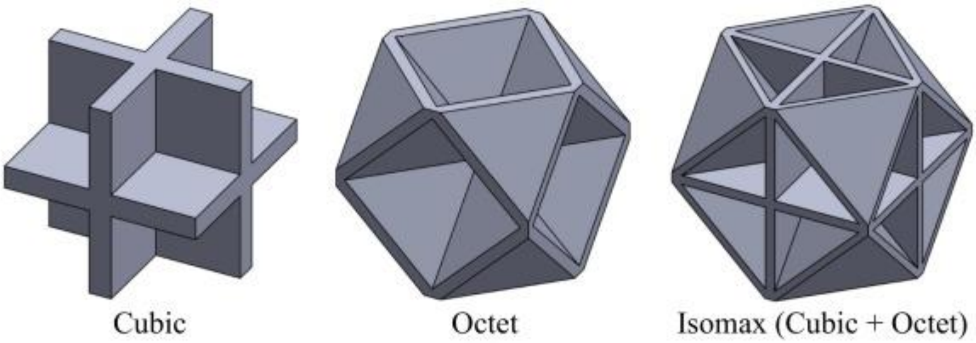
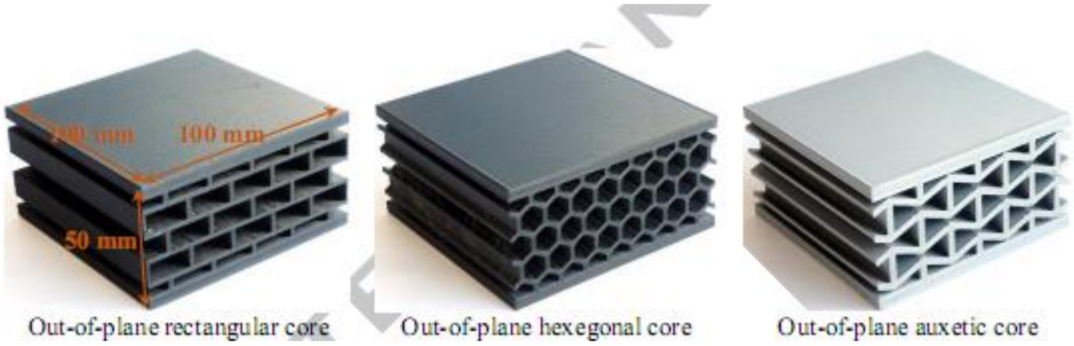

Cubic
Octet
Isomax (Cubic + Octet)

Figure 20: Unit cells of the mechanical metamaterial cellular cores [33].

In another research they [34] studied energy absorption and free vibration of 3D printed architected polymeric sandwich panels. Three different patterns such as Out-of-plane rectangular core, Out-of-plane hexegonal core and Out-of-plane auxetic core were assumed for patterns of core (Figure 21). A representative unit cell was modeled in ANSYS mechanical APDL and was discretized with 8-node 3D Solid185 elements. Their results showed that if relative density of the auxetic cellular core is selected appropriately for a specific value of impact energy, the sandwich panels with auxetic cores can have a higher level of energy absorption capability up to 33% compared to the rectangular and hexagonal sandwich panels. Architected sandwich panels with auxetic cellular cores exhibit a desirable combination of high-energy absorption capability with a low peak value of response force.



Out-of-plane rectangular core
Out-of-plane hexegonal core
Out-of-plane auxetic core

Figure 21: Three different patterns of core [34].

Geramizadeh *et al.* [35] studied numerical and experimental investigation for enhancing the energy absorption capacity of the novel three-dimensional printed sandwich structures. The main goal of this article was to improve the energy absorption capacity of the out-of-plane honeycomb sandwich beam. The novel Beta VI and Alpha VI were designed in order to achieve this target. The face sheets and core were made of PLA. The structure (Face sheets and core) was meshed by four-node bilinear plane stress quadrilateral and reduced integration (CPS4R) element. Their results indicated that the Alpha VI is an excellent structure that has an energy absorption capacity greater than the honeycomb and Beta VI. The comparison shows that the energy absorption capacity in the Alpha VI has been raised by 53.9%.

