Title:
An Innovative Two-Wheeler Helmet with Auxetic Honeycomb Lattice Structure: Design and Analysis

Authors:
Rajnandini Das, dasrajnandini95@gmail.com, Indian Institute of Technology Madras, INDIA
Gurunathan Saravana Kumar, gsaravana@iitm.ac.in, Indian Institute of Technology Madras, INDIA

Keywords:
Auxetic honeycomb, Helmet, 3D modeling, Impact analysis.

DOI: 10.14733/cadconfP.2023.323-328

Introduction:
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 helmet serves as a protective shield over the head, preventing injuries to the skull and the brain. The helmet serves as a crucial purpose in significantly decreasing and preventing impact. It slows down the acceleration of the skull, spreads the force of the hit over a broader area, and serves as a barrier between the skull and the impacting object to prevent direct contact. Helmets have been used as protective equipment to guard the human head against injuries caused by road accidents, sports, construction work, military, industrial plants, and other human activities.

Manufacturers and researchers have suggested novel materials and designs to enhance the quality of helmets in terms of safety, comfort, and aesthetics. To improve the energy absorption during impact, several of the following novel ideas have been proposed. Aluminum honeycombs were used by Caserta et al. [1] 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. A finite element (FE) analysis study was performed on a two-part helmet, and the liner was modeled using honeycomb structure by Pakzad et al. [9]. Bicycle helmets with an innovative Angular Impact Mitigation (AIM) system that uses an elastically suspended aluminium honeycomb lining were proposed by Hansen *et al.* [2]. Khosroshahi *et al.* [3] designed a helmet where the solid liner has been replaced with a lattice liner of prismatic and tetrahedral lattices. According to the findings, prismatic lattices perform better at preventing brain injury than tetrahedral lattices and the common EPS liner found in helmets. Teng *et al.* [10] designed a novel semispherical cone liner and a bicycle helmet model incorporating the liner. 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. Computer-aided design (CAD) makes it possible to represent designs more accurately, and with the help of additive manufacturing, our creativity and designs can now become a reality. When subjected to impact loading, auxetic metamaterials possessing a negative Poisson's ratio show improved energy absorption capabilities. They are, therefore, appealing alternatives for parts that offer crash or impact protection in automotive and aeronautical applications. It can therefore be employed in the design of a helmet's liner to lower impact velocity and acceleration and to improve energy absorption.

In this study, intending to achieve the minimum impact transmission to the head during an impact, we propose a novel helmet design with a liner containing auxetic honeycomb pores and an outer shell. The finite element 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 indicates that the proposed aux-pore (auxetic porous) liner helmet design shows improved energy absorption and thus has a potential to offer better user safety.

Materials and Methods:

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 helmet's hanging mechanism ensures its appropriate installation, a proper fit, and the comfort of the wearer. The proposed design consists of an auxetic pore-structured liner instead of conventional solid liners. The performance comparison was established using a FE analysis, simulating various impact scenarios. The 3D modeling and FE analysis in this work were carried out using commercial software, namely, Solidworks™ and Abaqus™.

Design

Shell is the outermost part of the helmet and one of the primary components which shields the head from impact. The shell's purpose is to safeguard the head by deterring foreign objects which might directly harm the skull during impact by penetration. Commonly used shell thickness for the manufacture of helmets is between 3 and 5 mm. Acrylonitrile-Butadiene-Styrene (ABS) is one of the materials that is used to form the shell [8]. The liner offers energy management. 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 [7]. Modern helmet liners typically range in thickness from 30 to 40 mm. Helmets for motorcycles and bicycles frequently use expanded polystyrene (EPS) foams as liners, which are sophisticated materials with high energy absorption [5]. For the present investigation, a shell made of ABS and a thick liner made of EPS are considered.

