Effects of Skull Stiffness on Intracranial Responses of a Child Head

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Abstract. Skull stiffness of children is of great significance to protect brain tissues during traffic accidents. In this paper, the effects of skull stiffness on traumatic brain injury (TBI) are investigated by using a validated 6-year-old child head finite element (FE) model according to Chinese standard GB/T 24550-2009 Results showed that the HIC value, intracranial pressure, Von Mises stress and shear strain of brain tissue increased with the decrease of skull stiffness during the impact of FE model with engine hood. Therefore, the injury risk of the child head decreases with the increase of skull stiffness. And the skull with higher stiffness can provide a better protection for brain tissues during traffic accidents.

Introduction

Recently, finite element (FE) method has become the effective way to investigate the head injury mechanism and evaluate the injury risk of head [1]. Many child head FE models have been developed and validated by reconstructing the traffic accidents or cadaver experiments of children [2]. To a certain extent the effectiveness of evaluating the traumatic brain injury (TBI) by using the FE models depends on the proper selection of mechanical properties of head materials. However, mechanical properties of head materials vary constantly in the process of child growth. For example, the skull stiffness of child head increases with the growth of children [3]. The role of the skull is to protect the head tissue during the impact. The aim of this paper is to investigate the effects of skull stiffness on the intracranial responses of child head by using a validated 6-year-old child head FE model according to Chinese standard GB/T 24550-2009 [4].

Materials and Methods

6-year-old child FE model description

Based on Ruan's validated FE model [5], intracerebral soft brain tissues were further divided, and hard tissues such as mandibular bones and facial bone were created based on the 6-year-old head CT data using the FE developing method in literature [3]. Mesh Qualities of the FE model were also optimized in this study. The detailed 6-year-old head FE model was shown in Fig 1, the brain soft tissues include cerebrum, corpus callosum, cerebellum, brainstem, ventricle, diencephalon, sinus, flax, CSF, and dura matter. The whole FE head model with 103,716 nodes mainly consisted of 17,346 shells (falx, dura matter and tentorium) and 96,128 bricks (other brain structures). The meshes among brain tissues, CSF and skull were connected with common nodes. The FE model has been validated in the literature [6].

Load and boundary setup of impact simulation experiments

The impact between child head model and engine hood was reconstructed according to Chinese standard GB/T 24550-2009 [4]. Engine hood surface at Location A where injurious structure of shock absorber exists (Fig 2a) is selected from child head form test zones as impact location [7]. Fig 2b shows the forehead of FE model impacts location A of the engine hood surface in the simulations, which were conducted by using PAM-CRASH code. The velocity of the center of mass of FE head is set at 35 km/h and the engine hood is stationary. Velocity direction of FE head was 50 degree with the horizontal plane, and impact direction was downward and rightward related to front structure on vehicle longitudinal vertical plane.

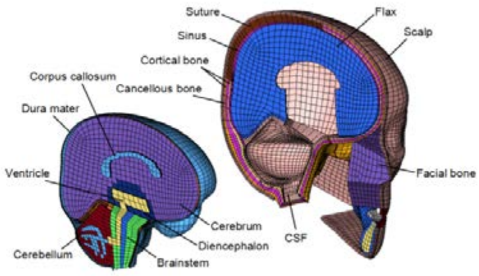
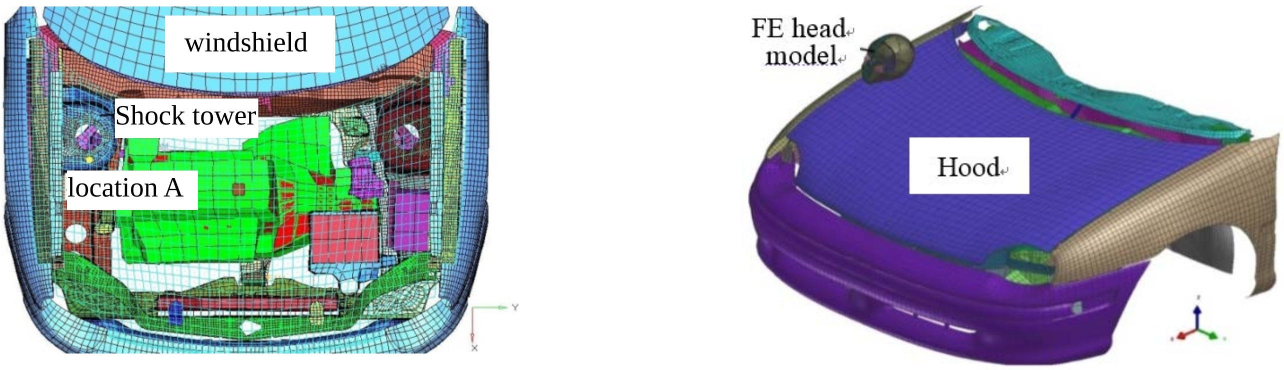


