Effects of Thickness and Material of Engine Hood on Head Response of Child Pedestrian

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***Abstract* — A child head-form is usually used to evaluate the head injury criterion (HIC) in the collision between the child pedestrian head and engine hood according to Chinese standard GB/T 24550-2009. However, intracranial response, such as principal strain and shear strain of brain tissues, cannot be evaluated by using head-form because of its poor bio-fidelity without detailed brain tissues. In this paper, a validated 6-year-old child head finite element (FE) model with detailed brain tissues was used to substitute the head-form to impact engine hood in order to investigate the effects of thickness and material properties of engine hood on head responses (HIC value, principal strain and shear strain). The results showed that the thickness of inner panel and outer panel of engine hood significantly influenced the head responses of 6-year-old child, while the effect of material properties of engine hood was not significant. The thinner engine hood could provide better protection for child pedestrian head.**

Keywords - child pedestrian head; Finite element model; Engine hood; Design of experiments; Head responses

I. INTRODUCTION

Automobile traffic accident is the leading cause of traumatic brain injury (TBI) of child between 1 to 14 years old [1]. How to develop protective device in order to decease head injury caused by traffic accidents is the main task for automobile manufactures. Collision experiments between the head-form and engine hood are usually performed to evaluate the effects of engine hood to protect the child pedestrian head according to automobile safety regulations of different countries, such as Euro-NCAP, IITHS, GB/T 24550-2009. The head injury criterion (HIC) calculated from the linear acceleration history at the center of gravity of the head-form in the collision experiments is an established head injury metric that accounts for both the magnitude and duration of linear acceleration. The HIC of pedestrian child in the collision experiments may be influenced by variety of engine hood parameters, such as material property, thickness [2]. Though HIC is a good indicator to evaluate head injury, it is highly controversial because HIC rarely consider the effect of head size and shape. With the quickly development of head finite element (FE) model, the head responses such as stress and strain of brain tissues calculated from traffic accidents simulation are thought to be an effective complement to head injury under linear head movement. However, head responses can't be analyzed by using.

Head-form in the collision experiments because of its poor bio-fidelity without detailed brain tissues. . In this paper, the validated finite element (FE) model of 6-year-old child with detailed brain tissues was used to simulate the collision between the child pedestrian head and engine hood according to Chinese standard GB/T 24550-2009 based on design of experiments [3]. Besides HIC, effects of engine hood parameters on stress and strain of brain tissues are investigated systematically.

II. MATERIAL AND METHODS

A. *Finite element model of 6-year-old child description*

Based on Ruan's validated FE model [4], intracerebral soft brain tissues are further divided, and hard tissues such as mandibular bones and facial bone are created based on the 6-year-old head CT data using the FE developing method in the literature [5]. Mesh Qualities of the FE model are also optimized in this study. The detailed 6-year-old head FE model is shown in Figure (1), and the brain soft tissues include diencephalon, sinus, flax, CSF, and dura matter. The whole brain tissues, CSF and skull are connected with common nodes. Table 1 summarizes the material properties of head used in the FE head model [6-10]. FE head model with 103,716 nodes mainly consists of 17,346 shells (falx, dura matter and tentorium) and 96,128 bricks (other brain structures). The meshes among different brain tissues, CSF and skull are connected with common nodes.

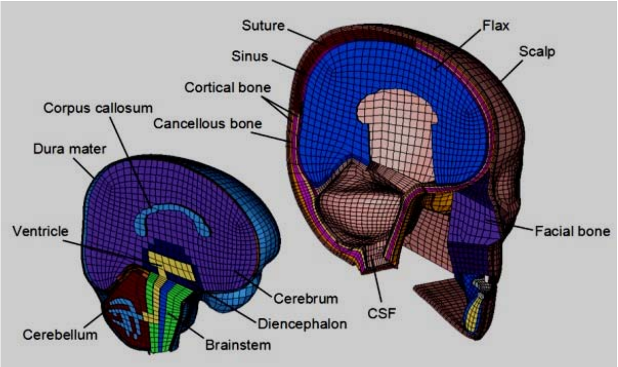


Figure 1. The FE model of a 6-year-old child head with detailed head anatomical structures.

TABLE I summarizes the material properties of head used in the FE head model[6-10].

