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Design, optimisation and analysis of a helmet made with graded honeycomb structure under impact load

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ABSTRACT
Due to increased attention to safety requirements, energy absorbents such as honeycomb structures have gained increased importance. This study proposes a design for a graded honeycomb structure to use as energy absorbent in helmets in order to reduce impact load during traffic accidents. The honeycomb structure was designed with thickness of 5.9 mm form polypropylene and is covered with a ABS layer. European and UK standards were used for impact test of helmets. Impact test simulation was carried out in ABAQUS software. In order to evaluate the simulation method, numerical results were compared with experimental ones. Based on the results of tests using both standards, designed structure can absorb the applied kinetic energy. Also the measured reaction force, acceleration and HIC are lower than standard thresholds. The behaviour of the proposed honeycomb structure was also compared with a helmet which was made of EPS foam. The impact absorbent structure of helmets was optimised using genetic algorithm; then graded honeycomb structure was compared with foam and foam-filled structures. Based on the results of simulation, honeycomb structure absorbs energy for a longer duration and transfers impact force to the user with lower acceleration compared to EPS.

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KEYWORDS
Graded honeycomb; helmet; impact; in-plane; foam; energy absorbent; ABAQUS

1. Introduction

With development of transportation technologies, the need for new methods to increase safety of these systems has also increased. In order to prevent injuries and fatalities in traffic accidents, it is necessary to use structures which are capable of absorbing impact forces. Impact absorbents are structures which transform kinetic energy into other forms of energy and reduce the impact load. In the previous decade, various materials and structures with high energy absorption capabilities such as honeycomb structures and thin-walled structures have been investigated for this purpose [1–5]. Mohammad Ali studied banana peel and discovered honeycomb structures inside the peel (Figure 1). He believed that banana's peel protects the fruits' soft insides form outside impacts [6].

Galehdari et al. investigated graded honeycomb structures under in-plane and out-plane impact loadings. They discovered that impact energy absorption of honeycomb structures is significantly higher in the out-plant direction compared to in-plane direction. But in-plane direction can significantly reduce the applied forces by absorbing suitable amounts of energy. On the other hand, graded structures in a way that structure's stiffness increases in the direction away from the applied force, can increase the time of energy absorption. In another study, they used genetic algorithm and SQP method to produce an optimum shock absorbent for helicopter seats in order to absorb energy and minimise reaction forces transferred to passengers' pelvis. Investigation of honeycomb shock absorbent under crushing conditions was carried out using ABAQUS software [7]. Helmets can help to minimise the danger of serious head and brain injuries by reducing the effects of the impact on riders' heads. It protects people in three ways which include reducing skull acceleration, controlling brain's movements and reducing impact to the brain. A soft material placed inside the helmet can absorb part of the impact energy, causing slower deceleration of the skull. This reduces the impact energy between skull and brain. Helmets also distribute impact force in a wider area and prevent concentration of forces at specific locations of the skull. Furthermore, helmets prevent direct impact between head and other objects [8]. Design of new energy absorbers has been performed based on different optimisation algorithms. Yildiz et al. [9] studied the grey wolf, whale, water cycle, ant lion and sine-cosine optimisation algorithms for the optimum design of vehicle components. They also investigated a newly developed moth-flame optimisation algorithm (MFO) is presented for solving optimisation problems in manufacturing industry after that a new optimisation algorithm, called the cuckoo search algorithm (CS) algorithm, is introduced for solving manufacturing optimisation problems[10,11]. Pholdee et al. have presented a many-objective hybrid real-code population-based incremental learning and differential evolution algorithm (MnRPBILDE) is proposed based on the concept of objective function space reduction. The method is then implemented on

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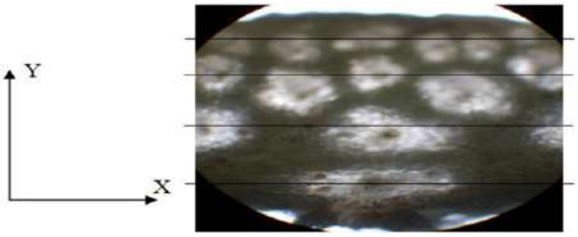

Figure 1. Banana's peel surface temperature.

real engineering design problems [12]. Yildiz et al. [13] have derived a new hybrid optimisation algorithm based on gravitational search algorithm and Nelder-Mead algorithm is introduced to improve crash performance of vehicles during frontal impact. In the other research they presented a comparison of evolutionary-based optimisation techniques for structural design optimisation problems is presented [14]. In order to improve the crashworthiness of the protective structures some optimisation methods have been utilised [15]. Karagoz et al. [16] used recent optimisation techniques to improve crash performance of a thin-walled tube considering influence of the forming history. Furthermore, Kiani et al. [17] have studied metamodeling and five well-known metaheuristic optimisation algorithms in order to reduce the weight and improve crashworthiness of a vehicle. Based on the mentioned benefits of the graded honeycomb structure and different optimisation methods, an optimum design of a helmet made of GHS is performed in this paper.

2. Helmet design

In order to design the honeycomb structure, helmet is considered as a hemisphere with internal radius of 9 cm and external radius of 14.9 cm. The geometrical parameters of a honeycomb cell are shown in Figure 2.

A graded honeycomb structure is designed with thickness of 5.9 cm. Geometrical parameters of this honeycomb structure include $c = 6$ mm, $l = 5$ mm and $\varphi = 43°$. Row thickness of the structure decreases from upper to lower rows with uppermost row having a thickness of 0.59 mm and last row having a thickness of 0.1 mm. This structure is designed with eight rows with each row having 15 cells. Figure 3 shows the schematic of honeycomb structure in CATIA software.

