Auxetic Honeycomb Lattice Structure in Thin Solids for Enhanced Energy Absorption: Innovative Two-Wheeler Helmet Design and Analysis

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Abstract. Products designed for impact loading, like helmets, can achieve higher safety criteria with the use of enhanced energy-absorbing structures. Auxetic metamaterials demonstrate a negative Poisson's ratio and enhanced energy dissipation properties when subjected to impact loads. Many novel designs of auxetic lattice structures are reported in the literature, and their mechanical properties are analyzed. To incorporate them in a traditional CAD modeling framework that allows customization to a specific product design, one needs novel design methodologies. In the present work, in order to obtain custom auxetic lattice designs on thin solids, a design methodology is proposed, illustrated, and implemented in a commercial CAD software SOLIDWORKS™. The design of the helmet liner is chosen as an illustrative case study. The liner in the helmet follows the head form and is a crucial part of the helmet that helps prevent head injuries by absorbing energy in cases of accidents. In this study, aiming to have a minimal force transmission to the head, an innovative helmet was designed, where auxetic honeycomb pores were introduced along the perimeter of the liner to have better energy absorption. The performance of the auxetic porous liner helmet was compared with that of a conventional helmet using crash simulation, and it was found that the new innovative helmet showed better energy absorption than the traditional one.

Keywords: Custom lattice design, Thin solids, Auxetic honeycomb, 3D modeling, Helmet, Impact analysis.
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1 INTRODUCTION

Cellular structures such as honeycombs and lattices are used in construction to achieve lightweight structures while maintaining strength and energy absorption. In these constructions, the material is optimally placed where it is needed. The fabrication of various lattice structures with distinctive mechanical properties is now possible due to recent developments in additive manufacturing [31]. Additionally, finite element models enable the assessment of the influence of several model parameters of these cellular structures in a way that would be too expensive for actual experimental testing. Recent advances in anisotropic cellular structures utilize topology optimization, FE mesh of either continuum or discrete elements to optimally distribute material in the material layout [37]. The ordered construction of lattice structures allows customization to achieve the desired mechanical properties and offers a chance to surpass the energy absorption efficiency of traditional foams [6].

Auxetic metamaterials possessing a negative Poisson's ratio show improved energy absorption capabilities when subjected to impact loading [1, 7, 9, 28]. One popular example of a periodic auxetic metamaterial is the re-entrant honeycomb structure. Qi *et al*. [32] conducted an experimental and numerical study of the impact and close-in blast performance of sandwich panels containing re-entrant honeycomb cores to investigate the dynamic behavior and energy absorption capability. It was seen that such sandwich panels with re-entrant honeycomb cells perform exceptionally well in terms of blast protection and force mitigation. There are numerous other experimental and computational studies where auxetic honeycomb structures have shown to be more effective in absorbing energy [18, 20, 35]. They are, therefore, appealing alternatives for parts that offer crash or impact protection in automotive, aeronautical, and sports applications. However, because of the geometry complexity of lattice structures and the customizability required for a specific design, typical CAD modeling and design optimization techniques are insufficient, tedious, and time-consuming, if not impossible.

There are reported studies on the creation of virtual lattice structures in three dimensions. However, these methods cannot instantiate lattice structures in CAD environments automatically. In CAD, an array of unit cells can be turned into a lattice structure using direct patterning, in which the units are repeated by simple rigid body transformation, or conformal patterning, in which the units are repeated in accordance with a specified surface geometry or using topology optimization, which can be used to not only to obtain the spatial replication of the unit cell throughout the entire design space but also to optimize the material distribution within a single unit cell [34]. Conformal patterning preserves the integrity of the unit cell, which is thought to be a better method to stiffen or strengthen the desired structure since it can distribute the load equally throughout the entire structure. Nguyen et al. [12] created a method that involves two phases and uses a specified part surface to produce a conformal lattice structure. To accommodate the unit cells, a 3D conformal hexahedral mesh is computed first. The second phase involves populating the unit cells to fill the hexahedral space left by the mesh elements from the first step. Because of the ability and flexibility of porosity control, more complex porosity distributions in implicit surface lattice structures can be achieved [8]. K3DSurf (or MathMod) [16] is a freely accessible programme for building implicit surfaces that are extensively utilised in scholarly work. A commercial programme called Simpleware ScanIP [29] has a CAD module that can create lattice structures inside of a given part using implicit functions. Selective Space Structures (3S), a user-friendly software tool for the building of lattice structures that has a standard unit cell library and enables the user to define unit cell type, was created by Netfabb [25]. Both Autodesk Within [3] and Altair OptiStruct [2] incorporate topology optimisation into the creation of lattice structures. Both 3-matic STL from Materialise [21] and Conformal Lattice Structure (CLS) from Paramount [27] enable the creation of conformal lattice structures based on a specified surface in a design space. Though there are several lattice design tools available, the Lack of an automatic module to assist product designers in generating custom lattice structures is one of the limitations of current techniques to construct lattice structures, making the creation process time-consuming. A comprehensive solution that addresses the scientific issues in modeling and assembling a collection of custom-designed unit cells, creation of lattice topology conformal to the designed surface, parametric editing of unit cells in an automatic platform is a significant need. In the present work, in order to obtain custom auxetic lattice designs on thin solids, a design methodology is proposed, illustrated, and implemented in a commercial CAD software SOLIDWORKS™. The design of the helmet liner is chosen as an illustrative case study. We propose a helmet with a novel liner design that contains auxetic honeycomb pores. Further, FE analysis of various crash scenarios was carried out, and the performance of the proposed design was compared with that of a conventional solid liner helmet.

