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Blast Resistance of an Innovative Helmet Liner Composed of an Auxetic Lattice Structure

A. A. Naderi*

Department of Engineering, Imam Ali University, Tehran, Iran

ABSTRACT: Helmet liners are employed to prevent or reduce head injuries caused by impact or blast loads. Liners minimize the damage by shock attenuation and absorbing the dynamic energy. In order to improve blast resistance and crashworthiness characteristics of helmet liner under air-blast, in the present study, an innovative structure designed by an arrow-head auxetic lattice structure is suggested to replace the conventional expanded polystyrene foams usually employed in the liner section. An explicit finite element method is employed to model the innovative helmet structure under blast loading and results are compared with the conventional case based on the trend of acceleration, energy absorption, weight, and head injury criteria factor. Also, a parametric study is conducted on the effect of lattice structure's cell size in the protective performance of helmets. Results indicate a great improvement in blast resistance of helmet when the suggested liners are employed so that the HIC number could be decreased by 71% when AH4 configuration is used while the overall energy absorption capacity of the helmet is increased about 34% compared to the basic model.

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1- Introduction

To protect the human's head area, helmets are used in dangerous environments when the head is at risk of injuries. Head injuries are mainly caused by accidents including dynamic loadings. Physical head damages could be considered as two main kinds. Injuries caused by direct contacts, which may lead to bleeding or skull breakages and brain traumas resulting from mechanical shock waves or heavy strokes. Damages of direct contacts are prevented in a helmet mostly via the outer shell. Depending on the application and usage conditions, helmet shell materials fall into two groups: more basic thermoplastics (Acrylonitrile Butadiene Styrene (ABS), polycarbonate, and compounds that are a blend of both) and composite materials made of various fiber and resin systems (fiberglass, Kevlar, carbon fiber, and composite blends) manufactured in various thicknesses. On the other hand, helmet liners are employed to absorb most of the dynamic energy and protect the head from mechanical shocks. Because liners are in constant contact with the human head, besides the energy absorption characteristics, other important issues such as comfort, light-weight, and probability of airflow (to allow perspiration) narrow the final choice for the liner's material. Cellular materials, having the best combination of the above-mentioned factors, are used in the liner section of helmets in form of foam. Foams are one of the conventional cellular materials used in this area because of their reasonable price and simple manufacturing process. Many investigations have been carried out to improve the protection feature of helmets. Farajzadeh et al. [1] [Khosroshahi, 2018 #302][Khosroshahi, 2018 #1][Khosroshahi, 2018 #1][1] studied[Khosroshahi, 2018 #1] the feasibility of using a hierarchical lattice architecture for helmet liners. Their research showed the potential of significantly reducing the risk of head injury compared to a helmet with a traditional Expanded Polystyrene (EPS) liner and could potentially be considered as the new generation of energy-absorbing liners for helmets. Also, Blanco et al. [2] [1]proposed an innovative structure consisting of an ABS plastic lamina with deformable cones for energy absorption to minimize the likelihood of head injuries for standard impact cases. Najmon et al. [3] [1] developed a helmet liner through bio-inspired structures and topology optimized compliant mechanism arrays. Inspiration was drawn from bone, animal infrastructures, and microscopic skeletal structures, and the final liner was compared against an expanded polypropylene foam liner to appraise the protection capabilities of the proposed liner. In order to better protect the head area from Traumatic Brain Injury resulting from Improvised Explosive Devices, it is necessary to better understand the material properties involved in air blast mitigation. Schimizze et al. [4] studied the mitigation properties using sandwich samples made from a vinyl-nitrile foam shell filled with materials which were selected to

*Corresponding author's email: aa.naderi@modares.ac.ir

span a range of material properties using experimental and numerical methods. As a result of the investigation, density and acoustic impedance mismatch are shown to be of primary importance while porosity is shown to have an effect as well. Furthermore, Lockhart and Cronin [5] investigated helmet liner evaluation to mitigate head response from primary blast exposure. Five measures reflecting the potential for brain injury that were investigated included intracranial pressure, brain tissue strain, head acceleration (linear and rotational), and the head injury criterion. Candidate materials were then identified using the predicted optimal material values and as a result, the polymeric foam was found to meet the density and modulus requirements. Like helmets, most of the systems designed for blast protection are fabricated in the form of a laminated structure or sandwich panel. They are consisted of at least one layer of a high-strength thin-walled shell, which is considered to prevent perforation of any probable explosion debris and a relatively thick layer (core) with high energy absorption capacity to reduce the mechanical shock wave. To protect a military vehicle from harmful blast loads such as a landmine explosion, Yang and Qi [6] utilized sandwich armor structures with aluminum foam and developed a system-level dynamic finite element model to simulate the blast event and to evaluate the blast-resistant performance of the sandwich armor structure. The results show that the blast-resistant capability of the innovative sandwich armor structure with the isolating layer increases remarkably. Dass Goel et al. [7] examined the response of the aluminum cenosphere syntactic foam core stiffened and unstiffened structures subjected to blast load. The study was carried out with the objective of understanding the effects of the foam thickness, strain rate, and stiffener configurations on the response of the sandwich structure to the blast load. The results obtained indicated that the provision of the stiffeners and foam core considerably improves the blast resistance as compared to both, the unstiffened panels with foam core and without using syntactic foam core. Further studies to investigate the effect of using metallic foam cores under blast are conducted by Radford et al. [8]. In their study, the dynamic responses of clamped circular monolithic and sandwich plates of equal areal mass have been measured by loading the plates at mid-span. The performance of rigid polyurethane foams, as an energy absorbent core of sandwich panels covered with two exterior steel sheets, was investigated numerically by Andami & Toopchi-Nejad [9] through finite element methods, and as a result, An increase in the thickness of the foam layer, to a certain extent, was found to be beneficial to the mitigation capability of sandwich panel.