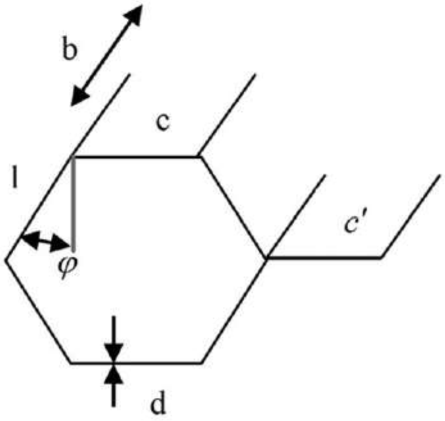

Figure 2. Honeycomb cell parameters.

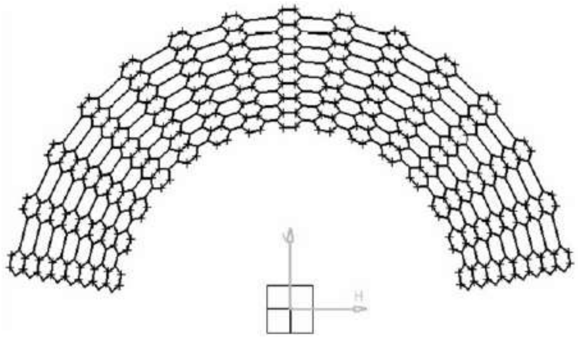

Figure 3. 2D view of graded honeycomb structure.

Table 1. Materials property of ABS and polypropylene [18].

Material	Density $\rho(^{Kg}/_{m^3})$	Young module $E(GPa)$	Poisson's ratio υ	Yield stress $\sigma_y(MPa)$
Poly propylene	932	1.35	0.38	25
(ABS)	1200	2	0.37	34.3

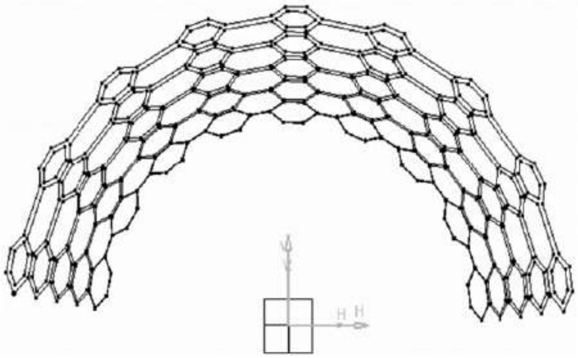

Figure 4. Five rowed optimum graded honeycomb structure.

The honeycomb structure is made from polypropylene with a coating of ABS with thickness of 4 mm and its characteristics are shown in Table 1.

Energy absorption of the designed helmet is simulated in ABAQUS software. The numerical results such as energy absorption and reaction force history were compared with standard values.

2.1. Optimum design

First, specific energy is optimised by keeping the mass of structure constant while changing its geometrical parameters. Optimisation is carried out using genetic algorithms. The goal of optimisation is to determine approximate values of parameters in a certain range. Specific energy equation for honeycomb structures is $e = \frac{U}{m}$. Graded honeycomb structure is made from five rows and nine cells per row as shown in Figure 4.

Energy and mass equations for the structure are shown in Equations (2) and (3):

$$\begin{aligned}U = (2l\cos\phi) \times [(((c + c'_1 + 2l\sin\phi) \times b_{15}) \times \sigma_{P1}\varepsilon_{d1}) + (((c + c'_2 + 2l\sin\phi) \times b_{25}) \times \sigma_{P2}\varepsilon_{d2}) \\ +(((3c + 3c'_3 + 6l\sin\phi) \times \sum_{b=4}^{6} b_{3i}) \times \sigma_{P3}\varepsilon_{d3}) + (((5c + 5c'_4 + 10l\sin\phi) \times \sum_{b=3}^{7} b_{4i}) \\ \times\sigma_{P4}\varepsilon_{d4}) + ((((8c + 8c'_5 + 16l\sin\phi) \times \sum_{b=1}^{8} b_{5i}) + (c_1 + 2l\sin\phi) \times b_{59}) \times \sigma_{P5}\varepsilon_{d5})\end{aligned} \tag{2}$$

$$\begin{aligned}m = \rho \times [((((32l + 16C + 8C'_1) \times \sum_{i=1}^{8} b_{1i}) + ((4l + 2C) \times b_{19})) \times d_1) + ((((32l + 16C + 8C'_2) \times \sum_{i=1}^{8} b_{2i}) + ((4l + 2C) \times b_{29})) \times d_2) \\ +((((32l + 16C + 8C'_3) \times \sum_{i=1}^{8} b_{3i}) + ((4l + 2C) \times b_{39})) \times d_3) + ((((32l + 16C + 8C'_4) \times \sum_{i=1}^{8} b_{4i}) + ((4l + 2C) \times b_{49})) \times d_4) \\ +((((32l + 16C + 8C'_5) \times \sum_{i=1}^{8} b_{5i}) + ((4l + 2C) \times b_{59})) \times d_5)]\end{aligned} \tag{3}$$

In this algorithm, the objective function is defined as ratio of structure mass to absorbed energy. The design variables, upper and lower limits are shown in Table 2.

It is necessary to consider some constraints in the structure design in order to meet standard requirements. If $\frac{d}{l} < 0.25$, bending moment would be the main cause of structure's deformation. Studies on forces applied to skull shows that skull fracture occurs at forces between 4000 and 15,000 N [19]. Another constraint is defined for the algorithm in order to meet the maximum thickness requirement of structure (absorber layer). This limit means that structure thickness should not exceed 5 cm. Algorithm constraints are shown in Equation 4.

$$\frac{d}{l} < 0.25$$

$$m = 0.1Kg \tag{4}$$

$$\sigma_p A \le 13832N$$

$$10l\cos\phi + d_1 + d_2 + d_3 + d_4 + d_5 \le 5cm$$

Table 2. Design variations in optimisation.