TABLE II. MATERIAL PROPERTIES USED IN THE 6-YEAR-OLD CHILD HEAD MODEL

Components	Density /kg·m-3	Possion's ratio	Elastic modulus/MPa
Meninges	1140	0.45	31.5
CSF	1040	0.49	0.012
Scalp	1200	0.42	16.7
Cortical bone of skull	2150	0.22	9870
Cancellous bone of skull	2150	0.22	3690
Sutures	2150	0.22	1100

B. *Boundary setup of impact simulation experiments*

The collision between child head model and engine hood is reconstructed according to Chinese standard GB/T 24550-2009 [3]. Engine hood surface at Location A where injurious structure of shock absorber exists (see Figure 2) is selected from child head-form test zones as impact point [7]. Simulation that the forehead of FE model impacts location A of the engine hood surface is conducted by using PAM-CRASH code. During the collision, the velocity of the center of mass of FE head is set at 35 km/h and the engine hood is stationary (as shown in Figure 3). Velocity direction of FE head is 50 degree with the horizontal plane, and impact direction is downward and rightward related to front structure on vehicle longitudinal vertical plane.

C. *Design of experiments of collision simulations*

Effects of thickness and material properties of engine hood on the head responses are investigated parametrically by using the validated 6-year-old child FE head model. In the simulation experiments, full factorial design with 2 levels and 4 factors are conducted in TABLE III.The engine hood structure is composed of two layers (outer and inner plate). In order to avoid the confusion of the results caused by the inner panel and the outer panel, the thickness and material properties of outer panel and inner panel are determined as the factor A, B, C and D respectively. All the factors have 2 levels. In order to ensure the reliability of experiments, the high level and the low level of all factors should be selected in a reasonable range as far as possible [11]. According to the principle of random, the design of full factorial experiments with two levels is summarized in TABLE IV.

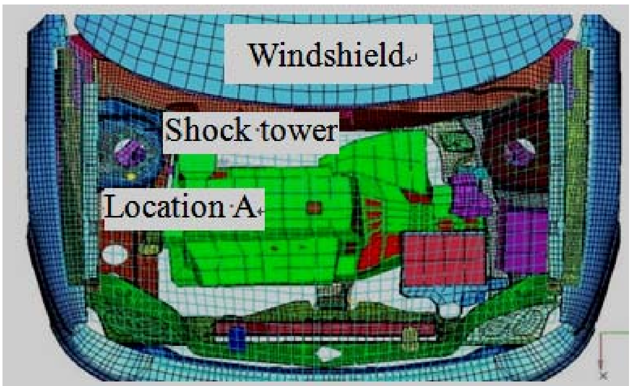


Figure 2. Impact location beneath the engine hood.

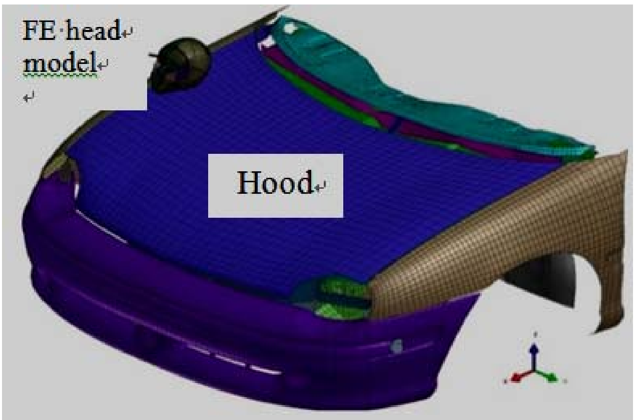


Figure 3. Simulation of collision between the FE head model and engine hood.

TABLE V. FACTORS AND LEVELS OF ENGINE HOOD IN COLLISION SIMULATION

Factors	Levels	Parameters
Thickness of outer panel/ mm (A)	1	0.762
	2	1.524
Thickness of inner panel / mm (B)	1	0.674
	2	1.348
Material properties of outer panel (C)	1	Low-carbon steel
	2	Aluminum alloy
Material properties of outer panel (D)	1	Low-carbon steel
	2	Aluminum alloy

Head injury criterion (HIC) is widely adopted in the automobile safety regulations of different countries, so the

HIC values of child head should be determined as response of experiments. Besides HIC, the shear strain at corpus callosum is a good indicator for predicting diffuse axonal injury (DAI) and traumatic brain injury (TBI). Thus, it is selected as another head response. During the collision, the brain tissues are not only subjected to shear, but also to tensile action, hence the principal strain at corpus callosum is also determined as the head response.