Fig.1 The FE model of a 6-year-old child head with detailed head anatomical structures



(a) Impact location beneath the hood

(b) Simulation of impact between FE head model and hood

Fig.2 Load and boundary setup of impact simulation

In order to investigate the effects of skull stiffness variation on intracranial responses of the child head, a parametric study was conducted. The skull stiffness was divided into five levels, among which Young's modulus of cortical bone of skull varied at five levels of 98.7 (E1), 987 (E2), 9870 (E3), 98700 (E4) and 9870000 (E5) MPa respectively and that of spongy bone of skull varied at the five levels of 36.9 (E1), 369 (E2), 3690 (E3), 36900 (E4) and 3690000 (E5) MPa respectively. The middle level (E3) was adopted as the baseline experiment in the simulation.

Results and Discussion

Acceleration and HIC value

Head injury criterion (HIC) calculated from the resultant acceleration history of head is adopted to evaluate head injury in the Chinese standard GB/T 24550-2009.The peak resultant acceleration (58 g) and HIC15 (601) in E5 experiment is smaller than that in other experiments (Table 1). The peak acceleration and HIC value decreased with the increase of skull stiffness. During the impact between hood and child head, the hood will have a large deformation and absorb more impact energy if the stiffness of skull is high. However, the skull with lower stiffness will have a large deformation and absorb more energy if the stiffness of skull is lower than hood, which leads to higher peak acceleration and HIC value. Therefore, the skull with higher stiffness could lower the risk of head injury during the impact.

Intracranial pressure

The intracranial pressure curves of the child head in E1, E2, E3, E4 and E5 experiments were shown in Fig 3. During the impact, the skull with higher stiffness could decrease the deformation of skull and brain tissue, hence the coup pressure and contrecoup pressure decrease with the increase of skull stiffness. Data in Table 1 reveals that mechanical properties variation of skull has a certain influence on intracranial pressure of the child head.

Von Mises stress of brain tissue

Fig.4 showed the Von Mises stress distributions of brain tissue with different skull stiffness. Roth thought that the Von Mises stress of brain tissue was a good predictor for moderate neurological injury of head [8]. The Von Mises stress of brain tissue decreased with the increase of skull stiffness under the impact loading (Table 1), which indicated that the head with softer skull was more prone to brain injury than that with stiffer skull.

Table 1 Intracranial responses with different skull stiffness

Levels		E1	E2	E3	E4	E5
Peak acceleration (*g*)		91	83	75	69	58
HIC_{15}		1043	916	847	712	601
Peak of intracranial pressure (MPa)	Coup	0.35	0.19	0.18	0.17	0.11
	Contrecoup	-0.02	-0.03	-0.06	-0.08	-0.09
Max Von Mises stress of brain tissue (kPa)		12.7	9.4	8.9	7.1	6.3
Max shear strain of brain tissue		0.21	0.18	0.07	0.06	0.05