Design variable	lb	ub
c (m)	0.0085	0.009
l (m)	0.007	0.0075
ϕ (Radian)	0.6	0.95
d_1	0.00049	0.00059
d_2	0.00039	0.00049
d_3	0.00029	0.00039
d_4	0.00019	0.00029
d_5	0.00009	0.00019

Table 3. Optimised variations taken from genetics algorithm.

Variable	Genetics algorithm
c	0.009011
l	0.007023
ϕ	0.945
d_1	0.000490
d_2	0.000391
d_3	0.000295
d_4	0.000196
d_5	0.00009

In this method, initial population is 40 and maximum reproduction of next generations is 100. Genetic algorithm minimises the objective function. Therefore, the specific energy equation is reversed and is used as $e = \frac{m}{U}$. Optimised parameters determined using genetic algorithm are shown in Table 3.

These values show a range of dimensions for honeycomb structure used for structure's design. Helmet is considered as hemispherical with internal radius of 9 cm and outside radius of around 13 cm. Honeycomb structure is designed with thickness of 4 cm with dimensions based on genetic algorithm according to Table 3. Structure's thickness decreases from top to bottom. The optimum honeycomb structure with five rows and nine cells in each row is designed and covered with a 4-mm coating. The optimum designed structure was simulated in ABAQUS software in order to check the efficiency of the helmet.

The honeycomb structures usually are filled with ESP foam to increase the structure's energy absorption. The energy absorption of four kinds of helmets is studied. These structures are introduced as below:

1. Optimum polypropylene honeycomb structure
2. Optimum polypropylene honeycomb structure filled with ESP 25 density foam
3. Optimum polypropylene honeycomb structure filled with ESP 64 density foam
4. Helmet which is made from ESP 25 density foam.

The time history of energy absorption and reaction force of above structures were achieved from numerical simulation. Mechanical and physical properties of the ESP foam are shown in Table 4.

Table 4. EPS foam property [19].

Foam	Density $\rho(^{Kg}/_{m^3})$	Young module $E(MPa)$	Poisson's ratio υ	Yield stress $\sigma_y(MPa)$
EPS-25	25	4	0	0.18
EPS-64	64	9.58	0	0.48

Table 5. UK standard impact velocity [21].

Anvil type	First impact velocity (m/s)	Second impact velocity (m/s)
Flat	7.5	5.3
Half spherical	7	5

3. Crash standards

In this study, European and UK standards were used for impact test of the helmets. In European standard, two types of flat and Curbstone European anvils were used. Each anvil impacts the helmet in a single impact with velocity of 7.5 m/s. Maximum head acceleration in this standard should not exceed 275 g. According to this acceleration, maximum applied force to a head with mass of 4.7 kg is calculated using f = ma equation to be 12,680 N. In this standard, a head injury criterion (HIC) is also defined which should be lower than 2400. Equation (1) shows calculations for HIC [20].

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

In UK standard, two types of flat and hemispherical anvils are used. Each of these anvils impact the helmet in two stages in which the anvils first impact the helmet at a predetermined velocity with the second impact following at a different velocity. Anvil velocity in impact absorption test based on UK standard should be based on Table 5. Maximum acceleration applied to the head in this method should not exceed 300 g. Maximum applied force to a head with mass of 5 kg at this acceleration is equal to 14,715 N [21].

4. Numerical simulation

Regarding the material and geometrical characteristics of the structure, the mass and velocity of the weight which were mentioned in the standards, energy absorption of different kinds of designed helmets has been simulated in ABAQUS software. The FE model made of polypropylene of GHS helmet is demonstrated in Figure 5.

The dropped mass(anvil) is modelled by semi-hemispherical plate. S4R elements are used to mesh the structure, R3D4 elements are used to mesh the anvil and artificial head. The boundary conditions are defined by constraining the anvil, A, to move only in the Y-plane and by fixing all the rotational and translational degrees of freedom of the head. Interaction properties are imposed using a general contact condition for contact of each row and surface-to-surface kinematic contact conditions between the top-element-based surface of the structure and the anvil. Friction contact is considered for interaction between anvil and helmet and contact between helmet and artificial head. The friction coefficient between helmet and anvil is 0.55 and friction coefficient between helmet and artificial head

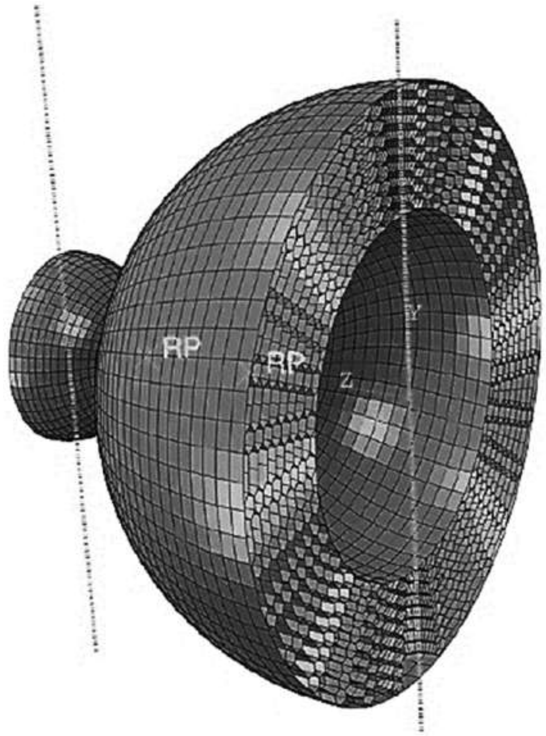

Figure 5. FE model of the helmet.

Table 6. Comparison of experimental & numerical deformation and reaction force at the time of 1.3 ms.