TABLE VI. DESIGN OF FULL FACTORIAL EXPERIMENTS WITH TWO LEVELS

Sequences	A	B	C	D
1	1	1	1	1
2	1	1	1	2
3	1	1	2	1
4	1	1	2	2
5	1	2	1	1
6	1	2	1	2
7	1	2	2	1
8	1	2	2	2
9	2	1	1	1
10	2	1	1	2
11	2	1	2	1
12	2	1	2	2
13	2	2	1	1
14	2	2	1	2
15	2	2	2	1
16	2	2	2	2

The organization of the lecture is as follows. After a general introduction of the effect of fault on the power system, the usefulness and requirement of a fault current limiter is presented to the students which has been discussed in section II. The traditional ways of fixing fault currents in power system has been discussed in section III. In section IV, operating principle, design details, and experimental results of magnetic current limiter has been presented. The analysis and simulation results of high temperature superconducting fault current limiter has been discussed in section V. The lecture has been concluded in section VI.

III. RESULTS PREPARE YOUR PAPER

A. *Preliminary analysis of collision results*

Each experiment of the full factorial experiments with two levels is repeated only once, so the experiment results did not have sufficient degree of freedom to directly evaluate the error variance. Therefore, effects of one factor or interaction on head response are firstly evaluated. The results show that the influence of thickness of outer panel and inner plate of engine hood and their interaction effects on head response, such as HIC value, the principal strain and shear strain at corpus callosum, is statistically significant. On the contrary, effects of material properties of outer and inner panel on response are not statistically significant. Therefore, the engine hood material is not of great importance for head protection, and light weight material can be used for engine hood in order to decrease whole automobile body weight.

B. *Projection analysis of the experiment design*

Because the effects of the material properties of inner and outer panel of the engine hood on the head responses is not statistically significant, these two factors are removed from the experiment. The projection of experimental design with two factors and two levels is conducted as shown in Table 4, which can be used to analyze the variance of the experimental error.

The degrees of freedom, partial variance, F value and P value of the head response such as HIC value, principal strain and shear strain at corpus callosum, are investigated respectively by using MINITAB software. ANOVA (analysis of variance) of HIC value, principal strain and shear strain is shown in TABLE VII. It can be seen that effects of thickness of inner and outer panel of engine hood and their interaction on the HIC value, principal strain and shear strain at corpus callosum of child head are really statistically significant (P≤0.001).

TABLE VIII. PROJECTION OF EXPERIMENTAL DESIGN WITH TWO FACTORS AND TWO LEVELS

Sequences	A	B	HIC Value	Principal strain (%)	Shear strain (%)
1	1	1	154.65	0.6954	6.658
2	1	1	167.26	0.7659	6.903
3	1	1	106.69	0.9631	7.565
4	1	1	266.51	1.1956	8.293
5	1	2	287.44	1.0192	7.112
6	1	2	290.28	1.0161	7.060
7	1	2	290.94	1.0127	7.125
8	1	2	287.44	1.0068	7.066
9	2	1	371.53	0.9387	7.128
10	2	1	367.46	0.9297	7.082
11	2	1	360.32	0.9283	6.982
12	2	1	356.30	0.9224	6.938
13	2	2	792.54	1.5387	11.034
14	2	2	771.93	1.5050	10.856
15	2	2	761.58	1.5088	10.828
16	2	2	740.70	1.4751	10.646

TABLE IX. ANOVA (Analysis of Variance) of HIC, Principal Strain and Shear Strain

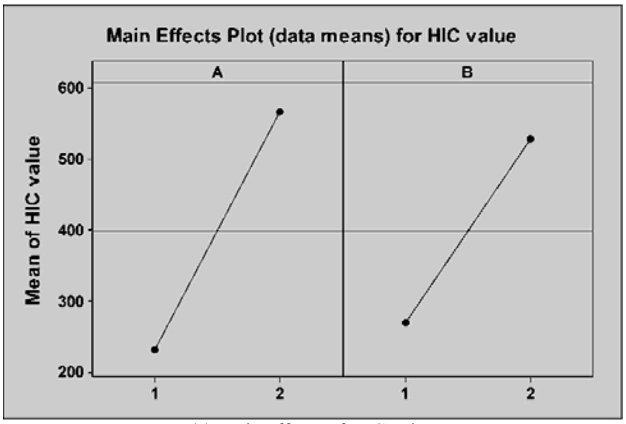
	Source	DF	Seq SS	Adj MS	F	P
HIC value	A	1	445940	445940	355.39	0.000
	B	1	268358	268358	213.87	0.000
	A*B	1	82678	82678	65.89	0.000
	Error	12	15057	1255		
	Total	15	812033			

	Source	DF	Seq SS	Adj MS	F	P
Principal strain	A	1	0.26830	0.26830	20.99	0.001
	B	1	0.47036	0.47036	36.81	0.000
	A*B	1	0.21942	0.21942	17.17	0.001
	Error	12	0.15336	0.01278		
	Total	15	1.11143			