The produced deformations pattern and the head form acceleration indicate that the proposed Aux-pore (auxetic porous) liner helmet design shows improved energy absorption and thus has the potential to offer better user safety.

2 MATERIALS AND METHODS

In this study, a generic design methodology is proposed to create a thin solid as an extruded surface with an architected lattice structure. A surface is broken into a set of rectangular topology parametric surface patches with suitable continuity on which a custom-designed 2D lattice is conformally mapped before the lattice structure is extruded with the Boolean operation to create a thin solid. As a case study, the specific application of designing the helmet liner intending to achieve the minimum impact transmission to the head during an impact is illustrated. The designed helmet with a porous liner is analyzed for impact analysis.

2.1 Lattice Structure Design for Thin Solids

A generic methodology for lattice-structured thin solids using custom unit cell design is proposed. A surface/shell of the product that requires a lattice structure is extracted and divided into rectangular topological parametric surface patches while maintaining adequate continuity. As illustrated in Figure 1 with an example of a spherical surface decomposed into sets of rectangular topology surface patches. The average patch length along the parametric directions u and v are computed using arc lengths of the patch edges, and its average is computed as s_{u_avg} and s_{v_avg} for a surface patch S. This step helps in the parametrization of the cellular pattern on the surface. The number of unit cells along each parametric direction, i.e., u and v, is decided by the user based on the average patch dimensions as computed above and the physical cell dimensions required on the patch. Any custom unit cell design as provided by the designer or chosen from a library is then chosen for the pattern. As an example, an auxetic honeycomb cell is considered in Figure 1, which is patterned to be mapped onto the surface patch. The next step is pattern generation using the chosen cell design. A rectangular patterning is done on the parametric domain uv based on the number of cells as computed based on arc length and unit cell dimension. A conformal mapping is then done for this pattern using a suitably chosen parametric representation r for the surface patch S. As an example, if the surface patch is approximated by a bilinear patch, each coordinate of the auxetic cell in the parametric space is mapped to physical space as;

$$r_{bilinear}(u,v)=(1-u)\left[(1-v)r_{00}+vr_{01}\right]+u\left[(1-v)r_{10}+vr_{11}\right]$$

where, r_{ij} are the corner vertices of the surface patch S with a normalized parameter range for u and v. Better approximates of surface patch S can be obtained using surface by boundary as;

$$r(u,v)=\left[(1-u)r_{0v}+ur_{1v}\right]+\left[(1-v)r_{u0}+vr_{u1}\right]-r_{bilinear}$$

where, r_{ov} represents the surface edge corresponding to $u=0$ Similarly are the notations for other edges. The parameterization scheme helps in conformal mapping without any abnormal distortion of the lattice design. The parameterization of S using $r(u,v)$ involves an interpolation error in the interior. The magnitude of error depends on the number of subdivisions as well as the parametrization of $r(u,v)$. To remove this error for each point on $r(u,v)$ defining the lattice, a projection is done from $r(u,v)$ onto S using the normal estimated from $r(u,v)$ as shown in Figure 1. This lattice patterns obtained on the surface patch S is then used for further Boolean operation and or offset to obtain the thin solid with the lattice structured design as illustrated in Figure 1.

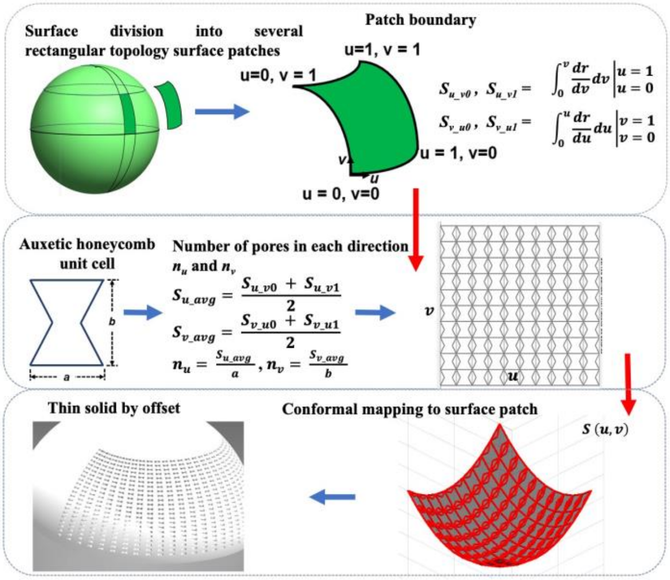

Figure 1: Proposed design methodology for mapping lattice structures into thin solids.

2.2 Case Study: Novel Design of Helmet Liner

The design for the two-wheeler helmet consists of a shell (the outermost part) and the liner, which is the main energy absorption element during an event of impact. The proposed design consists of an auxetic pore-structured liner instead of the conventional solid liner. The 3D modeling and FE analysis for this case study were carried out using commercial software, namely, Solidworks™ and Abaqus™. The helmet models were created using the Consumer Product Safety Commission (CPSC)'s recommended design criteria.