	Numerical	Experimental [23]	Error %
Reaction force (N)	624	600	3.4
Deformation (mm)	29	27.5	5.6

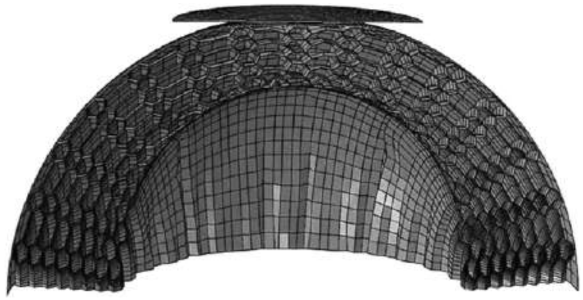

Figure 6. Graded honeycomb structure crush.

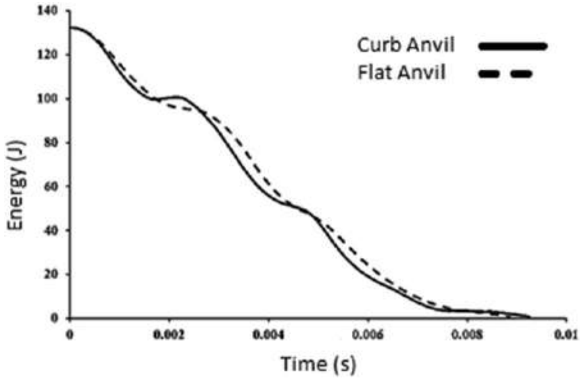

Figure 7. Energy absorption – time diagram for European Standards.

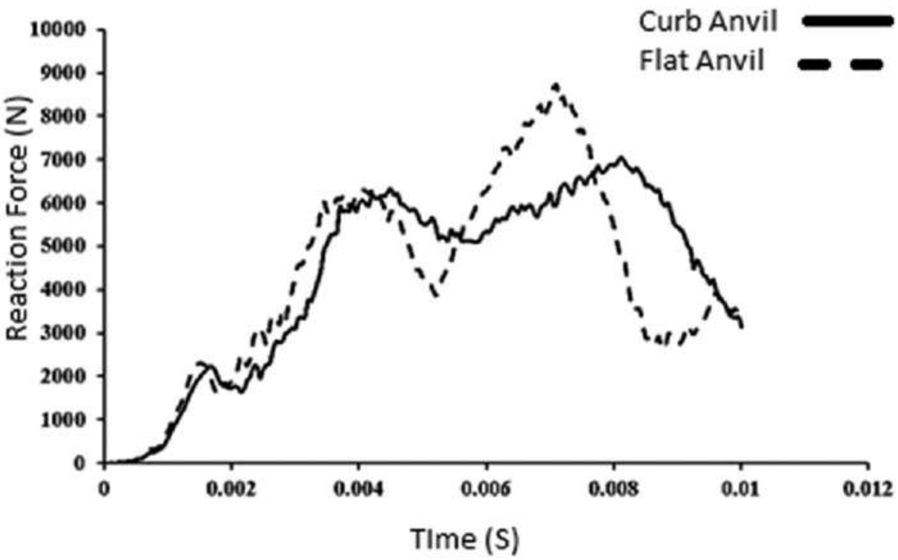

Figure 8. Reaction force – time diagram for European Standards.

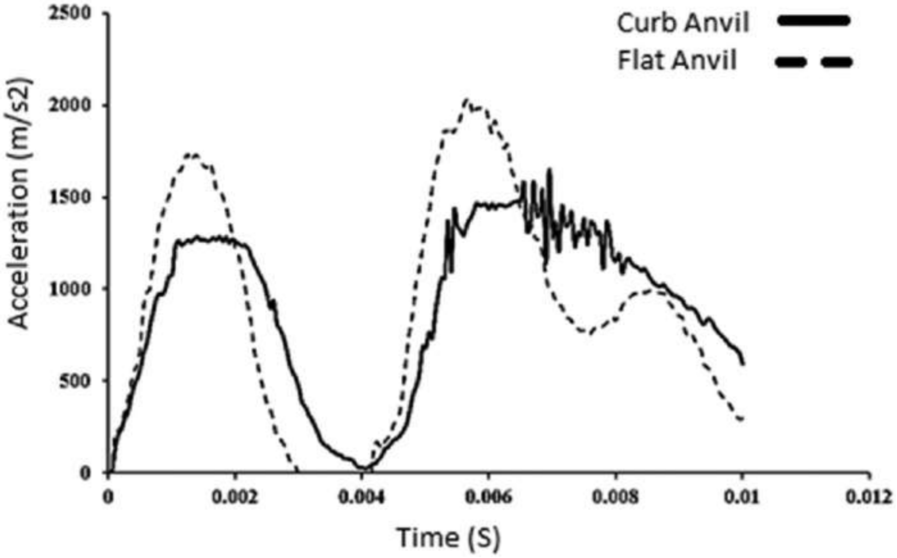

Figure 9. Head's acceleration – time diagram for European Standards.

Table 7. European standard's HIC amounts.

Curb type	Flat anvil	Curb anvil
HIC	799.381	811.348

is 0.45 [22]. Impact velocity of the anvil is defined based on the utilised standards. The FE problem is solved by dynamic/explicit solver. In this simulation, the reaction force-time and kinetic energy-time diagrams of the different helmets were compared to each other.

4.1. Validation of numerical simulation method

Galehdari et al. [23] carried out empirical drop-weight test on graded aluminium honeycomb structures with low velocity. The results of numerical simulation in ABAQUS software were compared to these results in order to validate the numerical results. The thickness of first to sixth rows of graded honeycomb structure used in their research are 1.6, 1.27, 1.016, 0.8125, 0.635 and 0.508 mm, respectively. For this structure the other geometrical parameters are $l = 12$ mm, $c = 15$ mm and $\varphi = 36°$. The height and width of the structure are 130 mm while its depth was 28.5 mm. All rows were made from Al6061-O. Impact test was carried out using Drop-weight test equipment. In this test, a weight of 9776.6 g was released from height of 1.2 m. The velocity of the dropped weight measured at the moment of impact was equal to 4.5 m/s. An accelerometer was also used to measure the weight's acceleration during the moment of impact and absorption of kinetic energy. Based on geometrical properties and material characteristics of the sample, weight and impact velocity of the impactor, loading and boundary conditions of the empirical tests were simulated in ABAQUS software.

