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Crashworthiness Study of an Innovative Helmet Liner Composed of an Auxetic Lattice Structure and PU Foam

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KEYWORDS

Helmet liner
Polyurethane foam
Auxetic structure
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LS-DYNA

ABSTRACT

Helmet liners are employed to prevent or reduce head injuries caused by impact loads. Liners minimize the collision damage by impact shock attenuation and absorbing the collision energy. In order to improve crashworthiness characteristics of helmet liner, in the present study, an innovative structure designed by a combination of Polyurethane (PU) foam and auxetic lattice structure is suggested to replace the conventional EPS foams usually employed in the liner section. The baseline liner section is divided into two main layers. In one layer, PU foam is used instead of EPS and in the second layer, an arrowhead pattern auxetic structure is used to improve energy absorbing capacity. By employing three kinds of PU foam with different densities and four 3D printable materials for the lattice structure, 6 combinations of the modified liner are presented. An explicit finite element method is employed to model the innovative helmet structure under impact loading and results are compared with the conventional case based on the trend of acceleration, energy absorption, weight, and Head Injury Criteria (HIC) factor.

1. Introduction

To protect a human's head area, helmets are used in dangerous environments when the head is at risk of injuries. Head injuries are mainly caused by high or low speed collisions. Physical head damages could be considered as two main kinds. Injuries caused by direct contact may lead to bleeding or skull breakages and brain traumas resulting from mechanical shock waves or heavy strokes. Damages of direct contact 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 (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 impact energy and protect the head from collision shocks. Because liners are in constant contact with a 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 above mentioned factors, are widely used in the liner section of helmets. Foams are one of the conventional cellular materials used in this area because of their reasonable price and simple manufacturing process. To develop a comprehensive constitutive law to be implemented into FEM codes for impact analysis, Di Landro et al. [1] performed an experimental study on the deformation mechanisms and energy absorption capability of polystyrene foams and polycarbonate shells for protective helmets and demonstrated that the energy absorption capability of these materials can be controlled at both macroscopic and microscopic scales. Also, D.S. Liu et al. [2] investigated the effect of environmental factors such as hot-wet and pre-compression on energy absorption degradation of polystyrene foam in protective helmets. To confirm the use of the FE approach as a tool to optimize the performance characteristics of the energy absorbing liner of an existing helicopter pilot helmet, Smith et al. [3] compared energy absorption of 13 different foams (including

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Expanded Polystyrene (EPS), Poured Blend Foam (EPU), Expanded Polypropylene (EPP), Polyethylene Laminate (EPE), Rubberized Expanded Polystyrene and Expanded Polyethylene) used as a helmet liner and concluded that there are several currently available materials which could be used as energy absorbing liners to improve the impact performance of the existing helicopter helmet in the impact tests simulated. According to the cross-sectional structure of the helmet, the composition of shell and liner could be considered as a multi-layer panel with foam core. Some efforts have been made to understand the theoretical basis of such structures' behavior under low velocity impact. Zhu et al. [4] studied the dynamic response of foam core sandwich panels with composite face sheets during low-velocity impact and penetration. In the research, the penetration processes under low-velocity impact were considered and an analytical model based on the energy approach is developed to predict contact force, contact time, impactor displacement, energy absorption, and failure modes. Also, Qin et al. [5] investigated the low-velocity impact performance of square sandwich plates with a metal foam core while a large deflection effect was included in the analysis by considering the interaction between the plastic bending and stretching. To determine the behavior of composite sandwich panels with PVC or Poly Urethane (PU) foam, Mostafa et al. [6, 7] performed experimental, theoretical, and numerical investigations. Furthermore, to investigate the load-carrying capacity and failure mechanisms of sandwich beams and panels with elastomeric foam core and composite laminate face sheets, Nazari et al. [8] conducted an experimental study and concluded that due to non-brittle behavior of the core material under loading, a large compression resistance is observed after the failure of the top skin which led to the recovery of the load-carrying capacity in the sandwich panels. The behavior of sandwich panels with foam cores is also studied in case of outer shell failure. Feli and Jafari [9] analytically modeled the perforation of foam‑composite sandwich panels under high‑velocity impact. Also, Rizov and Mladensky [10] investigated the influence of the foam core material on the indentation behavior of sandwich composite panels. An alternative approach to improve the crashworthiness of thin-walled panels is to use corrugated layers inside the structure. Odaci et al. [11] compared the effect of using two different cores such as aluminum corrugated layers and aluminum foam on the impact performance of fiberglass composite panels. Their research showed that the aluminum foam core provided higher resistance than corrugated aluminum cores in the sandwich panels against projectile impact at similar weights. This was attributed to the relatively higher strength of the foams investigated and the ability to distribute the incident impulse to a relatively large area in the backing composite plate. Moreover, in some cases researchers investigated the influence of using both of the above mentioned approaches at the same time, e.g. employing PVC foam inside the corrugated core [12] and using aluminum honeycomb filled with foam [13] in a composite sandwich panel.

