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Investigating the Role of Helmet Layers in Reducing the Stress Applied During Head Injury Using FEM

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ABSTRACT

Background: Motorcycle accidents and sport accidents lead yearly to many head injuries like head fractures and concussion. So finding the most proper helmet for reducing the injuries to head can be very helpful for head protection in such cases.
Methods: After 3D modeling of the helmet and head and meshing the model, a compressive impacting load of 1.31MPa was exerted on head and the model was analyzed using FEM. The helmet was considered as a two-layered helmet composing of an inner and an outer layer. Skull and CSF were considered as external layers of head. The analysis was repeated for a helmet with an inner layer made of extruded polystyrene (XPS), a helmet with an inner layer of expanded polystyrene (EPS) and finally a helmet with two internal layers of XPS and EPS.
Results: The amounts of maximum displacement of the outer layer in the helmet with a XPS inner layer, the helmet with an EPS inner layer and the helmet with two internal layers were 2.82, 3.15 and 2.98mm, respectively and the respective amounts of stress were 32.05, 43.38 and 34.3MPa. The amounts of maximum stress in the inner and outer layer of the helmet with a XPS inner layer were respectively 16.4% and 6.6% less than those in the helmet with two internal layers.
Discussion: Since the helmet with a XPS inner layer reduces the stress more than the helmet with two internal layers, it is the most optimal model for mitigating the head injury due to an impacting load. It should be noted that for simplifying the models, the dura was modeled together with the skull and the thicknesses of the XPS and EPS foam layers were considered to be equal.

Keywords: Helmet; Impact Loading; Head Injury; Extruded Polystyrene; Expanded Polystyrene

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INTRODUCTION

Head is one of the most sensitive and vulnerable parts of the human body and the impact injuries to it may have severe consequences. One of the most important characteristics of human head is its ability to move three-dimensionally thanks to its attachment to several bones and muscles. Although this motion characteristic provides appropriate degrees of freedom for head movement, it may lead to an instable head position and raise consequently its vulnerability to injury [1].

According to available statistics, many individuals die in USA due to the intensity of injuries to head as a result of motorcycle accidents. So the head injuries due to motorcycle accidents is one of the major causes of death in this country [2,3]. By the way, concussion as a result of using improper helmet is among the most severe injuries to head in accidents. So using proper helmets is of great importance to reduce the injuries to head in motorcycle accidents. Researches have demonstrated that the helmet can protect the head in an unstable head position and prevent serious injuries to head [1,4]. The statistical investigations show that using a proper helmet can reduce the injuries to head in accidents by 70% to 88% and the injuries to face area by almost 65% [5-8].

Helmet, which is used for head and face protection, consists principally of two main parts: outer layer and inner layer [1]. The outer layer is designed as a barrier to prevent sharp-pointed or harmful objects from penetrating into the helmet. It is therefore made of materials with high strength like reinforced polymers, thermoplastics or polycarbonate, which has both acceptable impenetrability and strength and is light as well [1]. The inner layer is the most important part of the helmet and plays a significant role in head protection since it prevents injuries and damages to head by reducing the velocity of the force exerted on the helmet and absorbing the force. An important point to be considered in designing and fabricating the outer layer of helmet is that this part should be made of isotropic materials which have similar properties in all directions in order that it can protect the head equally in all directions during the exertion of external loads. Various materials are used for making the inner layer of helmets, however, practical experiences and experimental studies have shown that materials like extruded polystyrene (XPS) and expanded polystyrene (EPS) are the best materials for helmet inner layer [1,9].

