International Journal of Sustainable Transportation Technology
Vol. 5, No. 2, October 2022, 70-79

Cellular Structure Design and Manufacturability for Electric Vehicle: A Review

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Abstract

Cellular structures can be classified into foams, honeycombs, and lattice structures. Each type of structure has its characteristics. Various applications of cellular structures can be found in aviation, bioengineering, automotive, and other fields. In the automotive sector, cellular structures have been used for structural applications and impact-absorbing modules, for example, for protecting the electric vehicle battery pack against impact loading. The challenges that limit the application of cellular structures today include systematically designing pseudo-random cellular structures, assessing which cellular patterns are most suitable for a particular application, and mastery of manufacturing technology for efficient mass production of cellular structures. In this paper, the authors examine the state-of-the-art technology in geometry, applications, and manufacturing of various cellular structures carried out by researchers to obtain an overview of the current conditions for further development of these cellular structures. Limited manufacturing capabilities encourage researchers to design an optimal cellular structure to be applied to a particular function but have high manufacturability. The development of additive manufacturing technology has provided opportunities for researchers to produce an optimal cellular structure commercially soon.

Keywords

Cellular structure; Design; Applications; Manufacturability; Electric vehicles

1 Introduction

According to Bhate et al. [1], cellular structures are defined by a unit cell that is some combination of material, space, and unit cell repetition to obtain a large structure or surface. It can be classified into foams, honeycombs, and lattice structures [2]. Each type of structure has its characteristics and peculiarities. Nature has provided researchers with examples of cellular structure design, so the adoption of cellular structure from various types of plants and animals that can adapt to the environment has been widely carried out. Recently, the development of engineering technology and product manufacturing has been overgrown. Currently, the focus of design and manufacturing is on lightweight products that still have good performance according to their function. The adoption of structures from plants and animals has begun to be carried out by engineers and researchers in recent decades [3], [4]. Various types of structures that have been tested generally refer to cellular structures. Cellular structures are defined by a unit cell that combines material, space, and unit cell repetition to obtain a large structure or surface [1]. Several challenges limit the application of cellular structures, including the lack of understanding of the bulk behavior, a methodology for designing cellular structures, approach methods for assessing which cellular patterns are most suitable for a particular application, and mastery of manufacturing technology for cellular structures [1].

Many studies on cellular structure have been carried out, but there is a gap in the unique structures designed for specific needs. Thus, the study of cellular structure is still fascinating and can be developed. The application of the cellular structure in the automotive sector has begun to be applied by engineers, as in [5]–[7]. The application of cellular structures is not only limited to Internal Combustion Engine (ICE) vehicles. However, it is also applied to electric vehicles (EVs) considering the characteristics of this structure, which are rigid, light, and able to absorb kinetic energy.

This paper reviews the state-of-the-art development, manufacture, and application of various types of cellular structures, particularly the prospect of structure, crashworthiness, battery protection, and thermal management for electric vehicles. This review is part of the research on developing a cellular structure applied to structural crashworthiness for electric vehicles with good manufacturability.

2 Methodology

The significant benefit of the cellular structure is to put materials only where it is needed, especially for a

Received August 14, 2022, Revised August 19, 2022, Accepted for publication October 21, 2022

particular application. An essential characteristic of the cellular structure is its relative density, defined as the ratio of the density of the cellular structure to the solid material from which it is made [8]. Examples of cellular structures can be seen in Figure 1 to Figure 3. The design of cellular structures can be carried out in three approaches. The first is analytical, in which the behavioral principles of the structure are modeled in the form of a mathematical model. The second approach is empirical, in which engineers perform experiments or computations to develop predictive models or compare one material with another. The third approach involves the use of computational tools. In practice, a combination of these approaches may be most helpful, particularly in more complex multi-objective contexts.

