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Design and analysis of a helmet equipped with graded honeycomb structure under impact of flat and Hemi-spherical anvils

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Abstract

According to the importance of safety, lightweight energy absorbers such as honeycomb structures have drawn researchers' attention in recent years. In this research, a graded honeycomb structure is proposed in order to reduce head impact injuries during car accidents. Polypropylene polymer is used for the graded honeycomb structure. The structure was modeled by means of Abaqus software and according to the Japanese standard JIS T8133, flat and hemi-spherical anvils were considered to simulate head impact by initial velocities of 5.8 m/s and 4.8 m/s, respectively. Moreover, oblique impact by angle of 60 degrees was studied. Finally, the critical parameters such as absorbed energy, load magnitude and acceleration variations were attained. The obtained results were compared with associated criteria which confirmed the capability of the proposed structure to protect head during accidents.

Keywords: Graded honeycomb; helmet; impact; in-plane; energy absorption

1. Introduction

By developing transportation systems and automotive industry crushing energy absorption devices has become one of the most important research areas [1-7]. Numerous thin-walled energy absorbing structures such as honeycombs are investigated in recent years [8-22]. Galehdari et al. [23] studied graded honeycomb structure under in-plane and out-of-plane loading conditions. They did find out that energy absorption of the structure is much higher in out-of-plane direction although kinetic impact energy is dissipated through in-plane direction as well.

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Furthermore, it was revealed that implementing a graded structure is a promising way to extend the energy absorption time period and therefore enhance the capability of the structure as an energy absorption device. There are other applications of honeycombs such as ship design industry [24]. Galehdari et al. [25] investigated low velocity impacts on aluminum honeycombs through numerical simulations. Moreover, a graded honeycomb shock absorber for a helicopter seat was designed and analyzed based on a crash condition [26]. Design of crushing energy absorbers needs a deep understanding of structural dynamics and deformation mechanisms [27]. In addition to the aforementioned merits of honeycombs, these structures are implemented in aerospace industry as lightweight panels [28]. Various impact directions [29] and different impact velocities [30, 31] are studied by many researchers. Chang et al. [32, 33] established a finite element model based on realistic geometric features of a motorcycle to simulate the standard shock absorption test for evaluating the dynamic response and fit effects of a helmet. Caccese et al. [34] studied the choice of optimal parameters to minimize the thickness of the honeycomb structure while providing adequate protection to prevent injury to head impact.

In this research, a helmet with graded honeycomb structure is proposed in order to reduce head impact during motorcycle accidents. Finite element simulations were conducted by means of Abaqus software and the obtained results are fetched to evaluate the efficiency of the structure in absorbing crushing energy and preventing injury to head.

Nomenclature

GHS	Graded Honeycomb Structure	U	Strain energy
A	Cross section area of GHS	σ_y	Yield stress
b	Depth of GHS cell	ρ^*	Density of honeycomb structure
c	Cell horizontal wall length	ρ_s	Density of honeycomb structure material
d	Cell wall thickness	ε_d	Locking strain
e	Specific absorbed energy	ϕ	Cell wall angle
l	Cell inclined wall length	σ_p	Plateau stress
ν	Poisson ratio		
m	GHS mass		
m_c	Mass of each cell		

2. Honeycomb structure

Relative density and plateau stress are two effective parameters in energy absorption of honeycombs [29]. Fig. 1 shows a honeycomb cell with associated geometrical parameters.

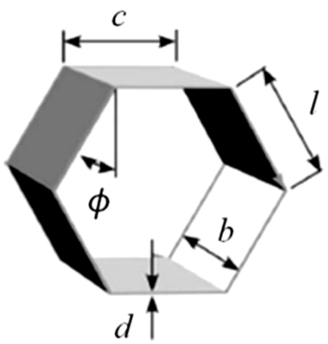

Fig. 1. honeycomb's cell structure

Plateau stress can be obtained, by considering elastic-perfectly plastic behavior [36], through:

$$\sigma_P = \frac{\sigma_y}{2} \times \frac{d^2}{(c + l\sin\phi)(l - d)\sin\phi} \tag{1}$$

Density of honeycomb structure is achieved by:

$$\rho = \frac{\left(\frac{d}{l}\right)\left(\frac{c}{l} + 2\right)}{2\left(\sin\phi + \frac{c}{l}\right)\cos\phi}\rho_s \tag{2}$$

Densification strain, which is the compression value of strain of each row of honeycomb cells at the densification point, is yielded by:

$$\varepsilon_d = 1 - \rho^* = 1 - \frac{\left(\frac{d}{l}\right)\left(\frac{c}{l} + 2\right)}{2\left(\sin\phi + \frac{c}{l}\right)\cos\phi} \tag{3}$$