The studies in this regard can be divided into two categories. The first category includes studies dealing with mathematical models for analyzing the impact on head regardless of the factors such as helmet which mitigate the head injury. This studies simulate only the mechanism of head injury using mathematical models. The Head Impact Power has been introduced as a new kinematic-based measure of head injuries potential in a recent study, in which the coefficients in various directions are suggested to be used for normalizing the measure with respect to a number of failure levels determined for a specific direction [10]. In another study, it was tried with several limitations to combine the thresholds for translational and rotational kinematics [11]. In the second category of studies, the influence of helmet as a head injury mitigating factor has been investigated. Zahid et al compared the results of experimental impact tests on an anti-riot police helmet produced by continuous textile reinforcement using the ABAQUS software [12]. Pinnoji et al took the helmet with both inner and outer layer as well as the cerebrospinal fluid (CSF), skin, skull, brain, flax and tentorium as head layers into account and investigated and compared the effect of changes in the thickness of the helmet outer layer and the density of helmet inner layer on the intensity of damage due to impact to head in various conditions [1]. Kostopoulos et al assessed the effect of the stiffness of the composite outer layer of the helmet on damage intensity and found out that using a composite outer layer in helmets raises the amount of energy absorption and reduces the injury to motorcyclist's head [13]. Deck et al simulated a two-layered helmet under impact loading using FEM. The outer layer of the helmet was made of polycarbonate thermoplastic and the inner layer made of EPS foam. They investigated the biomechanical parameters resulted from loading the frontal area of the head [14]. Elragi et al and Childs et al have investigated the EPS foam properties and their relation to the degree of energy absorption during rotational motion of the head [15,16]. Ganpule et al investigated the effect of explosive impact loading on head injuries [17]. Tse et al investigated recently the effect of impact directions during a ballistic impact on a head protected with helmet and came to the conclusion that more pads of smaller size in helmet may lead to better protection of head [18]. Rodríguez-Millán et al performed a study on possible brain injuries in various blast conditions with the aim of providing more insight into injury mechanisms and predicting unsuspected brain injuries [19]. Jacob et al investigated the helmet effect under various boundary conditions like object height and cyclist's velocity and presented the results in charts [20]. Darling et al analyzed a football helmet using FEM and investigated the axonal damages and neuronal cell death under crown impact conditions [21].

In the present study, the main head parts playing an important role during an impact to head were analyzed under impact loading and the effects of the number and type of helmet protective layers on head protection and head injury reduction were investigated and compared.

MATERIALS AND METHODS

Geometry

In the present study, the skull and CSF as main head parts and the hard surface (outer layer) and the foam (inner layer) of helmet as protective layers of head were modeled and FEM-analyzed using ABAQUS version 6.14. Figure 1 shows the layers of head and helmet.

Material Properties and boundary conditions

In the present study, XPS foam was used as the inner layer of helmet [1,15,16]. Table 1 shows the material properties of various four layers of head and helmet [1,22,23].

