Chapter

Head Impact Injury Mitigation to Vehicle Occupants: An Investigation of Interior Padding and Head Form Modeling Options against Vehicle Crash

Ermias G. Koricho and Elizabeth Dimsdale

Abstract

Traumatic Brain Injuries (TBI) occur approximately 1.7 million times each year in the U.S., with motor vehicle crashes as the second leading cause of TBI-related hospitalizations, and the first leading cause of TBI-related deaths among specific age groups. Several studies have been conducted to better understand the impact on the brain in vehicle crash scenarios. However, the complexity of the head is challenging to replicate numerically the head response during vehicle crash and the resulting traumatic Brain Injury. Hence, this study aims to investigate the effect of vehicle structural padding and head form modeling representation on the head response and the resulting causation and Traumatic Brain Injury (TBI). In this study, a simplified and complex head forms with various geometries and materials including the skull, cerebrospinal fluid (CSF), neck, and muscle were considered to better understand and predict the behavior of each part and their effect on the response of the brain during an impact scenario. The effect of padding thickness was also considered to further analyze the interaction of vehicle structure and the head response. The numeral results revealed that the responses of the head skull and the brain under impact load were highly influenced by the padding thickness, head skull material modeling and assumptions, and neck compliance. Generally, the current work could be considered an alternative insight to understand the correlation between vehicle structural padding, head forms, and materials modeling techniques, and TBI resulted from a vehicle crash.

Keywords: vehicle interior padding, traumatic brain injury (TBI), head model, vehicle occupants safety, finite element model (FEM)

1. Introduction

Traumatic Brain Injury (TBI) can occur when the head is suddenly impacted by an object and the reaction forces cause internal tissue damages and alter the normal brain function. Traumatic Brain Injury (TBI) is a major contributing factor to a third (30.5%) of all injury-related deaths in the United States. About 75% of TBIs that occur each year involve concussions or other forms of mild injuries [1].

Recently, worldwide the number of people affected with war related TBI has increased due to terrorism, civil and military conflicts [2, 3]. To minimize the severe illness and mortality resulting from blasts, vehicle crashes, and projectiles, several types of head protective equipment with different material options have been proposed since the end of the 19th century. Starting from the 1960s, multi-layers composite materials became a preferred option for personal armor applications, resulting in improved body armor with lightweight, good protection, flexibility, and improved comfort [4]. On the other hand, padding has been used for improving energy absorption in protective structures, packaging systems, sports equipment, handheld devices, as well as comfort and support systems. Particularly, the interior of motor vehicles has been identified as an area where severe head and neck/spinal injuries can occur in frontal, side, rear, roll over, or oblique impacts. Hence, there is a critical need to reduce occupant injuries, including potential head injury. Several researchers have investigated head impacts with the roof, pillars (A-Pillar, B-Pillar), and support structures [5–9]. For instance, Friedman and Nash [8] have proposed preventing head contact with the vehicle interior through interior padding and increased headroom to prevent serious injury during rollover crashes. Lim [9] investigated the energy absorption characteristic of foam and plastic paddings used for vehicle interior and the head injury performance. Results showed that depending on the type of materials and countermeasure space, the energy absorption and the resulting head injury varied.

However, despite evidence of correlations among impact energy, materials, and head acceleration, all of the above research did not present the influence of padding material and geometry variations on the skull-brain relative motion and the resulting strain and stress values.

In this study, simplified and complex head models with various geometries and materials including the skull, cerebrospinal fluid (CSF), muscle, and neck were considered to better understand and predict the behavior of each part and their effect on the brain response during the impact scenario. The effect of padding thickness was also considered to further analyze the interaction of the vehicle structure and the head. Particularly, the response of the head was evaluated based on the peak and rate of acceleration, strain, and stress at various locations in the brain.

2. Numerical model

2.1 3D head model

The head form was developed using Blender v. 2.79 3D computer graphics software toolset. Multiple digital pictures of a human head form were taken from different directions (top, front, rear, left, and right views) using a digital camera and imported into Blender to create the desired computer aided design (CAD) models, as shown in **Figure 1**.

As can be found in the open literature, the human head consists of a scalp, bone, and a series of three fibrous tissue layers namely Dura mater, Arachnoid, and Pia mater, known as the meninges [10], as shown in **Figure 2**. In this work, the head form was symmetrical to reduce the computation time. The brain and various skull parts were developed in SolidWorks by taking several cross-sections of the MRI sagittal, lateral, and transverse head images and corresponding dimensions [10]. Additional features such as neck bone and muscle were also incorporated in the model, as shown in **Figure 2**.