Furthermore, 3D printers have provided the access to complicated energy absorbing structures through an additive manufacturing process. Lan et al. [10, 11] studied the dynamic response of cylindrical sandwich panels with an aluminum foam core, hexagonal honeycomb core, and auxetic honeycomb core and compared their functionality by numerical approach. The findings of their study can guide well the theoretical study and optimal design of cylindrical sandwich structures subject to external blast loading. Qi et al. [12] conducted a study which aims to examine the performance of a new protective system utilizing auxetic honeycomb-cored sandwich panels for mitigation of shock loads from close-in and contact detonations of high explosives and showed that the proposed auxetic panels performed better than conventional honeycomb panels of the same size, areal density, and material. Moreover, Kalubadanage et al. [13] focused on the near-field blast loading conditions where liquid Nitromethane (NM) spherical charges were detonated in close proximity to the main structure and performed field blast tests on metallic re-entrant honeycomb-cored sacrificial cladding systems as protective structures for steel plate structures. Imbalzano et al. [14, 15] analyzed equivalent sandwich panels composed of auxetic and conventional honeycomb cores and metal facets and compared their resistance performances against impulsive loadings. Findings proved that auxetic panels demonstrated interesting crushing behavior, effectively adapting to the dynamic loading by progressively drawing material into the locally loaded zone to thereby enhance the impact resistance. Also, a 2D-based large-scale metallic auxetic Double Arrowhead Honeycomb Core Sandwich Panel (DAHSP) was proposed by Chen et al. [16] and its deformation response, energy dissipation characteristics, and associated mechanisms under air blasts were investigated using a validated numerical model. Furthermore, in a study carried out by Wang et al. [17], a novel sandwich panel with a three-dimensional Double-V Auxetic (DVA) structure core, which can produce isotropic mechanical behavior, was proposed for air blast protection purpose. Its primary structural parameters and their relations were discussed, and a parametric numerical model was established. Novak et al. [18] used the Selective Electron Beam Melting method to fabricate Chiral auxetic cellular structures from Ti6Al4V alloy and performed experimental tests under quasi-static and dynamic compression loading conditions. Also, some theoretical works are carried out to understand the behavior of auxetic-cored panels under blast e.g. investigation of Duc et al. [19] which used analytical solution to investigate dynamic response and vibration of composite double curved shallow shells with negative Poisson’s ratios in auxetic honeycombs core layer on elastic foundations subjected to blast and damping loads.

It is concluded from the literature that while several studies are conducted about effects of cellular materials such as 3D printed lattice structures in blast protective systems, shock attenuation and energy absorption performance of polymeric auxetic structures employed as helmet liner was not studied. According to a previous study conducted by Remennikov et al. [20] in which energy absorption of five different 3D printed auxetic structures was compared, it was concluded that the Arrowhead type auxetic lattice sample had the most energy absorption capacity. Therefore, the Arrowhead pattern is used in the lattice structure of the helmet liner. Thus in the present work, an innovative structure, combined of an Arrow-head auxetic lattice structure fabricated by Polyethylene (PE) material, is used for the first time as a helicopter helmet liner to reduce the air-blast shock transmitted to the human head.

Table 1. Material properties of foams employed in liners.

Foam	Mass density ($\frac{kg}{m^3}$)	Young's modulus (MPa)	Poisson's ratio	Yield stress (MPa)
EPS [24]	90.1	20.0	0	1.255
PU [25]	108.6	7.86	0.3	0.817

Also, because of the excellent performance of Polyurethane (PU) foam at blast wave reduction, the material of the foam pad located between the helmet liner and head is changed from Expanded Polystyrene (EPS) to PU for further improvements. Design dimensions are based on a conventional helicopter helmet and an average sized head-form of 4.58 kg was used to study the structure's performance under air blast loading. The investigation is carried out in two stages. At first, the blast behavior of the baseline helmet with EPS liner is compared with the helmet fabricated using a thin-walled auxetic lattice liner based on Head Injury Criteria (HIC) and crashworthiness properties. Afterwards, a parametric study is performed on the effect of cell sizes of the auxetic structure on the protection performance of the helmets to find the best performing configuration.

2- Numerical Simulations

2- 1- Materials

Helmet liners are conventionally manufactured using Expanded Polystyrene (EPS) foam which is lightweight and has acceptable mechanical properties. But the most important reason for using EPS is cost-efficiency while there are other foam materials with better crashworthiness performance. One of the improved kind of polymeric foams with significant energy absorption capacity is Polyurethane (PU) foam [21, 22, 23]. According to previous studies, PU foam shows a notable crashworthiness performance at dynamic loadings. Due to weight considerations, low density PU foam with a density of 108 $\frac{kg}{m^3}$ is selected to be replaced with the conventional EPS. To simulate foam's behavior in LS-DYNA, material model No. 57 (MAT_LOW_DENSITY_FOAM) is employed. In this material model besides the basic mechanical data such as density, Young's modulus, and Poisson's ratio, a stress-strain curve is required. Mechanical properties of EPS and PU foams and corresponding stress-strain curves are inserted in LS-DYNA and validated using the experimental data provided in [24, 25]. The basic material properties of EPS and PU foams are presented in Table 1.

There are a wide range of polymeric materials which could be employed in additive manufacturing. Among available materials, PE is an extremely durable thermoplastic. Properties of higher temperature resistance, flexibility, machinability, and strength make PE a preference for engineers where mechanical uses are important. Therefore, PE is chosen to fabricate the energy-absorbing lattice structure. For a better prediction of 3D printable material's behavior, the material model should have the ability of functioning based on the material's stress-strain curve in addition to considering strain rate parameters. Thus material model No. 24 (MAT_PIERCWISE_LINEAR_PLASTICITY) is selected. The strain rate effect is calculated based on the Cowper-Symonds model which can be written as Formula (1) to define the relationship between dynamic yield stress (σ) and static yield stress (σ_0). In the formula, C and P are material parameters to be determined from experimental observations and in this study, the values of C and P are inserted as 104 and 4.26, respectively. Numerical configurations of selected materials are evaluated based on experimental tests conducted in Ref. [26].

$$\sigma = \sigma_0 \left[1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{1/p} \right] \tag{1}$$

Brand-new helmet shells are manufactured using fiberglass, fiber carbon, aramid, or a mixture of mentioned composite materials. In this study, the shell is considered as a fiberglass/epoxy composite. The behavior of this material is also modeled using Mat. No. 24 using data provided in Ref [27]. Inserts of material model No. 24 are listed in Table 2 for each material.

2- 2- Validation

To confirm the accuracy of configurations used for the selected material models, a numerical simulation is performed for each case using the corresponding sample geometry and boundary condition mentioned in each reference. Results are compared with the respective experimental data in Fig. 1. In the experimental tests, properties of fiberglass/epoxy composite and PE were obtained using tensile tests. Therefore, besides the trend of diagrams, the maximum stress before failure is also a considerable parameter to evaluate the accuracy of the Finite Element (FE) model. On the other hand, the foam materials were tested under compressive loading.

Table 2. Material properties of base materials for lattice structure.