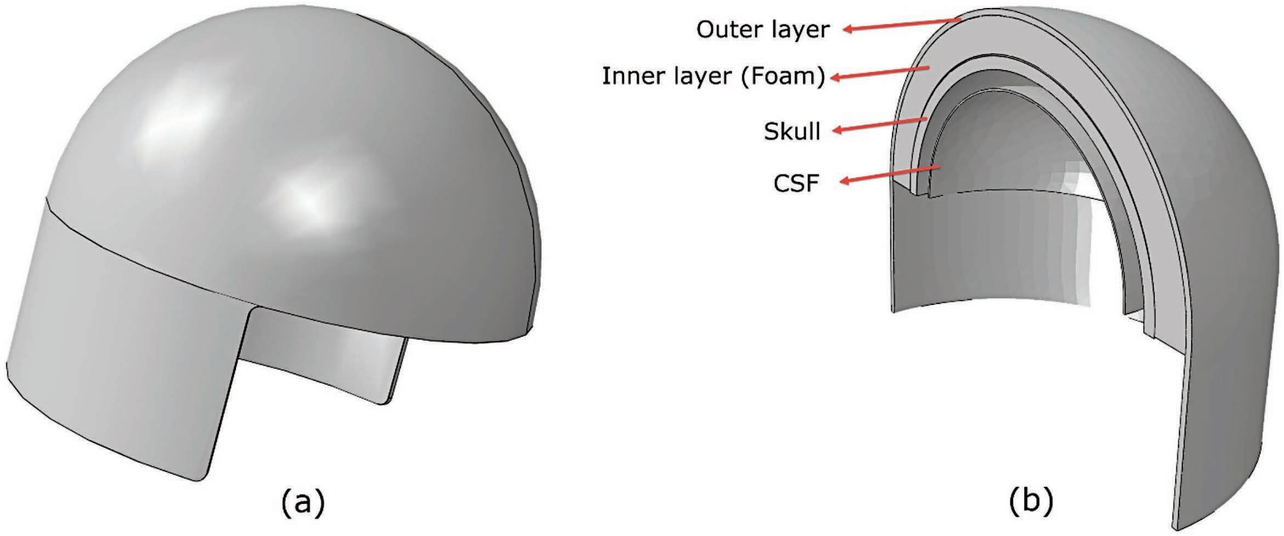

Figure 1. Panel (a) shows Helmet model Panel (b) shows the layers of head and helmet.

Table 1. The material properties of various layers of head and helmet.

	Passion`s ratio	**Elastic modules (Mpa)**	**Density (g/cm^3)**
Outer layer of the Helmet (ABS)	0.37	2000	1200e-12
Internal layer of the Helmet (EPS)	0.05	18	22e-12
Internal layer of the Helmet (XPS)	0.35	17.7	26e-12
SKULL	0.21	15000	1800e-12
CFS	0.49	0.012	104e-12

In order to simulate the impact to head, helmet and head were loaded with a compressive impacting load of 1.31MPa which was exerted on the posterior part of the helmet (Figure 2).

The mechanism of surface contact with a tied interface constraint was used to apply the boundary conditions to various layers of helmet and head. In this mechanism, two surface points are constrained with respect to each other by a tie constraint and their degrees of freedom become identical and this leads to satisfaction of the following stress boundary conditions [24]:

$$\frac{\sigma_z^2}{S_n^2} + \left(\frac{\sigma_{xz}^2 + \sigma_{yz}}{S_s^2}\right) \geq 1 \tag{1}$$

σ_z, σ_{yz} and σ_{xz} in equation (1) are normal plane stress and shear inter-laminar stresses, respectively. S_n and S_s are normal plane strength and shear inter-laminar strength, respectively.

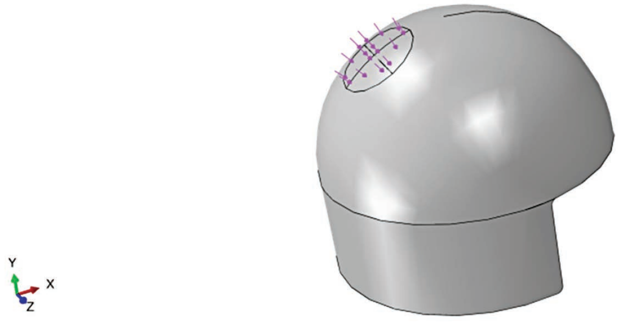

Figure 2. The location of exerting the external load on helmet.

The simulation in this study was performed using two helmets with different inner layers. The inner layer in one helmet was made of XPS foam and in the other helmet of EPS. Following meshing and analysis of models, the results of the biomechanical analysis of head injury were compared with each other. To select the most proper material for the helmet inner layer, the analysis was repeated with a helmet having a composite inner layer made of EPS-XPS foam combination. It should be noted that the mechanical properties of head layers and helmet outer layer were considered to be the same in all these analyses.

Grid Independence study

The tetrahedral element type was used for models. In order to assess the grid independency and the convergence of responses in numerical solution, the displacements of helmet outer layer due to external impacting load were compared for various mesh numbers. According to Figure 3, the numerical difference between displacements due to impacting load decreases significantly with the increase in element number so that the difference between the medium and fine nodes is less than 3.8% in all analyses.

Captions

RESULTS AND DISCUSSION

In the present study, the helmet outer layer and skull were considered as elastic layers and the helmet inner layer and CSF as the shock absorbing layers. Since XPS and EPS foams have the highest flexibility and shock absorbing ability, the effect of these two foams as helmet inner layer was investigated in analysis of impact to head.

In order to assess the effect of helmets with XPS and EPS inner layers, it is necessary first to calculate the amount of displacement and the resulting stress in helmet layers. Thereafter, the results must be compared to find out which foam is more proper to be used as helmet inner layer. The biomechanical factor which reduces the head injury is the energy absorbed by the shock absorbers, i.e. foam and CSF. The more the energy absorption during force exertion, the less the injury to head. Since the CSF conditions don't change, the injury reduction with the change of foam material was evaluated in the present study.