2.2.1 Design

The proposed design of the helmet is illustrated in Figure 2. The auxetic pore structure for the liner, which is a thin solid, is obtained as per the methodology presented in section 2.1. The shell of the helmet is the outermost part of the helmet and one of the primary components which shields the head from impact. Commonly used shell thickness for the manufacture of helmets is between 3 to 5 mm. Acrylonitrile-Butadiene-Styrene (ABS) is one of the materials that is used to form the shell [24]. Head acceleration is caused by impact forces both linearly and rotationally. By lowering the maximal force of impact to less than 10 KN and lowering the maximum head accelerations, the helmet liner's crushing prevents or lessens brain damage [23]. Helmets for motorcycles and bicycles frequently use expanded polystyrene (EPS) foams as liners, which are sophisticated materials with high energy absorption [18]. For the present investigation, a shell made of ABS and a thick liner made of EPS are considered. Auxetic materials and structures have a negative Poisson ratio and thus, when compressed, they shrink perpendicularly to the direction of compression. Penetration and impact protection is a particularly fascinating and potential field of application, and such structures with a negative Poisson's ratio have certain benefits in this regard and thus used for the liner design. The mechanical performance of such structures primarily depends on the topology of the unit cell, such as the re-entrant angle, strut length, and thickness, as shown in

Figure 2(a). A study discovered that the energy absorbed by this type of structure is highest when the re-entrant angle is 20° [22]. Therefore, for better energy absorption in this investigation, the re-entrant angle was set at 20°.

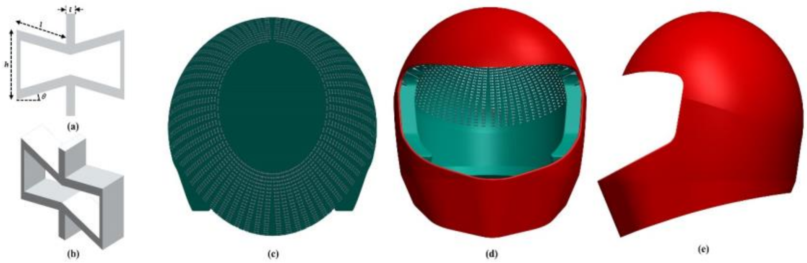

Figure 2: (a) Representation of an auxetic honeycomb unit cell, (b) Isometric view of the unit cell, (c) Top view of the helmet liner containing auxetic honeycomb pores, (d) Front view of the aux-pore liner helmet, (e) Side view of the helmet.

2.2.2 Simulation

To assess the performance of the helmet, simulation models as per the norms of the CPSC were used. A comparison between the proposed Aux-pore liner helmet and the traditional solid liner helmet has been made. Impact testing simulation was carried out using a medium head form following the standard, and designed in the CAD software Solidworks™ and positioned and assembled with the helmet model. The impacts of the chin pad, chin strap, and comfort liner were not taken into account in the investigation. Each part was meshed in Abaqus™, avoiding twisted and distorted elements and with the convergence of results as criteria for mesh. Solid tetrahedral elements with a single integration point were used for the outer shell, head form, and anvil to simulate the model. The outer shell was modeled using 25376 solid tetrahedral elements. The head form was considered to be made of aluminum [17] and meshed using 25376 solid tetrahedral elements. The Aux-pore liner consists of 18732 shell elements, whereas the solid liner consists of 18197 shell elements. In this study, a hemispherical anvil was used to strike the helmets to evaluate their dynamic response. General automatic contact-type elements were used to implement the contact surfaces of the models. Additionally, interpenetration was prevented by using automatic surface pairs contact between the ABS shell and the EPS foam liner and also between the foam and the head form model. A friction coefficient of 0.5 was used. The helmet was positioned very close to the anvil to significantly reduce the computational time needed and assigned a predefined impact velocity rather than being dropped. The helmet-head form combination was given a velocity of 4.8 m/sec, as per the CPSC standard, to simulate impact. The simulations for frontal, rear, and sideways impact, as shown in Figure 3, are presented in this study.

3 RESULTS AND DISCUSSIONS

3.1 Efficacy of Proposed Lattice Structure Design for Thin Solids

Creating the precise lattice pattern and guaranteeing its compliance with the intended surface necessitates knowledge of geometry and the intricate details of lattice design. Obtaining the required lattice shape on a surface frequently requires manual editing and iterative tweaking and is a time-consuming task. A technique for automated design of custom lattice structure conformal to a surface is presented in this study and implemented in Solidworks™ platform. The methodology is illustrated in Figure 1.