According to the cell's geometry, energy equation can be written as:

$$U = 2bl\cos\phi(17c + 18l\sin\phi)\sum_{i=1}^{5}\sigma_{P_i}\varepsilon_{d_i} \tag{4}$$

And then mass of the structure is:

$$m = \rho_s b(36l + 26c)\sum_{i=1}^{5} d_i \tag{5}$$

Hence, specific energy equation is:

$$e = \frac{U}{m} = \frac{2bl\cos\phi(17c + 18l\sin\phi)\sum_{i=1}^{5}\sigma_{P_i}\varepsilon_{d_i}}{\rho_s b(36l + 26c)\sum_{i=1}^{5} d_i} \tag{6}$$

3. Energy absorber of helmet

3.1. Problem definition

There are number of standards that are being used to test helmets such as UN/ECE Regulation No. 22 ،DOT FMVSS 218 و BS 6658. In this study the Japanese standard JIS T8133 was implemented in which the head size with mass 4.7 kg and half-type helmet were selected. Impact tests were performed for two anvils from which the first one was a flat anvil by diameter of 13 cm and initial velocity of 5.8 m/s while the second anvil was hemi-spherical by diameter of 5 cm and impact velocity of 4.8 m/s. Two impact conditions were considered from which the first one was toward top of helmet and the other one was a frontal impact by angle of 60 degrees. According to the JIS T8133 standard the allowable impact acceleration is 300g and then the critical impact load was obtained about 13832 N [37]. It is suggested in [38] that the thickness of absorber layer of helmet should be in range of 2-5 cm. The inner radius of helmet was 9 cm while the outer radius was 13 cm. The absorber layer was made of Polypropylene polymer which was covered by an ABS plastic layer by thickness of 4 mm. Fig. 2 shows the CAD model of helmet. The geometrical parameters of honeycomb are c= 9 mm, l = 7 mm, and $\phi = 56^{\circ}$.

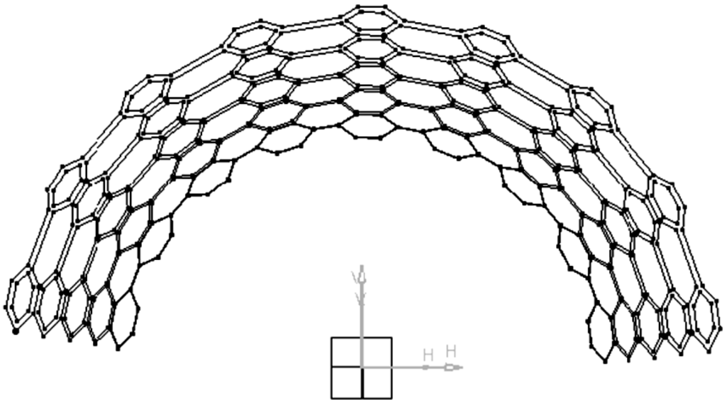

Fig. 2. CAD model of the helmet

3.2. Finite element simulation

Three dimensional model of helmet was imported to Abaqus software in order to simulate impact analysis. Mechanical properties of used materials are listed in Table 1.

Table 1. Mechanical properties of the materials

Material	$\rho_s\ (\frac{kg}{m^3})$	$E\ (Pa)$	ν	$\sigma_y\ (Pa)$
Polypropylene polymer	932	1.35×10^{9}	0.38	25×10^{6}
ABS plastic	1200	2×10^{9}	0.37	34.3×10^{6}

Surface to surface contact algorithm was considered address the interaction of helmet with head and anvil by friction coefficients of 0.45 and 0.55, respectively [39]. The absorber and skin layers of helmet were meshed by S4R shell elements while the anvil and head were meshed by R3D4 rigid elements, Fig. 3.

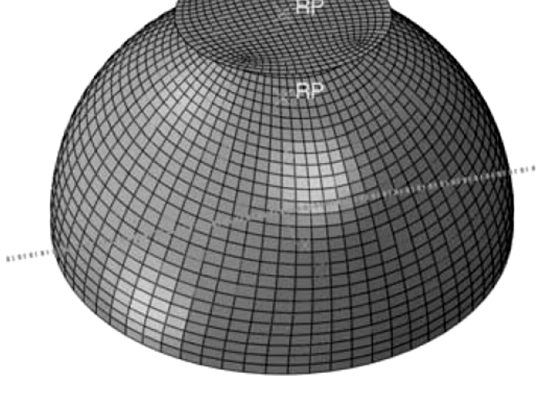

Fig. 3. FE model of the helmet

4. Results and discussion

Fig. 4 illustrates deformation of the helmet under impact. Destruction of honeycomb layers absorbs the incoming force and transfer it to distributed loads on the beneath layers.