Evaluation of displacement

The results obtained from Figure 4 show that the

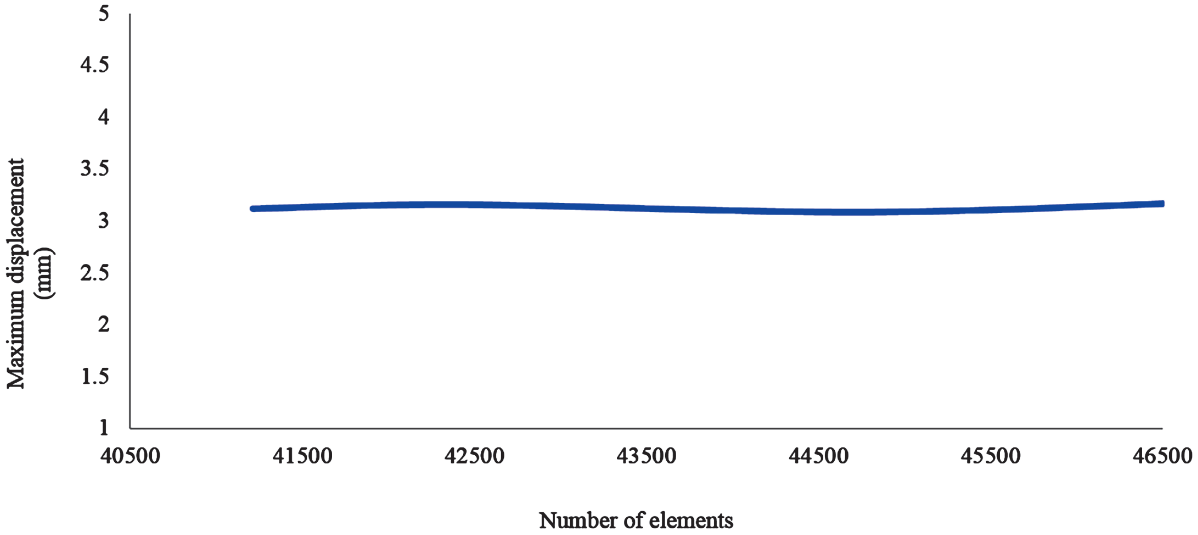

Figure 3. Grid independence and convergence study for responses.

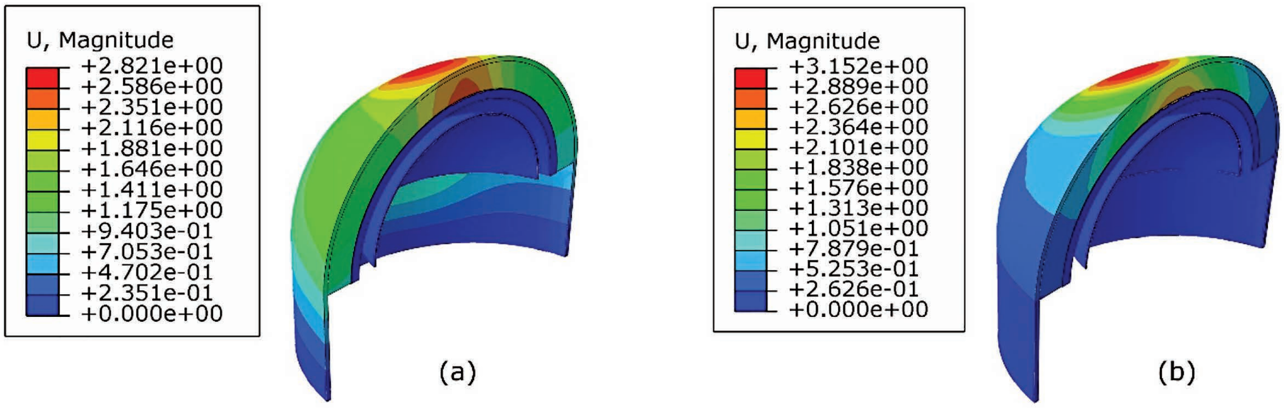

Figure 4. The displacement distribution due to an impacting load in a helmet with an inner layer made of (a) XPS foam and (b) EPS foam.

greatest amount of displacement in helmet outer layer when using XPS and EPS foams has been 2.821 and 3.152 mm, respectively. Therefore, the amount of displacement in the helmet with XPS inner layer is 11.73% less than that in the helmet with an EPS inner layer.