Furthermore, 3D printers have provided the access to complicated energy absorbing structures through an additive manufacturing process. Based on experimental and numerical researches that Zuhal et al. [14, 15] conducted on energy absorption in lattice structures under quasi-static and impact load, specimens made by additive manufacturing method were tested in different strain rates. Results showed the great energy absorption capacity of such cellular lattice structures and demonstrated that there is significant scope for lattice structures to serve in a number of protective applications. Many efforts have been made to the energy absorption capacity of 3D printed lattice structures into applicable use [16, 17, 18, 19, 20]. Baykasoglu et al. [21] employed lattice structures manufactured based on body-centered cubic (BCC) and the body-centered cubic with vertical strut (BCC-Z) patterns in a thin-walled metallic tube and optimized the crashworthiness of the novel structure. Al Rifaie [22] and Turner et al. [23] in their researches investigated the low-velocity impact behavior of composite sandwich panels with cores comprised of lattice truss structures (LTS) in different configurations and discussed the difference in energy absorption according to load-displacement diagrams. A branch of 3D printable lattice structures is called "Auxetics" which was developed based on negative Poisson's ratio and has shown notable crashworthiness performance. In some cases, researchers investigated the possibility of using three-dimensional lattice structures as a helmet liner to enhance head protection. Farajzadeh et al. [24] investigated the feasibility of using a hierarchical lattice architecture as a helmet liner and consequently, a notable reduction was reported in peak accelerations for direct and oblique impact compared to conventional EPS foam. Also, as a result of an investigation conducted by Najmon et al. [25], a helmet liner was developed through bio-inspired structures and topology optimized compliant mechanism arrays.

It is concluded from the literature that while several studies are conducted about the effects of using foams and 3D printed lattice structures, the energy absorption performance of using foams and polymeric auxetic structures together was not studied. In the present work, an innovative structure, combined of a Polyurethane (PU) foam layer and an auxetic lattice structure fabricated by ABS material, is used as a helicopter helmet liner to reduce the impact shock transmitted to the human head. According to a previous study conducted by Remennikov et al. [26] 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. Design dimensions are based on a conventional helicopter helmet and an average sized head-form of 4.5 kg was used to study the structure's performance at impact speeds of 3 and 6 m/s. The investigation is carried out in two stages. At first, the impact behavior of the baseline helmet with EPS liner is compared with modified helmets. Three brand-new helmets are designed for this stage with liners manufactured by PU foam with different densities while 3D lattice is fabricated using Acrylonitrile Butadiene Styrene (ABS). In the second stage, the effect of replacing base material of the lattice structure is investigated to find the best performing configuration. As a result, an innovative and feasible structure is introduced which could be replaced with the conventional EPS liner in helmets. Data shows that the upgraded helmets absorb a greater portion of energy and perform much better at attenuation of the impact shock which has led to a considerable reduction in the risk of head injury and severe brain traumas could be prevented.

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 kinds of polymeric foams with significant energy absorption capacity is Poly Urethane (PU) foam [27, 28, 29]. According to previous studies, PU foam shows a notable crashworthiness performance at dynamic loadings. Due to weight considerations, low density PU foam with 3 different densities 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 PU and EPS foams and corresponding stress-strain curves are inserted in LS-DYNA and validated using the experimental data provided in [30, 31]. The basic material properties of EPS and PU foams are presented in Table 1.