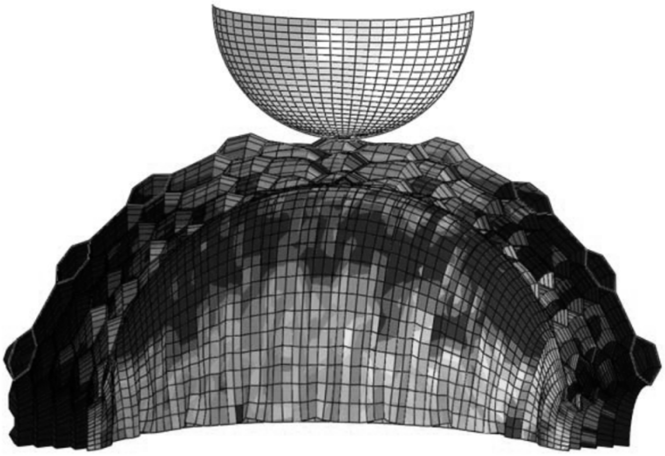

Fig. 4. Deformation of honeycomb structure under impact loads

4.1. Kinetic energy

It can be seen in Fig. 5 that the kinetic energy of structure is higher in the case of flat anvil. Moreover, the time duration of energy absorption of frontal impacts is higher than that for top impacts. Finally, it is clear that in all cases the structure absorbed impact energy completely.

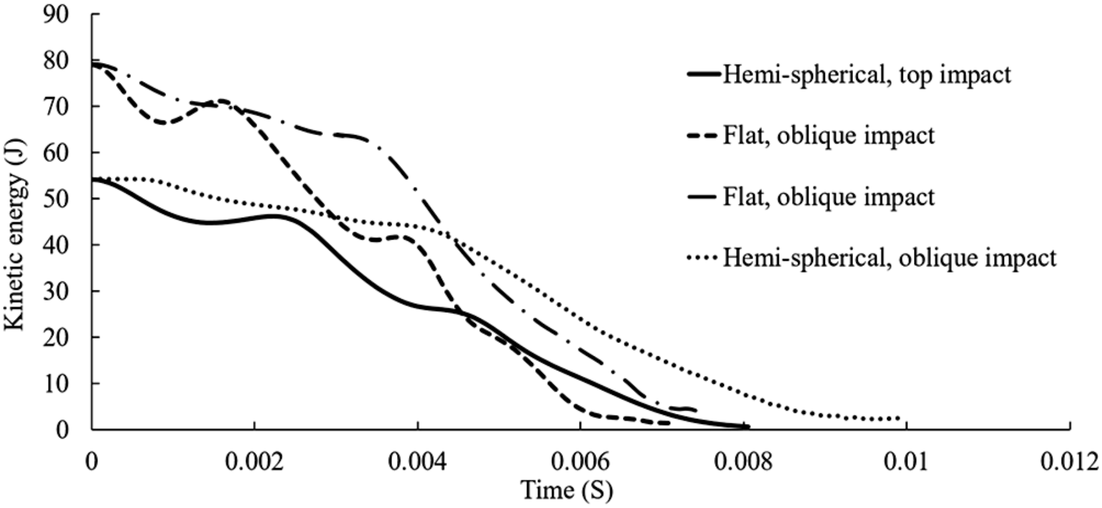

Fig. 5. kinetic energy of flat and hemi -spherical anvils

4.2. Impact load

According to the JIS T8133 standard that the allowable reaction force of head is less than 13832 N. It can be seen in Fig. 6 that the maximum impact load of flat and hemi- spherical anvils under impact in top direction are 9042 N and 5304 N, respectively.