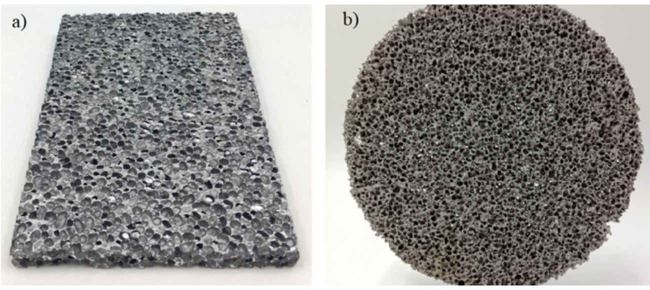

Figure 1 Typical metal foam structures: a) closed cell foam b) open cell foam by China BeiHai corp. (accessed on August,10th 2022) [9]

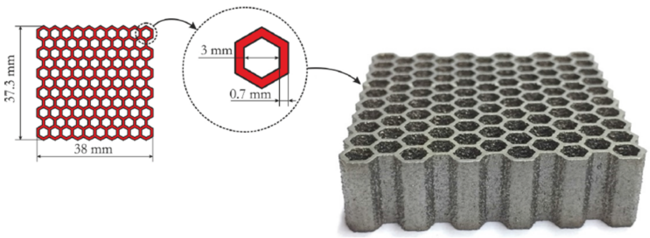

Figure 2 Typical type of honeycomb structure [10]

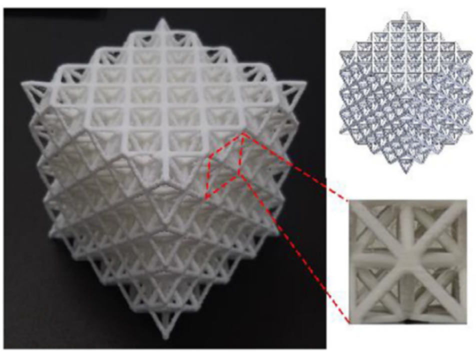

Figure 3 Typical type of lattice structure [11]

There are four main questions in the design of a cellular structure, namely: what are the optimum average size of unit cells, how should the size of the cells vary spatially, what are the optimum cell parameters, and how best should the cells be integrated with the larger form [12]. Unit cells can be designed by many different methods, such as implicit surface-based, primitive-based, and topology optimization methods.

2.1 Foam-type cellular structures

Metal foam is a cellular structure consisting of a solid metal primarily porous. The foam-type structure offers the potential for a lightweight structure. It has a unique combination of properties, such as impact energy absorption capacity, ability to flow fluids, unusual acoustic properties, low thermal conductivity, and good electrical insulation properties. Their applications include shock and impact absorbers, dust and fluid filters, engine exhaust mufflers, porous electrodes, high-temperature gaskets and seals, heaters and heat exchangers, flame arresters, catalyst supporters, and others.

Many researchers have carried out various studies related to metal foam. Santosa and Wierzbicki performed the crushing behaviour of a truncated cube model as a closed-cell aluminium foam structure that applies [13]. Chin-Jye Yu and John Banhart found a strong relationship between elasticity and density. It was also known that the damping ability of the foam would increase as the density of the metal foam decreased [14]. The density of the foam will determine the deformation behaviour that occurs. Researchers have used metal foam as a beam filler as a solution to increase rigidity and energy absorption when the beam is under load. Many researchers studied the effect of aluminium foam-filled tubes of ellipse, circle, square, and conical cross-sections in energy absorption and specific energy absorption, as in [15]–[18]. Metal foams have also been extensively studied for sandwich construction cores [19]–[21]. Experimental and numerical test results show that foam-filled beams have significantly improved bending or torsional resistance. Several selected papers related to foam-types cellular, which the researcher develops, can be seen in Table 1.

There are several recommendations for designing a sandwich structure with a metal form as a core from Ashby [22] that need to be considered, including (1) determining the boundary conditions in the structure and the required stiffness or strength limits; (2) if the stiffness limitations are required, determine the minimum limits using the appropriate equation, set explicitly where the construction costs and the ratio are concerning with the construction; (3) when the required strength is limit (especially when buckling is limited), the rules governing the sandwich structure are still not well formulated so that a numerical method is needed to compare and distinguish the type of construction with rigid construction. It is recommended to carry out detailed simulation and testing to assess the feasibility of sandwich construction.