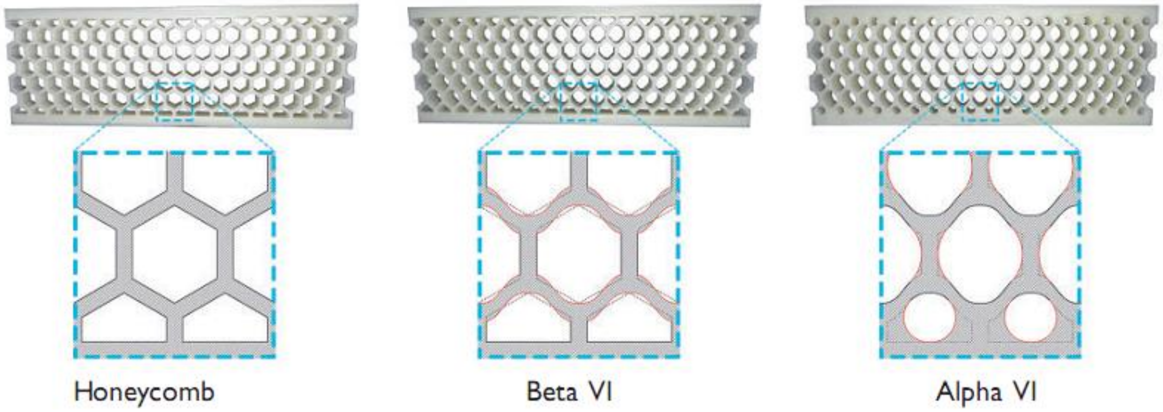


Figure 22: The geometry of 3D printed sandwich structures [35].

Hyder Siddique *et al.* [36] presented a comprehensive review paper about 3D printed bio-inspired porous structures for impact energy absorption. In this review paper, categorization of different types of biomimetic porous structure and energy absorption capabilities of the 3D printed biomimetic structure were presented and discussed. Choudhari *et al.* [37] presented an article about 3D printing of composite sandwich structures for aerospace applications. The investigation enlightened the types of core, joining method, advantages and performance of 3D printing composite sandwich structure intended to aerospace industries was investigated in details. Ma *et al.* [38] presented a comprehensive study about 3D-printed spherical-roof contoured-core (SRCC) composite sandwich structures for aerospace applications. This article was focused on investigating the novel SRCC sandwich panels with spherical-roof contoured-core and its diamond-shaped notch core design subjected to quasi-static loading. Kumar Sahu [39] evaluated cell parameter variation on energy absorption characteristic of thermoplastic honeycomb sandwich structure numerically and experimentally. The honeycomb sandwich structures were fabricated with thermoplastic elastomer nylon core and OD/2D hybrid polymer nanocomposite were used for fabrication of skin. It is concluded that the cell size variation infuences the out-of-plane energy absorption apart from the in-plane cushioning capability of the honeycomb structure. TPE filament had sufficient flexibility for fabrication of cushioning and energy absorbing structures and can be used as a backing layer in bulletproof vest beneath the conventional Kevlar layer. In tandem, it will aid in absorbing the incident energy and resist the inward perforation of the bullet, which otherwise was a reason for feeling shocks, blunt trauma and scare on the body. A review of sandwich composite structures with 3D printed honeycomb cores was presented by Wannarong and Singhanartb [40]. They reviewed the articles that their structures were made of PLA and ABS. The bending stiffness was discovered to be enhanced by the re-entrant core which is the core that exhibits negative Poisson’s ratio or auxetic behaviour. Also, they showed that the bending and fatigue performance of sandwich structures was controlled by the core densities, core designs, component materials, face sheet thickness, and face sheet stacking sequence.