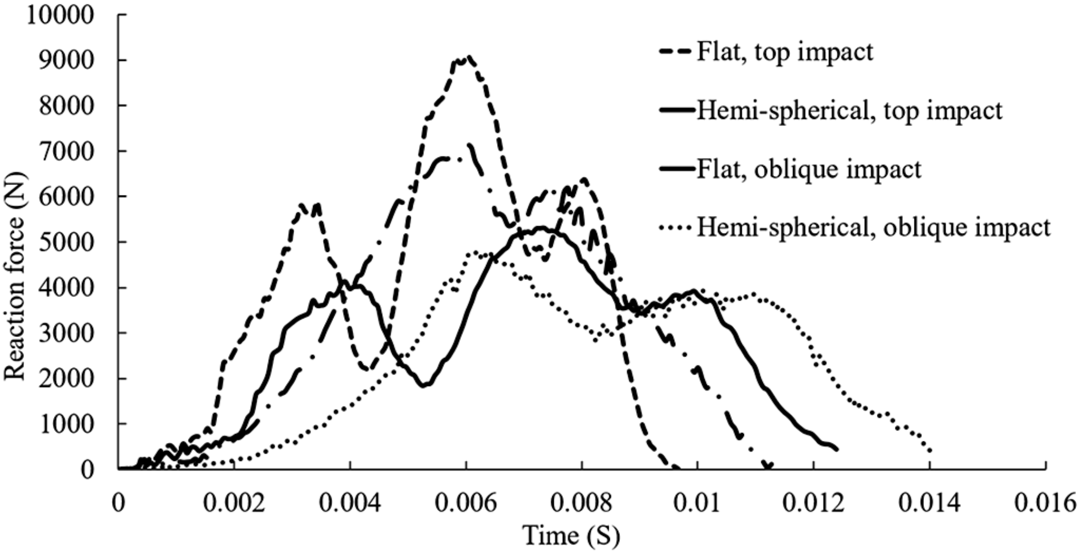

Fig. 6. Impact load of flat and hemi-spherical anvils

In the case of oblique frontal impact, the maximum reaction force of flat and hemi-spherical anvils is 6905 N and 4775 N. The obtained values of reaction forces reveal that the helmet satisfies the safety criterion.

4.3. Acceleration

According to the JIS T8133 standard the maximum magnitude of acceleration during first 4 ms should be less than 300g which is equal to 2940 m/s^2.

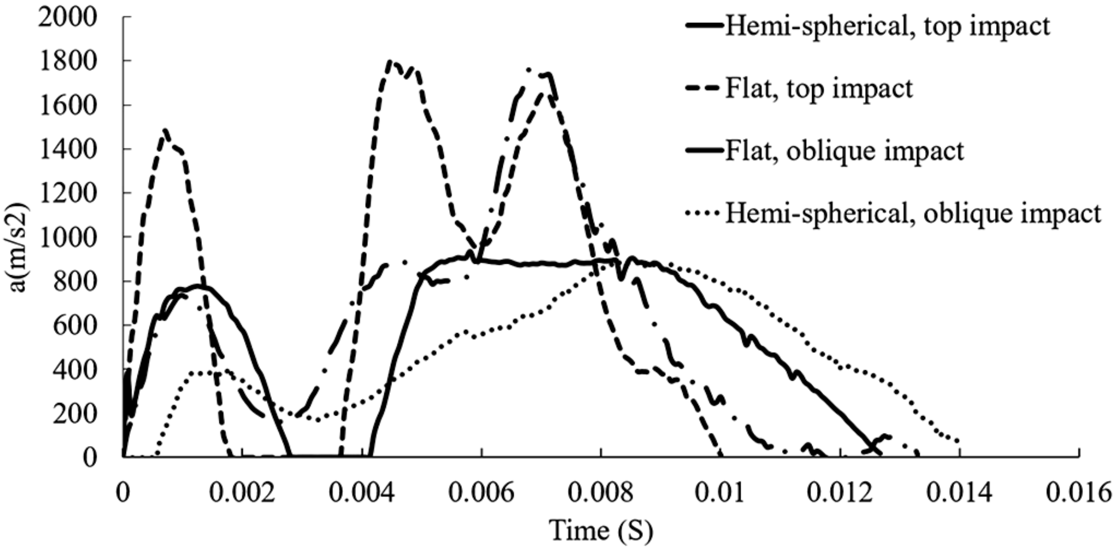

Figure 7 Accelerations of flat and hemi-spherical anvils

In Figure 7 it can be seen that the maximum acceleration of flat and hemi-spherical anvils under impact in top direction is 1804 m/s^2 and 905 m/s^2, respectively while these values under oblique impact are 1780 m/s^2 and 893 m/s^2.

5. Conclusion

In this research the crushing of helmet availed by honeycomb structure was studied. Two anvils were considered and it did find out that the structure is able to absorb all of the imposed crushing energy. Comparing to the relative design standard, it was revealed that the reaction forces induced by impacts are below the allowable limit. Moreover, the acceleration was in the permissible range. Furthermore, it was illustrated that that in frontal oblique impacts the energy absorption takes longer time than top impacts. Moreover, the maximum load and acceleration in frontal oblique impacts were less than those ones in top impacts. Therefore, less injuries stem from frontal impacts.

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