Table 1 Research topics related to foam-type cellular structure

Research Study	Methods	Author
Mechanical Properties of Metallic Foams	Experimental	Yu 1998 [14]
Crushing response of foam-filled: thin-walled square columns, conical tubes, different cross-sections, graded layer, taper structure,	Experimental, Analytical, Numerical	Ahmad 2009 [16], Shojaeifard 2012 [15], Djamaluddin 2019 [23],
Investigation of metal foam-composite hybrid structures	Experimental, Numerical	Sun 2018 [24]
Processing functionally graded polymer foam	Review	Suethao 2020 [25]
Response of foam or graded sandwich panel	Experimental, Numerical	Santosa 2017 [20], Pratomo 2021 [21]

2.2 Honeycomb-type cellular structures

The term honeycomb is inspired by a bee cage which is then used to describe each repeating cell which is generally hexagonal. However, honeycomb shapes are not limited to hexagonal shapes but can also be triangular, square, or rhombic [8]. The difficulty of studying the complex form-type cellular is one of the reasons the use of honeycomb-type cellular is more popular and has been studied by many researchers. Honeycombs are much more accessible. Large-scale models can be made of rubber, plastic, metal, and ceramic. Due to the regular geometry of honeycombs, the deformations that occur can be analyzed precisely to obtain equations that describe their properties. Wierzbicki has theoretically studied the damage response of metal honeycombs to predict the mean crushing force of thin-walled structures [26]. Aminanda *et al.* have investigated the honeycomb structure made by Nomex^{TM}, aluminum alloy, and paper through testing to understand the crushing mechanism [27]. Various bio-inspired engineering of honeycomb structures has been studied by Zhang *et al*. [28]. As well as metal foam, the honeycomb structure is widely studied by researchers as a sandwich core to determine its response and characteristics due to impact loads analytically, experimentally, and numerically [29]–[32]. Exploration of honeycomb structures is currently developing and is inspired by origami and auxetic designs such as those developed in [33]–[35]. Several selected research studies related to honeycomb cellular types can be seen in Table 2.

Liu proposed the design method for a two-level stochastic honeycomb structure [36]. Firstly, determine the initial parameters of the honeycomb structure design, then perform finite element analysis on the initial structure (determine boundary conditions, loads, and material properties, complete meshing, and create a finite element model). Next, calculate the performance index, stress distribution function, and centroidal Voronoi Tessellation (CVT) density distribution function, then perform finite element analysis again on the structure. Next, calculate the total reduction area, determine the total removal material and calculate the material area that must be added to the design. If the results are still not satisfying, return to the finite element analysis step until the appropriate results are obtained.

Table 2 Research topics related to honeycomb-type cellular structure

Research Study	Author
The effect of honeycomb thickness	Becker1998 [37]
The effect of honeycomb relative density	Balawi 2008 [38]
Comparison of honeycomb structure with various cell and or reinforced	Yin 2011[39], Wang 2015 [40]
Honeycomb sandwich panels	Yahaya 2015 [30], Sun 2018 [41], Roudbeneh 2018 [32]
Hierarchical honeycomb structures	Yin 2018 [42], Zhang 2018 [43]
Optimization of two-level stochastic honeycomb structure	Liu 2019 [36]
Characteristics of origami-inspired honeycomb sandwich structures	Dong 2019 [33], Townsend 2020 [34], Jiaqi Qi 2021 [35]

2.3 Lattice-type cellular structures

The lattice structure is defined as an object in the form of a unit cell, generally made of a continuous repeating bar structure that is interconnected in three dimensions [44]. In general, the lattice structure can be divided into three types: randomized, uniform, and pseudo-periodic [45]. These types of lattices can be seen in Figure 4. The shape and size of randomized lattice cells are randomly distributed in the design domain. Unlike randomized lattice structures, uniform lattice structures consist of periodically distributed unit cells with the same shape, topology, and size. Thus, every cell in this type of lattice structure has the same topology and size. The uniform lattice structures can be further divided into homogeneous uniform and heterogeneous uniform lattice structures. The homogeneous lattice structure means all the struts (3D lattice) or walls (2D lattice) have the same thickness. In contrast, the thickness of the strut or wall inside a heterogeneous lattice varies over the entire structure. The third type of lattice structure is called pseudo-periodic lattice structures, where the size and shape of lattice cells in the design space vary, though sharing the same topology to achieve some unique properties.