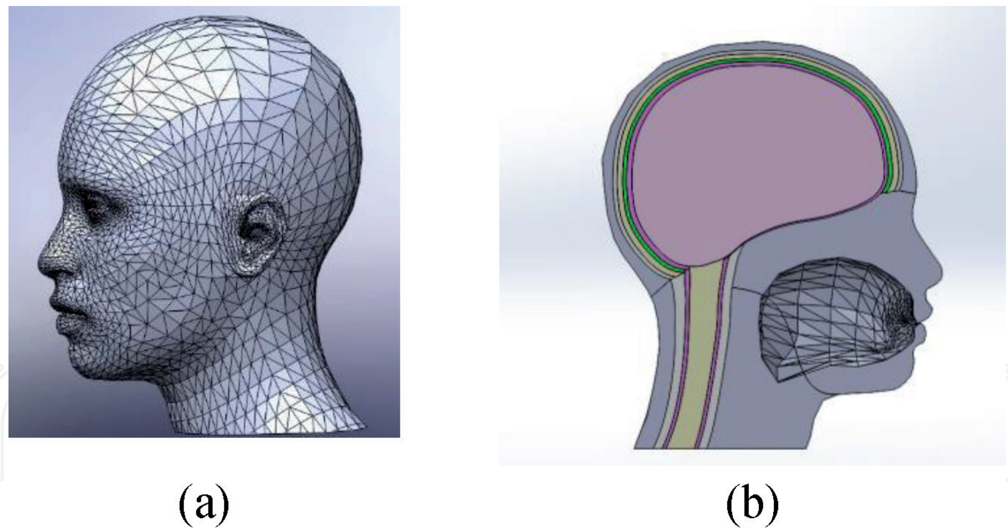

Figure 1.
3D head model: (a) Exterior section, (b) detailed modified interion section.

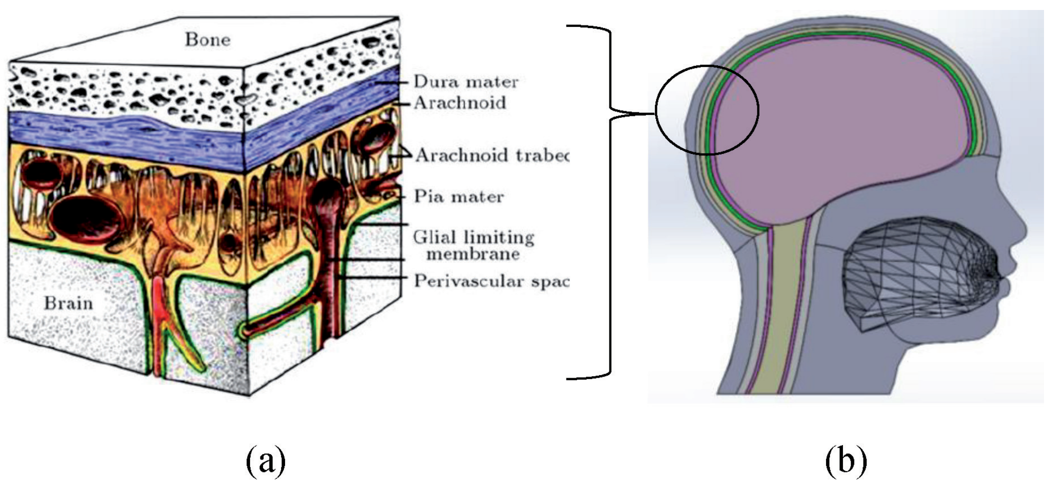

Figure 2.
(a) Schematic diagram of the subarachnoid space (SAS) space, trabeculae, pia, and arachnoid. [10]; (b) detailed 3D head model.

2.2 Materials model

2.2.1 Materials model for head

The mechanical properties of different sections of the head are the most critical and challenging parts to develop in order to construct a reliable finite element method (FEM) based head model. The material models chosen for the brain were isotropic and elastic linear viscoelastic with shear and bulk relaxation behaviors described by

$$G(t) = G_0\left[1 - \sum_{k=1}^{N} \underline{g}_k^P \left(1 - e^{-t/\tau_k}\right)\right] \tag{1}$$

$$K(t) = K_0\left[1 - \sum_{k=1}^{N} \underline{k}_k^P \left(1 - e^{-t/\tau_k}\right)\right] \tag{2}$$

The characteristic parameters of the Prony law used in Abaqus, g_k and k_k, are the weight factors, defined as.