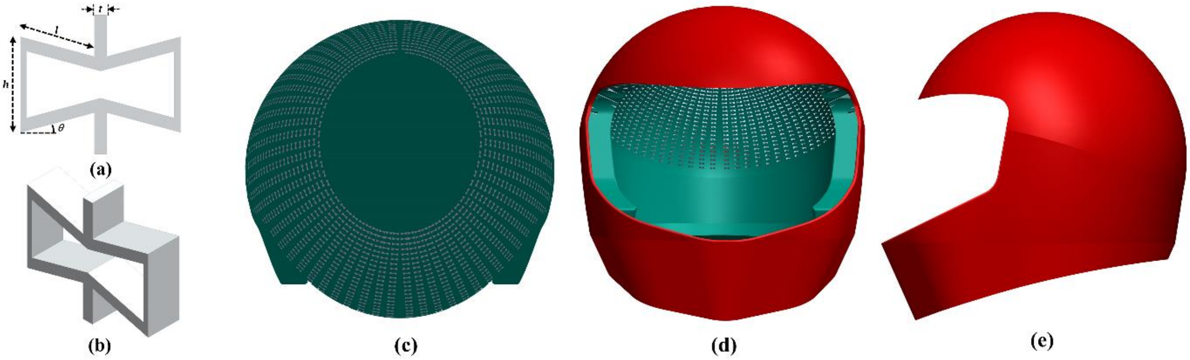

Fig. 1: (a) Representation of an auxetic honeycomb unit cell, (b) Isometric view of the unit cell, (c) Top view of the helmet liner containing auxetic honeycomb pores, (d) Front view of the aux-pore liner helmet, (e) Side view of the helmet.

The proposed design for the helmet consists of auxetic honeycomb pores introduced to the liner of the helmet. Auxetic materials and structures are defined by having a negative Poisson ratio. 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. Comparing this structure to solid structures made of the same materials, it processes a better energy adsorption capability. The helmet models were created using the Consumer Product Safety Commission (CPSC)'s recommended design criteria. The proposed design of the helmet is illustrated in Fig. 1. 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 Fig. 1(a). A study discovered that the energy absorbed by this type of structure is highest when the re-entrant angle is 20˚ [6]. Therefore, for better energy absorption in this investigation, the re-entrant angle was set at 20˚.

Impact 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 this investigation.

Each part was meshed, avoiding twisted and distorted elements and with the convergence of results as criteria for mesh. Solid tetrahedral elements 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 [4] 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. 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 assigned. The helmet was positioned very close to the hemispherical 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 Fig. 2, are presented in this study.

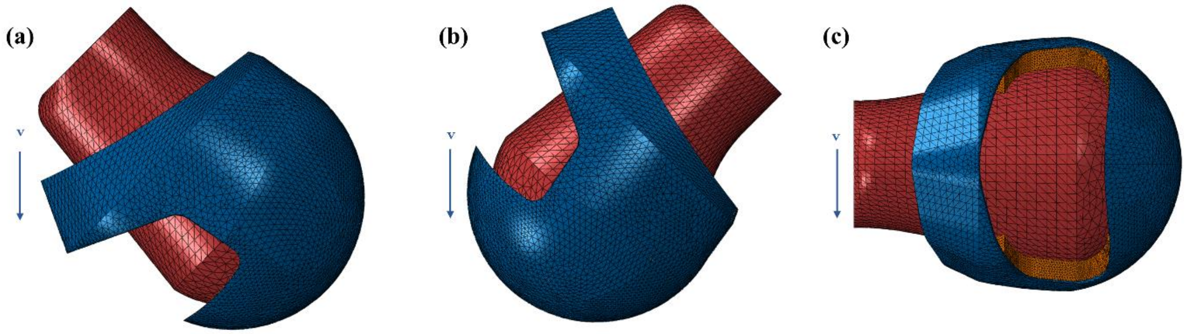

Fig. 2: (a) Front, (b) back, and (c) right impact simulation configuration.

Results and Discussion:

The effectiveness of the proposed aux-pore liner helmet compared to the standard solid liner was demonstrated by comparing the deformation contours of the helmets under different impact scenarios. Tab. 1 compares the deformations in the frontal, rear, and sideways impact between the outer shell of the proposed aux-pore liner helmet and a solid liner helmet. The aux-pore liner helmet's outer shell deformation is not substantially different from that of a solid liner helmet. But 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%. In the case of a rear impact configuration, the solid liner experiences 26% and 15% higher deformation in the *x* and *z* directions, respectively, than the aux-pore liner. 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. 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 energy. However, the model presented here is a prototype where auxetic pores were inserted only on the upper portion of the liner. The liner might also be modelled by creating auxetic pores on the entire liner, and a comparison could be made. A representative deformation behavior of the aux-pore liner helmet and solid liner helmet is shown in Fig. 3.