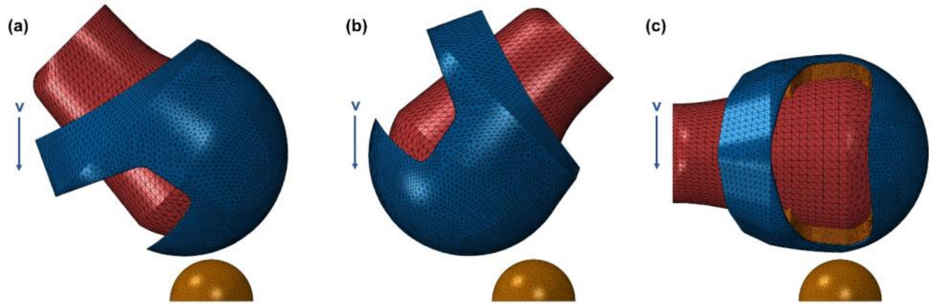

Figure 3: (a) Front, (b) back, and (c) right impact simulation configuration on spherical anvil.

The method can create thin solids and allows for parametric tunability of unit cells in an automatic platform which will increase the design flexibility significantly. A product design involving lattice structure is selected to illustrate the efficacy of the methodology. A helmet liner design with custom lattice is taken up as case study and the design process for the helmet is described in section 2.2.1. The process for designing the CAD model of the Aux-pore liner in Solidworks™ is briefly illustrated in Figure 4. S1 through S9 refers to the various geometric construction steps, consisting of sketching, surface revolution, lofting, Aux-pore lattice pattern, surface offset to create thin solid. The methodology proposed in section 2.1 is used to create the auxetic porous structure in step S6 and S7. In S9, the split command is used to make the front opening of the helmet. The developed method is less time-consuming and is user friendly. Since the computing is done patch wise and involves linear interpolations for parameterization of lattice design, it does not require high computing resources.

3.2 Performance of the Proposed Aux-pore Liner Helmet

The effectiveness of the proposed aux-pore liner helmet compared to the standard solid liner was demonstrated by comparing both deformation contours and peak head form translational acceleration value of the helmets under different impact scenarios. Table 1 compares the deformations in the frontal, rear, and sideways impact between the outer shell of the proposed Aux-pore liner helmet and a traditional solid liner helmet. The Aux-pore liner helmet's outer shell deformation is not substantially different from that of a solid liner helmet.

Direction of Impact	*Helmet Type*	*Deformation*	
		u_1	u_3
Front	Aux-pore Liner Helmet	16.84	11.21
	Solid Liner Helmet	16.81	11.22
Sideway	Aux-pore Liner Helmet	26.57	14.11
	Solid Liner Helmet	26.57	14.09
Rear	Aux-pore Liner Helmet	9.59	26.49
	Solid Liner Helmet	8.92	26.34

Table 1: Deformation result of the outside surface of the shell for Aux-pore liner helmet and solid liner helmet for three impact directions under a hemispherical anvil. All dimensions in mm. Here, u_1 and u_3 refer to the deformation in the *x* and *z* directions, respectively.

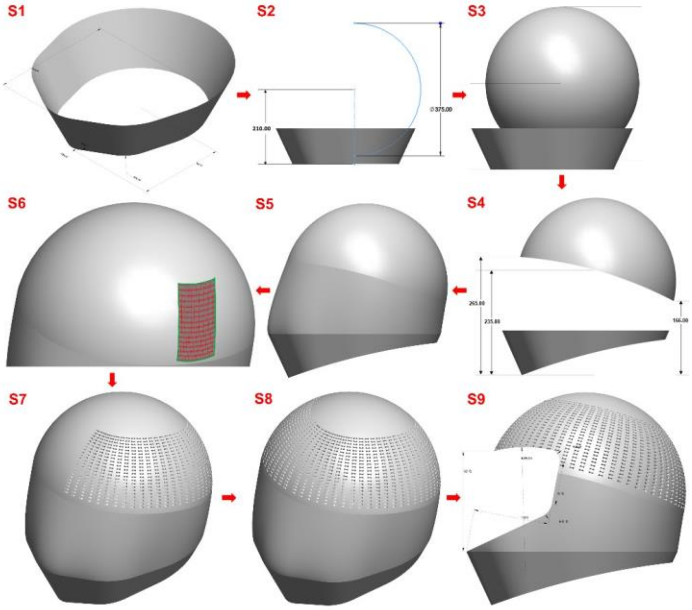

Figure 4: 3D CAD model development of the Aux-pore liner using SolidworksTM. The step S6 and S7 are as per the proposed methodology and implemented as an automatic module in Solidworks™.

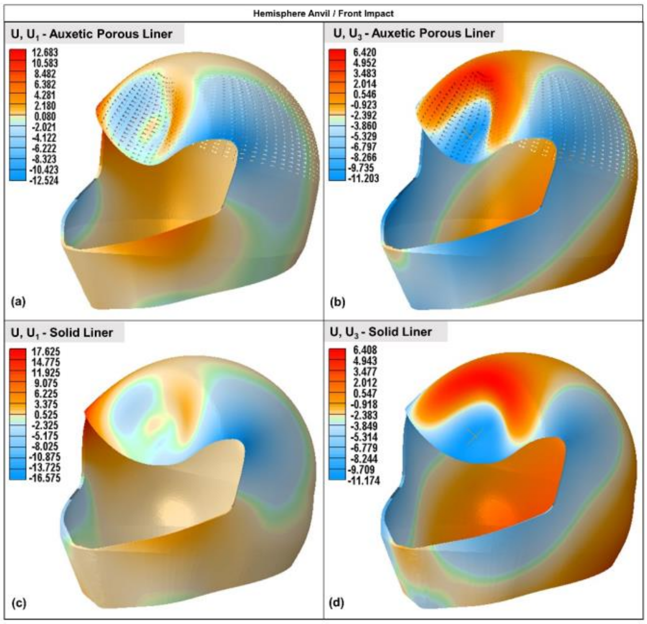

Figure 5: Comparison of u_1 and u_3 deformation between Aux-pore and solid liner when subjected to front impact configuration under hemispherical anvil (a) u_1 deformation contour of the Aux-pore liner, (b) u_3 deformation contour of the Aux-pore liner, (c) u_1 deformation contour of the solid liner, (d) u_3 deformation contour of the solid liner.