The main purpose of this review study is to recognize various cells fabricated by 3D printer and to show that the performance of these cells are different under various loadings including buckling or transverse vibration. On the other hand, a cell with high natural frequencies in a certain structure, like beam, may be weak under buckling load and has the minimum stiffness versus buckling load. Besides, in most previous studies, the deformation of cells is supposed based on external loading which is employed to the global structure; then, by considering some assumption, like considering the cell as beam or truss, the effective mechanical properties are obtained. These mechanical properties depend on the mechanical properties of base printed material and the geometry of cell. In section 2, a novel simple method for analyzing these structures is suggested.

2. Suggestion for future works

Obtaining the effective mechanical properties of cells structure are usually difficult and dependent on the type of loading. On the other hand, the effective mechanical properties are different from a certain loading to another one. Based on finite element approach, a cell can be considered as a continuously group of truss, beam or frame element. In this regard, the stiffness of cell is estimated by assembling the elements of cell as shown in Figure 23. A remarkable feature of this method is its independence from the effective mechanical properties. Thus, it is not necessary to obtain the effective mechanical properties for new cells having various complex analytical procedure.

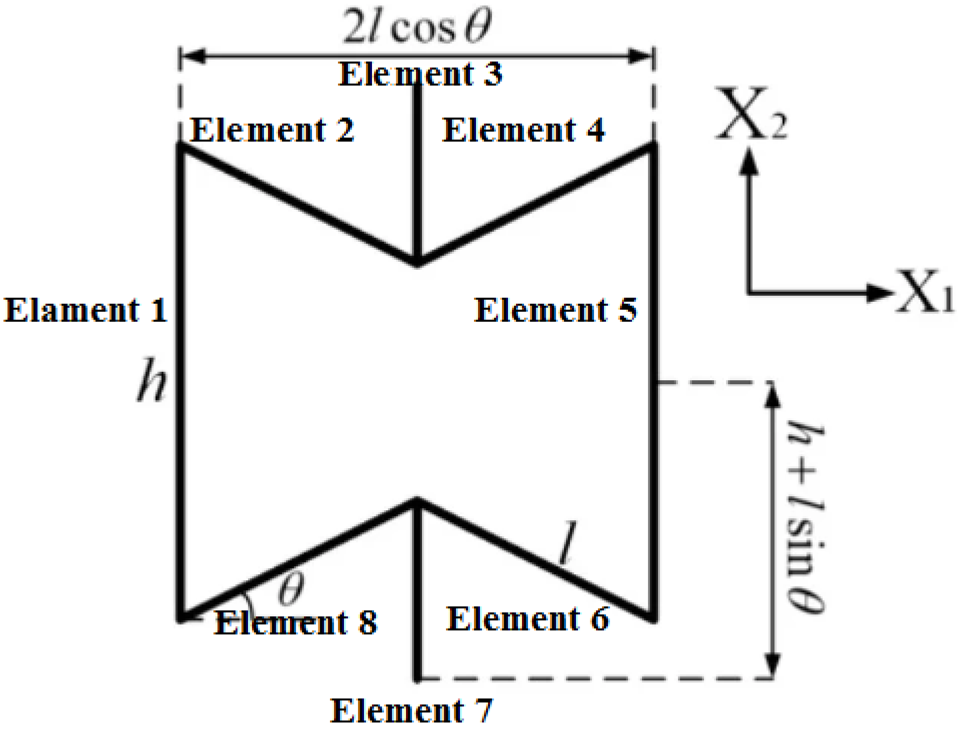


Figure 23: Cell geometry and the coordinate system used for the re-entrant hexagonal honeycomb, where h is the vertical length of the cell member, l is the inclined length of the cell member, and θ is the cell angle.