5. Results and discussion

After numerical simulation of the test specimen, final deformation *f* the sample and maximum reaction force in 1.3 ms time period is compared to the results of empirical tests as shown in Table 6.

According to Table 6, numerical results have good compatibility with empirical results, with maximum error of 5.6%. This validates the numerical simulation method and utilised parameters and means that numerical simulation method can be used to simulate impact test of honeycomb structured helmets.

Crash on first designed helmet was simulated in ABAQUS based on European and UK standards.

5.1. European standard

Figure 6 shows a honeycomb structure crashed after impact with the anvil. During the impact, four lowest rows are crushed.

The time history of energy absorption, reaction force and acceleration of this structure based on EU standards are shown in Figures 7–9, respectively.

Regarding to Figure 7, this structure has fully absorbed the kinetic energy. Both anvils have similar behaviours and have absorbed kinetic energy at almost the same time. This means that the structure meets the energy absorption requirements.

According to this standard, force transferred from absorbent to head should be lower than 12,680 N. Figure 8 shows that maximum force transferred for flat and Curbstone European anvils is 8723 and 6931 N, respectively which is lower than the threshold in EU standard. According to this figure, the transferred force of flat anvil is greater than Curbstone one. The reason is that flat anvil has a larger incident area compared to Curbstone European anvil which increases the force transferred, according to $F = \sigma A$ equation.

According to EU standard, maximum head acceleration should be 2697 m/s^2 (275 g). According to Figure 9,

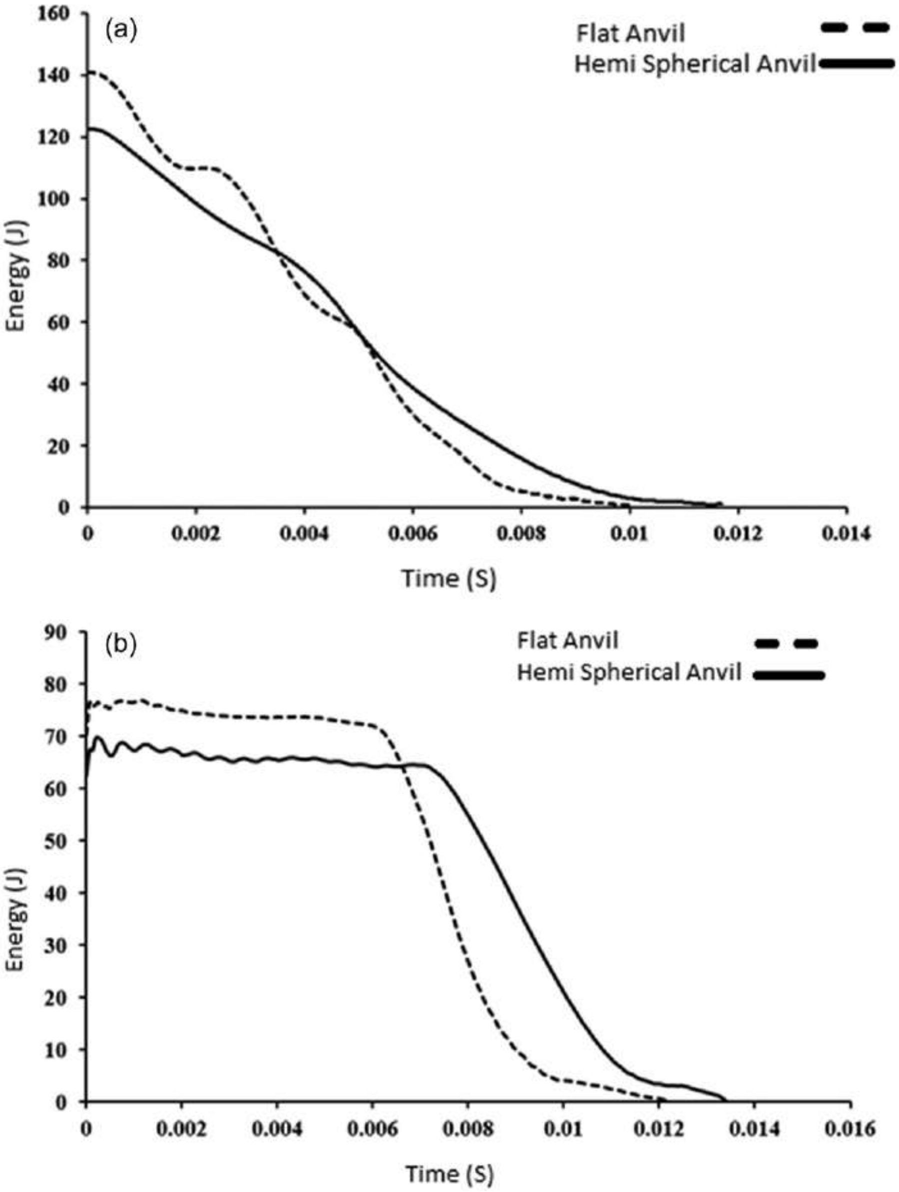

Figure 10. Energy absorption-time for UK Standard: (a) first impact, (b) second impact.

maximum head acceleration for flat and Curbstone European anvils is 2020 m/s^2 and 1652 m/s^2 which is lower than the required 275 g threshold. This means that the structure satisfies this standard requirement. Flat anvil causes more acceleration compared to Curbstone European anvil which means that in these conditions, flat anvil is more dangerous than Curbstone European anvil. For this condition the HIC values are presented in Table 7.

According to Table 7, the values of HIC for flat and Curbstone European anvils are 811.348 and 799.381, respectively which are significantly lower than the 2400 threshold value. This means that the honeycomb structure of the helmet meets this standard requirement.