Material	Mass density $(\frac{kg}{m^3})$	Young's modulus (MPa)	Poisson's ratio	Yield stress (MPa)	Cowper-Symonds Constants	
					C	P
PE [26]	945	930	0.35	17	104	4.26
Fiberglass [27]	1480	14920	0.27	210	1520	13.43

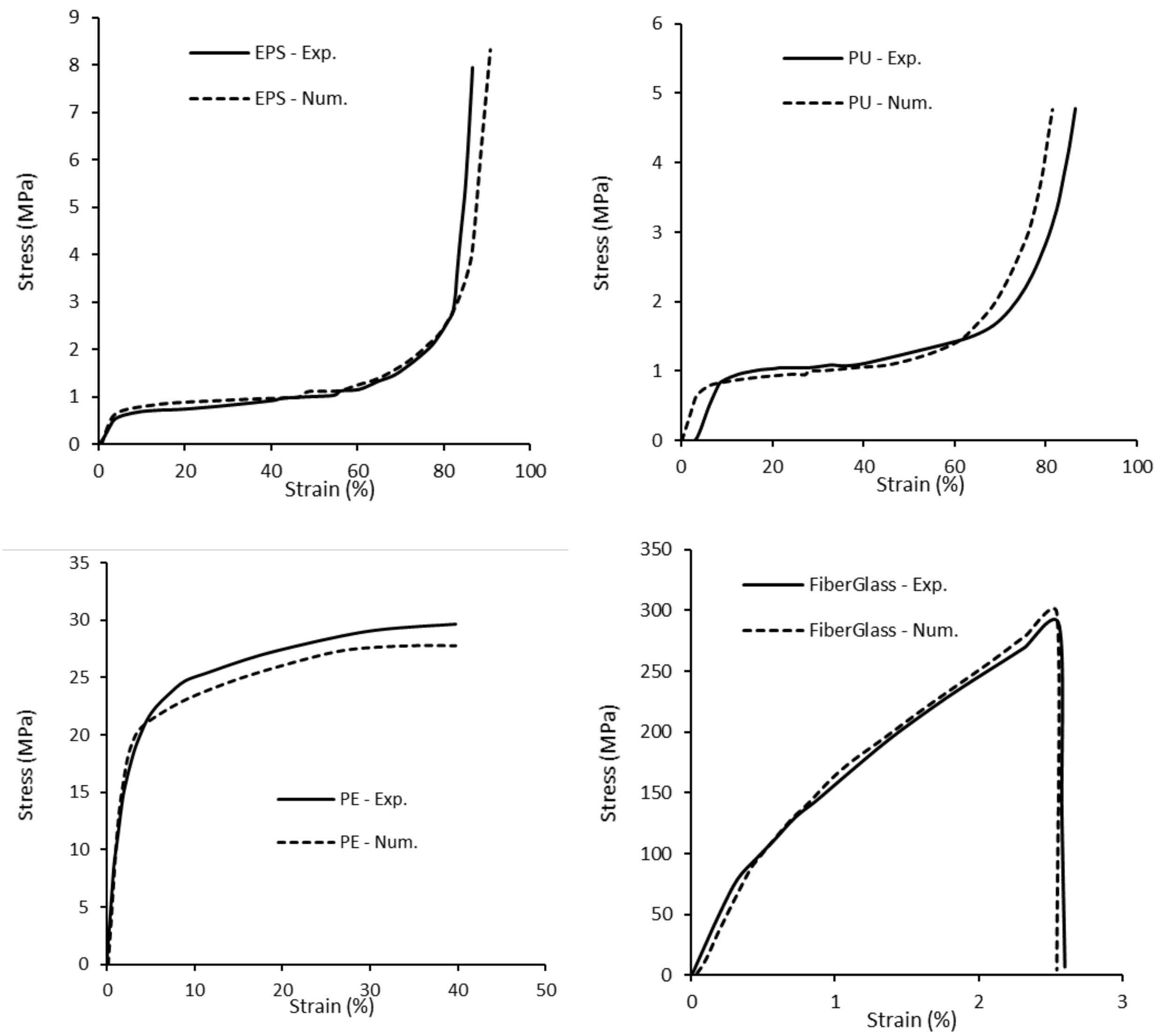

Fig. 1. Comparison of numerical simulations with the corresponding experimental data obtained from sample testing in Refs. [24, 25, 26, 27].

Table 3. Details of validating material models.

Sample	Plateau Stress (MPa)		Max. Stress (MPa)		Error (%)
	Exp.	Num.	Exp.	Num.	
EPS	0.89	1.01	-	-	13.4
PU	1.12	1.00	-	-	10.7
PE	-	-	29.6	27.6	6.7
Fiberglass	-	-	288	297	3.1

Thus, the plateau stress level is compared with the numerical simulations. Details of validation are presented in Table 3.

2- 3- Finite element modeling

A pedestrian head form for adults provided by LSTC [28] (code 180601) with a total weight of 4.58 kg is placed inside the helmet to measure loading data. Dimensions of the fabricated FE model are obtained from a conventional helicopter helmet. Outer shell thickness is set to 3 mm and the thickness of the basic liner section is 30 mm. Furthermore, helicopter helmets are equipped with an extra foam pad due to comfort and voice attenuation. The thickness of the foam pad is considered 10 mm. Foam components (liner and foam pad) because of their considerable thickness and amount of compression, are modeled with solid elements. Element formulation No. 3 in LD-DYNA is selected for solid sections to perform calculations as fully integrated quadratic 8 node elements. The helmet's outer shell and the cellular auxetic lattice are modeled using shell elements due to their thin thicknesses. Similar to the manufactured models in Ref. [29], the shell thickness of the auxetic structure in this study is set to 1 mm to achieve the desired flexibility while considering manufacturing limits. As recommended by LA-DYNA, formulation No. 2 (Belytschko-Tsay) is selected for shell sections.

To avoid instability and unwanted penetrations, two different kinds of contact card is used based on several try and errors [30, 31]. As a general approach, CONTACT_AUTOMATIC_NODES_TO_SURFACE is preferred to define the contact between every pair of neighbor components. For this contact type, the SOFT option in LS-DYNA is set to No. 1 to do the calculations based on soft constraint formulation. But in contact cases that the lattice structure is involved, CONTACT_AUTOMATIC_SURFACE_TO_SURFACE is used with SOFT=2 (pinball segment based contact). For simplification, no extra adhesive is modeled between liner and helmet shell. But instead, the friction ratio in the corresponding contact card is set to 0.4 [32] to simulate the interaction between liner and shell.