3. Conclusion

Literature review shows that a lot of investigations have been performed about 3D printed core structures to evaluate the performance of these structures in practical application in various industries. In some investigations, the patterns of core were assumed at first and in another one, the optimized pattern for core will be obtained for various targets such as achieving the maximum negative poison ratio or maximum energy absorption of these structures. Most of investigation have been conducted numerically and experimentally. The most often utilized filaments in 3D printing are ABS and PLA. Results of published studies showed that the geometrical parameters and the relative density of the core have a significant influence on their bending stiffness, maximum load and energy absorption capacity, while the core topology has limited effects on the bending stiffness but affects the maximum load and energy absorption remarkably. Also, truss, conventional honeycomb, and re-entrant honeycomb conventional honeycomb structures provide a non-auxetic behavior while the re-entrant honeycomb structure provides an auxetic behavior. Moreover, the re-entrant honeycomb sandwich structures exhibit sequential snap-through instabilities which significantly increase the energy absorption capacity.

References

[1] S. H. Huang, P. Liu, A. Mokasdar, L. Hou, Additive manufacturing and its societal impact: a literature review, *J The International journal of advanced manufacturing technology,* Vol. 67, pp. 1191-1203, 2013.

[2] S. Dhinesh, P. S. Arun, K. K. Senthil, A. Megalingam, Study on flexural and tensile behavior of PLA, ABS and PLA-ABS materials, *J Materials Today: Proceedings,* Vol. 45, pp. 1175-1180, 2021.

[3] S. Mollaei, M. Babaei, K. Asemi, Torsional buckling of functionally graded graphene reinforced composite laminated cylindrical panel, *J Archive of Applied Mechanics,* Vol. 93, No. 2, pp. 427-435, 2023.

[4] M. Khatoonabadi, M. Jafari, F. Kiarasi, M. Hosseini, M. Babaei, K. Asemi, Shear buckling response of FG porous annular sector plate reinforced by graphene platelet subjected to different shear loads, *J Journal of Computational Applied Mechanics,* Vol. 54, No. 1, pp. 68-86, 2023.

[5] F. Kiarasi, M. Babaei, K. Asemi, R. Dimitri, F. Tornabene, Free vibration analysis of thick annular functionally graded plate integrated with piezo-magneto-electro-elastic layers in a hygrothermal environment, *J Applied Sciences,* Vol. 12, No. 20, pp. 10682, 2022.

[6] M. babaei, F. Kiarasi, M. S. Tehrani, A. Hamzei, E. Mohtarami, K. Asemi, Three dimensional free vibration analysis of functionally graded graphene reinforced composite laminated cylindrical panel, *Part L: Journal of Materials: Design and Applications. 2022;236(8):1501-1514,* Vol. 236, No. 8, pp. 1501-1514, 2022.

[7] F. Kiarasi, A. Asadi, M. Babaei, K. Asemi, M. Hosseini, Dynamic analysis of functionally graded carbon nanotube (FGCNT) reinforced composite beam resting on viscoelastic foundation subjected to impulsive loading, *Journal of Computational Applied Mechanics,* Vol. 53, No. 1, pp. 1-23, 2022.

[8] M. Babaei, F. Kiarasi, S. M. Hossaeini Marashi, M. Ebadati, F. Masoumi, K. Asemi, Stress wave propagation and natural frequency analysis of functionally graded graphene platelet-reinforced porous joined conical–cylindrical–conical shell, *Waves in Random and Complex Media*, pp. 1-33.

[9] F. Kiarasi, M. Babaei, P. Sarvi, K. Asemi, M. Hosseini, M. Omidi Bidgoli, A review on functionally graded porous structures reinforced by graphene platelets, *Journal of Computational Applied Mechanics,* Vol. 52, No. 4, pp. 731-750, 2021.

[10] T. Li, L. Wang, Bending behavior of sandwich composite structures with tunable 3D-printed core materials, *Composite Structures,* Vol. 175, pp. 46-57, 2017.

[11] C. Peng, K. Fox, M. Qian, H. Nguyen-Xuan, P. Tran, 3D printed sandwich beams with bioinspired cores: Mechanical performance and modelling, *Thin-Walled Structures,* Vol. 161, pp. 107471, 2021.