5.2. UK standard

Figure 10 shows the results of energy absorption while Figure 11 shows the transferred forces and Figure 12 shows head's acceleration based on UK standard.

According to Figure 10, in the first impact, the structure absorbs all of kinetic energy. Hemispherical anvil has lower kinetic energy but its energy has been absorbed at a slower rate. In the second impact, structure has managed to again absorb all of kinetic energy and can even absorb more energy. In this stage, hemispherical anvil again absorbs energy at a lower rate. Therefore, the results show that the structure manages to absorb the kinetic energy and meets the first requirement.

Regarding to UK standard, reaction force applied to head should be lower than 13,832 N. According to Figure 11, maximum force transferred from flat and hemispherical anvils in the first impact is 8016 and 5476 N, respectively. The transferred force of second impact in flat and hemispherical anvils is 9995 and 8109 N. These values are lower than the standard threshold in both impacts which means that the structure meets this requirement.

Based on UK standard, maximum acceleration applied to the head should be 2940 m/s^2 (300 g).

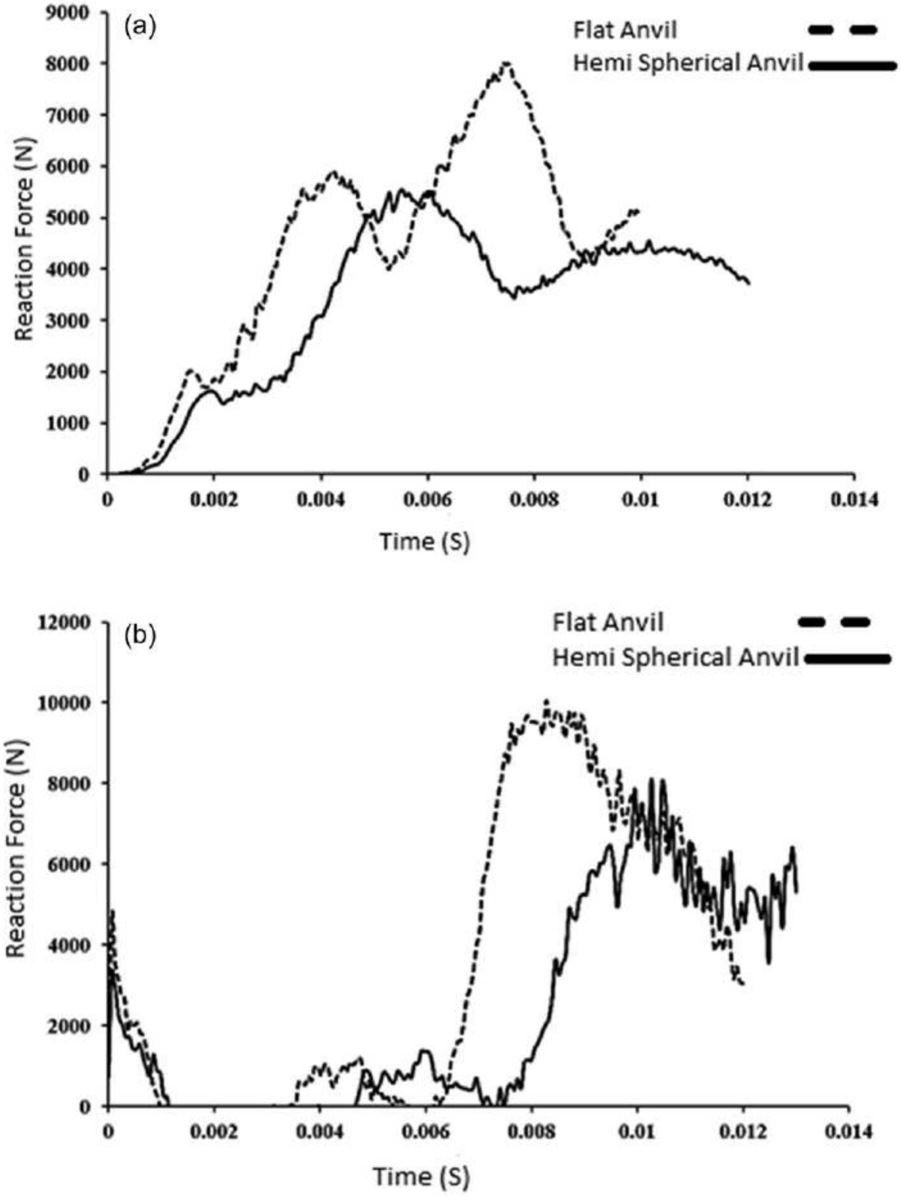

Figure 11. Reaction force-time for UK Standard: (a) first impact, (b) second impact.