Detonation of an explosive charge in air results in the formation of rapidly expanding gaseous reaction products which compress the surrounding air and move it outward with a high velocity that initially approaches the detonation velocity of the explosive [33]. The rapidly expanding detonation products create a shock wave, i.e. a wave which is associated with discontinuities in the hydrodynamic quantities (pressure, density, temperature, and velocity) [34]. Following Moore et al. [35], air-blast wave case was considered as an air-blast wave characterized by an 18.6 atm peak overpressure which corresponds to the 50% lethal dose (LD_{50}) for lung-injury related death and is equivalent to a free-air explosion of 0.324 kg of TNT at a standoff distance of 0.6 m. Load Blast Enhanced (LBE) method is employed in LS-DYNA to simulate the air-blast effects. To reduce computation time, 1/4 of the helmet is modeled. Also, the head form is restricted to move alongside the blast wave direction only. A cross-sectional view of the modeled specimens is illustrated in Figs. 2 and 3.

A few adjustments are applied to control the stability of the computations. Hourglass (HG) modes are nonphysical, zero-energy modes of deformation that produce zero strain and no stress. Hourglass modes occur only in under-integrated (single integration point) solid, shell, and thick shell elements. In LS-DYNA, the hourglass (HG) option with viscosity formulation No. 5 and coefficient of 0.5 is used for foam sections to prevent hourglassing of elements. Furthermore, during the solution LS-DYNA loop through the elements and determine a new time step size by taking the minimum value overall elements. The time step size roughly corresponds to the transient time of an acoustic wave through an element using the shortest characteristic distance. For stability reasons, the scale factor TSSFAC is typically set to a value of 0.90 (default) or some smaller value. Therefore, the scale factor for computed time step (TSSFAC) is reduced to 0.5. To analyze the whole effects of the blast wave, a termination time of 4 ms was enough for all simulations.

Mesh sensitivity was analyzed to ensure the convergence of the FE results and to determine the mesh size used for the

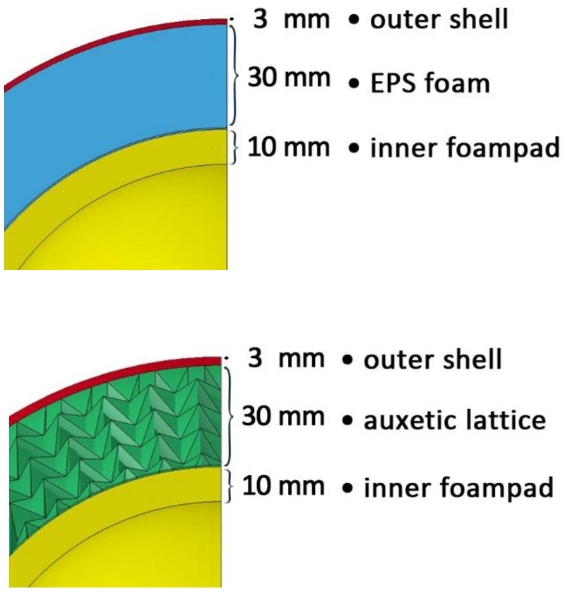

Fig. 2. Cross-sectional view of the modeled specimens. Top: Baseline helmet liner with EPS foam. Bottom: Helmet with innovative liner structure.

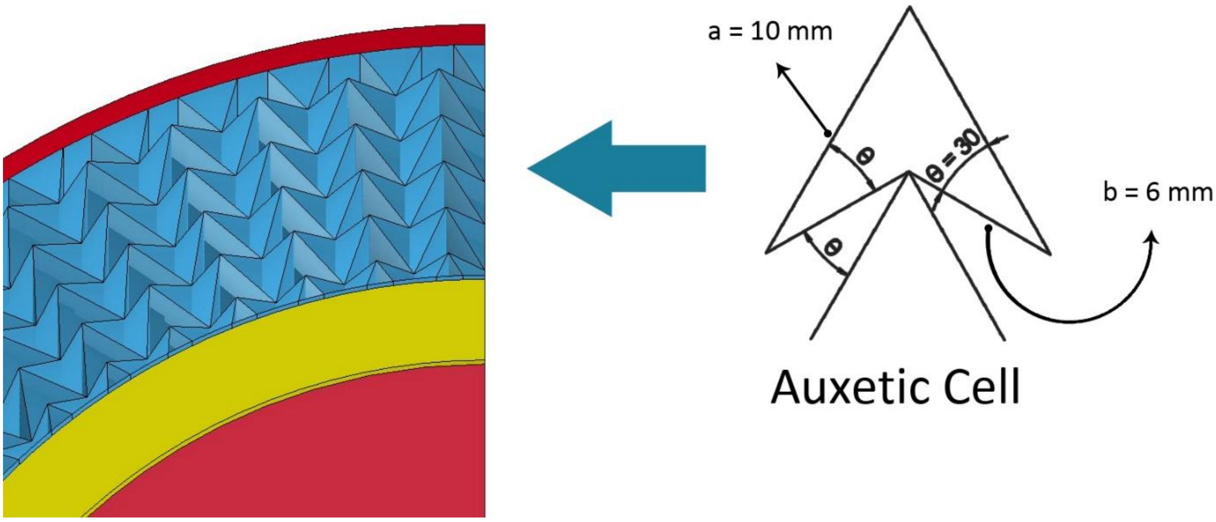

Fig. 3. Details of the auxetic structure employed in the proposed helmet liner.

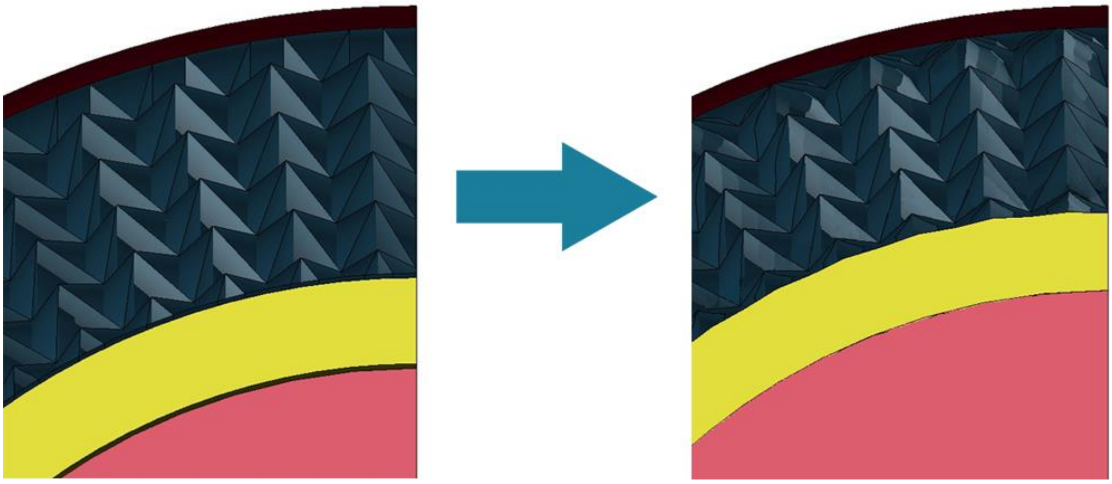

Fig. 4. deformation of the auxetic liner under blast loading.