There is a wide range of polymeric materials which could be employed in additive manufacturing. Among available materials, ABS is an extremely durable thermoplastic. Properties of higher temperature resistance, flexibility, machinability, and strength make ABS a preference for engineers where mechanical uses are important. Therefore, ABS is chosen to fabricate the energy absorbing lattice structure at the first stage of the investigation. At the next stage of the study, Thermoplastic Polyurethane (TPU), high-density Polyethylene (PE), and Polypropylene (PP) are also used as the base material for the lattice structure of the liner to compare the overall impact performance. 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. Numerical configurations of selected materials are evaluated based on experimental tests conducted in Refs [32, 33, 34, 35].

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 fiber glass/epoxy composite made from 15 layers of woven glass fabric impregnated with an epoxy resin binder under pressure and heat. Volume fiber content was 55% and the warp and weft directions of fabric were called lengthwise (0 degrees) and crosswise (90 degrees), respectively. The behavior of this material is also modeled using Mat. No. 24 based on data provided in Ref [36]. Inserts of material model No. 24 are listed in Table 2 for each material.

2.2. Finite Element Modeling

A pedestrian head form for adults provided by LSTC [37] (code 180601) with a total weight of 4.58 kg is placed inside the helmet to measure impact data. Dimensions of the fabricated FE model are obtained from a middle-sized Bell® helicopter helmet (Fig. 1).

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. Shell thickness of the auxetic structure in this study is set to 0.5 mm to achieve the desired flexibility. As recommended by LA-DYNA, formulation No. 2 (Belytschko-Tsay) is selected for shell sections.

Fig. 1. The Bell® helicopter helmet used to obtain geometrical dimensions.

Table 1. Material properties of foams employed in liners.

Foam	Mass density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio	Yield stress (MPa)
EPS	90.1	20.0	0	1.255
PU 56	56.9	4.71	0.3	0.314
PU 108	108.6	7.86	0.3	0.817
PU 137	137.1	18.37	0.3	1.466

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

Material	Mass density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio	Yield stress (MPa)
TPU	1175	24	0.35	5.15
PE	945	930	0.35	17
ABS	1000	1500	0.3	36
PP	950	7500	0.3	457
Fiber glass/ epoxy composite	1480	14920	0.27	210

Table 3. Specimen codes used in each stage of the study.

Specimen Code	EPS	PU 56	PU 108	PU 137	TPU	PE	ABS	PP
Lattice Material	-	ABS	ABS	ABS	TPU	PE	ABS	PP
Foam Material	EPS	PU 56	PU 108	PU 137	PU 108	PU 108	PU 108	PU 108
Stage	I	I	I	I	II	II	II	II

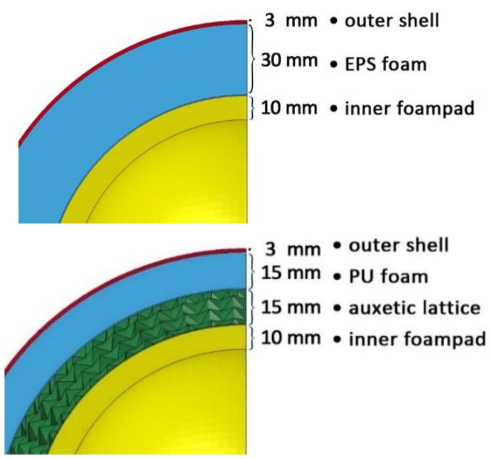

Fig. 2. Cross-sectional view of the modelled specimens. Top: Baseline helmet liner with EPS foam. Bottom: Helmet with innovative liner structure.

To avoid instability and unwanted penetrations, two different kinds of contact card is used based on several trials and errors. 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 calculate 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 [38] to simulate the interaction between liner and shell.

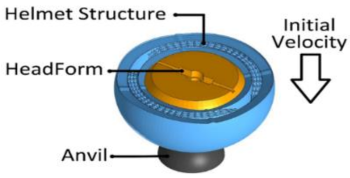

Fig. 3. Schematic of impact test simulation.

