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In-plane compression performance of additively manufactured honeycomb structures: a review of influencing factors and optimisation techniques

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Abstract

Purpose – Honeycombs enjoy wide use in various engineering applications. The emergence of additive manufacturing (AM) as a method of customisable of parts has enabled the reinvention of the honeycomb structure. However, research on in-plane compressive performance of both classical and new types of honeycombs fabricated via AM is still ongoing. Several important findings have emerged over the past years, with significance for the AM community and a review is considered necessary and timely. This paper aims to review the in-plane compressive performance of AM honeycomb structures.

Design/methodology/approach – This paper provides a state-of-the-art review focussing on the in-plane compressive performance of AM honeycomb structures, covering both polymers and metals. Recently published studies, over the past six years, have been reviewed under the specific theme of in-plane compression properties.

Findings – The key factors influencing the AM honeycombs' in-plane compressive performance are identified, namely the geometrical features, such as topology shape, cell wall thickness, cell size and manufacturing parameters. Moreover, the techniques and configurations commonly used for geometry optimisation toward improving mechanical performance are discussed in detail. Current AM limitations applicable to AM honeycomb structures are identified and potential future directions are also discussed in this paper.

Originality/value – This work evaluates critically the primary results and findings from the published research literature associated with the in-plane compressive mechanical performance of AM honeycombs.

Keywords Additive manufacturing, Honeycomb structures, Compression, Optimisation

Paper type Research paper

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Nomenclature

List of abbreviations:

ABS = Acrylonitrile butadiene styrene
AM = Additive manufacturing
AuxHex = Auxetic hexagonal
BJ = Binder jetting
CAD = Computer-aided design
DED = Direct energy deposition
FCC = Face-centred cubic
FEA = Finite element analysis
LENS = Laser-engineered net shaping
ME = Material extrusion
MJ = Material jetting
PBF = Powder bed fusion
PETG = Polyethylene terephthalate glycol
PHA = Polyhydroxyalkanoate
PLA = Polylactic acid
SLA = Stereolithography
TOP = Topology optimisation
TPMS = Triply period minimal surface
TPU = Thermoplastic polyurethane
VP = Vat photopolymerisation

List of symbols:

cs = Cell size
h = Cell wall height
l = Cell wall length
t = Cell wall thickness
x = Horizontal axis
X1 = In-plane compression along longitudinal direction (1)
X2 = In-plane compression along longitudinal direction (2)
X3 = Out-of-plane compression along vertical direction (3)
y = Transverse axis
z = Vertical axis
θ = inclination angle of cell wall

1. Introduction

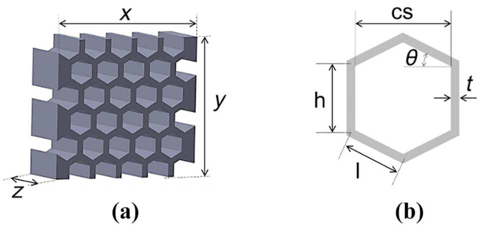
The typical honeycomb is comprised of hexagonal cells, which symmetrically (regularly) arranged in space. The geometry of the regular hexagonal honeycomb and the cell dimensional definitions along the length (x), width (y) and thickness (z) axis, namely the wall thickness, height, length, inclination angle and cell size are shown in Figure 1. Honeycombs have been traditionally produced via the adhesive bonding method, employing either the expansion or the corrugation process (Bitzer, 1997). However, the recent emergence of additive manufacturing (AM) has revolutionised their production process, since AM offers a more flexible and cost-effective alternative, reducing material wastage and production lead time. The emergence of AM has fuelled research interests in the manufacturing industry, exploring the capabilities offered by this technology, particularly optimising the mechanical performance of honeycomb structures (Ufodike *et al.*, 2021; Wei *et al.*, 2021a; Xu *et al.*, 2019a). Metal honeycombs have been commonly produced via powder bed fusion (PBF) and direct energy deposition (DED), whilst polymer honeycombs are typically fabricated via material extrusion (ME), binder jetting (BJ), material jetting (MJ) and vat photopolymerisation (VP).

In engineering applications one can find that honeycombs are subjected to in-plane (X_1 or X_2 direction) or out-of-plane (X_3 direction) compressive loading. A schematic representation of the in-plane and out-of-plane honeycomb loading directions is provided in Figure 2. However, when loaded in the X_1 or X_2 direction, the cell walls bend because the compressive strength is lower compared to when loaded in the X_3 direction, where compressive strength is higher, since the cell walls extend or compress axially (Gibson and Ashby, 1997).

Considering honeycombs subjected to in-plane compressive loading, in the linear-elastic region the cell walls bend when the honeycomb is loaded in the in-plane direction (X_1) as shown in Figure 3(a). Further, once the cell walls lose their load-bearing capacity, they experience buckling and they collapse plastically (plastic yielding), forming plastic hinges, illustrated in Figure 3(b) (Gibson and Ashby, 1997). As strain increases, this deformation process continues until the cell walls collapse completely and they contact each other, leading to densification (Gibson and Ashby, 1997). At this stage, the cell wall material is compressed, leading to a steep rise of stress, exhibited in the stress-strain curve, as shown in Figure 3(a), until all cells collapse. The full stress–strain curve and the different deformation modes of a honeycomb compressed in the X_1 direction are illustrated in Figure 3.