[12] Z. Liu, H. Chen, S. Xing, Mechanical performances of metal-polymer sandwich structures with 3D-printed lattice cores subjected to bending load, *Archives of Civil and Mechanical Engineering,* Vol. 20, pp. 1-17, 2020.

[13] G. D. Goh, S. J. C. Neo, V. Dikshit, W. Y. Yeong, Quasi-static indentation and sound-absorbing properties of 3D printed sandwich core panels, *Journal of Sandwich Structures & Materials,* Vol. 24, No. 2, pp. 1206-1225, 2022.

[14] C. Lu, M. Qi, S. Islam, P. Chen, S. Gao, Y. Xu, X. Yang, Mechanical performance of 3D-printing plastic honeycomb sandwich structure, *International Journal of Precision Engineering and Manufacturing-Green Technology,* Vol. 5, pp. 47-54, 2018.

[15] S. Ghannadpour, M. Mahmoudi, K. H. Nedjad, Structural behavior of 3D-printed sandwich beams with strut-based lattice core: Experimental and numerical study, *Composite Structures,* Vol. 281, pp. 115113, 2022.

[16] İ. K. Türkoğlu, H. Kasım, M. Yazıcı, Experimental investigation of 3D-printed auxetic core sandwich structures under quasi-static and dynamic compression and bending loads, *International Journal of Protective Structures,* Vol. 14, No. 1, pp. 63-86, 2023.

[17] X. Zhou, J. Li, C. Qu, W. Bu, Z. Liu, Y. Fan, G. Bao, Bending behavior of hybrid sandwich composite structures containing 3D printed PLA lattice cores and magnesium alloy face sheets, *The Journal of Adhesion,* Vol. 98, No. 11, pp. 1713-1731, 2022.

[18] N. K. Choudhry, S. R. Bankar, B. Panda, H. Singh, Experimental and numerical analysis of the bending behavior of 3D printed modified auxetic sandwich structures, *Materials Today: Proceedings,* Vol. 56, pp. 1356-1363, 2022.

[19] M. Ali, S. Batai, Bending behavior of sandwich composite structures of 3D-printed materials, in *Proceeding of,* Springer, pp. 281-287.

[20] M. Gunasegeran, P. Edwin Sudhagar, Free and forced vibration analysis of 3D printed bioinspired sandwich beam using HSDT: Numerical and experimental study, *Polymer Composites,* Vol. 43, No. 6, pp. 3659-3677, 2022.

[21] S. Hou, T. Li, Z. Jia, L. Wang, Mechanical properties of sandwich composites with 3d-printed auxetic and non-auxetic lattice cores under low velocity impact, *Materials & Design,* Vol. 160, pp. 1305-1321, 2018.

[22] R. Hedayati, A. Yousefi, M. Bodaghi, Sandwich structures with repairable cores based on truncated cube cells, *Composites Part B: Engineering,* Vol. 243, pp. 110124, 2022.

[23] A. I. Indreș, D. M. Constantinescu, O. A. Mocian, Bending behavior of 3D printed sandwich beams with different core topologies, *Material Design & Processing Communications,* Vol. 3, No. 4, pp. e252, 2021.

[24] Y. Cao, X. Geng, H. Han, Y. Lu, J. Wang, C. Zhao, Experimental and numerical investigation on the buckling of 3D printed sandwich structure with lattice core, *Journal of Sandwich Structures & Materials,* Vol. 24, No. 6, pp. 1923-1940, 2022.

[25] S.-Y. Jhou, C.-C. Hsu, J.-C. Yeh, The dynamic impact response of 3D-printed polymeric sandwich structures with lattice cores: Numerical and experimental investigation, *Polymers,* Vol. 13, No. 22, pp. 4032, 2021.

[26] Z. Guo, G. Hu, J. Jiang, L. Yu, X. Li, J. Liang, Theoretical and experimental study of the vibration dynamics of a 3D-printed sandwich beam with an hourglass lattice truss core, *Frontiers in Mechanical Engineering,* Vol. 7, pp. 651998, 2021.