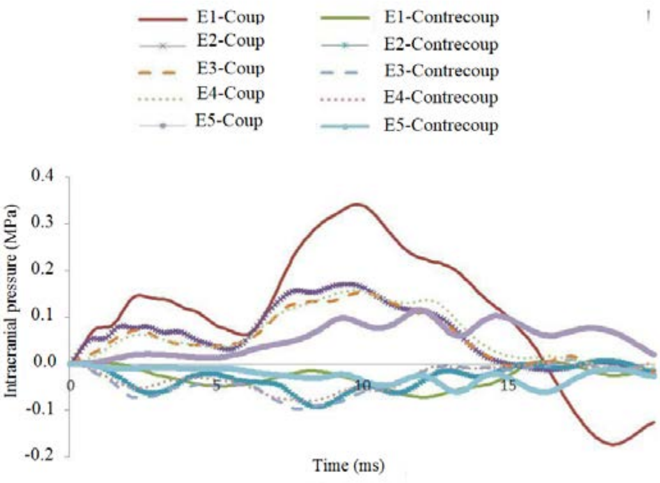
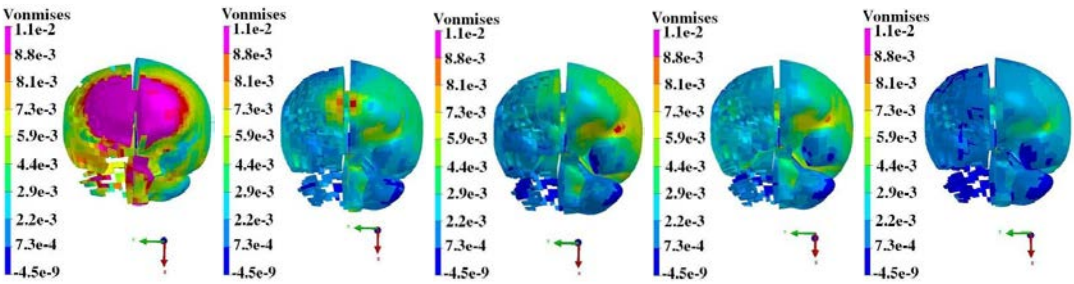


Fig.3 Intracranial pressure curves

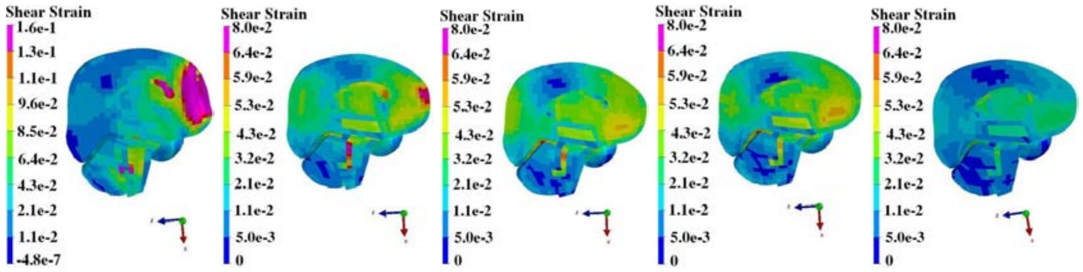


(a) E1 (b) E2 (c) E3 (d) E4 (e) E5

Fig.4 Von Mises stress distributions of brain tissue

Shear strain of brain tissue

The shear strain distributions and max shear strain of brain tissue with different skull stiffness were respectively shown in Fig 5 and Table 1. The skull with higher stiffness had a better deformation resistance during impact, thus the brain tissue near the internal surface of skull at the impact location wouldn't generate large strain. For E1 experiment, the skull deformed largely under the same impact loading because of its smaller stiffness, and then the brain tissues near the internal surface of skull would generate a large deformation under high compress stress caused by skull depression, which led to high shear strain. The shear strain of brain tissue was an effective tool to assess the injury level of DAI [9]. So the stiffer skull could lower the risk of diffuse axonal injury (DAI).



(a) E1 (b) E2 (c) E3 (d) E4 (e) E5

Fig.5 Shear strain distributions of brain tissue

Conclusion

This paper presents the intracranial responses of the child head with different skull stiffness using a validated 6-year-old child head FE model during the impact between the head model and engine hood. In general, the peak acceleration and HIC value of head and intracranial pressure, Von Mises stress and shear strain of brain tissue decreased with increasing the skull stiffness, which meant that the skull with higher stiffness could moderate the injury risk of the child head and provide a better protection to intracranial tissue.

Acknowledgements

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