To reduce computation time, 1/4 of the helmet is modeled. In the impact simulations, helmets and head-form have collided to a fixed hemispherical rigid barrier at speeds of 3 and 6 m/s. A cross-sectional view of the modelled specimens is illustrated in Fig. 2.

A few adjustments are applied to control the stability of the computations. Hourglass (HG) option with viscosity formulation No. 5 and coefficient of 0.5 is used for foam sections to prevent hourglassing of elements. Also, the scale factor for computed time step (TSSFAC) is reduced to 0.5. Since the impact has occurred in low velocity, a termination time of 10 ms was enough for all simulations.

A specific code is assigned to each specimen based on material combination and stage of study as listed in Table 3. Based on the table, specimens "PU 108" and "ABS" are technically the same but for more clarification in comparisons, different names are chosen at each stage.

3. Results and Discussion

3.1. Effect of using Different PU Foams

In comparing the impact 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 impact has occurred in a larger time interval. The a-t diagrams of tested specimens are illustrated in Fig. 4. at impact speeds of 3 and 6 m/s. Since the results should be compared based on the head's situation at impact, representing data are obtained from the head form`s center of mass. Also, linear displacement of head form is limited to move along the direction of the initial velocity. Therefore, the change in acceleration has only occurred in the direction of velocity. In the diagrams, the significant decrease in the peak acceleration is notable when the new structure is used. The curves representing EPS performance contain two peaks with one sudden drop in between. The steep slope and fast pace of change in the diagrams of the baseline model depict that the impact shock transmitted to the head form could be harmful. According to a previous study by Song et al. [39] on the interaction of foam core with a thin-walled shell, under loading, a high density region is formed in the foam due to compression, which leads to a considerable increase in overall resistance of the structure. This issue justifies the relatively high peak acceleration of the specimen with EPS liner. But when the failure has started in the foam, the extra resistance is dissipated and the acceleration level is dropped to a specific level. By continuing the progress of impact loading, foam is again compressed and peak load is increased until the initial energy is consumed and the helmet is rebounded from an anvil. As the diagrams depict, this action is highly prevented when an auxetic lattice structure is used beside the foam layer in upgraded specimens and the effect of foam densification due to compression is degraded by lattice section. By employing the brand-new liners, an average of 49% and 42% reduction in the peak acceleration is noticed at impact speeds of 3 and 6 m/s, respectively. Besides, the oscillation of corresponding diagrams is limited to a smaller range. At collision speed of 3 m/s, the duration of impact in specimens with upgraded liner is approximately equal and the lowest peak acceleration is observed when PU foam with density of 108 is employed. On the other hand, the impact duration is not the same when collisions have occurred at 6 m/s. For comparing the impact performance of innovative liners and selecting between three kinds of PU foams, 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 head form under impact should be studied more specifically. The HIC (Head Injury Criterion) is intended to judge the head injury risk quantitatively [40]. 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 Formula (1). As the formula indicates, HIC is dependent on both extents of acceleration and duration of impact. Meaning a large amount of acceleration could be tolerated in a short time interval and on the contrary, if impact 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. 5. for specimens at two impact speeds. The reduction of HIC when the conventional liner is replaced with an innovative structure is considerable. While the approximate reduction rate in 3 m/s impacts is 44%, in 6 m/s impacts the average of HIC is reduced by about 52% by using upgraded liner helmets.