The in-plane compressive performance of honeycombs can be controlled by varying its geometric features, including varying the cell wall thickness. For example, by increasing the relative thickness of the cell wall (i.e. relative density), an increase in the stiffness and compressive stress is achieved, at the expense of a decrease in the densification strain (Gibson and Ashby, 1997).

This review paper discusses the current research literature surrounding the in-plane compressive performance of AM polymer and metal honeycombs as influenced by geometrical features, such as topology shape, cell wall thickness, cell size and manufacturing parameters. Moreover, it reviews techniques and configurations commonly used for geometry optimisation toward improving mechanical performance with application in in-plane compression.



(a) **(b)**

Note(s): (a) geometry and dimensional definitions along the x (length), y (width) and z (thickness) axis and (b) cell dimensional definitions, namely height (h), length (l), wall thickness (t), inclination angle (θ) and cell size (cs)

Figure 1. Schematic representation of the regular hexagonal honeycomb structure

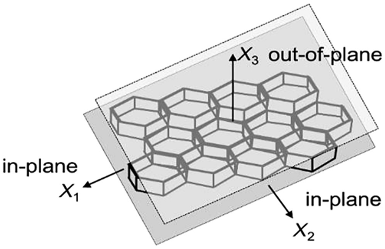


Figure 2. Schematic representation of the in-plane (X_1 and X_2) and out-of-plane (X_3) loading directions relative to the geometry of the honeycomb

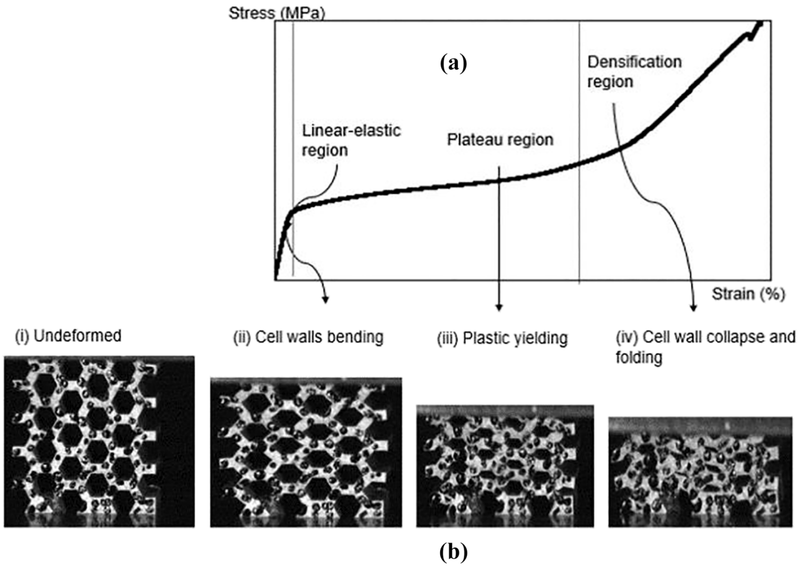


Figure 3. (a) A typical stress–strain curve for honeycombs loaded in the in-plane direction showing the elastic, plateau and densification regions; (b) in-plane deformation modes of AM honeycombs

Note(s): (i) undeformed honeycomb, (ii) cell walls bending, (iii) plastic yielding and (iv) cell wall collapse and folding

Source(s): Authors' own work

2. Influence of honeycomb geometrical features

The impact of a honeycomb's geometry is discussed, with a focus on the effect that the topology shape, wall thickness and cell size have on the resulting mechanical performance.

2.1 Topology features

Recently, Wei *et al.* (2021b) conducted an in-depth study into the influence of honeycomb topology features, including inclination angle (θ) and thickness to length ratio (t/l) on the mechanical characteristics of PBF Steel 316L auxetic star-triangular honeycombs by modulating θ (30°–45°). Experimental results confirmed that the Poisson's ratio, Elasticity Modulus and compressive performance of the honeycombs are indeed topology features-dependent, indicating that the inclination angle had a more profound effect on the Poisson ratio and on the Elasticity Modulus, than t/l. In addition, they found that the overall compressive characteristics of the star-triangular honeycomb structures are loading-direction dependent. To gain additional insights into the newly proposed auxetic structures *vis-à-vis* mechanical behaviour, Wei *et al.* conducted an extension study to corroborate their initial findings (Wei *et al.*, 2021a) and the experimental and numerical analysis has re-confirmed the existence of correlation between honeycomb topology and mechanical performance. It has also been discovered that the inclination angle did not particularly influence the deformation modes of these (star-type) honeycomb structures, albeit lower inclination angles exhibited an enhanced energy absorption capacity.