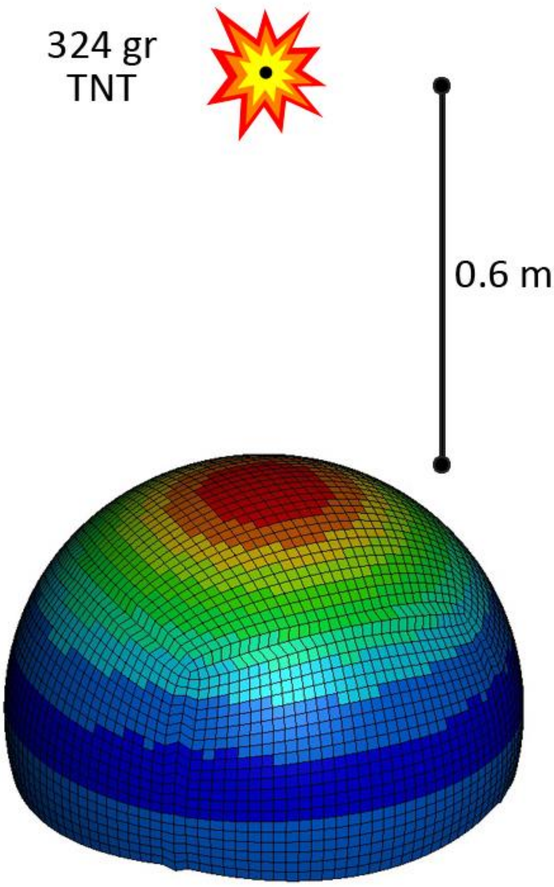

Fig. 5. Schematic of blast loading.

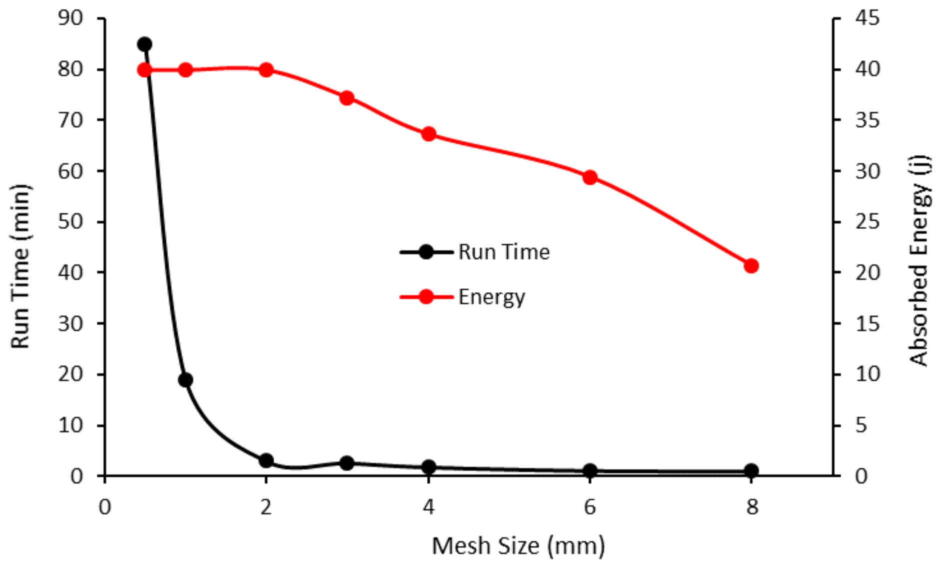

Fig. 6. Mesh convergence analysis.

remainder of this study's FE simulations. Numerical models Helmet with innovative liner structure were designed using a quadrilateral mesh with different mesh sizes. Models were created using maximum mesh sizes of 0.5, 1, 2, 3, 4, 4, and 8 mm. Based on the graph shown in Fig. 6, the element size of 2 mm is suitable for modeling considering the accuracy of the results and computation time.

3- Results and Discussion

3- 1- Effect of using auxetic lattice structure as a liner

In comparing the blast behavior of protective systems, the prior criterion is the trend of the acceleration-time diagram. In such studies, mostly the aim is to optimize the structure in a way that the amount of peak acceleration is reduced and loading occurs in a larger time interval. The a-t diagrams of the baseline helmet and the helmet modified with auxetic lattice liner are illustrated in Fig. 7. In the diagrams, the significant decrease in the peak acceleration is notable when the new structure is used. The curve representing the performance of the baseline model referred as EPS contains one large peak with a sudden drop in two stages. The steep slope and fast pace of change in the diagrams of the baseline model depict that the blast shock transmitted to the headform could be harmful. By employing the brand-new liner structure, a 22% reduction in the peak acceleration is noticed at the blast. Besides, the oscillation of the modified helmet's diagram labeled as Modified is limited to a smaller range. Since the presented data are obtained from headform's center of mass, the delay in the diagram of the modified helmet shows that the speed of the blast wave is slower in the innovative liner. However, for comparing blast performance of liners, analyzing the acceleration-time diagram is not enough and more advanced measurements are required. Since the only aim of using and upgrading helmets is to protect the head area, the situation of headform under blast loading should be studied more specifically. The Head Injury Criterion (HIC) is intended to judge the head injury risk quantitatively [36]. The HIC can be used to assess safety related to vehicles, personal protective systems, and sports equipment. Normally the variable is derived from the measurements of an accelerometer mounted at the center of mass of a crash test dummy's head, when the dummy is exposed to crash forces. The value of HIC is calculated based on Eq. (2). As the formula indicates, HIC is dependent on both extents of acceleration and duration of loading. Meaning a large amount of acceleration could be tolerated in a short time interval and on the contrary, if loading duration is relatively long, the average amount of acceleration shouldn't exceed a specific limit to avoid severe brain traumas. Calculated quantities of HIC are demonstrated in Fig. 7. The reduction of HIC when the conventional EPS liner is replaced with the innovative structure is considerable. Therefore, besides the decreased effect of blast shock, a reduction of 45% is also resulted from replacing the liner and the foam pad with proposed cases.