Based on the results of FEM simulation as seen in Table 2, the highest amounts of displacement in outer and inner layer of a helmet with an EPS inner layer due to force exertion are 3.152 and 3.149mm, respectively. So the displacement in outer layer is 0.09% percent greater than the displacement in inner layer (foam).

According to Table 2, the amount of displacement in outer and inner layer of a helmet with a XPS inner layer has been 2.821 and 2.804, respectively. So the displacement in outer layer of this helmet is 0.6% percent greater than the displacement in its inner layer (foam). The degree of impressibility of the outer layer in the helmet with EPS is 6.7 times that of the helmet with XPS. The results also show that the impacting load has led in none of the helmets to skull and CSF displacement. This means that the helmets designed with an either EPS or XPS inner layer have prevented the head injury.

Evaluation of stress

According to Figure 5, the maximum amounts of normal stress in outer layer of helmets with XPS and EPS foams are 43.38 and 32.05MPa, respectively. Therefore following the exertion of an impacting load, the stress produced in the outer surface of the helmet when the inner layer is made of XPS is 26.1% greater than that in the helmet with an EPS inner layer. Based on the results of the Table 2 and the modules of elasticity of foams in Table 1, the aforementioned conclusion is justifiable. According to Table 2, the maximum amounts of normal stress applied to the outer and inner layers of the helmet with XPS foam are 43.38 and 0.616Mpa, respectively. So the maximum normal stress applied to the outer layer of the helmet with XPS foam is 70.4 times the stress applied to its inner layer. The amounts of normal stress produced in the outer and inner layers of the helmet with an EPS inner layer following loading are 34.05 and 0.489MPa, respectively. This means that the normal stress in the outer layer of this helmet is 69.6 times the stress in its inner layer. It should be noted that stress, in a similar manner to displacement, has decreased perfectly in skull and CSF in both analyses. Therefore, considering the material of foams and the stress distribution in models, EPS is a more proper choice for helmet inner layer and causes less stress in the outer layer in comparison to the XPS foam.

Since there is no special stress concentration or no special influence of the geometrical shape of the models, the maximum stress is produced as expected at the location of the force application according to Figure 5 and consequently the maximum displacement occurs based on the Hook's law at the same location as demonstrated by the results in Figure 4.

Although specific modules of elasticity have been

Table 2. The maximum stress and displacement in helmet layers in the helmet with EPS and XPS foam due to force exertion on helmets.

	Maximum Displacement in outer layer (mm)	Maximum Displacement in internal layer (foam) (mm)	Maximum Stress in outer layer (MPa)	Maximum Stress in internal layer (foam) (MPa)
Helmet with XPS foam	2.821	2.804	32.05	0.489
Helmet with EPS foam	3.152	3.149	43.38	0.616