$$g_k = \frac{G_k}{G_0}, k_k = \frac{K_k}{K_0} \tag{3}$$

Where G_k and K_k are the bulk moduli associated with the relaxation time τ_k, and G_0 and K_0 represent the instantaneous glassy shear and bulk modulus, respectively,

where N, g_i^P, and τ_i^G, i = *1, 2, …, N* are material constants. Substitution in the small-strain expression for the shear stress yields

$$\tau(t) = G_0\left(\gamma - \sum_{i=1}^{N} \gamma_i\right) \tag{4}$$

$$\text{Where } \gamma_i = \frac{g_i^P}{\tau_i^G} \int_0^t e^{-s/\tau_i^G} \gamma(t-s)\,ds$$

Different authors [10–14] have proposed the short-time shear modulus G_0 from G_0 = 528 kPa to G_0 = 10 kPa and the long-time (infinite) shear modulus G_∞ from G_∞ =168 kPa to G_∞ =2 kPa. In this work, values of τ, G_∞, G_0, K, chosen for the FEM model are shown in **Table 1**.

In this work, the mechanical properties of the bone were considered as isotropic and elastic with the Young's modulus, E = 15GPa, the Poisson's ratio $\upsilon = 0.21$, and the materials' density $\rho = 1800\frac{kg}{m^3}$, [11]. The CSF had an average thickness of 2 mm and was considered as an elastic, incompressible medium with Young's modulus, E1 = E2 = 15 kPa, Poisson's ratio, v = 0.499, and shear modulus, G12 = 0.01 kPa [15]. The material properties for the neck bone, inner and outer tables, dipole, and neck muscles used in this work are summarized in **Table 2**.

The mechanical properties of the steel were found from the experimental tests performed in our lab, E = 210 GPa, $\upsilon = 0.3$, and $\rho = 7890\frac{kg}{m^3}$, yield strength, $S_y = 330\,MPa$, and ultimate strength $S_{ut} = 523\,MPa$. Also, the characteristic of polypropylene foam, which was utilized as an energy absorber for the vehicle structural padding, was taken from the previous work [19]. The material model

Shear modulus, G_0, **at** $t = 0$	$328 kPa$
Shear modulus, G_∞, at $t = \infty$	$168 kPa$
Bulk modulus, K	$307 kPa$
Density, ρ	1040 kg/m^3
Relaxation time, (τ)	τ_1 = 0.02 sec, $\tau_2 = 10^{-4}$ sec

Table 1.
The mechanical properties of brain tissue for a linear viscoelastic material model.

Parts	Young's modulus, [GPa]	Density [kg/m^3]	Poisson's ratio
Neck bone [16]	1	1300	0.24
Inner Tables [17]	12.2	2120	0.22
Outer Tables [17]	12.2	2120	0.22
Dipole [18]	1.3	900	0.22
Neck muscles [10]	0.01	1010	0.38

Table 2.
Material properties for the head model.

used for the foam was isotropic, elastoplastic, crushable foam with hardening and rate dependency.

2.3 Modeling and meshing

In this work, the numerical model was carried out using ABAQUS® version 2017–1. In the FEM model, three main parts were involved in the impact scenario: a steel pole, padding made of polypropylene foam, and the head, as shown in **Figure 3**. Three FEM head models were considered to evaluate the effect of modeling assumptions on the response of the head skull and the brain during an impact scenario, as shown in **Figure 3**: a) the simplified form, Skull-Brain (SB), b) Skull-CSF-Brain (SCB), and c) Composite Skull-CSF-Brain (SCCB). For the head models, 8-node solid elements with a size of 5 mm were used. For the steel pole and the padding, 4-node shell and hexahedral solid elements were used, respectively. To reduce computational resources, the head model was reduced to a symmetrical model, as shown in **Figure 3**. Depending on the padding thickness and the head skull models, the entire model consisted of a various number of elements and nodes.

The contact between the head and the pole was defined with penalty contact (for tangential behavior) and hard contact for normal behavior. The "hard contact" option allows automatic adjustment for the stiffness generated by the "penalty contact" algorithm to minimize penetration without detrimentally affecting the time increment. The coefficient of friction between the pole and the head was assumed to be $\mu = 0.3$. The padding was constrained with the steel pole using the