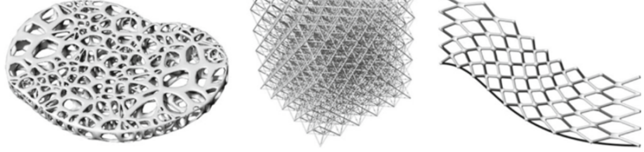

Figure 4 Three different of lattice structures [45]

The rapid development of additive manufacturing (AM) technology allows researchers to produce a complex and reliable lattice structure. Yan *et al.* [46] researched the development of manufacturing capability and performance of periodic cellular structures fabricated by direct metal laser sintering (DMLS) using an aluminum alloy, AlSi10Mg, as a pioneer. The lattice structure is designed by repeating a type of unit cell called a "diamond". Although many studies have been carried out using additive manufacturing processes, many problems are associated with applying lattice structure manufacturing techniques. The additive manufacturing process significantly affects the shape and functionality of the specimens produced. Many researchers have used Additive Manufacturing technology to investigate the properties and characteristics of the lattice structure. Several selected papers related to these can be seen in Table 3.

Dong has proposed a design procedure used to design a hybrid structure that is divided into two stages [47]. The initial stage is to determine the design space and non-design space. Then, perform topology optimization to divide the design space into solid and lattice spaces. The second stage is designing the lattice structure by selecting the topology of the lattice, modifying the wireframe lattice, and optimizing the thickness of the strut. Furthermore, the lattice structure is generated from the wireframe design and strut diameter. In the last step, the lattice structure is connected to the solid space to produce a hybrid lattice structure.

Table 3 Research topics related to lattice-type cellular structure

Research Study	Author
Design and or investigation of Lattice Structure	Pan 2020 [2], Wang 2020 [48], Nasrullah 2020 [49], Nashar 2021 [50]
Investigation of Lattices structure made by AM	Tang 2019 [45], Caprio 2019 [51], Zhao 2020[52], Do 2021 [53]
Investigation of Lattices structure made by AM – Selective Laser Melting (SLM)	Lozanovski 2019 [54], Sienkiewicz 2020 [55], Jiang 2021 [56]
Investigation of Lattices structure made by AM– Fused Deposition Modeling (FDM)	Egan 2019 [57], Patel 2020 [58], Dong 2020 [47], Sun 2021 [11]
Investigation of Lattices structure made by AM - Stereolithography (SLA)	Laird 2019 [59], Hassanieh 2021 [60], Silva 2021 [61],
Behavior of lattice structures made by Metal AM	Choy 2017 [62], Köhnen 2018 [63], Rosa 2018 [64],

3 Manufacturing Process

The manufacturing process of cellular structures is highly dependent on the type of cellular, the type of material, and the complexity of the unit cell. Conventional methods of fabricating metallic porous structures include melt gas injection [65], investment casting [66], physical vapor deposition [67], and sheet metal technology [68].

However, the shape of the lattice structure is still challenging to manufacture by these conventional methods. Technological developments led to Additive Manufacturing (AM) technology, such as selective laser melting (SLM) [69] and electron beam melting (EBM) [70], Metal lattice structures with complex geometries can now be manufactured.

The Additive Manufacturing techniques allow the creation of objects with complex shapes based on the process of joining materials, layer upon layer, differently from subtractive manufacturing methods. Hence, complex geometries can be directly manufactured in a single setup, rather than the tedious multiple setups of conventional subtractive machining. More importantly, the manufacturability-related complexity restrictions in designing the geometry have been mainly eliminated because of the additive approach. Therefore, AM leads to revolutionary changes in manufacturing and unleashes great opportunities for design-for-manufacturing. So far, AM has been applied to various areas, including health care, aerospace, architecture, and industrial heat transfer applications. On the other hand, the paradigm of design-for-manufacturing has not been timely examined, and most of the existing methods are still exclusively tailored for conventional manufacturing techniques.