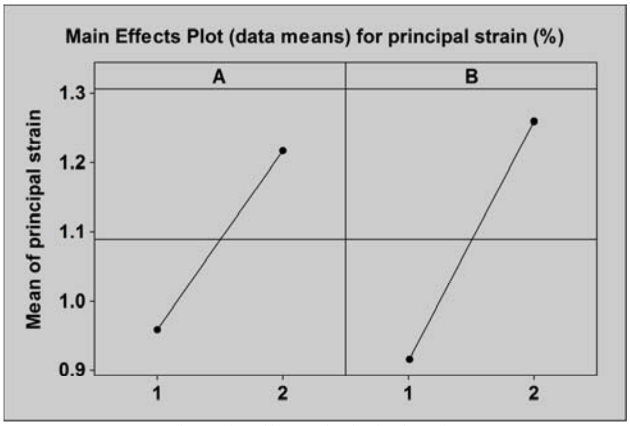
	Source	DF	Seq SS	Adj MS	F	P
Shear strain	A	1	11.751	11.751	82.18	0.000
	B	1	12.563	12.563	87.86	0.000
	A*B	1	16.585	16.585	115.98	0.000
	Error	12	1.716	0.143		
	Total	15	42.616			

C. *Analysis of main effects*

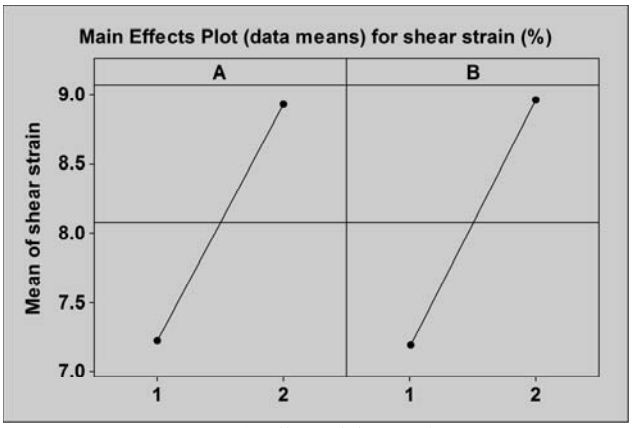
The thinner panel could significantly reduce the mean value of HIC, principal strain and shear strain at corpus callosum as shown in Figure (4). The increase of HIC value with the thickness increase of outer panel is more significant than that of inner panel, which means that the thickness of outer panel is more important in head protection. In the meantime, the effects of thickness of inner and outer panel on the principal strain and shear strain at corpus callosum are almost same. It can also be found from Figure (5) that the effects of the inner and outer panel at low level on the HIC value, principal strain and shear strain at corpus callosum are less than that of high level. Besides, effects of the thickness of outer panel at low level on head responses are not significant, while effects of the thickness of outer panel at high level on head responses are significant. As shown in Figure (5c), the lines representing thickness of inner and outer panel respectively intersect with each other, which means that effects of thickness of outer panel on HIC value, principal strain and shear strain at corpus callosum are determined by that of inner panel.



(a) Main effects of HIC value

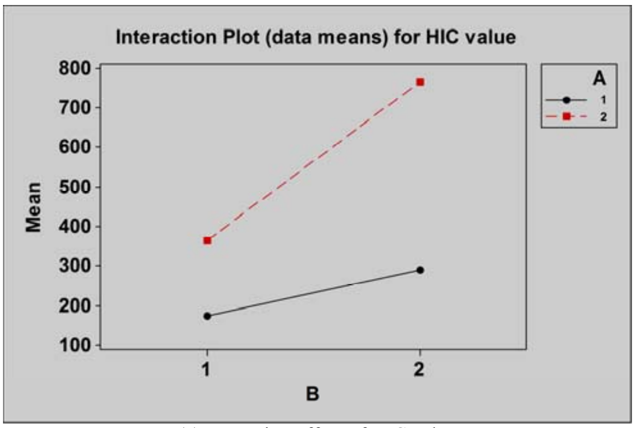


(b) Main effects of principal strain



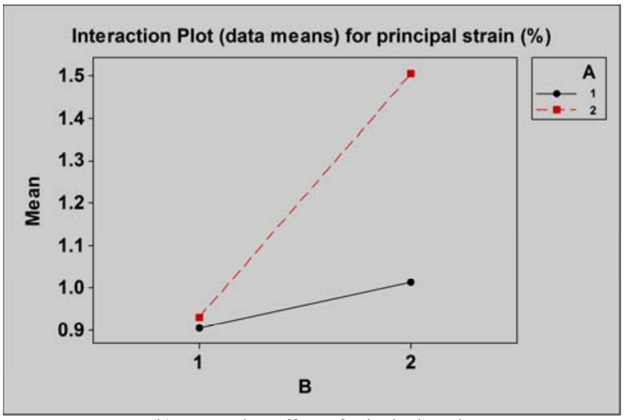
(c) Main effects of shear strain

Figure 4. Main effects of head responses.