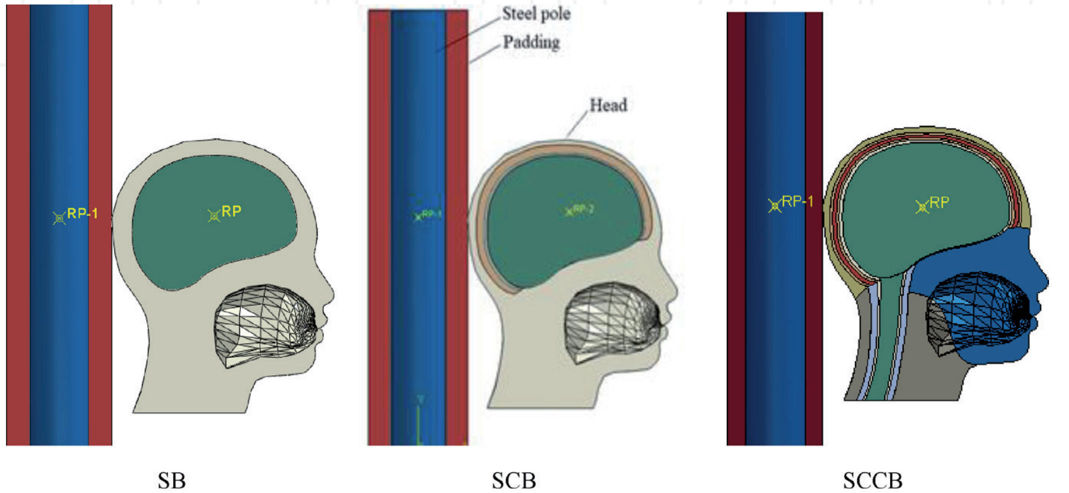

Figure 3.
FEM head models.

"Tie option" interaction available in ABAQUS®. Similarly, at the interface between the skull and the CSF, the CSF and the brain, as well as the skull and the scalp, a tie option was also implemented. In this work the pole was constrained with a fixed boundary condition at the two ends. The initial condition was imposed on the head with a predefined velocity of 4 km/hr. towards the pole.

3. Result and discussion

As shown in **Figure 4**, in all head form models, the head peak accelerations were delayed when the pole was laminated with various padding thicknesses as compared with the head when it impacted against the steel pole (SB_0, SCB_0, SCCB_0). For the simplified head form model, SB, increasing of the padding thickness exhibited an insignificant peak acceleration reduction, however, the rate of acceleration reduced as the padding thickness increased From a point of vehicle crashworthiness, delaying the peak acceleration can significantly reduce the head/brain injury. Recent studies have indicated that a high rate of onset acceleration, i.e. high jerk, during a low-speed vehicle collision increases the risk of whiplash injury by triggering inappropriate muscle responses [20, 21].

It is also worth mentioning that the development of a representative head form model plays a crucial role to obtain the actual acceleration/deceleration and predict the injury level resulting from the vehicle crash. As shown in **Figure 4(c)**, the head form, SCCB, that consisted of the scalp, composite skull, CSF, neck, and muscle exhibited the highest acceleration and became more responsive to padding thickness and (a reduction of acceleration) when it impacted the steel pole: at 25 mm padding thickness, the lowest acceleration was obtained by the SCCB. On the other hand, the more rigid and simplified model, SB, exhibited the lowest acceleration at zero padding thickness and was less responsive to the change in padding thickness;