A review of the characterization and impact of the lattice structure made through additive manufacturing has been carried out by Nagesha *et al.* [71]. A review of the Additive Manufacturing process used in the biomedical field has also been carried out by Martorelli *et al.* in [72]. However, concerning this biomedical field, it is reported that there are still obstacles, especially in the compatibility of some materials and mechanical properties that are not yet suitable. The identified cellular structure manufacturing processes for foam, honeycomb, and lattice structures can be seen in Table 4.

The Additive Manufacturing process most widely used by researchers is selective laser melting [73]. Dong et al. developed the concept of modelling the lattice structure using additive manufacturing technology [74], as shown in Figure 5.

Table 4 Manufacturing process of cellular structures

Foams	Honeycomb	Lattice
▪ Melt gas injection (air bubbling); ▪ Gas-releasing particle decomposition in the melt; ▪ Gas-releasing particle decomposition in semi-solids; ▪ Investment casting method used to manufacture open cell foams; ▪ Powder Metallurgy (slurry foaming, loose powder sintering, fibre metallurgy, sintering slurry saturated sponge); ▪ Metallic deposition; ▪ Sputter deposition;	▪ Sheet metal forming/folding ; ▪ Additive Manufacturing ; ▪ Expansion method; ▪ Corrugation method; ▪ Adhesive bonding; ▪ Resistance welding; ▪ Brazing ▪ Diffusion bonding; ▪ Thermal fusion;	▪ Additive Manufacturing : SLM, FDM, SLA, LBM, etc. ▪ Sheet metal forming/foldin g; ▪ Investment casting; ▪ Rapid-Investment Casting.

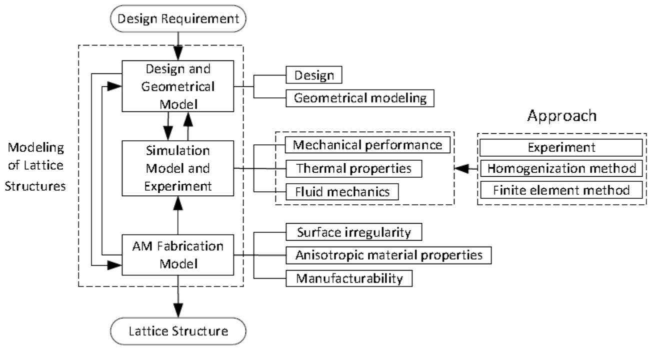

Figure 5 The concept of modeling of lattice structure for AM process [74]

AM technology capabilities provide new opportunities for highly significant improvements in product performance, multi-function, and lower overall manufacturing costs. These capabilities include Complexity of shape, Complexity of material, and Complexity of hierarchies [75]. Rosen proposed a concept called Design for Additive Manufacturing (DFAM) that can support part modelling, process planning, and manufacturing simulations. This method includes the solution of algorithms, analysis codes, libraries of materials and mesostructures, process planning, and analysis of the manufactured model. The concept of mesostructured materials is motivated by the desire to put material only where it is needed for a specific application. So for the development of the cellular structure, an important aspect to consider is how to make the cellular structure, especially related to the commercialization process in the future.

4 Applications

Researchers have found wide adoption in various applications such as sandwich panels, packaging, cooling layers, catalytic, and heat exchange [1]. On the other hand, cellular structures have also begun to be widely applied to vehicle structure construction, collision feasibility technology, and even cooling systems for batteries, power electronics, and electric motors.

Sandwich construction generally consists of a lightweight core of foam, honeycomb, or lattice sandwiched between two rigid surfaces. Sandwich structures are widely applied in many areas due to their superior energy absorption capacity, high specific stiffness, low density, high strength, and favourable mechanical properties. Sandwich structures using honeycomb have been investigated for many years, and currently, the focus of sandwich structure development is on using origami models as sandwich cores as in [33]–[35]. The sandwich structure has also been developed to protect armoured vehicles against bomb blasts [21]. The sandwich structure consists of three layers: the occupant side plate, aluminium foam core, and the struck side plate, as shown in Figure 6. Passenger side plates require high-strength materials such as 1100T, 1300T, and 1500T. At the same time, the side plate of the explosion source is used to absorb the energy of the explosion so that it uses medium-strength steel with high ductilities such as CR420 and HR550.