Besides the impact honeycomb topologies have on compressive performance, they have also been found to affect the applicability of analytical (mechanistic/empirical) models used for predicting mechanical properties. Gibson and Ashby (Gibson and Ashby, 1997) have established a series of analytical expressions to predict the mechanical performance of honeycombs, particularly thin honeycombs (with relative density <0.25). In an attempt to validate the equation proposed by Gibson and Ashby (Gibson and Ashby, 1997), Hedayati *et al.* (2016b) applied the Gibson and Ashby Elasticity Modulus analytical equation for ME polymer thick honeycombs and have found that to deviate from the experimental results with the increase of relative density (>0.25). Consequently, Hedayati *et al.* introduced a set of empirical models specifically for ME honeycombs with relative density >0.25. Utilising the Hedayati *et al.* Elasticity Modulus model, Hussein *et al.* (2020) modelled the elastic behaviour of laser PBF Steel 304L honeycombs with a varying cell wall thicknesses (from 0.2 to 0.5 mm), while keeping their cell size constant at 3.97 mm. Their experimental and computational analysis results further confirmed the efficacy of the Hedayati *et al.* model. Chen *et al.* (2018) similarly corroborated the findings of Hussein *et al.* (2020), confirming again the correlation between geometrical features and resulting mechanical performance. An extension of the Gibson and Ashby (1997) plastic collapse stress equation has recently been proposed by the authors of the present review paper (Obadimu and Kourousis, 2022) by incorporating a viscoplastic dependence of the ME and laser PBF Steel 316L material response occurring from strain rates within a quasi-static loading conditions' range.

Habib *et al.* (2018) attempted to investigate, via a computational analysis, the relationship between cell topology *vis-à-vis* the compressive performance of ME Nylon-12 honeycombs. Habib *et al.* (2018) modelled via finite element analysis (FEA) the in-plane compressive performance of the honeycombs by using data obtained from a prior experimental study (Habib *et al.*, 2017), keeping relative density constant at 0.15. They studied nine different cell topologies, including hexagonal, regular quadratic, staggered quadratic, diamond, octagonal, dodecagonal, regular circular, staggered circular and triangular topologies (Habib *et al.*, 2018). The FEA results indicated that despite having the same base material and keeping relative density constant for all topologies, the honeycombs exhibited a differing compressive behaviour. Additionally, they classified these behaviours into two distinct categories, namely an "I" band deformation mode, dominated by an undulating plateau region on the stress-strain curve due to plastic buckling of the cells and an inclined "I" band deformation, with a more stable plateau region on the curve as a result of the bending of cells. Similarly, in their study on ME polymer honeycombs, Zaharia *et al.* (2020) confirmed the existence of correlation between topology and mechanical performance, finding that the type of cell topology can influence the failure mechanism experienced by the structure under compression. Hedayati *et al.* (2016a), Panda *et al.* (2018) and León-Becerra *et al.* (2021), who employed both a numerical and an experimental analysis approach in their investigations on ME polymer honeycombs, also verified that topology can have an important impact on compressive performance. The effect of cell size of ME Steel 316L honeycombs has also been investigated by the authors of the present review paper, as reported in a recent study, identifying a clear dependence with the in-plane compressive behaviour of the structures (Obadimu and Kourousis, 2022).

2.2 Cell wall thickness

With the same aim of understanding the influence of honeycomb geometric features, Habib *et al.* (2017) focused their investigation on identifying whether there is correlation between the honeycomb's cell wall thickness and mechanical performance. They have studied Nylon-12 polymer honeycombs fabricated via MJ, varying their cell wall thicknesses (from 0.45 mm to 1 mm). From a compressive test campaign, they have discovered the existence of a linear relationship between cell wall thickness and mechanical performance, i.e. the latter increased with an increase in the former (from 0.45 mm to 1 mm). Interestingly, besides corroborating the findings of Habib *et al.* (2017), Joseph *et al.* (2021) attributed the enhanced mechanical performance of ME polymer honeycombs with thicker cell walls to the "larger availability of material" in the walls, which induces progressive deformation under compression, as opposed to honeycombs with thin cell walls with less material content.

2.3 Cell size

Baranowski *et al.* (2019) has investigated the influence of cell sizes, 3 mm and 5 mm, on the compressive performance of DED Ti-6Al-4V honeycombs. As expected, they found that honeycombs with 3 mm cells outperformed their 5 mm counterparts, complementing similar results reported by Panda *et al.* (2018) who worked with ME polymers. Building upon the work of Baranowski *et al.* (2019) and Antolak-Dudka *et al.* (2019), who also investigated DED Ti-6Al-4V, attributed the high compressive properties of the 3 mm honeycomb cells to the higher geometrical stiffness relative to those having larger cell sizes (4 mm–6 mm). Another interesting finding is related with variation between the computer-aided design (CAD) model and the produced AM honeycombs. In particular, it was observed that the 3 mm cell size honeycombs exhibited a rougher surface quality and higher dimensional deviations from the CAD model for honeycombs than that of the other sizes. Overall, Antolak-Dudka *et al.* (2019) also concluded that varying cell sizes could optimise the in-plane compressive performance of honeycomb structures.

2.4 Defects

Rahman *et al.* (2017) studied (experimentally and numerically) the performance of ME polymer honeycombs having artificially-induced defects (such as irregular thicknesses, missing cell walls and disconnected joints). Following a comprehensive analysis, the honeycombs were found to exhibit sensitivity to defects, which caused changes in their in-plane compressive mechanical performance, besides the reduction in their overall mechanical properties (including yield strength and Elasticity Modulus values). Furthermore, they noted that researchers should be mindful of fabricating via ME honeycombs that may have intricate geometric features, as the fabrication toolpath or nozzle travel path might induce microscopic or macroscopic defects.