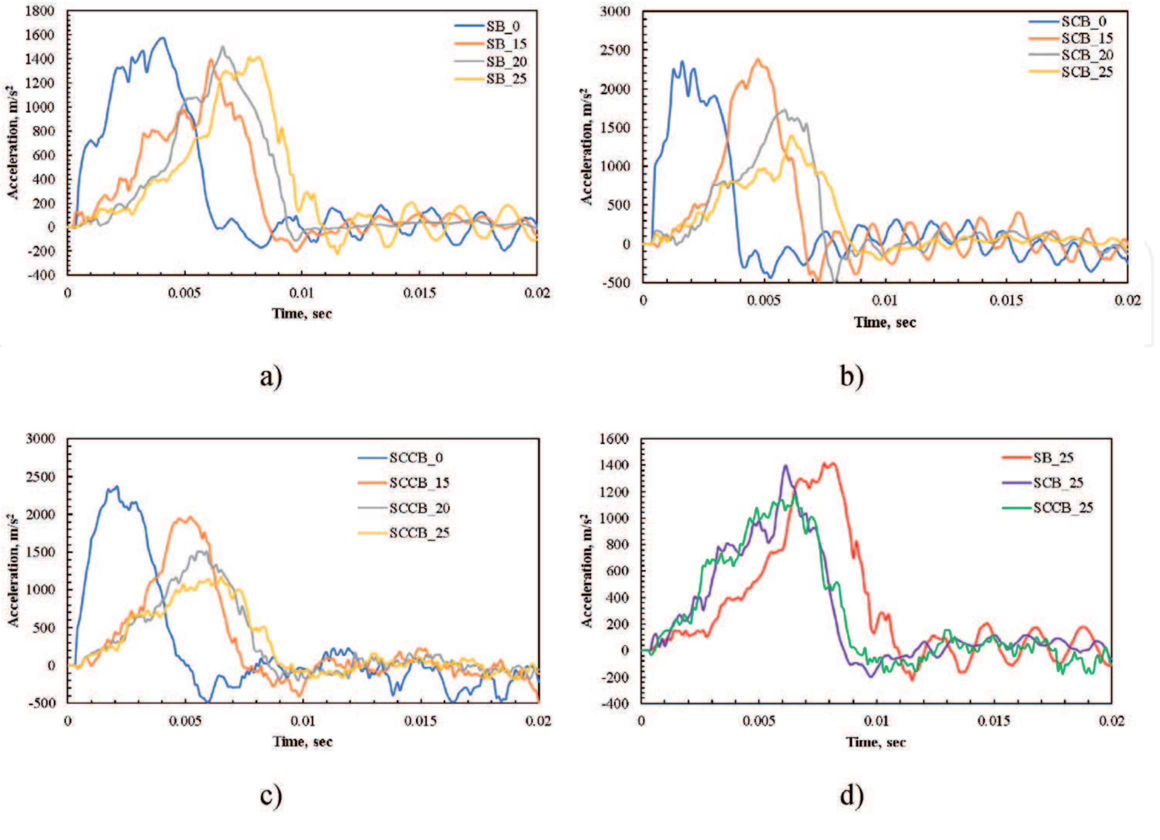

Figure 4.
Comparison of acceleration-time graph: (a) SB, (b) SCB, (c) SCCB, (d) 25 mm padding thickness.

at 25 mm padding thickness, the highest acceleration was obtained by the SB, as shown **Figure 5(d)**. This phenomenon can be explained by the fact that in the SB model, the skull, CSF, neck, and muscle were represented by a single material type, the bone, that increased the stiffness of the model and reduced the energy absorption resulting from the interactions among the head form parts and the pole. Generally, padding of the interior part of a vehicle structure with energy absorbing materials, regardless of the type of head model (simplified or detailed model), significantly reduced the peak and the rate of acceleration.

Figures 5 and **6** show the results for the strain time-histories in three regions of the brain (coup (back), contrecoup (front), and middle (reference point (RP), **Figure 3**)). **Figure 5** displays the strain versus time-history of the coup for a duration of 20 milliseconds for various padding thicknesses for each head model. **Figure 6** shows the strain for the contrecoup and middle regions of the brain as well, for a similar time history for the three head models at a padding thickness of 25 mm. As expected, the simulation results for each case concluded with a general decrease in the peak strain present within all regions of the brain as the thickness of the padding increased. By analyzing the various models, it was concluded that the presence of the CSF resulted in a quicker strain response, as well as a damping effect on the peak strain present within the brain. The most simplified model, SB, resulted in a delay of the peak strain on the contrecoup compared to the more detailed models, SCB and SCCB, due to the rigidity of the system corresponding with the absence of the CSF, shown in **Figure 6(b)**. The stress delay on the contrecoup also corresponds with the absence of materials, including the skull and the CSF within the system, resulting in a larger time duration before the strain from the impact transfers to the contrecoup. Due to the fluid material properties of the CSF, a damping effect of the strain present within the brain upon impact was also applied to the models where CSF was implemented, SCB and SCCB, resulting in a