Figure 5–7 compares the deformation contour in the *x* and *z* directions of the solid liner and the Aux-pore liner during impact against the hemispherical anvil. As demonstrated in Figure 5, the solid liner exhibits about 40% more *x*-direction deformation than the Aux-pore liner. The aux-pore liner experiences slightly more deformation than the solid liner in the *z*-direction, although the difference is minimal—less than 0.3%. The deformation contour of Figure 6 shows that, in the case of a rear impact configuration under a hemispherical anvil, the solid liner experiences 26% and 15% higher deformation in the *x* and *z* directions, respectively, than the Aux-pore liner. In Figure 7, the difference between Aux-pore and solid liner deformation in both directions is relatively small in the case of side impact configuration under the hemispherical anvil. Although the difference is less, it is clear from the front, rear, and sideways impact scenarios in Table 1 that the aux-pore liner helmet exhibits greater outer shell deformation in both deformation directions than the solid one under the hemispherical anvil impact. Additionally, when exposed to front and rear impact, the aux-pore liner helmet deforms significantly less on the inner surface of the liner than the solid one. Less deformation of the outer shell means more energy is transferred to the head, leading to severe damage. When the deformation is more, the head receives the least transmitted force, resulting in higher energy absorption. Furthermore, reduced deformation of the auxetic porous liner's inner surface suggests that the energy was greatly absorbed by the liner. When the sideways impact configuration occurs, the Aux-pore liner helmet's outer shell deforms more than the solid one in both directions, and the liner's inner surface deforms less in the *x* direction but slightly more (0.15%) in the *z* direction in comparison to the solid liner, which again suggests that the auxetic porous liner absorbed more energy.

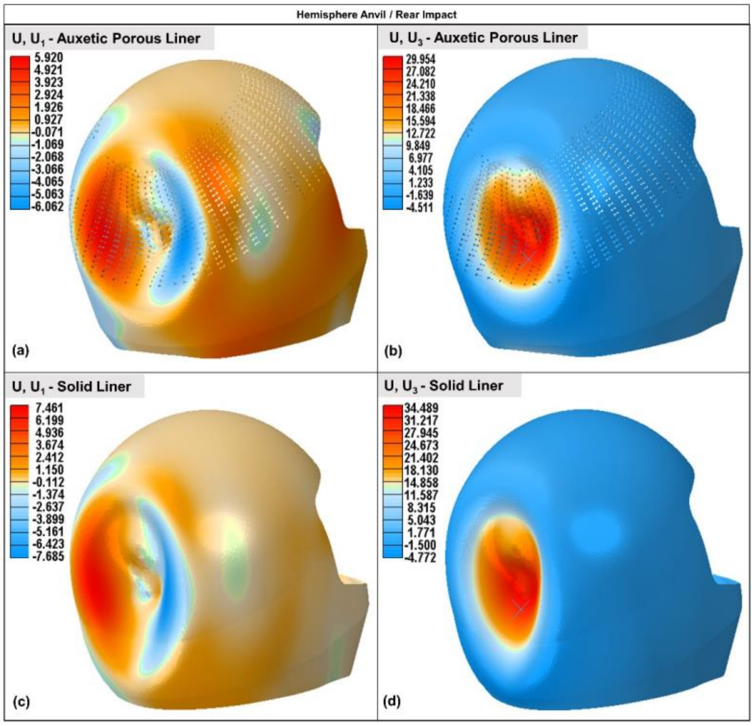

Figure 6: Comparison of u_1 and u_3 deformation between Aux-pore and solid liner when subjected to rear impact configuration under hemispherical anvil (a) u_1 deformation contour of the Aux-pore liner, (b) u_3 deformation contour of the Aux-pore liner, (c) u_1 deformation contour of the solid liner, (d) u_3 deformation contour of the solid liner.

A comparison of the peak translational acceleration of the head form caused by impact against the hemispherical anvil between the solid liner and the Aux-pore liner is shown in Figure 8. The safety criteria (300 G) were met for all peak values except for the solid liner in the front impact configuration. The solid liner resulted in higher peak values (340, 130, and 247 G) compared to the Aux-pore liner (279, 126, and 246 G) for front, rear, and sideways locations during impact with the hemispherical anvil. The average head form peak acceleration for the solid liner was 10% higher than that of the Aux-pore liner during impact with the hemispherical anvil.