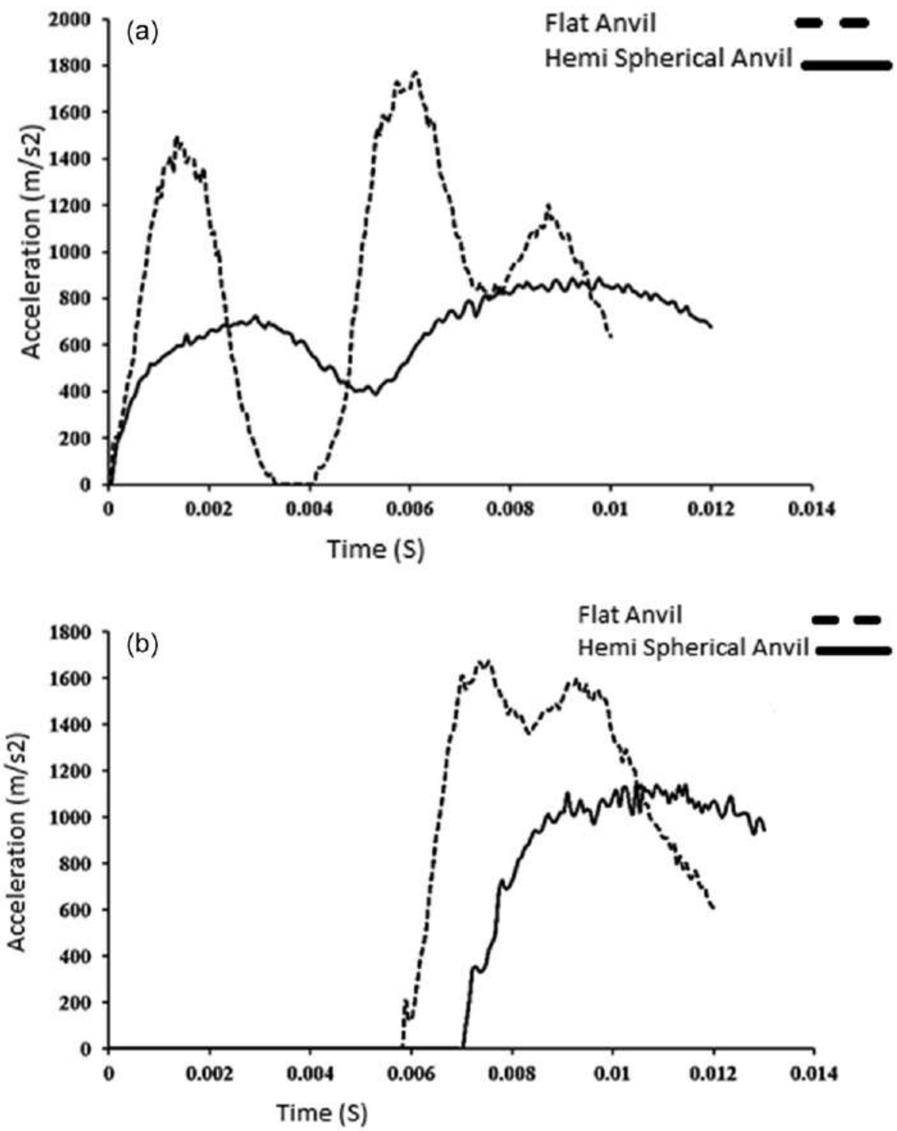

Figure 12. Head's acceleration-time for UK standard: (a) first impact, (b) second impact.

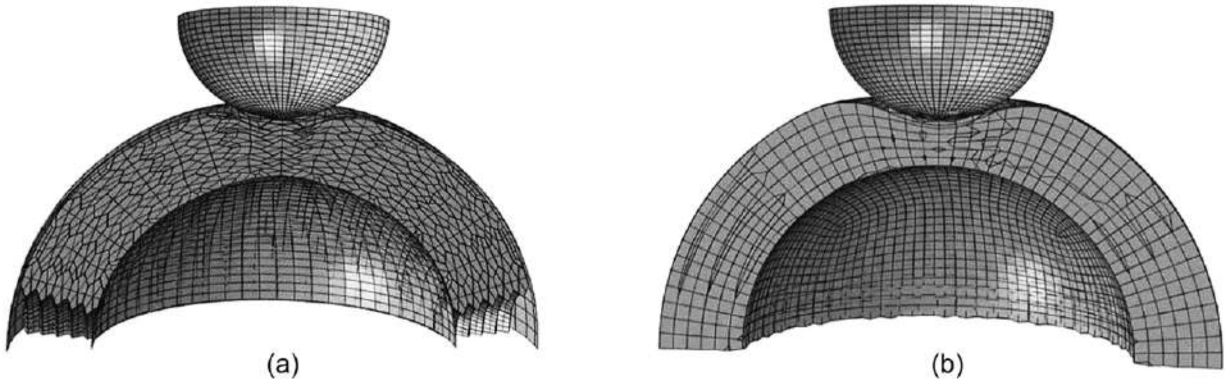

Figure 13. Crushed: (a) graded honeycomb structure filled with foam, (b) helmet foam.

According to Figure 12, maximum acceleration for flat and hemispherical anvils is 1770 and 885 m/s^2, respectively, which are lower than standard threshold. For the second impact, acceleration for flat and hemispherical anvils is 1662 and 1142 m/s^2. In both impacts, these values are lower than the standard threshold which confirms the structure's compliance with standard requirements.

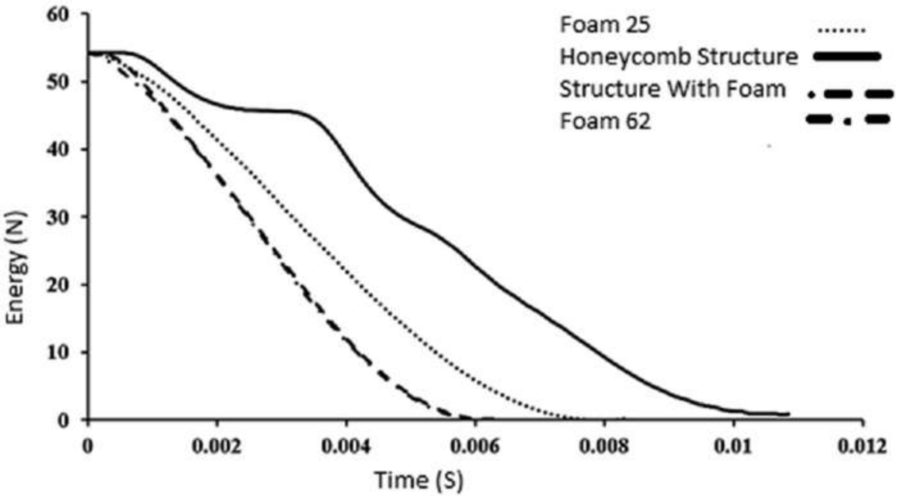

Figure 14. Energy absorption based on type of absorbent.