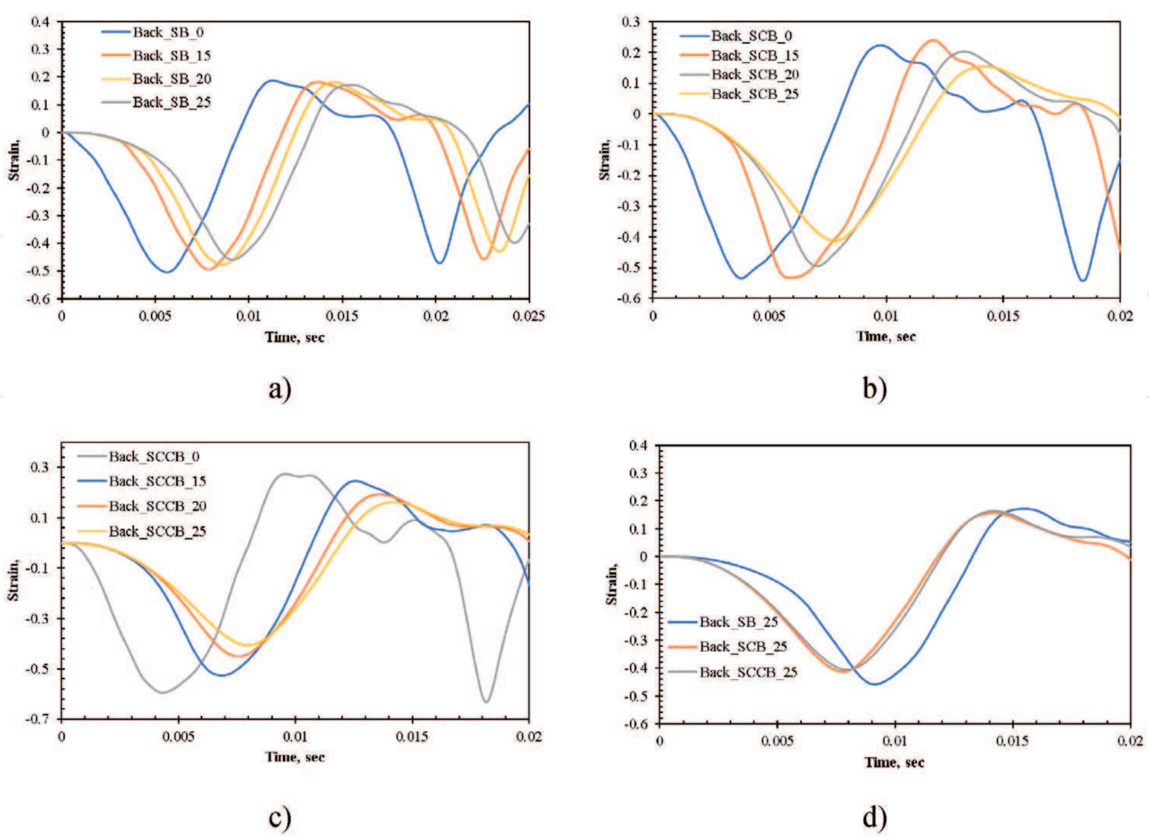

Figure 5.
Comparison of strain-time graphs for three head form models: (a) SB, (b) SCB, (c) SCCB, (d) at 25 mm padding thickness.

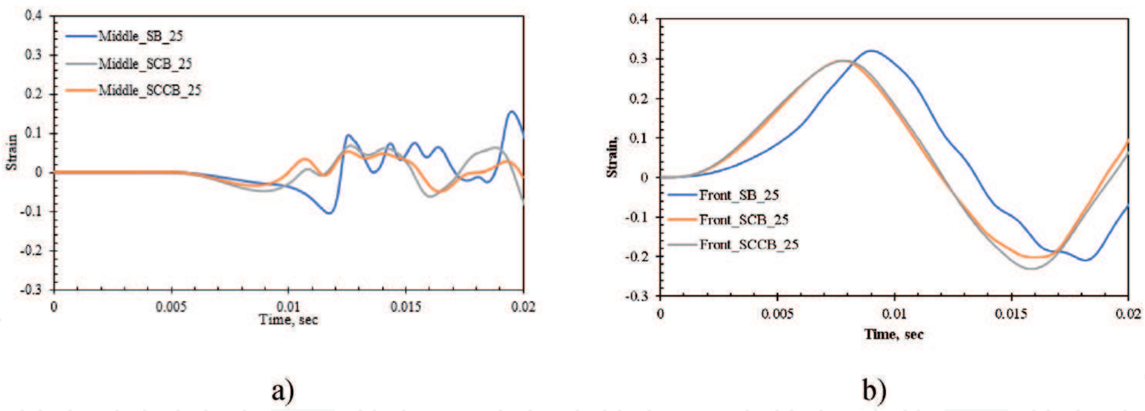

Figure 6.
Strain-time graph: (a) middle, (b) front.

significant decrease of the peak strain values. However, when analyzing the middle region of the brain, the peak stresses resulted in a much lower value, overall. The stress wave fluctuations in this region, shown in **Figure 6(a)**, also resulted in a decrease of peak strain values with the presence of the CSF. However, for the most simplified model, SB, the drastic change in strain value due to the stiffness of the system, as well as the stress fluctuations between the coup and contrecoup could potentially cause a significant shear tear-out behavior of the brain tissue. Such behavior could lead to a diffuse injury, or shear injury, which is an important aspect involved in the causes of long-term TBI [22].

Figure 7 illustrates the pressure being transmitted through the brain due to the impact with a padding thickness of 25 mm at various time histories. The pressure