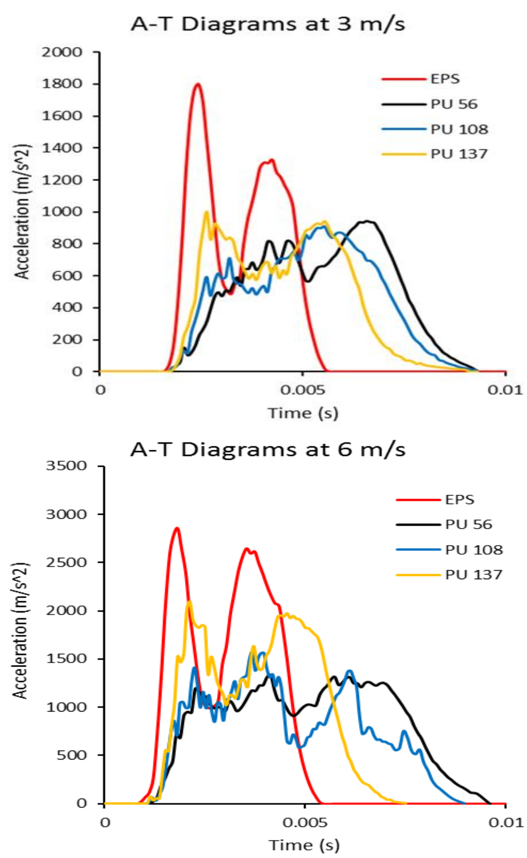

Fig. 4. Acceleration vs. time diagram of helmets fabricated at stage I.

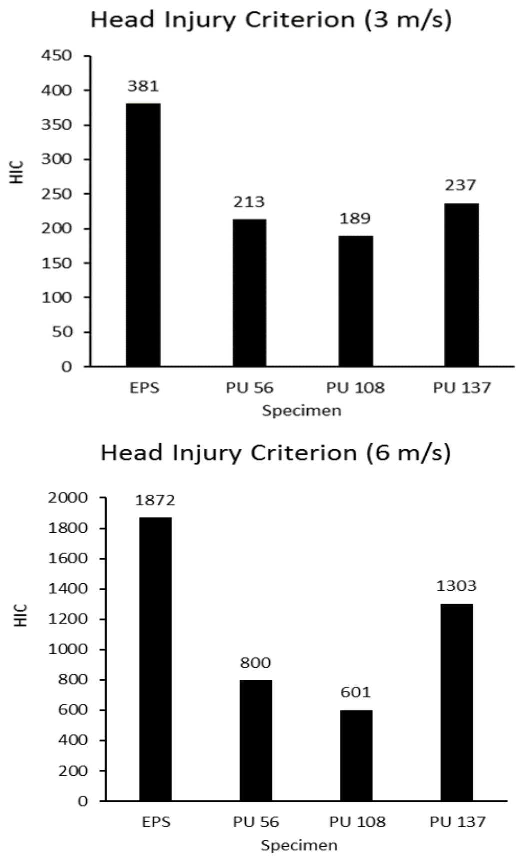

Fig. 5. HIC number of helmets fabricated at stage I.

Furthermore, the chart's data depicts that the modified helmet with PU 108 foam with HIC parameter of 189 in 3 m/s and 601 in 6 m/s provides the best protection among brand-new specimens.

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

The function of the liner in the helmet is to absorb impact energy and in the upgradig process of this section, energy absorption should be studied. The trend of changing internal energy versus time is plotted for specimens in Fig. 6. LS-DYNA calculates both elastic and plastic work done to structures and the summation is presented in terms of "internal energy". Thus a small reduction is observed in diagrams of all cases when impact duration is completed and elastic work is eliminated. Based on data, impact energy absorption is increased when the innovative structure is employed as a helmet liner. Furthermore, the best result is achieved when PU foam with density of 108 is used. 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 Formula (2), 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 impact are presented in charts of Fig. 7. Data shows that using the new structure as a liner has risen the SEA parameter in all cases. While SEA of cases PU 108 and PU 56 are almost equal at an impact speed of 3 m/s, a significant difference is observed between SEA of mentioned specimens when impact speed is 6 m/s and PU 108 has performed better at energy absorbing. This issue depicts that in lower speeds considering the weight of structures, using PU foams with densities of 108 and 56 are both justifiable. But at higher strain rates, the functionality of PU 56 is significantly decreased due to lower strength and more percentage of failure.