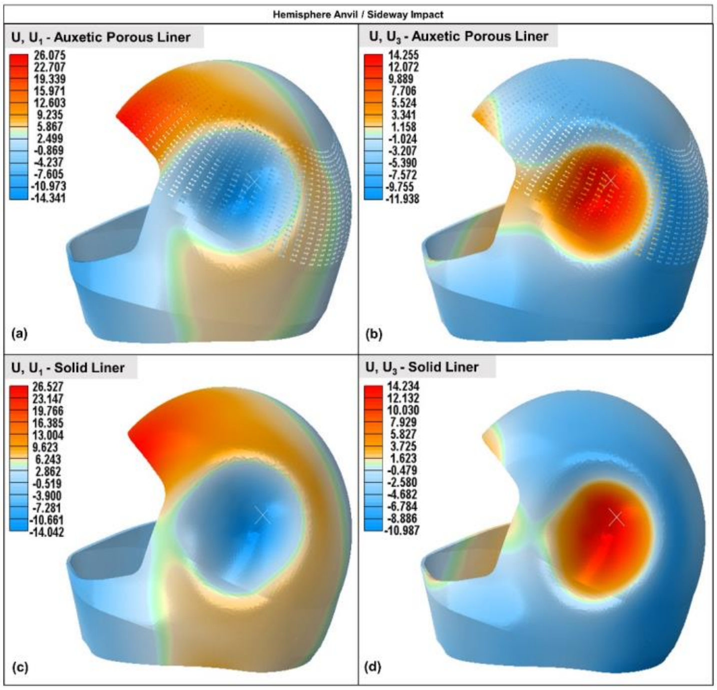

Figure 7: Comparison of u_1 and u_3 deformation between Aux-pore and solid liner when subjected to sideways impact configuration under hemispherical anvil (a) u_1 deformation contour of the Aux-pore liner, (b) u_3 deformation contour of the Aux-pore liner, (c) u_1 deformation contour of the solid liner, (d) u_3 deformation contour of the solid liner.

3.3 Discussion

Despite the availability of lattice design tools, one drawback is the lack of an automatic module that aids product designers in the creation of custom lattice structures. Creating unique lattice structures requires defining criteria such as lattice type, density, unit cell shape, and connection. Due to computational constraints, for example, there may be restrictions on the minimum feature size, maximum lattice density, or the capacity to incorporate specific design components. It can be difficult to strike a balance between conformity and structural integrity. The automated method described in this work, which can produce conformal lattice structures for thin solids based on user-defined design requirements, will greatly simplify the process. Further development with FE that uses homogenization techniques shall help in creating design modules that can take input characteristics like load needs, structural limits, and aesthetic preferences and produce custom lattice structures that fit those standards. Designers would save time and effort, as a result, allowing them to explore a greater range of design ideas.

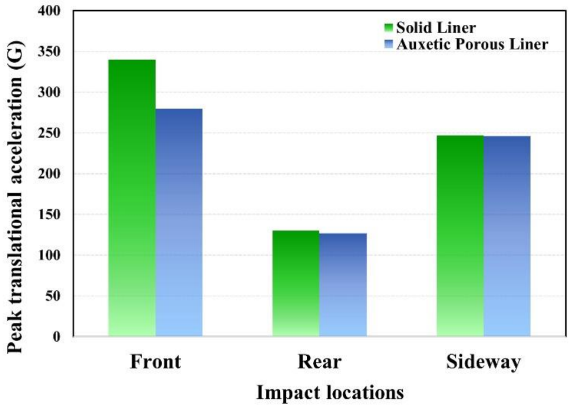

Figure 8: Comparison of the head form peak translational acceleration of the solid liner and the Aux-pore liner during three different impact configurations against the hemispherical anvil.

As per WHO, low- and middle-income nations account for more than 90% of traffic fatalities. Optimal helmet design can lower the likelihood of fatal injuries by 42% and head injuries by 69%. The primary helmet component that lessens head injuries in accidents is the liner. Thus, a significant consideration in enhancing helmet performance can be achieved by replacing the helmet liner by using higher energy-absorbing materials and structures to meet higher safety standards. Many researchers have used different types of material combinations for the liner and the shell material of the helmet to enhance performance [10, 15, 30, 33, 36]. Aluminum honeycombs were used by Caserta *et al*. [5] to replace a portion of the helmet's liner and serve as reinforcement. Although the performance of this design proved inferior to the conventional EPS liner in strikes against a flat surface, it performed better in impacts against curbstone anvil. Kholoosi *et al*. [13] designed a helmet by introducing a graded honeycomb structure in place of the solid interior material of the liner to lessen head impact during accidents. Bliven et al. [4], Hansen et al. [11], and Khosroshahi et al. [14], Pakzad *et al*. [26] are a few other studies in which the standard helmet liner was replaced by different lattices to enhance energy absorption and lower headform acceleration. Liner design has been modified in a few more studies; for example, Teng et al. [32] designed a novel semispherical cone liner, and Liu et al. [19] designed an innovative open-face helmet with three ventilation openings on the upper side of the helmet. Although the design and material qualities of the shell and liner have been designed and optimized over the past few decades to give high levels of protection, further effort is required to enhance the energy absorption offered by contemporary helmets. The present design methodology and proposed Aux-pore design are efforts in that direction.