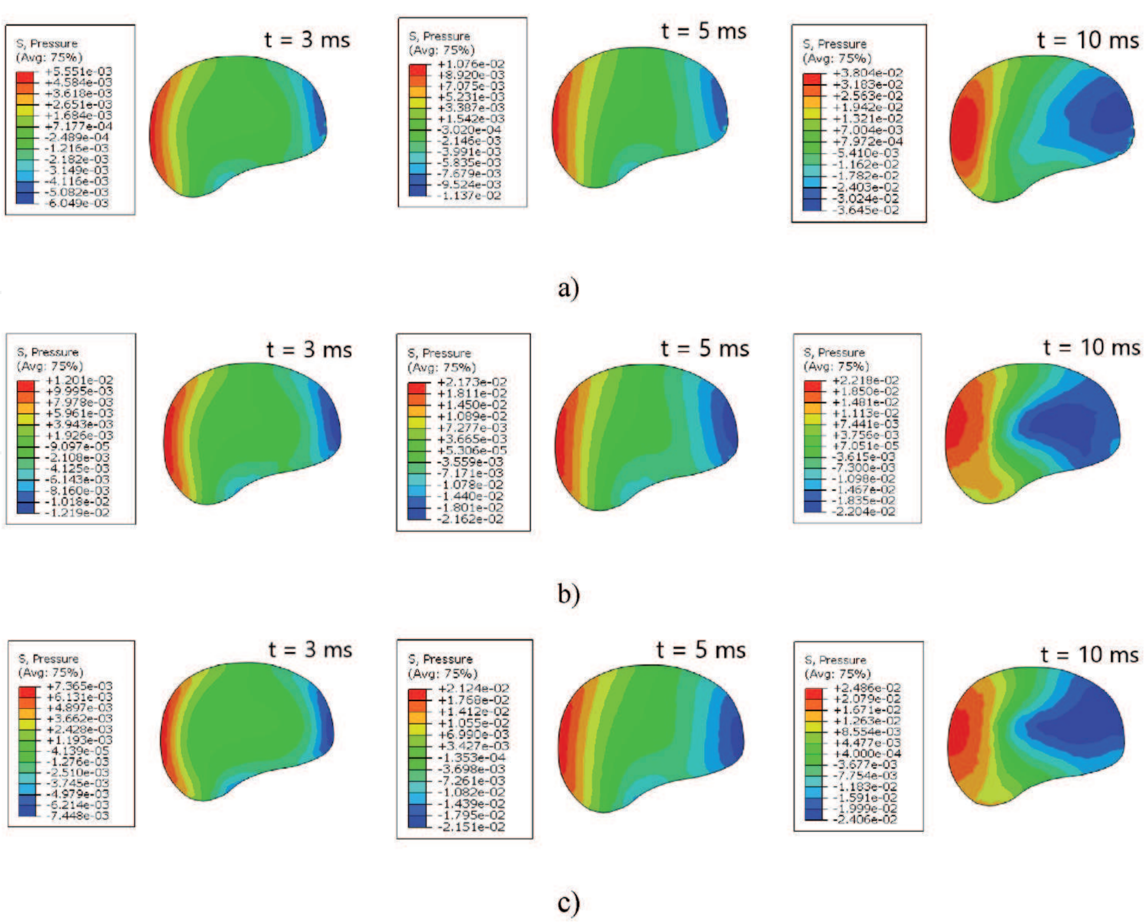

Figure 7.
Pressure response: (a) SB, (b) SCB, (c) SCCB.