$$SEA = \frac{Energy\ Absorption\ (j)}{Weight\ (kg)} \quad (2)$$

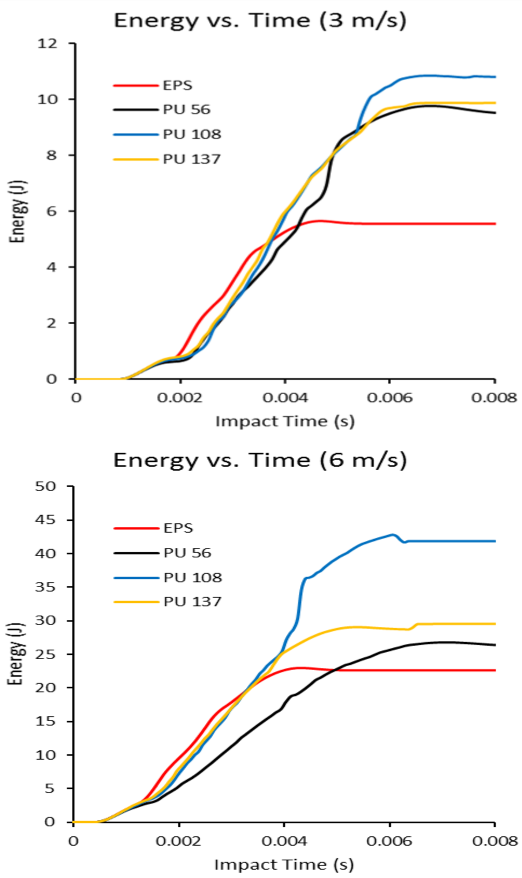

Fig. 6. Energy absorption of helmets fabricated at stage I.

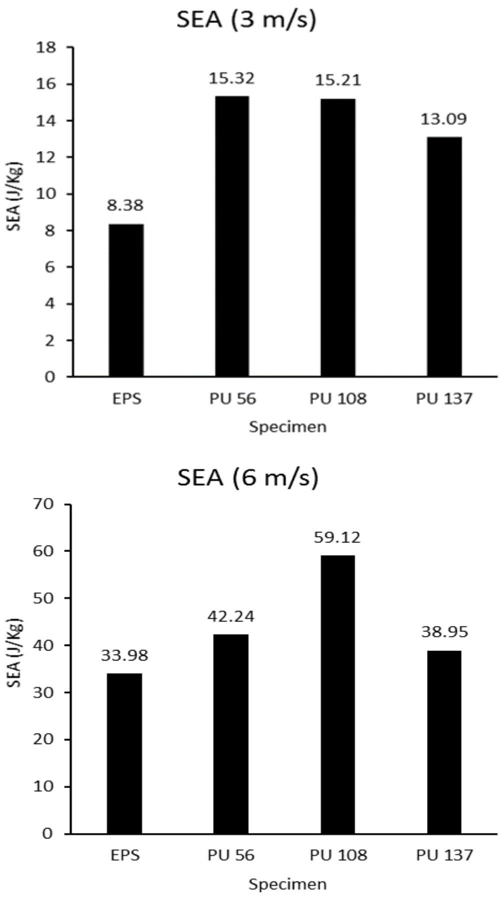

Fig. 7. Specific energy absorption of helmets fabricated at stage I.

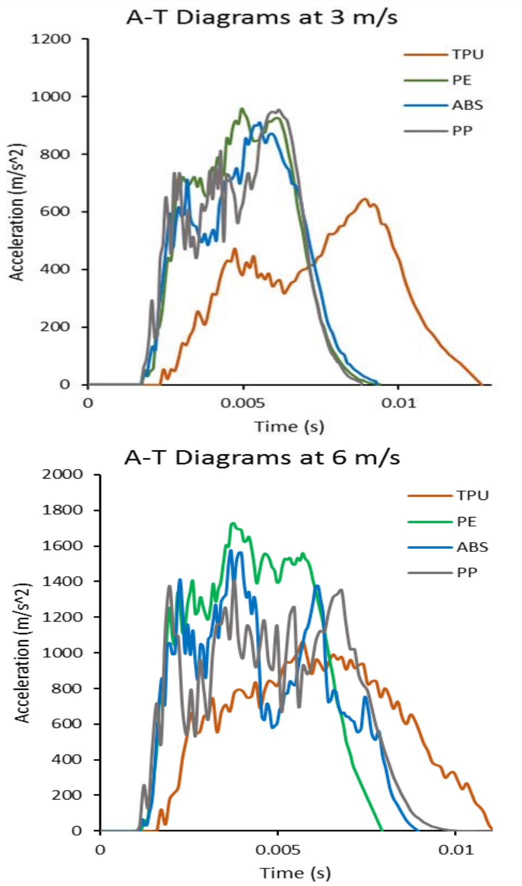

Fig. 8. Acceleration vs. time diagram of helmets fabricated at stage II.