4 CONCLUSIONS

This article proposes a geometric design methodology for custom lattice design for thin solids and demonstrates its efficacy in a case study of helmet liner design. The methodology is implemented in Solidworks™. A novel helmet liner design using an auxetic lattice structure with enhanced energy beneficial in preventing brain injury is presented as a case study. The auxetic pore lattice structure is modeled using the methodology proposed in this work, which enabled the conformal lattice pattern of the custom design without much manual effort. Further, the performance analysis of the designed helmet liner was carried out in Abaqus™ using three different impact configurations against a hemispherical anvil. Results showed that the auxetic porous liner is a better energy absorber, and it also reduced the head form acceleration to a great extent in comparison to the solid helmet. Introducing pores in the liner also made the helmet lighter in weight. Further improvement in energy absorption might be achieved using a liner with an optimal auxetic honeycomb structure. More impact test configuration can also be evaluated for a comprehensive analysis.

REFERENCES

[1] Allen, T.; Shepherd, J.; Hewage, T.A.M.; Senior, T.; Foster, L.; Alderson, A.: Low-kinetic energy impact response of auxetic and conventional open-cell polyurethane foams, Physica Status Solidi (b), 252(7), 2015, 1631-1639. https://doi.org/10.1002/pssb.201451715

[2] ALTAIR [online] Available: http://www.altairhyperworks.com/product/OptiStruct.

[3] Autodesk [online] Available: http://www.autodesk.com/products/within/overview.

[4] Bliven, E.; Rouhier, A.; Tsai, S.; Willinger, R.; Bourdet, N.; Deck, C.; Madey, S.M.; Bottlang, M.: Evaluation of a novel bicycle helmet concept in oblique impact testing, Accident Analysis & Prevention, 124, 2019, 58-65. https://doi.org/10.1016/j.aap.2018.12.017

[5] Caserta, GD.; Iannucci, L.; Galvanetto, U.: Shock absorption performance of a motorbike helmet with honeycomb reinforced liner, Composite Structures, 93(11), 2011 Oct 1, 2748-2759. https://doi.org/10.1016/j.compstruct.2011.05.029

[6] Deshpande, V.S.; Fleck, N.A.; Ashby, M.F.: Effective properties of the octet-truss lattice material, Journal of Mechanics and Physics of Solids, 49(8), 2001, 1747–1769. http://dx.doi.org/10.1016/S0022-5096(01)00010-2

[7] Duncan, O.; Shepherd, T.; Moroney, C.; Foster, L.; Venkatraman, P.D.; Winwood, K.; Allen, T.; Alderson, A.: Review of auxetic materials for sports applications: Expanding options in comfort and protection, Applied Sciences, 8(6), 2018, 941. https://doi.org/10.3390/app8060941

[8] D. Yoo.: Heterogeneous minimal surface porous scaffold design using the distance field and radial basis functions, Medical Engineering & Physics, 34(5), 2012, 625-639. https://doi.org/10.1016/j.medengphy.2012.03.009

[9] Evans, K.E.; Alderson, A.: Auxetic materials: functional materials and structures from lateral thinking!, Advanced Materials, 12(9), 2000, 617-628. https://doi.org/10.1002/(SICI)1521-4095(200005)12:9%3C617::AID-ADMA617%3E3.0.CO;2-3

[10] Gohel, G.; Bhudolia, S.K.; Elisetty, S.B.S.; Leong, K.F.; Gerard, P.: Development and impact characterization of acrylic thermoplastic composite bicycle helmet shell with improved safety and performance, Composites Part B: Engineering, 221, 2021, 109008. https://doi.org/10.1016/j.compositesb.2021.109008

[11] Hansen, K.; Dau, N.; Feist, F.; Deck, C.; Willinger, R.; Madey, S.M.; Bottlang, M.: Angular Impact Mitigation system for bicycle helmets to reduce head acceleration and risk of traumatic brain injury, Accident Analysis & Prevention, 59, 2013, 109-117. https://doi.org/10.1016%2Fj.aap.2013.05.019

[12] J. Nguyen.; S. Park.; D.W. Rosen.; L. Folgar.; J. Williams.: Conformal lattice structure design and fabrication, Solid Freeform Fabrication Symposium, 2012. http://dx.doi.org/10.26153/tsw/15339

[13] Kholoosi, F.; Galehdari, S.A.: Design and analysis of a helmet equipped with graded honeycomb structure under impact of flat and Hemi-spherical anvils, Procedia engineering, 173, 2017, 1299-1306. https://doi.org/10.1016/j.proeng.2016.12.165

[14] Khosroshahi, S.F.; Duckworth, H.; Galvanetto, U.; Ghajari, M.: The effects of topology and relative density of lattice liners on traumatic brain injury mitigation, Journal of biomechanics, 97, 2019, 109376. https://doi.org/10.1016/j.jbiomech.2019.109376

[15] Kostopoulos, V.; Markopoulos, Y.P.; Giannopoulos, G.; Vlachos, D.E.: Finite element analysis of impact damage response of composite motorcycle safety helmets, Composites Part B: Engineering, 33(2), 2002, 99-107. https://doi.org/10.1016/S1359-8368(01)00066-X

[16] K3DSurf [online] Available: http://k3dsurf.sourceforge.net/.