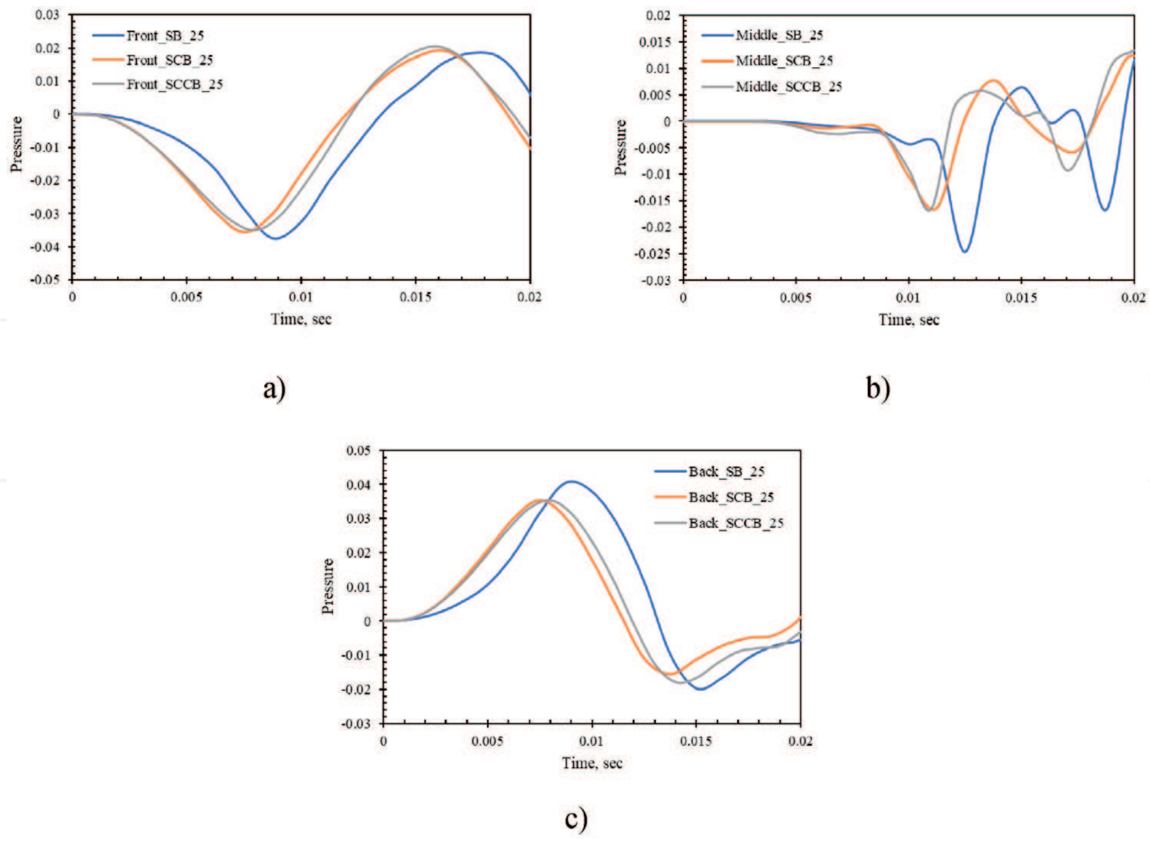

Figure 8.
Pressure–time graph: (a) front, (b) middle, (c) Back.

in the brain for each head model, SB, SCB, and SCCB, is illustrated for t = 3 ms, t = 5 ms, and t = 10 ms. **Figure 7** displays specific parameters, including the pressure versus time-history for the coup, middle, and contrecoup of the brain in order to visualize the quantitative tensile and compressive behaviors of the brain upon impact. Comparable to the strain versus time-history results in **Figures 5** and **6**, the initial peak pressure values of the more detailed models, including the CSF, significantly decreased compared to the simplified model, SB, shown in **Figure 7**, along with the corresponding graphical results in **Figure 8(a)-(c)**. These outcomes similarly correspond with the results provided from previous studies [23] that displayed the reduction of pressure oscillation due to the damping factor provided by elastic materials, such as CSF. The buoyancy of the CSF, as well as the effect of mass due to the presence of the skull and CSF layers, results in a reduction in the peak pressure values for the coup, middle, and contrecoup, corresponding with the reduction in the peak strain values as well. However, when analyzing the simplified model, the decreased acceleration, illustrated in **Figure 4(d)**, corresponds with an increase in pressure, **Figure 8(c)**, within the brain due to the inflexibility of the model. On the other hand, when comparing the similar pressure behaviors of SCB and SCCB, it is seen from **Figure 8(a)** that the peak pressure of the contrecoup increases for SCCB while the acceleration increases as well, shown in **Figure 4(d)**, due to the flexibility of the neck from the alteration of the modulus of elasticity in the most detailed model.

4. Conclusion

This current work has studied the effect of vehicle interior padding thickness on the response of three head form FEM models subjected to an impact loading. The numeral results revealed that the responses of the head and the brain under impact load were highly influenced by the padding thickness, the head skull material modeling and assumptions, and neck compliance. The results from this study are summarized as follows:

- Padding of the interior part of a vehicle structure, regardless of the type of head model (simplified or detailed model), significantly reduced the peak and the rate of acceleration.

- The buoyancy of the CSF, as well as the effect of mass due to the presence of the skull and CSF layers, results in a reduction in the peak pressure values for the coup, middle, and contrecoup, corresponding with the reduction in the peak strain values as well.

- Simplified model, SB, exhibited a drastic change in strain value and the stress fluctuations between the coup and contrecoup that could potentially be interpreted as an indication of a significant shear tear-out behavior of the brain tissue. Such behavior could lead to a diffuse injury, or shear injury, which is an important aspect involved in the causes of long-term TBI [22]. However, the buoyancy of the CSF in SCB and SCCB models had significantly reduced the strain and the pressure fluctuation. This implies that a detailed head form model, such as the SCCB, is essential to predict the head injury, particularly the TBI, resulting from vehicle crash. Hence, unrealistic or over-simplified FEM model (e.g. SB) could mislead not only the interpretation of the results by overestimating/underestimating key parameter such as strain, pressure, and rate of acceleration but also the effect design modification on vehicle crashworthiness.

Overall, the numerical simulations have provided qualitative and quantitative information about the response of the head against impact loading. The current work could be considered an alternative insight to understand the correlation between the vehicle interior padding, various types of head form models, materials modeling, and output parameters such as acceleration, strain, and pressure that can be correlated to TBI resulting from a vehicle crash.

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