[27] Y. Solyaev, A. Babaytsev, A. Ustenko, A. Ripetskiy, A. Volkov, Static and dynamic response of sandwich beams with lattice and pantographic cores, *Journal of Sandwich Structures & Materials,* Vol. 24, No. 2, pp. 1076-1098, 2022.

[28] Y. Duan, B. Du, X. Shi, B. Hou, Y. Li, Quasi-static and dynamic compressive properties and deformation mechanisms of 3D printed polymeric cellular structures with Kelvin cells, *International Journal of Impact Engineering,* Vol. 132, pp. 103303, 2019.

[29] G. Ye, H. Bi, L. Chen, Y. Hu, Compression and energy absorption performances of 3D printed Polylactic acid lattice core sandwich structures, *3D Printing and additive manufacturing,* Vol. 6, No. 6, pp. 333-343, 2019.

[30] S. Chahardoli, Flexural behavior of sandwich panels with 3D printed cellular cores and aluminum face sheets under quasi-static loading, *Journal of Sandwich Structures & Materials,* Vol. 25, No. 2, pp. 232-250, 2023.

[31] H. TEWANI, D. BONTHU, H. BHARATH, M. DODDAMANI, P. PRABHAKAR, Dynamic Impact Resistance of Composite Sandwich Panels with 3-D Printed Polymer Syntactic Foam Cores, in *Proceeding of*.

[32] B. D. de Castro, F. de Castro Magalhães, J. C. C. Rubio, Numerical analysis of damage mechanisms for 3D-printed sandwich structures using a meshless method, *Modelling and Simulation in Materials Science and Engineering,* Vol. 30, No. 5, pp. 055003, 2022.

[33] H. Y. Sarvestani, A. Akbarzadeh, A. Mirbolghasemi, K. Hermenean, 3D printed meta-sandwich structures: Failure mechanism, energy absorption and multi-hit capability, *Materials & Design*, Vol. 160, pp. 179-193, 2018.

[34] H. Y. Sarvestani, A. Akbarzadeh, H. Niknam, K. Hermenean, 3D printed architected polymeric sandwich panels: Energy absorption and structural performance, *Composite Structures*, Vol. 200, pp. 886-909, 2018.

[35] H. Geramizadeh, S. Dariushi, S. J. Salami, Numerical and experimental investigation for enhancing the energy absorption capacity of the novel three-dimensional printed sandwich structures, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications,* Vol. 235, No. 7, pp. 1622-1634, 2021.

[36] S. H. Siddique, P. J. Hazell, H. Wang, J. P. Escobedo, A. A. Ameri, Lessons from nature: 3D printed bio-inspired porous structures for impact energy absorption–A review, *Additive Manufacturing*, pp. 103051, 2022.

[37] C. J. Choudhari, P. S. Thakare, S. K. Sahu, *3D printing of composite sandwich structures for aerospace applications,* in: *High-performance composite structures: additive manufacturing and processing*, Eds., pp. 45-73: Springer, 2021.

[38] Q. Ma, M. Rejab, M. M. Hanon, M. Idris, J. Siregar, *3D-Printed spherical-roof contoured-core (SRCC) composite sandwich structures for aerospace applications,* in: *High-Performance Composite Structures: Additive Manufacturing and Processing,* Eds., pp. 75-91: Springer, 2021.

[39] S. K. Sahu, N. D. Badgayan, S. Samanta, P. Rama Sreekanth, Evaluation of cell parameter variation on energy absorption characteristic of thermoplastic honeycomb sandwich structure, *Arabian Journal for Science and Engineering,* Vol. 46, pp. 12487-12507, 2021.

[40] D. Wannarong, T. Singhanart, A Review of Sandwich Composite Structures with 3D Printed Honeycomb Cores, *Engineering Journal,* Vol. 26, No. 6, pp. 27-39, 2022.