$$HIC = \max_{t_1, t_2}\left[(t_2 - t_1)\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right)^{2.5}\right] \quad (2)$$

The function of the liner in the helmet is to absorb unwanted dynamic energy and in the upgrading process of this section, energy absorption should be studied. The trend of changing internal energy versus time is plotted for specimens in Fig. 8. LS-DYNA calculates both elastic and plastic work done to

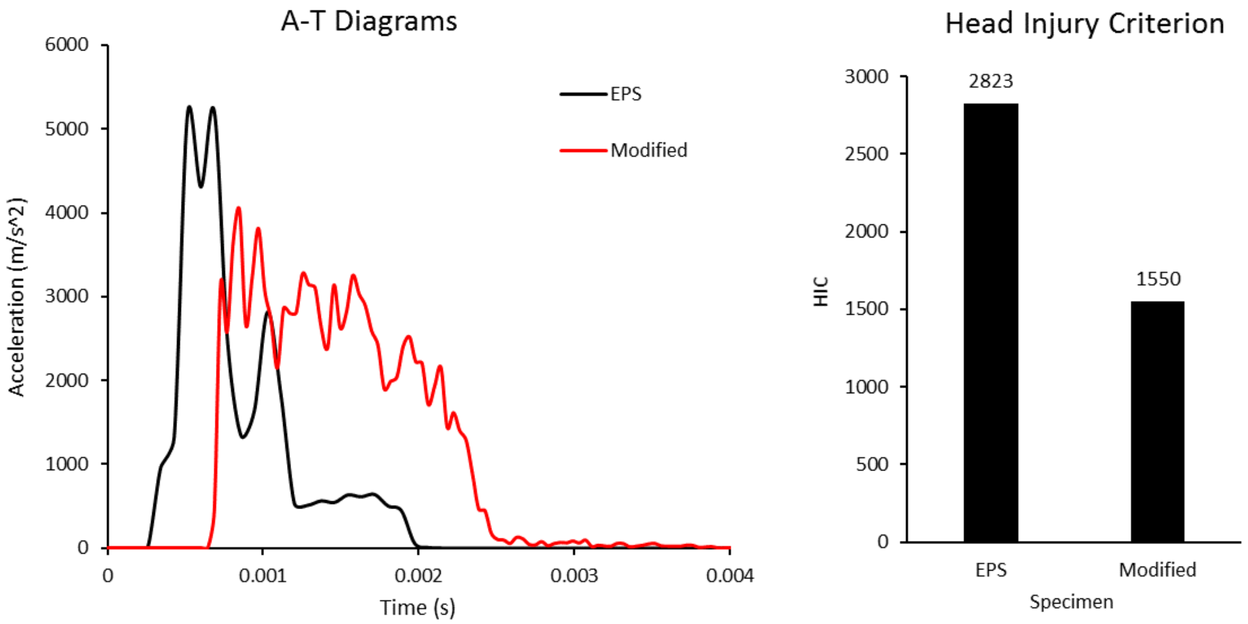

Fig. 7. Comparison of the modified helmet with baseline model under blast: Left) Acceleration vs. time diagrams, Right) HIC numbers.

structures and the summation is presented in terms of internal energy. The auxetic liner has more flexibility compared to the conventional EPS, thus when the loading duration is completed and elastic work is dissipated, the amount of total internal energy is decreased. Based on data, the energy absorption is increased when the innovative structure is employed as a helmet liner. However, in the presented chart, the total mass of the helmets is not considered. Since the pilot has to bear the weight of the helmet for a considerable period of time, light-weighting is extremely important. Moreover, lightweight design is a fundamental factor in fabricating energy absorbers because if structures' weight was not an issue, obviously more material was put into use, and energy absorption capacity was easily increased by multiplication of plastic works under loadings. To consider the total mass in the crashworthiness studies, engineers use the Specific Energy Absorption (SEA) parameter. Based on Eq. (3), SEA defines the ratio of absorbed energy to the weight to justify the efficiency of added mass regarding the scale of enhancement. SEA of helmets under air blast are presented in charts of Fig. 8. Data shows that using the new structure as the liner has risen the SEA parameter by 18.5% which justifies the use of the suggested innovative liner.

$$SEA = \frac{EnergyAbsorption(j)}{Weight(kg)} \tag{3}$$

3- 2- Parametric study on the effect of geometry in performance of the innovative liner

In the next stage of the investigation, a parametric study is carried out to investigate the effect of changing the density of cells in the lattice structure on the overall performance of the helmet under air blast. As illustrated in Fig. 3, cells are arranged in 5 rows. To change the density, the number of rows is changed in different designs. Since the geometrical similarity is valid for each cell, the value of θ is unchanged in all specimens. According to Fig. 9, AH3 in this section is equal to the specimen referred as Modified in the previous section. The deformation pattern in specimens designed for the parametric study is illustrated in Fig. 10. Acceleration vs. time diagrams related to the proposed cases is presented in Fig. 11. Diagrams depict that in general, by increasing the density of cells in the lattice liner, peak load is increased. But by using lattice liners with lower density, the occurrence of peak acceleration is delayed and the shock effect is decreased.

HIC numbers of mentioned helmets are also compared in Fig. 12. According to Eq. (2), the HIC value is highly dependent on the integral of the *a-t* diagram. Therefore, while AH1 has the highest peak acceleration, the HIC number of AH2 is higher. Between the upgraded helmets, AH4 has the lowest HIC level and provides the highest protection against blast shock wave. However, by using the lower density lattice liner in AH5, neither the peak acceleration is decreased nor the HCI is reduced. The reason is because of the small number of auxetic cell rows which prevents the proper function of