3. Influence of manufacturing parameters

Basurto-Vázquez *et al.*, (2021) investigated experimentally the influence of varying manufacturing parameters on the in-plane compressive performance of ME polymer honeycombs. In particular, they have varied infill density between 30 and 100%, and print orientations, upright, on-edge and flat, whilst keeping constant, amongst others, print bed temperature, layer height and raster angle. Their experimental results indicated that the honeycomb structures produced with 100% infill density outperformed their counterparts. They have also highlighted the need for optimisation when selecting the ME manufacturing parameters in view of achieving enhanced energy absorption capacity. In terms of the failure modes, Basurto-Vázquez *et al.* (2021) noted that the failure mode of ME honeycombs depends primarily on the fabrication orientation and on the infill density, with those printed “upright” with 100% infill density exhibiting a more stable deformation mode (i.e. ductile fracture with progressive folding). Panda *et al.* (2018) varied the honeycomb’s wall thickness and cell size whilst retaining layer thickness, print orientation and raster angle unchanged. Their experimental and computational results suggest that the yield strength and the Elasticity Modulus decreases with an increasing cell size. They have recommended that by retaining the wall thickness size at ~3 mm and the cell size at ~4 mm it is possible to improve the compressive response of the honeycomb.

Other than the ME and PBF process commonly employed to produce metal honeycombs, another AM process is DED, with an example of that being the Laser-Engineered Net Shaping (LENS) technique. Unlike the PBF process, powder is extruded from the nozzle during the LENS DED fabrication process (Prasad and Kumar, 2021). In their attempt to optimise the mechanical performance of as-built and heat-treated DED Ti-6Al-4V honeycomb structures, Baranowski *et al.* (2019) employed the LENS technique to produce honeycombs with two different cell sizes, 3 mm and 5 mm. As expected, the heat-treated honeycombs exhibited superior mechanical performance when compared to the as-built ones. Antolak-Dudka *et al.* (2019), building upon the work of Baranowski *et al.* (2019), concluded that heat treatment facilitates an improved energy absorption capacity for DED Ti-6Al-4V honeycombs, besides preventing brittle failure when operating under compression.

Further honeycomb improvement methods have been explored by Ahsan and Khoda (2021) and Pollard *et al.* (2017). In particular, Ahsan and Khoda (2021) have found that superior mechanical properties can be achieved for ME polymer honeycombs, besides preserving geometrical accuracy. Thus, they proposed a "continuous honeycomb toolpath scheme" with a unique stacking pattern, i.e. "three distinct layers of parallel kinked lines" connected in a zigzag pattern during the fabrication process compared to standard stacking and printing sequence. Depending on the honeycomb architecture employed, Ahsan and Khoda (2021) highlighted that the proposed fabrication method could introduce anisotropic mechanical characteristics to the structure when under compression. On the same premise, Pollard *et al.* (2017) studied the relationship between fabrication toolpath and the subsequent mechanical performance of ME polymer honeycombs, further confirming that the print toolpath can influence mechanical properties substantially.

4. Geometry optimisation

Various geometry optimisation techniques have been developed and used by AM researchers and engineers to enhance the in-plane compression response of different types of honeycombs. In the following sections, a review of these techniques is presented, in reference to the honeycomb structures most commonly reported in the published literature. These structures are illustrated schematically in Figure 4 and discussed in detail in the sequel.

4.1 Auxetic structures

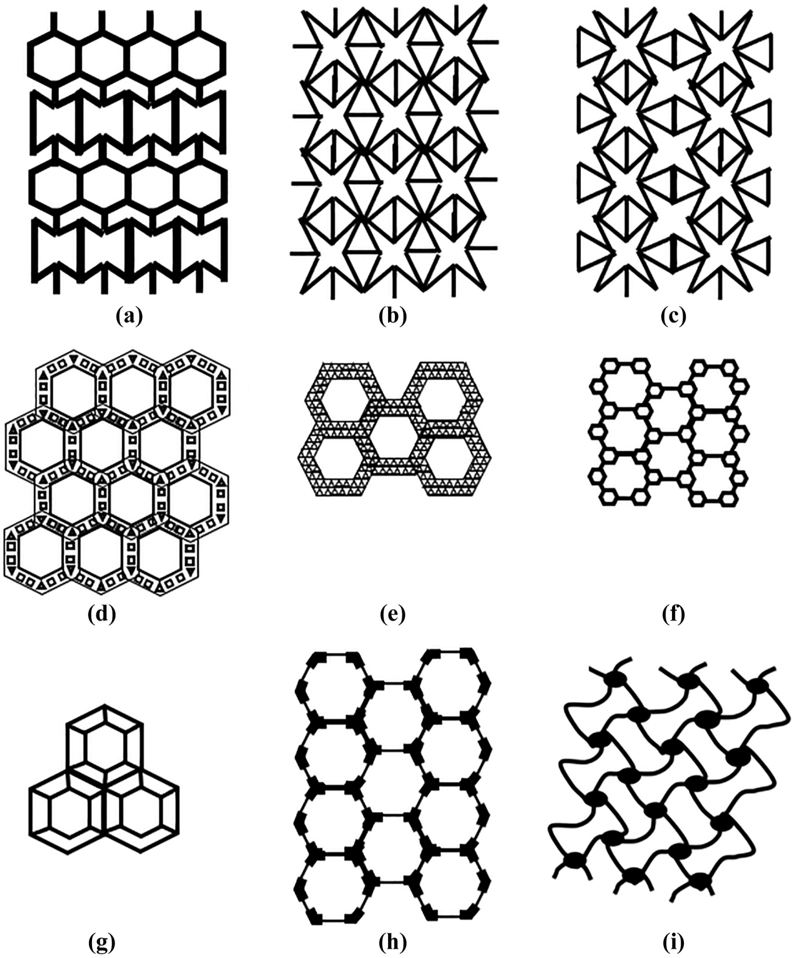
Xu *et al.* (2019a) proposed a novel auxetic hexagonal (AuxHex) structure, consisting of both honeycomb and auxetic cells [Figure 4(a)]. Following an experimental, theoretical and computational analysis, polymer (Nylon-12) AuxHex structures fabricated via MJ were found to exhibit significant improvements in collapse stress and stiffness (both at >16%) and over 38% enhancement in specific energy absorption capacity (in the in-plane direction), compared to the regular honeycombs they similarly studied. Thus, Xu *et al.* (2019a) recommended further research to gain additional insights into the mechanical behaviour of the new AuxHex structure. Following this recommendation, Xu *et al.* (2020) conducted an experimental and computational study on the metallic AuxHex honeycomb by utilising PBF-produced Stainless Steel 304 structures, reporting similar findings in terms of superior in-plane compressive properties. Other types of auxetic honeycombs examined for improved mechanical properties include those in star-like arrangement, such as shown in Figure 4(b) and Figure 4(c) and investigated by Wei *et al.* (2021b).