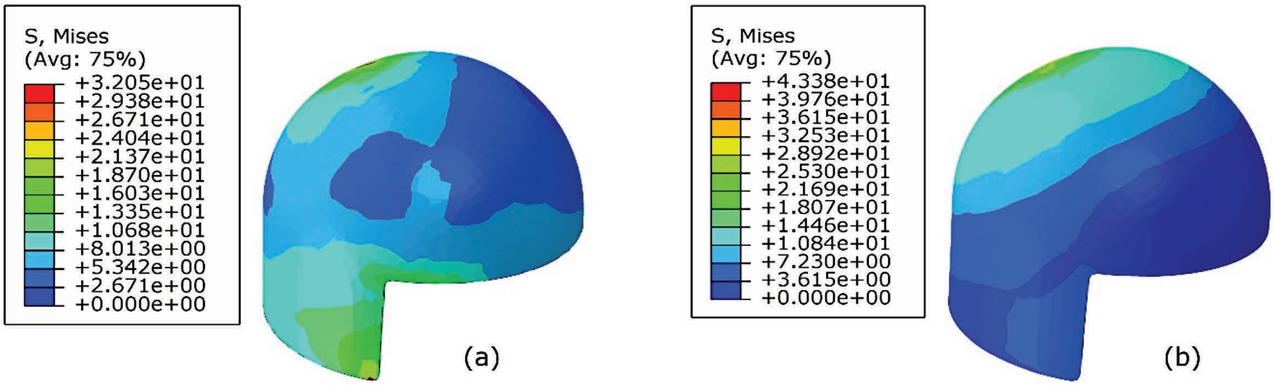

Figure 5. The stress distribution due to an impacting load in a helmet with an inner layer made of (a) EPS foam and (b) XPS foam.

considered for CSF and foam layers, the CSF and foam play in fact the role of damper terms and the helmet outer layer and skull play the role of spring terms. Since 4 layers (including two layers of helmet, a skull layer and a CSF layer) were considered in both analyses, the performed simulation can be assumed to be equivalent to a viscoelastic model according to Figure 6a. It should be noted that the layers of helmet, skull and CSF can almost be assumed as parallel elements when the external load is tangent to the outer surface of the helmet but in case that the external load is vertical to the helmet surface as in the present study, the elements can be assumed to be in series. The module of elasticity of springs (helmet outer layer and skull) and the mechanical properties of CSF were the same in both analyses (helmets with EPS or XPS inner layer) and only the damper used in the inner layer (EPS and XPS foams) had different damping effects in these analyses.

Evaluation of helmet model with two internal layers

In the viscoelastic model shown in Figure 6a, the resilience of skull and helmet outer layer has been considered to be constant in order to improve the helmet conditions for reducing the injury to head. In the viscoelastic model shown in Figure 6b, however, it has been attempted to reduce the stress produced in head by increasing the number of dampers. The helmet in this new model is composed of three layers with the mechanical properties presented in Table 1. The layers from outside to inside are outer layer (with the same conditions as before), the first inner layer made of XPS and the second inner layer made of EPS. Figure 7 shows the results of maximum displacement. The maximum amounts of displacement due to the impacting load in outer and internal layers of the helmet are 2.98 and 2.96mm, respectively. According to data in Tables 2 and 3, the maximum displacement in internal layers of the

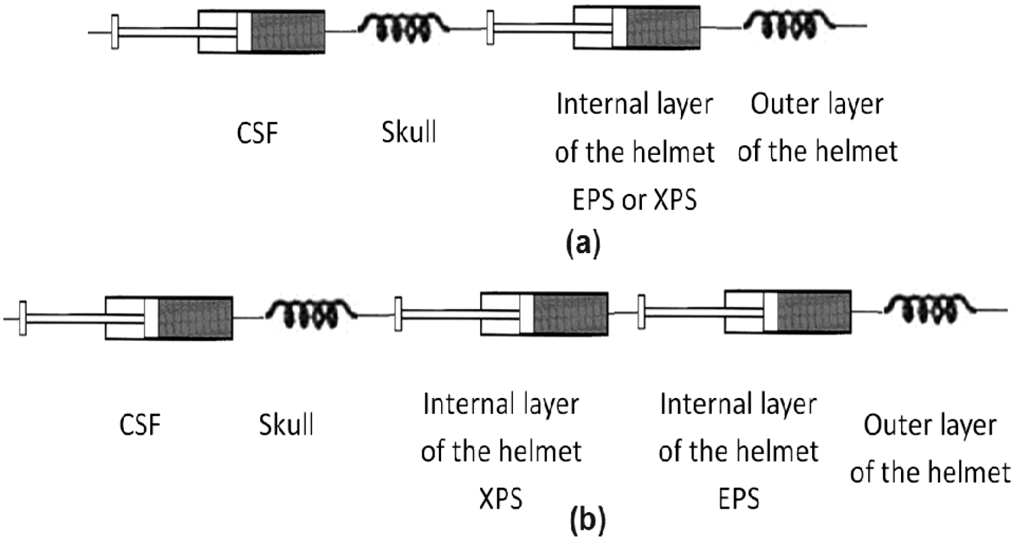

Figure 6. The viscoelastic model of head and helmet with 4 layers (a) and this viscoelastic model with 5 layers (b).