Using experiments and numerical simulations, Kim et al. [76] and Zhang et al. [77] thoroughly investigated some sandwich structures as shown in Figure .

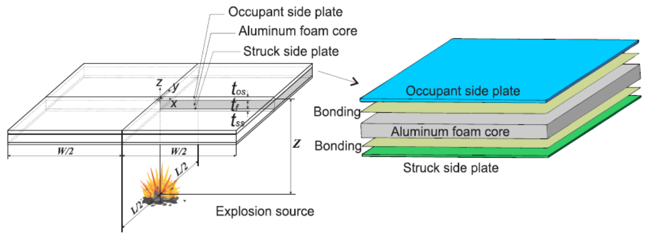

Figure 6 Sandwich structure construction [21]

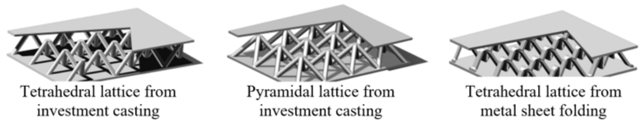

Figure 7 Multifunctional sandwich panels with metallic lattice cores [77]

This type of sandwich construction is widely used in engineering products or components. Other potential applications for cellular structures as reviewed in [22], [65], [78] can be seen in Table .

Table 6 Potential applications for cellular structures

Foams	Honeycomb	Lattice
▪ Automotive industry: structural light-weight panel, crash energy absorption, noise control, mechanical damping, etc. ▪ Aerospace industry: turbine blade, seals ▪ Ship building: elevator platforms, structural bulkheads, antenna platforms, pyrotechnic locker. ▪ Railway industry: crash energy absorption ▪ Building industry ▪ Machine construction: axles, rolls, platforms, structural body, etc. ▪ Sporting equipment: shinbone protectors ▪ Biomedical industry: ▪ Functional applications: filtration, heat exchangers, cooling machine, silencers, spargers, water purification, acoustic control, filter for oil, gasoline, refrigerants, polymer melts, aqueous suspensions, etc.	▪ Decoration material: aluminum honeycomb curtain wall composite board; ▪ Household appliances: air purifier grille ▪ Lighting industry: all kinds of lighting, traffic light barriers ▪ Audio industry: headphones, speakers, etc. ▪ Transportation industry: decorative materials such as carriages, train doors, partitions, etc. ▪ Furniture industry: office furniture, display furniture ▪ Architecture ▪ Chemical engineering ▪ Nanofabrication ▪ Biomedicine	▪ Automotive: Heat exchanger; ▪ Aerospace: Heat exchanger, Aircraft sections, Fan blades; ▪ Space telescope; ▪ Submarine bodies; ▪ Biomedical: Implant, Hip implant, Orthopedic implant, Bone scaffold, femoral stem, Bone implant;

4.1 Application for vehicle structure

The importance of the safety aspect and the need for a lightweight construction on the vehicle is something that cannot be avoided. Various efforts were made by researchers and engineers, ranging from determining vehicle dimensions to the application of cellular structures as vehicle structures. The structure of the vehicle is designed in such a way that it can absorb energy during a collision and must be able to protect passengers.

Zhang *et al.* [79] have developed a Negative Poisson's Ratio (NPR) vehicle body structure consisting of various materials and structures. Comparison with traditional materials and structures shows that vehicle bodies made of NPR structures have significantly higher shear strengths.

4.2 Application for vehicle crashworthiness

A vehicle's crashworthiness is the vehicle's ability to absorb energy at the time of a collision, according to the Motor Vehicle Safety Standards. The crashworthiness evaluation can be ascertained by a combination of tests and analytical methods based on numerical simulations. Passenger safety is the most important and challenging requirement in vehicle design.

Research on the investigation and development of crash boxes filled with gradient lattice structures has been carried out by Wu, Zhang, and Shao [80]. The force and energy absorption efficiency trend showed a better result. Li *et al.* have also developed the bumper, the crash box, and the front rail by applying the foam structure as a filler [81]. This study shows an increase in performance from the initial design. The foam-filled crash box can absorb impact energy better.