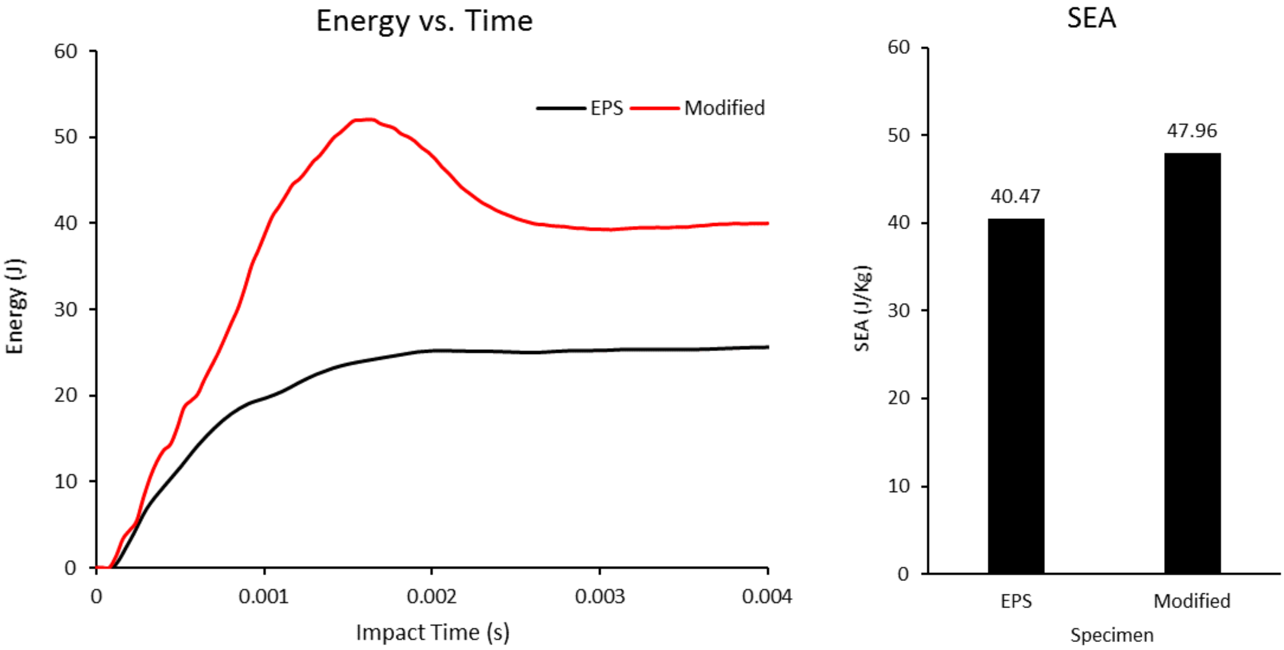

Fig. 8. Comparison of energy absorption characteristics of the modified helmet with baseline model under blast: Left) Absorbed Energy, Right) Specific Energy Absorption.

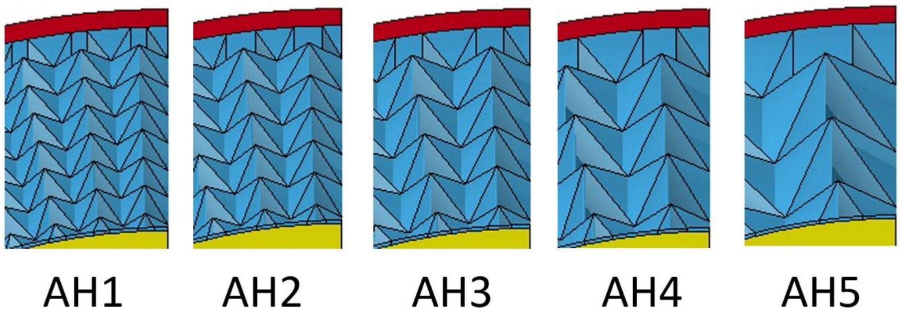

Fig. 9. Designs of the auxetic liner to achieve different densities.

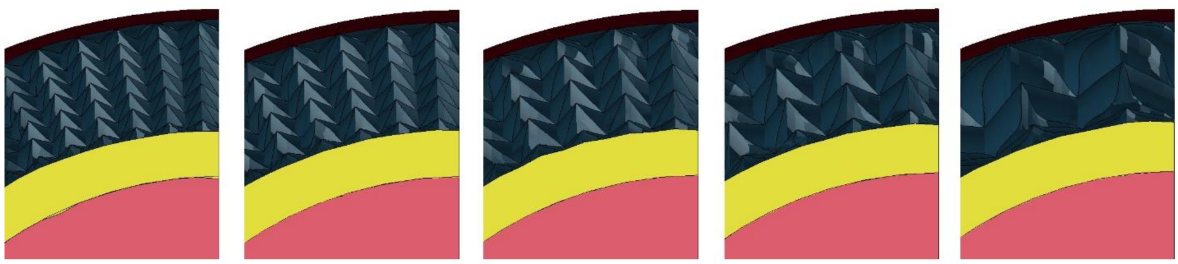

Fig. 10. Deformation pattern in specimens designed for parametric study.

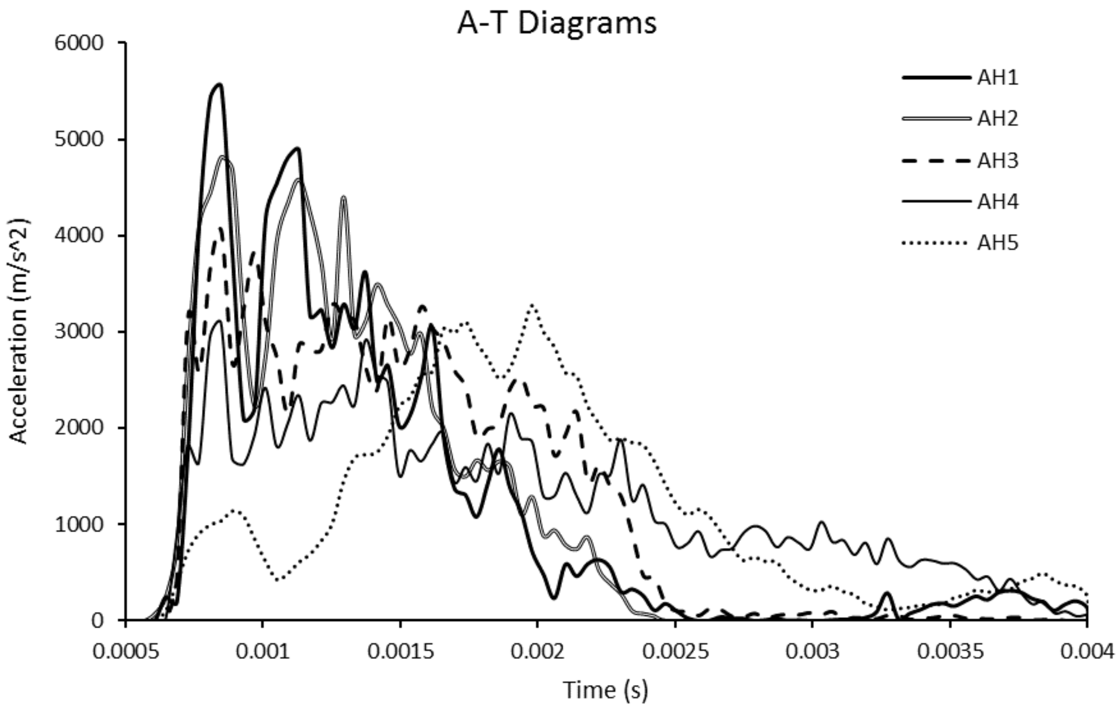

Fig. 11. Acceleration vs. time diagram of modified helmets with different auxetic cell sizes.