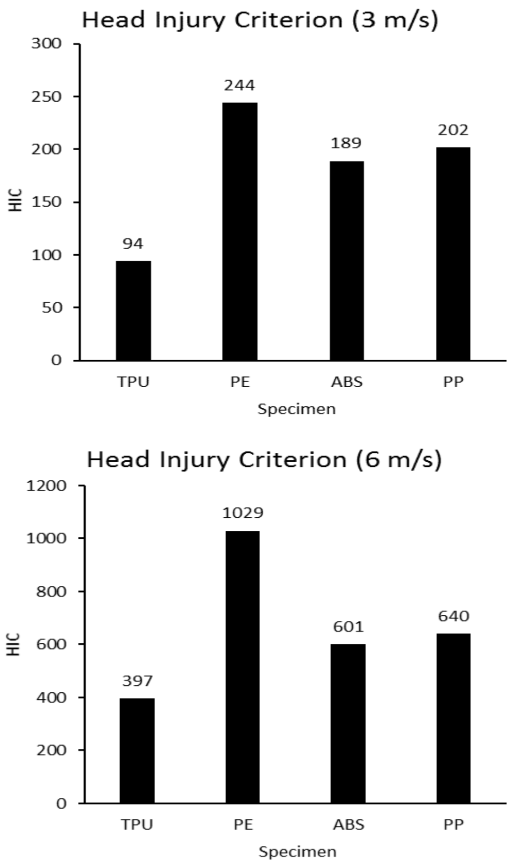

Fig. 9. HIC number of helmets fabricated at stage II.

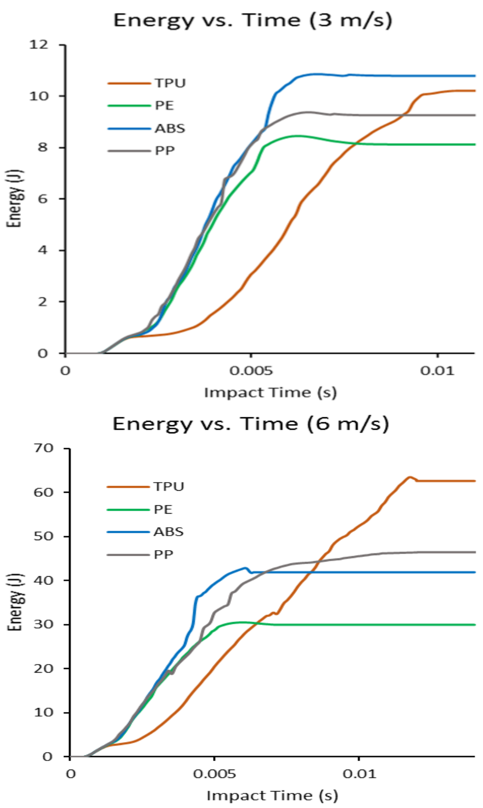

Fig. 10. Energy absorption of helmets fabricated at stage II.

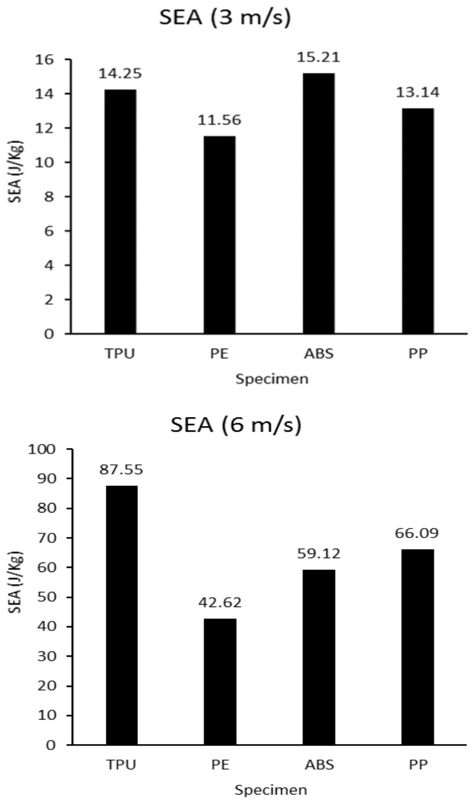

Fig. 11. Specific energy absorption of helmets fabricated at stage II.