Researchers have widely published the ability of vehicle structures to protect passengers, cargo, or batteries in electric vehicles during collisions in recent decades [82]–[87]. Crashworthiness design for urban electric vehicles due to side impact with impact absorbers placed inside the door in the form of a structure filled with aluminium and complementing the battery storage compartment with canal structure impact absorbers was carried out by Setiawan and Salim in [88].

One of the critical components of EVs is the battery system. Electric vehicle batteries have more functions and require protection from mechanical loading and thermal runaway [89]. Research and development are needed to protect electric car battery systems because this system has new and unique challenges, as in [90]–[93]. Facts show that some lithium-ion batteries can catch fire while others can catch fire in accidents leading to death. Battery packs are designed for safety-related challenges such as mechanical, electrical, and thermal abuse [90], [91], [94]–[97]. According to the author's knowledge, the application of the cellular structure to the design of battery packs has not been carried out by many researchers. The nature-inspired design of the cellular structure for the battery compartment of an electric vehicle has been developed by Mudassir *et al.* [98]. A multi-layer casing protects the electric car battery module. Typically, there is an aluminium underbody guard, an aluminium extrusion ring for impact absorption, a steel body with flanges and inner walls for the battery module, and a steel housing cover, as shown in Figure 7.

The shape of the battery pack is very diverse, depending on the vehicle's condition. It can be square or irregular according to the battery cells' shape. Hao *et al.* optimized the battery pack's structure to improve electric vehicles' feasibility through frontal simulation as in [84]. Xia *et al.* investigated cell and battery pack damage due to ground impact [99]. Based on the simulation results of a frontal collision, it turns out that vehicle acceleration can be reduced by designing a flexible battery compartment structure. Two critical factors that can increase the feasibility of impact absorption are the structure of the battery compartment and the working pressure. The position of the battery pack is also an important issue because the battery pack is quite heavy and requires a large amount of space. The safety requirement aspect of this system is very important as in [87].

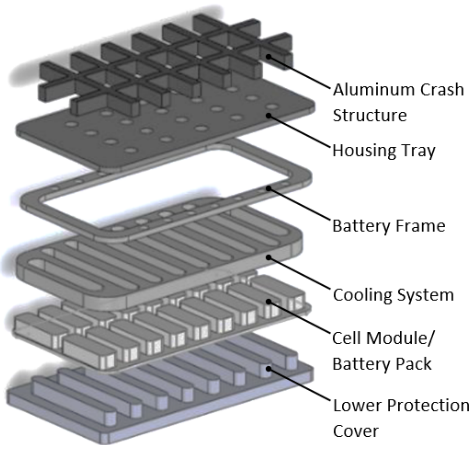

Figure 7 Illustration of a multi layered housing for battery casing [98]

4.3 Application for cooling system

Development of optimization methods to optimize the lattice structure as an effective refrigerant channel through the liquid has been carried out by Takezawa *et al.* [100]. The Brinkman-Forchheimer equation approximates fluid flow through a lattice structure. A review of the thermal runaway mechanism of lithium-ion battery for electric vehicles has been carried out by Feng *et al.* [94]. Various possible battery failures due to accidents include mechanical abuse, electrical abuse, thermal abuse, and internal short circuits. Mechanical abuse can trigger electrical abuse, whereas electrical abuse releases heat and induces thermal abuse.

5 Conclusion

In summary, the research and development of cellular structures in foam, honeycomb, and lattice-type structures have grown significantly over the past few decades. Generally, they have good characteristics of having high specific stiffness, low density, high strength, and favourable mechanical properties, including superior energy absorption capacity. The advancement of various manufacturing techniques, including additive manufacturing, makes it possible to create cellular structures in a relatively-controlled manner. However, to apply it to a specific task in engineering, the consistency of bulk behaviour must be ensured. Moreover, the application of such structures accurately, incorporating their pseudo-random nature, requires a robust material characterization and design methodology. Numerous researchers have proposed a design methodology to apply such structures to various applications but less systematically. Due to increasing manufacturing technology, it becomes a challenge in the ongoing research to apply cellular structures, particularly in electric vehicle crashworthiness.

Acknowledgment

ITB partially funds the ongoing research on the impact-absorbing structures for electric vehicles through P2MI scheme in 2022, for which the authors express their gratitude.

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