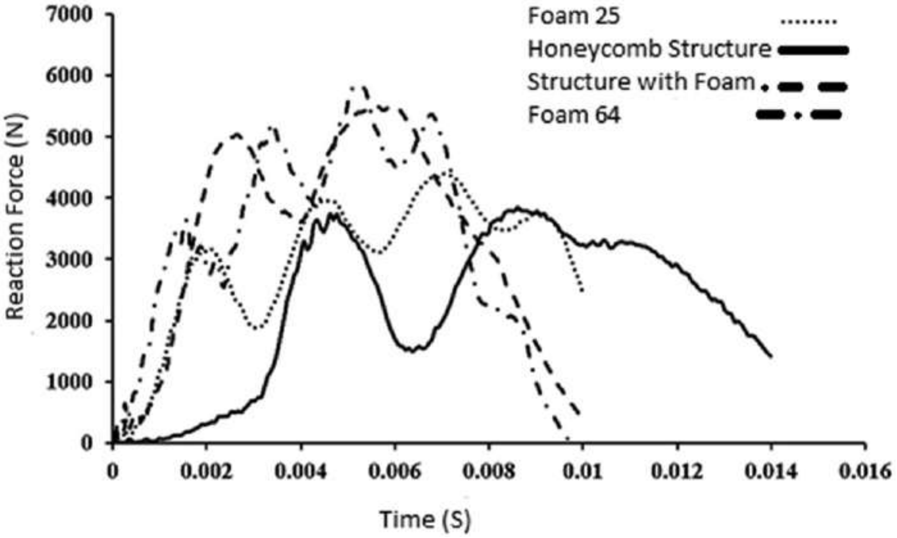

Figure 15. Substituted force graph according to absorbents type.

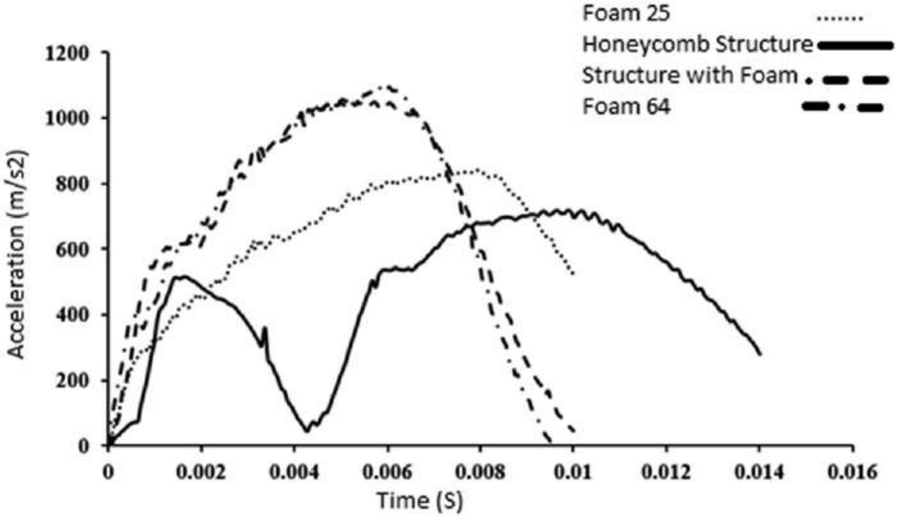

Figure 16. Acceleration graph according to absorbents type.

5.3. Optimum structure

Crash on optimum helmet, foam filled GHS and foam helmet have been simulated in ABAQUS. As can be seen in Figure 13, foam-filled honeycomb structure and foam have lower deformation and can absorb higher amounts of energy.

The time history of energy absorption, reaction force and acceleration of this structure are shown in Figures 14–16, respectively.

As can be seen in Figure 14, all absorbents fully absorb the energy. Honeycomb structure without foam absorbs energy at a slower rate while EPS-64 foam and foam-filled structure (density of 25) absorb the energy faster. Therefore, these results show that graded honeycomb structure is more applicable due to absorbing energy over a longer period of time despite the fact that foam-filled honeycomb structure absorbs more energy.

According to Figure 15, all absorbents apply forces below both standard thresholds to the head. Maximum force transferred to the head is 3657 N for graded honeycomb structure, 4300 N for foam with density of 25, 5490 with foam-filled honeycomb structure and 5800 N for foam with density of 64. This means that graded honeycomb structure transfers a lower amount of energy to the head.

Based on Figure 16, all absorbents result in head acceleration below standard thresholds. Maximum acceleration for graded honeycomb structure, EPS-25, EPS-64 and foam-filled structure are 730 $\frac{m}{s^2}$, 810, 1050 $\frac{m}{s^2}$, and 1110 $\frac{m}{s^2}$, respectively. Honeycomb structure leads to head acceleration for a longer duration. This means that this structure is the best absorbent among structures. Behaviour of honeycomb structure filled with EPS-25 foam is similar to EPS-64 foam shows that although foam-filled structure absorbs more energy, it also leads to more transferred force and acceleration of the head.

6. Conclusion

Comparison between graded polypropylene honeycomb structure (GHS) and EPS foam for impact absorption in helmets showed that graded honeycomb structure leads to lower transferred force and acceleration. Decrease in density and yield stress of the EPS foams reduces acceleration and force transferred to the head. The results obtained from honeycomb structures filled with EPS foam shows that foam-filled honeycomb structures have better energy absorption compared to foam itself but these foam-filled structures increase the force transferred to the head and also causes higher head acceleration. Based on the results of numerical simulation of impact test of honeycomb structure, flat anvil leads to higher reaction force applied to the artificial head compared to Curbstone European anvil. This means that the chances of head injury are higher when the rider's head hits a flat surface. For two-impact standard, the results showed that designed helmet can absorb both first and second impacts and can even absorb more energy in the second impact. Force transferred to the head is lower than the standard threshold in both first and second impacts. New generation of helmets are designed and analysed in this research. Because of optimum helmet's advantages comparing to other ones, it can be manufactured and applicable for riders.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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