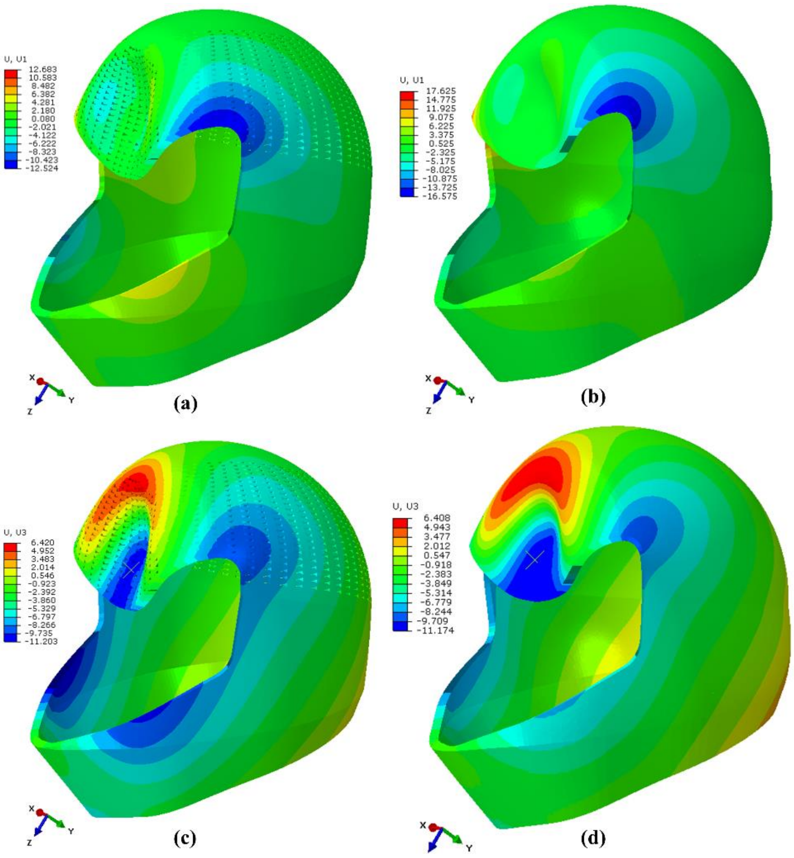

Fig. 3: Comparison of u_1 and u_3 deformation between Aux-pore and solid liner when subjected to front impact configuration (a) u_1 deformation contour of the aux-pore liner, (b) u_1 deformation contour of the solid liner, (c) u_3 deformation contour of the aux-pore liner, (d) u_3 deformation contour of the solid liner.

Direction of Impact	*Helmet Type*	*U_1*		*U_3*	
		Outside Surface of Shell	*Inside Surface of the Liner*	*Outside Surface of Shell*	*Inside Surface of the Liner*
Front	Aux-pore Liner Helmet	16.848	12.683	11.211	11.203
	Solid Liner Helmet	16.817	17.625	11.219	11.174
Sideway	Aux-pore Liner Helmet	26.576	26.075	14.115	14.255
	Solid Liner Helmet	26.573	26.527	14.092	14.234
Rear	Aux-pore Liner Helmet	9.597	6.062	26.489	29.954
	Solid Liner Helmet	8.921	7.685	26.336	34.489

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

Conclusions and Further Work:

This article proposes a novel helmet design for enhanced energy absorption and safety purposes due to the significance of the helmet, its beneficial function in preventing brain injury, and the benefit of customizing this sort of helmet with 3D printing. Compared to the conventional helmet, the novel helmet performed better in this aspect. Introducing pores in the liner will also make the helmet lighter in weight. Improved energy absorption might be achieved using a liner with an optimal auxetic honeycomb structure. More points of impact configuration can also be evaluated using different kinds of anvils.

References:

[1] Caserta GD; Iannucci L; Galvanetto U.: Shock absorption performance of a motorbike helmet with honeycomb reinforced liner, Composite Structures, 93(11), 2011, 2748-59. https://doi.org/10.1016/j.compstruct.2011.05.029

[2] Hansen, K.; Dau, N.; Feist, F.; Deck, C.; Willinger, R.; Madey, S.M. and 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

[3] Khosroshahi, S.F.; Duckworth, H.; Galvanetto, U. and 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

[4] Liu, B.; Villavicencio, R.; Soares, C.G.: Failure characteristics of strength-equivalent aluminium and steel plates in impact conditions, Analysis and Design of Marine Structures, 2013 Mar 11:167. https://doi.org/10.1201/b15120-25

[5] Liu, D.S.; Chang, C.Y.; Fan, C.M.; Hsu, S.L.: Influence of environmental factors on energy absorption degradation of polystyrene foam in protective helmets, Engineering Failure Analysis, 10(5), 2003, 581-91. https://doi.org/10.1016/S1350-6307(03)00040-2

[6] Mercer, C.; Speck, T.; Lee, J.; Balint, D.S.; 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, Nov 1, 169, 2022, 104315. https://doi.org/10.1016/j.ijimpeng.2022.104315

[7] 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, 67–180. http://doi.org/10.1243/14644207JMDA100

[8] 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

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

[10] 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