3.2. Effect of replacing Base Material of Lattice Structure

In the next stage of the investigation, 3 other materials are considered to be used as the base material of the lattice structure. In all cases, 3D structures are fabricated in a combination with the selected PU foam. Acceleration vs. time diagrams related to the proposed cases are presented in Fig. 8. Also, the data representing the performance of specimen “PU108” is plotted in the diagrams as “ABS” to compare the results. While no significant difference is observed between the acceleration-based performance of specimens PE, ABS, and PP, diagrams of TPU depict that the process of impact attenuation has occurred at a lower level of acceleration in a larger period of time when TPU is used to fabricate auxetic lattice structure. This is because of the lower elastic modulus of TPU material which makes the whole liner more flexible.

HIC numbers of mentioned helmets are also compared in Fig. 9. It is notable that the HIC of PE at an impact speed of 6 m/s is considerably higher than the average value. According to Formula (2), the HIC value is highly dependent on the integral of the a-t diagram. While the acceleration of specimens ABS and PP is decreased in the middle of the impact process, no reduction is observed in the diagram of PE (Fig. 8). Thus the area under the corresponding a-t diagram is larger and the higher HIC is justified. However, sudden changes in acceleration are recognized as shock and such impact could cause more damage. But because of the rather simple formula of HIC, the effect of shock is not considered. This issue confirms the importance of comparing the results from various points of view. Since the HIC number of TPU is in the best condition as well as the a-t diagram at two different impact speeds, better functionality of TPU material as the base material of lattice structure is proven.

Furthermore, the energy absorption and SEA parameters of specimens with different lattice materials are compared in Figs 10 & 11. A comparison of the energy absorption trend in ABS and TPU shows that in the helmet upgraded by ABS material, a specific amount of energy is absorbed in a relatively smaller time interval. On the other hand, the energy absorption of TPU has risen gradually.

But in higher impact speed, a significant increase is observed in the capacity of energy absorption. This behavior is because of the lower range of acceleration in the TPU-made specimen which makes the structure absorb the impact energy without a sudden rise in contact load level. In fact, the more flexible behavior of TPU has prevented the formation of dense areas in the foam section by local deformations.

4. Conclusion

In this study, an innovative helmet liner is numerically developed using a combination of arrow-head auxetic lattice structure and PU foam. Three different PU foams and four 3D printable polymeric materials including TPU, PE, ABS, and PP were considered to be employed in the new liner structure to find out the best configuration. A series of impact tests were carried out on both modified and baseline helmets to determine the ideal design. Tests were conducted at speeds of 3 and 6 m/s in which specimens have collided to a rigid hemispherical anvil. The study is carried out in two levels. First, the performance of modified helmets with a fixed material for the liner's lattice structure and different PU foams are compared with the basic helmet to find the best performing PU foam. Then further models are designed using different polymeric materials employed in the auxetic section along with the selected foam. In all cases, the modified helmets have shown better efficiency at impact shock attenuation. It was shown that the head form has experienced lower shock and injury at impact when PU foam with density of 108 kg/m^3 is employed based on acceleration-time diagrams and HIC number. Also from the crashworthiness point of view, specimen fabricated by PU108 foam has better energy absorption capability and higher SEA value. By replacement of lattice structure's base material with TPU, a significant reduction has occurred in the peak acceleration and according to HIC numbers, the damage experienced by head form due to impact is reduced. In lower impact speed, no considerable difference is noted between the energy absorption of specimens manufactured by TPU and ABS. However, when the speed is increased, the greater energy absorption capacity of the TPU base structure is shown and the corresponding SEA parameter is increased up to 48% compared with the ABS-based helmet.

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