[17] Liu, B; Villavicencio, R; Soares, CG.: Failure characteristics of strength-equivalent aluminium and steel plates in impact conditions, Analysis and Design of Marine Structures, 2013, 167. https://doi.org/10.1201/b15120-25

[18] Li, T.; Liu, F.; Wang, L.: Enhancing indentation and impact resistance in auxetic composite materials, Composites Part B: Engineering, 198, 2020, 108229. https://doi.org/10.1016/j.compositesb.2020.108229

[19] Liu, D.S.; Chen, Y.T.: A finite element investigation into the impact performance of an open-face motorcycle helmet with ventilation slots, Applied Sciences, 7(3), 2017, 279. https://doi.org/10.3390/app7030279

[20] Logakannan, K.P.; Ramachandran, V.; Rengaswamy, J.; Ruan, D.: Dynamic performance of a 3D re-entrant structure, Mechanics of Materials, 148, 2020, 103503. https://doi.org/10.1016/j.mechmat.2020.103503

[21] Materialise [online] Available: http://www.materialise.com/.

[22] Mercer, C.; Speck, T.; Lee, J.; Balint, DS.; Thielen, M.: Effects of geometry and boundary constraint on the stiffness and negative Poisson's ratio behaviour of auxetic metamaterials under quasi-static and impact loading, International Journal of Impact Engineering, 169, 2022, 104315. https://doi.org/10.1016/j.ijimpeng.2022.104315

[23] Mills, N. J.; Gilchrist, A.: Bicycle Helmet Design, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 220(4), 2006, 167–180. http://doi.org/10.1243/14644207JMDA100

[24] Najafi, M.; Ahmadi, H.; Liaghat, G.: Evaluation of the mechanical properties of fully integrated 3D printed polymeric sandwich structures with auxetic cores: experimental and numerical assessment, The International Journal of Advanced Manufacturing Technology, 122(9-10), 2022, 4079-98. http://doi.org/10.1007/s00170-022-10147-w

[25] Netfabb [online] Available: http://www.netfabb.com/.

[26] Pakzad, S.; Shah, Hoseini, A.; Dehghani, M.; Khalkhali, AB.: Design and analysis of bicycle helmet made of PETg and ABS with honeycomb structure against external impacts using Abaqus software, ADMT Journal, 14(1), 2021, 83-90. https://doi.org/10.30495/admt.2021.1896746.1185

[27] PARAMOUNT [online] Available: http://www.paramountind.com/conformal-lattice-structures.htm.

[28] Qi, C.; Remennikov, A.; Pei, L.Z.; Yang, S.; Yu, Z.H.; Ngo, T.D.: Impact and close-in blast response of auxetic honeycomb-cored sandwich panels: Experimental tests and numerical simulations, Composite Structures, 180, 2017, 161-178. https://doi.org/10.1016/j.compstruct.2017.08.020

[29] SIMPLEWARE [online] Available: http://www.simpleware.com/.

[30] Shuaeib, F.M.; Hamouda, A.M.S.; Wong, S.V.; Umar, R.R.; Ahmed, M.M.: A new motorcycle helmet liner material: The finite element simulation and design of experiment optimization, Materials & Design, 28(1), 2007, 182-195. https://doi.org/10.1016/j.matdes.2005.04.015

[31] Tao, W.; Leu, M.C.: Design of lattice structure for additive manufacturing, In 2016 International Symposium on Flexible Automation (ISFA), IEEE, 2016, 325-332. https://doi.org/10.1109/ISFA.2016.7790182

[32] Teng, T.L.; Liang, C.C.; Nguyen, V.H.: Assessment of a bicycle helmet liner with semispherical cones, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 230(1), 2016, 344-352. http://dx.doi.org/10.1177/1464420715569290

[33] Tinard, V.; Deck, C.; Willinger, R.: Modelling and validation of motorcyclist helmet with composite shell, International Journal of Crashworthiness, 17(2), 2012, 209-215. https://doi.org/10.1080/13588265.2011.648465

[34] W. Tao.; M. C. Leu.: Design of lattice structure for additive manufacturing, 2016 International Symposium on Flexible Automation (ISFA), Cleveland, OH, USA, 2016, 325-332. https://doi.org/10.1109/ISFA.2016.7790182

[35] Yang, S.; Qi, C.; Guo, D.M.; Wang, D.: Energy absorption of an re-entrant honeycombs with negative Poisson's ratio, In Applied Mechanics and Materials, 148, 2012, 992-995. https://doi.org/10.4028/www.scientific.net/AMM.148-149.992

[36] Yani, M.; Lubis, R.W.; Arfis, A.; Putra, B.W.; Hardiansyah, W.: Design and manufacturing processes of half face motorcycle palm fiber reinforced composite polymer, In Journal of Physics: Conference Series, 2193(1), 2022, 012011. https://doi.org/10.1088/1742-6596/2193/1/012011

[37] Zhongkai, Ji.; Dawei, Li.; Wenhe, Liao.; Yi, Min, Xie.: AI-aided design of multiscale lattice metastructures for controllable anisotropy, Materials & Design, 223, 2022, 111254. https://doi.org/10.1016/j.matdes.2022.111254.