4.2 Hierarchical structures

Chen *et al.* (2018) investigated the in-plane compressive behaviour of ME polymer hierarchical honeycombs consisting of triangular lattices (instead of regular cell walls) [Figure 4(e)]. Their experimental results suggest all-around improved mechanical properties, both in terms of recoverability (i.e. stiffness) and energy absorption, when compared to regular honeycombs. Mansour *et al.* (2019) conducted a similar study, focussing on hierarchical honeycomb structures with cells at the nodes (*in lieu* of regular nodes) and with struts/cell walls connecting the cells [Figure 4(f)]. Following in-plane quasi-static compression tests, these hierarchical honeycombs were able to sustain deformation and to resist the compressive loads better than their regular counterparts. Mishra and Kumar (Mishra and Kumar, 2021) attributed their enhanced performance to the bending-dominated structure infill, i.e. the presence and distribution of secondary honeycomb unit cells across the structures (Figure 4g).

4.3 Topology-optimised structures

Taking advantage of the flexibility offered by AM, Zhang *et al.* (2020) achieved significant improvements in the mechanical performance of VP polymer honeycombs by introducing thickened joints across their cells [Figure 4(h)]. Following testing and computational analysis, the thickened honeycomb design was found to be suitable for optimising/



Note(s): (a) Auxetic hexagonal (AuxHex) structure (Xu *et al.,* 2019, 2020); (b) Auxetic star honeycomb (Wei *et al.,* 2021a); (c) Auxetic star-triangular honeycomb (Wei *et al.,* 2021b); (d) Bamboo biomorphic structure (Ufodike *et al.,* 2021); (e) Hierarchical honeycomb with triangular lattices (Chen *et al.,* 2018); (f) Hierarchical honeycomb consisting of honeycomb cells at the nodes (Mansour *et al.,* 2019); (g) Hierarchical honeycomb with an infill of secondary unit cells (Mishra and Kumar, 2021); (h) Honeycomb with thickened joints (Zhang *et al.,* 2020); (i) Triply period minimal surface (TPMS) topology-optimised gyroid-based structure (Maskery and Ashcroft, 2020)

Figure 4.
Schematic representation of honeycombs proposed and commonly studied in the literature

tailoring the mechanical properties. Interestingly, the thickened joint approach is comparable to the topology optimisation (TOP) technique, commonly employed in the literature for other types of lattice structures, including face-centred cubic (FCC) and body-centred cubic (BCC) lattices (Obadimu and Kourousis, 2021). A TOP technique can optimise the geometrical characteristics of lattice structures (dimensions of the members) so as to achieve an improvement of the overall mechanical behaviour. In parallel, TOP reduces the material wastage during the AM fabrication process, by minimising the unused material, with no or minimal effect on the integrity of the structure (Xiao *et al.*, 2018; Xu *et al.*, 2019b).

The triply periodic minimal surface (TPMS) technique has also been effective in achieving enhanced mechanical performances. Unlike the TOP approach, strictly based on engineering judgement, TPMS uses a unit cell optimisation algorithm on the basis of the Weierstrass numerical formulation, amongst other mathematical algorithms. This enables design engineers to vary the volume fraction, the size of the unit cell and, overall, the lattice's geometrical characteristics and dimensions (Yan *et al.*, 2015). By employing TPMS, Maskery and Ashcroft (Maskery and Ashcroft, 2020) investigated the in-plane compressive performance of TPMS gyroid-based honeycombs with curved walls [Figure 4(i)]. Although the structures exhibited loading direction-dependent anisotropy, the honeycomb design possessed unique plastic deformation characteristics in addition to their tailorable (compressive) properties, offering attractive benefits for blast or impact protection.