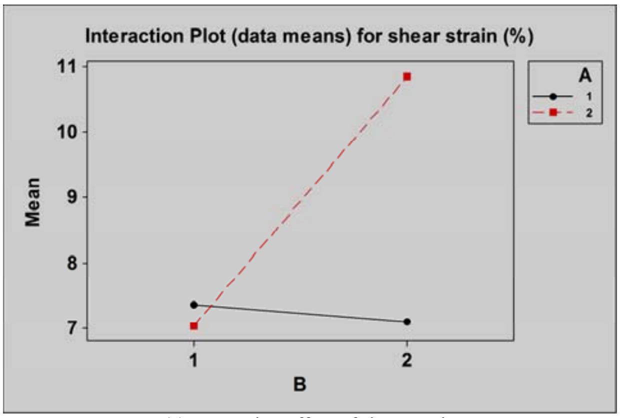


(a)Interaction effect of HIC value

Figure 5. continues on the next page



(b) Interaction effect of principal strain



(c) Interaction effect of shear strain

Figure 5. Interaction effects of head responses.

IV. DISCUSSION

The results show that head responses can be significantly affected by the thickness of inner and outer panel of the engine hood, while effects of material properties of engine hood on head responses of child are not significant. Experimental data in Table 4 mean that the head responses value increase with the increase of the thickness of inner and outer panel. Margulies et al thinks that the brain tissue may be suffered from injury when the shear strain at corpus callosum reaches 5%-10% [13]. In the collision, the shear strain at corpus callosum reaches above 10% which exceeds the injury threshold (5%-10%) when the thickness of inner and outer panel are both high in test 13, 14, 15, 16 (Table 4), and the HIC value reaches 750 which also exceeds the injury threshold according to Euro-NCAP [12]. The thicker inner panel and outer panel is less prone to deformation than thinner level, therefore they will absorb less impact energy and child pedestrian head will absorb more energy during collision experiments, which will lead to severe injury to child pedestrian head. The total thickness of inner and outer panel in the first 12 tests (TABLE X) is less than that in test 13, 14, 15, 16, therefore the HIC value is also less. Though the HIC value less than 400 means no head injury according to automobile regulations, the shear strain at corpus callosum is above 6% means that the brain has the risk of injury. Therefore, head injury evaluated only by HIC value has certain limitations. Furthermore, the principal strain at corpus callosum is smaller than that of the shear strain (Table 5). The main reasons which lead to this are as follows. On one hand, the bulk modulus of brain tissue is 10000 times greater than shear modulus, the brain tissue is nearly incompressible and vulnerable to enduring shear action in the collision simulations. Therefore, the brain is more prone to generating shear deformation, and the shear strain is also higher than normal strain at the same time. On the other hand, the motion of head consists of translation and rotation because the impact direction between the child head and engine hood in the simulation (Figure 3) is not just along the center of gravity of head, and the rotation of head will make the brain tissues endure a larger shear deformation.

The results show that the thickness of inner and outer panel is statistically significant to head response, while the material of engine hood is not statistically significant. In order to verify the results, more simulation experiments are carried out. When the thickness of engine hood is reduced to half and 1/4 of this investigation, and more engine materials such as low carbon steel (Q235) and low carbon high strength steel (TP600) are selected, the simulation results also show that the thickness of inner and outer panel is statistically significant to head response while the material of engine hood is not.

Also, the results show that the effect of thickness of the inner and outer panel on head response is mutually dependent. The thinner outer panel for engine hood is usually helpful to decrease pedestrian head injury severity during traffic accident and the inner panel can be thinner or a little thicker.

V. CONCLUSIONS

The validated 6-year-old child head FE model is a good substitute for child head-form to evaluate head injury by using head response in the collision between the child head and engine hood. According to Chinese standard GB/T 24550-2009, effects of thickness and material properties of the engine hood on head responses (HIC value, principal strain and shear strain at corpus callosum) are investigated based on design of experiments. Results showed that the effects of the thickness of inner and outer panel of engine hood on head responses were significant, while the effects of the material properties of engine hood on head responses were not significant. The thinner engine hood could provide better protection for child pedestrian head during the impact.

ACKNOWLEDGMENT

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