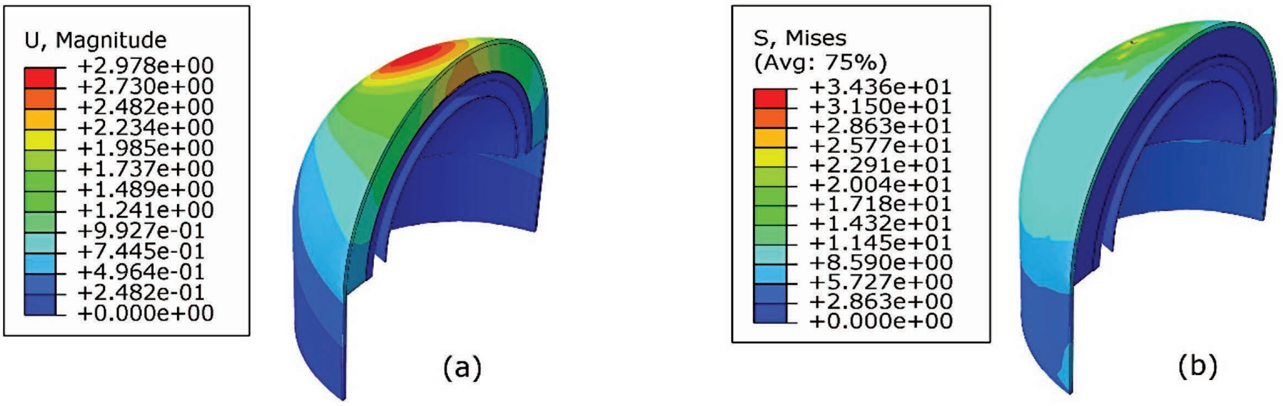

Figure 7. (a) Displacement and (b) stress distributions due to an impacting load in a helmet with two internal layers.

Table 3. Displacement and stress in layers of a helmet with two internal layers.

	Maximum Displacement in outer layer (mm)	Maximum Displacement in internal layers (mm)	Maximum Stress in outer layer (MPa)	Maximum Stress in internal layers (MPa)
Helmet with two internal layers	2.978	2.966	34.3	0.585

helmet with two internal layers is almost 5.7% and 5.8% greater than that in the helmet with a XPS inner layer and the helmet with an EPS inner layer, respectively.

According to Figure 7 and Table 3, the maximum amounts of stress in the outer layer and internal layers of the helmet are 34.3 and 0.58MPa, respectively. So the maximum stress in the outer layer of the helmet with two internal layers is 6.6% and 26.5% greater than that in the helmet with a XPS inner layer and the helmet with an EPS inner layer, respectively.

As seen, the amounts of maximum stress and displacement in the helmet with two internal layers are between the respective amounts of stress and displacement in helmets with one inner layer. Although the total thickness of the internal layers in the helmet with two internal layers is greater than the thickness of the inner layer in the helmets with one inner layer, the maximum stress in the inner and outer layer of the helmet with a XPS inner layer is 16.4 and 6.6% less than the respective stresses in the helmet with two internal layers. As the helmet with a XPS inner layer has reduced the stress more than the helmet with two internal layers, it is the most proper and optimal model for reducing the head injury when an impacting load is applied to the head.

CONCLUSION

For biomechanical modeling of the impact to head, two four-layered and one five-layered viscoelastic models of helmet and head were FEM-analyzed in the present study. By making changes in the inner layer of helmet as a damper for reducing the head injury due to an impacting load, the amounts of maximum displacement and stress were calculated and compared. The results showed that the amounts of maximum stress and displacement in the helmet with two internal layers were between the amounts of stress and displacement in the helmets with one inner layer made of EPS and XPS. It was also demonstrated that the helmet with a XPS inner layer is a more proper choice for reducing the head injury when an impacting load is exerted on head.

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