4.4 Biomorphic structures

Ufodike *et al.* (2021) proposed bio-inspired (denoted as biomorphic) honeycombs, resembling the structure of the bamboo plant, towards achieving enhanced in-plane compressive mechanical performance [Figure 4(d)]. They have reported up to four times higher energy absorption capacity and a more uniform stress distribution than the regular honeycombs under the same compressive loading conditions (Ufodike *et al.*, 2021).

5. Conclusions

Ample research has been devoted in exploring the mechanical performance of AM honeycomb structures fabricated from metal (with most fabricated via laser PBF), as well as polymer materials (the majority is fabricated via ME). Other than the laser PBF and the ME AM process, VP (Zhang *et al.*, 2020) and DED (Antolak-Dudka *et al.*, 2019; Baranowski *et al.*, 2019) are other choices, which indicates some diversity in the AM processes used for the production of honeycomb structures for a variety of applications. A classified summary of the types of materials, AM methods and honeycomb types reviewed in the present paper is presented schematically in Figure 5, with the corresponding frequencies also indicated.

The effect of the honeycomb's relative density, cell size and cell wall thickness on mechanical behaviour is of note. Simulating and predicting the mechanical response of honeycombs depends on these features. For example, the honeycomb's cell size has been widely reported to influence the overall mechanical properties (Antolak-Dudka *et al.*, 2019; Baranowski *et al.*, 2019; Panda *et al.*, 2018). Researchers have also identified that by varying unit cell size will affect not only their mechanical properties, but also their deformation modes when subjected to compressive loading. In summary, the following important insights result from the analysis of the effects:

1. The mechanical characteristics of honeycombs, including compressive properties, can be improved by heat treatment;
2. There is a relationship between the honeycomb's relative density and the resulting mechanical performance, including energy absorption capacity;
3. The process of energy absorption can be controlled by varying wall thickness and introducing optimised unit cells, such as bamboo biomorphic micro-unit cells;
4. The ME fabrication toolpath induces defects in honeycomb structures, which subsequently affects their mechanical performance.

The repeatability of the AM process for the production of lattice structures, including honeycombs, has been questioned owing to the variation between CAD drawings and the

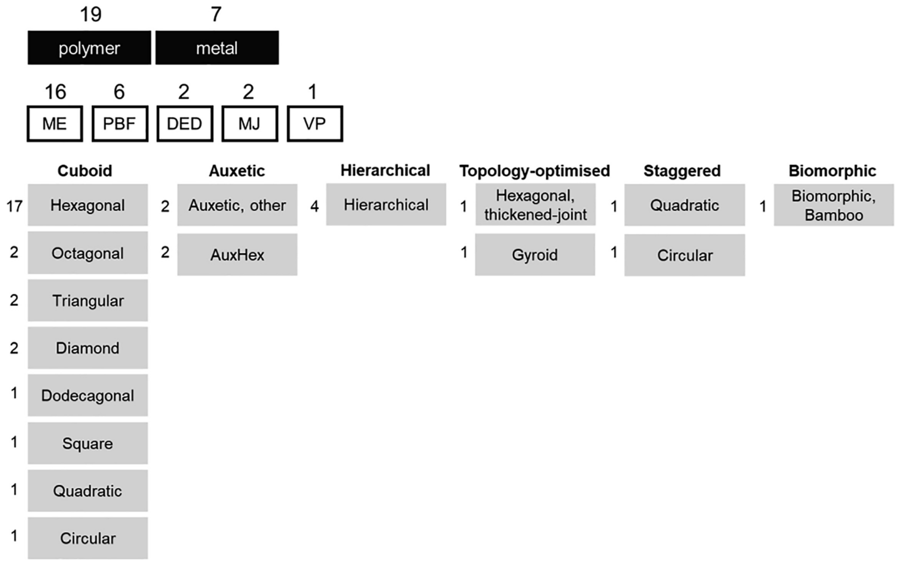


Figure 5.
Classified summary of the present literature review's findings on the types of materials, AM methods and honeycombs are listed, with corresponding frequencies also indicated

produced structures/parts. These key issues have continued to impede the application of AM parts/components in safety-critical systems. Hence, the need to further mitigate process-induced irregularities is discussed in the literature (Baranowski *et al.*, 2019; Hedayati *et al.*, 2016b).

The study of the in-plane compressive behaviour of honeycombs has not been restricted to experimental analysis. Both empirical models (Habib *et al.*, 2017; Hedayati *et al.*, 2016a, b) and FEA models (Hedayati *et al.*, 2016a, b; Hussein *et al.*, 2020; León-Becerra *et al.*, 2021) have been reported to achieve sufficiently accurate results, in terms of predicting and simulating the mechanical response of AM honeycombs. Nevertheless, the predicted mechanical properties can deviate from the experimental values owing to the sensitivity of the models to geometric irregularities, including variation between the CAD drawings and the fabricated structures (i.e. observed from deviations in cell wall thickness, etc.). This confirms the calls from Hedayati *et al.* (2016b), Rahman *et al.* (2017) and Leary *et al.* (2016) to the AM researchers to be mindful during the fabrication of the parts, their experimental analysis and when using empirical/mechanistic models for prediction purposes. It is characteristic, for example, that Hedayati *et al.* (2016b) proposed empirical models specifically for thick honeycomb structures.