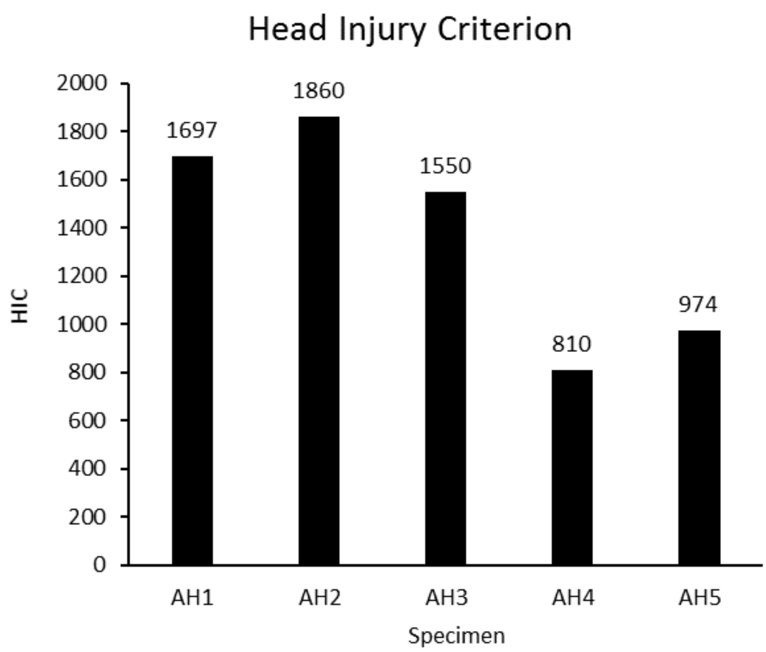

Fig. 12. HIC number of modified helmets with different auxetic cell sizes.

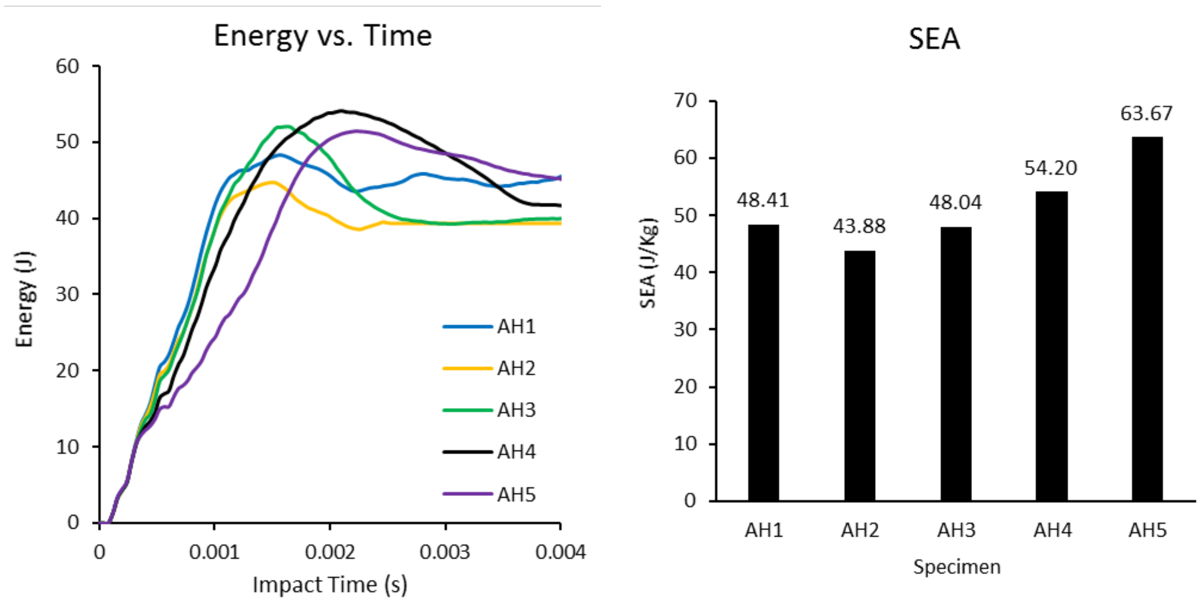

Fig. 13. Comparison of energy absorption characteristics of modified helmets with different auxetic cell sizes: Left) Absorbed Energy, Right) Specific Energy Absorption.

the auxetic structure. Thus, despite the improvements caused by using lower cross-sectional densities of auxetic lattice, a minimum number of rows are required to obtain the expected auxetic behavior.

Furthermore, the energy absorption and SEA parameter of specimens with different rows in the lattice are compared in Fig. 13. As indicated in the charts, no significant difference in the energy absorption capacity is observed between the modified cases. While the highest SEA number is achieved in AH5, this case was not accepted because of the auxetic structure's malfunctioning. The second best specimen from a crashworthiness point of view is AH4 with SEA of 54.2, which was also selected based on the HIC number.

4- Conclusion

In this study, an innovative helmet liner is numerically developed using an arrow-head auxetic lattice structure. A series of air-blast tests were carried out on both baseline and modified helmets to determine the ideal design. The study is performed in two levels. First, the blast performance of a basic helmet with EPS foam liner is compared with the helmet modified by a medium-sized auxetic lattice liner and a foam pad manufactured by PU foam. Afterwards, a parametric study was carried out to investigate the effect of lattice liner's density by employing similar arrow-head auxetic structures with different cell sizes. The main achievements obtained from this investigation may be summarized as below:

By using a medium-sized auxetic lattice structure instead of EPS liner, the peak acceleration and HIC number recorded from headform are decreased by 22% and 45%, respectively which shows a significant improvement in the blast protection.

Employing the innovative liner in a conventional helmet has resulted in a 56% increase in the energy absorption capacity under blast loading.

In the parametric study on the effect of auxetic cell sizes (auxetic density), AH4 with the HIC number of 810 was selected as the best performing configuration. Using the AH4 liner structure, HIC is reduced by 71% compared to the baseline helmet with EPS liner, and the peak acceleration is also decreased by 40%.

The SEA parameter of the helmet with AH4 configuration is increased by 34% compared with the baseline model.

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