The regular (hexagonal) honeycomb structure is amongst the most popular choices of geometries as found widely in the literature. However, AM researchers have proposed other honeycomb models, such as the hierarchical, AuxHex, auxetic star and bamboo biomorphic honeycomb structures due to the better mechanical properties that they may offer than common/regular honeycombs.

Techniques employed for structural optimisation purposes have been geared around varying fabrication (process) parameters (i.e. laser power and scan speed for PBF methods and raster angle and nozzle extrusion temperature for ME methods) and (part) design characteristics, as they are both considered very influential. Examples of optimisation approaches and outcomes include the proposed use of thickened joints and the introduction of new and complex honeycombs.

The overall findings of this literature review are summarised and briefly commented in Table 1.

Table 1. Summary reviewed literature, with details provided on research focus, recommendations/challenges/future work, materials and methods used and type of honeycomb structured studied

Publication reference	Research focus	Recommendations/Challenges/Future work	Material(s) studied		Additive manufacturing method	AM equipment	Type of honeycomb
Ahsan and Khoda (2021)	Effectiveness of the continuous honeycomb toolpath scheme for honeycomb fabrication	Further research on honeycombs fabricated via the proposed continuous honeycomb toolpath scheme	Polymer	Polylactic acid (PLA), Thermoplastic Polyurethane (TPU)	Material Extrusion (ME)	Creality Ender-3 Pro	Hexagonal
Antolak-Dudka *et al.* (2019)	Energy absorption capability of LENS fabricated honeycombs subjected to quasi-static and dynamic loading	Observed that honeycombs with high relative density are sensitive to strain-rate effects. Thus, recommended designing honeycombs with low relative density to minimise the effects of impact force during the early stages of deformation	Metal	Ti-6Al-4V	Directed Energy Deposition (DED)	Optomec LENS MR-7	Hexagonal
Baranowski *et al.* (2019)	Compressive behaviour of LENS fabricated honeycombs under quasi-static loading	Recommended compression of LENS honeycombs under dynamic loading rates. Also, to study the influence of manufacturing parameters on mechanical performance	Metal	Ti-6Al-4V	Directed Energy Deposition (DED)	Optomec LENS MR-7	Hexagonal
Basurto-Vázquez *et al.* (2021)	Influence of varying manufacturing parameters on the compressive performance of honeycombs	Recommended optimum combination of manufacturing parameters to achieve excellent mechanical properties	Polymer	Polyethylene Terephthalate Glycol (PETG)	Material Extrusion (ME)	Zortrax M200 Plus	Hexagonal
Chen *et al.* (2018)	In-plane compressive performance of AM hierarchical honeycombs	To explore other AM techniques to fabricate hierarchical honeycombs	Polymer	VeroWhite (opaque PolyJet resin)	Material Jetting (MJ)	Stratasys Objet260 Connex	Hexagonal, Hierarchical
Habib *et al.* (2017)	In-plane quasi-static compressive behaviour of AM polymeric honeycombs	Additional work to study the compressive behaviour of the honeycombs under dynamic loading rates	Polymer	Nylon-12 (Polyamide PA2200)	Material Extrusion (ME)	Stratasys Fortus 450mc	Hexagonal

(*continued*)

Table 1.

Publication reference	Research focus	Recommendations/Challenges/ Future work	Material(s) studied		Additive manufacturing method	AM equipment	Type of honeycomb
Habib *et al.* (2018)	Effect of cell topology on compressive performance	There is a correlation between honeycomb cell topology and their compressive performance	Polymer	Nylon-12 (Polyamide PA2200)	Material Extrusion (ME)	Not Applicable (simulation only)	Hexagonal, Quadratic, Circular, Quadratic, Octagonal, Dodecagonal, Triangular, Diamond
Hussein *et al.* (2020)	Experimental and theoretical analysis of the elasticity moduli of laser PBF honeycombs	Further investigation is required for complete modelling of honeycomb cellular structures	Metal	Stainless Steel 304	Powder Bed Fusion (PBF)	Renishaw AM250	Hexagonal
Joseph *et al.* (2021)	Load-rate effect on the in-plane compressive characteristics of ME honeycombs	Recommended using their research findings as a basis for similar honeycomb studies	Polymer	Polylactic acid (PLA), Acrylonitrile Butadiene Styrene (ABS)	Material Extrusion (ME)	Anycubic i3 Mega	Hexagonal
León-Becerra *et al.* (2021)	Effect of relative density on in-plane compressive performance	Noted that experimental and FEA compression results can also be validated via analytical models	Polymer	Polylactic acid (PLA)	Material Extrusion (ME)	Geeetech A10	Hexagonal, Square, Triangular
Mansour *et al.* (2019)	In-plane compressive performance of AM hierarchical honeycombs	Further studies into hierarchically honeycombs and varying cell wall thicknesses	Polymer	Polylactic acid (PLA)	Material Extrusion (ME)	Ultimaker 2+	Hierarchical
Maskery and Ashcroft (2020)	Compressive performance of TPMS-based honeycombs	Proposed further application of TPMS-based honeycombs	Polymer	Nylon-12 (Polyamide PA2200)	Powder Bed Fusion (PBF)	EOS P100	Triply periodic minimal surface (TPMS)-based gyroid
Mishra and Kumar (2021)	In-plane compressive performance of AM hierarchical honeycombs	Inserting reinforcing walls into honeycombs unit cells improves compressive performance	Polymer	Polylactic acid (PLA)	Material Extrusion (ME)	Global 3D Labs (unspecified model)	Hierarchical

(continued)

Table 1.

Publication reference	Research focus	Recommendations/Challenges/ Future work	Material(s) studied		Additive manufacturing method	AM equipment	Type of honeycomb
Obadimu and Kourousis (2022)	Effect of strain rate and cell size on honeycombs	Quasi-static load rates influence compressive behaviour; Variation of cell size can optimise compressive behaviour	Metal	Stainless Steel 316L	Material Extrusion (ME), Powder Bed Fusion (PBF)	GE Concept Laser Mlab cusing R	Hexagonal
Panda *et al.* (2018)	Impact of cell size on the compressive performance of honeycombs	Varying manufacturing parameters and studying other types of cellular structures	Polymer	Acrylonitrile Butadiene Styrene (ABS): ABS P400	Material Extrusion (ME)	Stratasys Dimension SST 1200es	Hexagonal
Pollard *et al.* (2017)	Mechanical properties of ME honeycomb structures fabricated via different toolpath	Confirmed that print toolpath indeed affects the compressive behaviour of ME honeycombs. Recommended exploring other forms of mechanical testing, including impact and torsion testing and further investigations using alternative ME materials	Polymer	Polylactic acid (PLA), Acrylonitrile Butadiene Styrene (ABS)	Material Extrusion (ME)	BFB RapMan 3.2	Hexagonal
Rahman *et al.* (2017)	In-plane stiffness of AM hierarchical honeycombs	Care should be taken when employing the ME process in order to reduce process-induced defects	Polymer	Acrylonitrile Butadiene Styrene (ABS): ABS P400	Material Extrusion (ME)	Not specified	Hexagonal, Hierarchical
Hedayati *et al.* (2016a)	Mechanical properties of octagonal honeycombs	FEA and analytical model show good agreement with experimental results. The former can also be used to predict compressive properties of lattices	Polymer	Polylactic acid (PLA)	Material Extrusion (ME)	MakerBot Replicator	Octagonal
Hedayati *et al.* (2016b)	Compressive properties of thick honeycombs	Proposed analytical equations for thick honeycombs	Polymer	Polylactic acid (PLA)	Material Extrusion (ME)	MakerBot Replicator	Hexagonal

(*continued*)

Table 1.

Publication reference	Research focus	Recommendations/Challenges/ Future work	Material(s) studied		Additive manufacturing method	AM equipment	Type of honeycomb
Ufodike *et al.* (2021)	Design and modelling the in-plane compressive performance of bamboo biomorphic structure	Process of energy absorption can be controlled by varying wall thickness and introducing bamboo biomorphic micro-unit cells	Polymer	Acrylonitrile Butadiene Styrene (ABS): ABS P400	Material Extrusion (ME)	Dremel DigiLab	Hexagonal, Bamboo Biomorphic
Wei *et al.* (2021b)	Compressive performance of auxetic star-triangular honeycombs	Observed that "STH" honeycombs are loading direction dependent	Metal	Stainless Steel 316L	Powder Bed Fusion (PBF)	Not specified	Auxetic
Wei *et al.* (2021a)	Compressive performance of auxetic star honeycombs	Recommended varying the topology of STH structures according to requirements to achieve optimum mechanical properties	Metal	Stainless Steel 316L	Powder Bed Fusion (PBF)	Not specified	Auxetic
Zaharia *et al.* (2020)	Compressive performance of cellular structures with different topologies	The type of cell topology employed influences the failure mechanism of the structure	Polymer	Polylactic acid (PLA)/ Polyhydroxyalkanoate (PHA)	Material Extrusion (ME)	BCN3D Sigma D25	Hexagonal, Diamond
Xu *et al.* (2019a)	In-plane mechanical performance of polyamide "AuxHex" structures	Additional work to further study and improve the mechanical properties of "AuxHex" structures	Polymer	Nylon-12 (Polyamide PA2200)	Material Jetting (MJ)	Stratasys Object350 Connex3	Auxetic Hexagonal (AuxHex)
Xu *et al.* (2020)	In-plane mechanical performance of SS304 Auxhex structures	Recommended using "AuxHex" structure design for multifunctional applications	Metal	Stainless Steel 304	Powder Bed Fusion (PBF)	Techgine TZ-TS300 A	Auxetic Hexagonal (AuxHex)
Zhang *et al.* (2020)	Compressive behaviour of thickened-joint honeycombs	Recommended further design and use of thickened-joint honeycombs for structural applications	Polymer	Somos EvoLVe 128 (Stereolithography (SLA) resin)	Vat Photopolymerisation (VP)	Lian Tai RS Pro600	Hexagonal, thickened-joint

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