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Development of Motorcycle helmet for pre-school Children Using Metal Foam

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Abstract. Thailand is second in the road fatality rankings published by World Health Organization in 2015. Almost 80% of traffic deaths involves motorcycles and many of the passengers are children. However, there are still no appropriate head protection equipment for small child pillions. The child helmet should also be lightweight and have high energy absorption. This paper aims to develop a child helmet by using metal foam. The impact tests of the smallest size commercial motorcycle helmet were performed in TIS 369-2557 standard. The finite element model of an existing child helmet was developed and employed to simulate the helmet impact tests using both rigid dummy head and deformable child head. The helmet model was validated with experimental tests to obtain the baseline model. Good agreements can be observed. In addition, the deformable child head can give detail information of brain injury experience by the child during impact. The existing helmet model was redesigned with aluminium foam and was compared with the baseline model after impact tests. Improvement in terms of helmet weight and head injury mitigation can be seen.

1. Introduction

The use rate of motorcycles in Thailand and Southeast Asia are very high compared to other type of vehicles. In addition, it is the type of vehicles that causes the highest risk of severe injuries and fatalities. Thai Ministry of Public Health 2015 report on injury surveillance data from 33 injury surveillance sentinel sites showed transport accidents are leading causes of severe injury and death of children under 15 years old (39.17% of severe injuries and 61.46% of deaths) [1]. Save the Children Thailand has reported that there are 1.3 million child pillion passengers on motorcycles [2]. However, there are still no appropriate head protection equipment for small child pillions, nevertheless most of helmets sold for children are reduced-size adult helmets. Inappropriate head protection equipment for small child pillions bring the injuries to head and neck that could cause severe injury and disability among child pillions passengers. Most of existing helmets sold in the market are reduced-size adult helmets which are not appropriate for small children (4-7 years old). Children have different anthropometry, injury mechanism from adult [3]. Their cervical spine is weaker than adults and therefore the child helmet should be lightweight and at the same time must have high energy absorption to mitigate the head acceleration. In order to reduce helmet weight, common practice is to use lower density foam liner or to reduce the thickness of the foam liner. This can lead to lower head protection performance. One of the advanced material which has been used as energy absorber in automotive industry is metal foam. It is light weight and has high strength to weight ratio as well as good energy absorbing capability [4,5]. The automotive industry has applied metal foam to many parts of car such as the crush box [5]. Pinnoji et. al [6], did research that focused on the weight of motorcycle helmet and came out with metal foam for shell part in the helmet. The results showed metal foam gave a better performance when compared to the normal shell. Caserta et. al [7], did a study in enhancement of motorcycle helmet with aluminium honeycomb as a material for helmet liner and it provided a better result in term of protection. To reduce the helmet weight and maintain the head protection performance according to the standards, the paper, therefore, aims to develop a child helmet by using metal foam. The effectiveness of the proposed helmet will be compared with the existing small helmet for children.

2. Helmet Impact

2.1. Helmet impact test set up

Helmet impact test of a commercial child helmet was performed for finite element model validation. The test conditions are based on TISI 369-2557 [8] which adopted impact test condition for half helmet from DOT FMVSS 218 [9]. Four locations, including crown, front, rear and side, of a half helmet must have impact tests. The helmet impact testing machine and all equipment needed are shown in figure 1. The DOT headform size small and an accelerometer to measure the peak acceleration were required. The helmet was fit to the headform. Two types of anvil including flat anvil and hemisphere anvil were employed. The headform together with the helmet were raised to 1.83 m and 1.37 m for flat and hemi anvil respectively. They were dropped to impact the target below. With this height, the impact speed will be approximately 6 m/s.

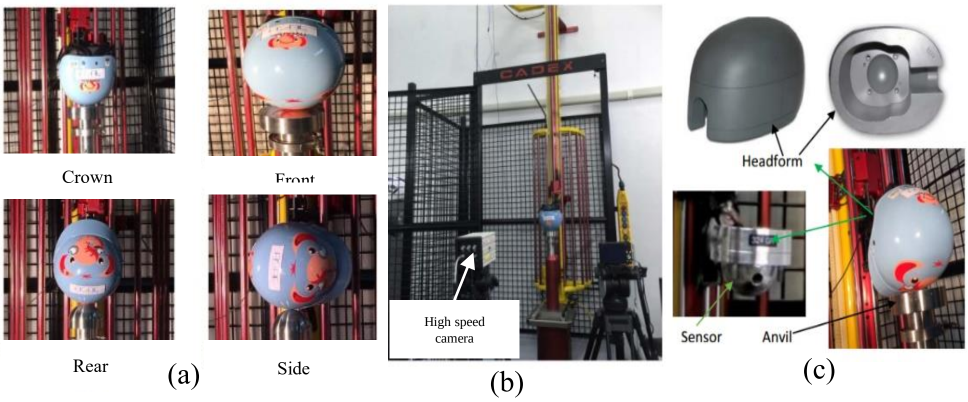


Figure 1. Shows child helmet impact test at four locations (a)crown, front, rear, side. (b) helmet impact testing machine and (c) equipment for helmet impact test.

2.2. Impact test results

Linear acceleration-time graph of each test is shown in figure 2. The peak acceleration and Head injury criteria (HIC) [10] of all four impact configurations are summarized in table 1. DOT FMVSS 218 certainly adopted this maximum force as a guide to set peak linear acceleration at 400g. The peak acceleration obtained from the front impact was higher than the maximum allowable value of 400g. This helmet failed in the impact test. Improvement of performance in the frontal area is strongly required.

Table 1. Summary of the helmet impact test results.

Impact Location	Drop height (m)	Impact speed (m/s)	Anvil type	Peak Acc(g)	HIC	Pass or fail
Crown	1.832	5.8320	Flat	250.4	1473	Pass
Front	1.83	5.8122	Flat	435	2206	Fail
Side	1.372	5.0596	Hemi	212.8	961	Pass
Rear	1.370	5.0829	Hemi	220.1	859	Pass

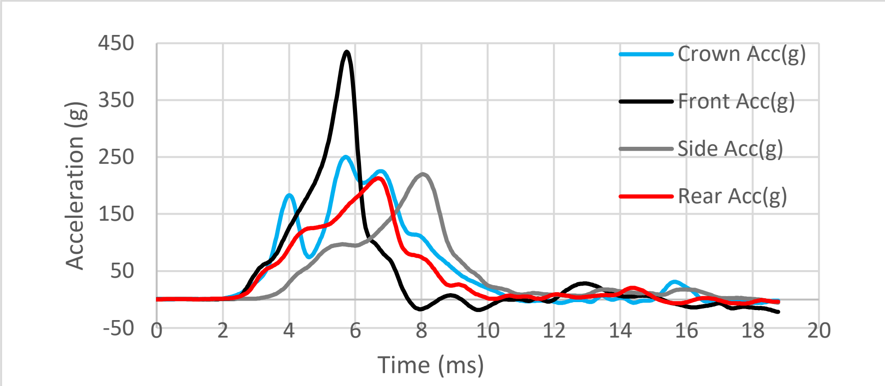


Figure 2. Shows acceleration-time graph of helmet impact testing experiments

3. Development of finite element model for helmet impact testing and validation

3.1. Finite element model set up

The finite element model was developed for the same type and brand of the small helmet used in the impact test. The current helmet was 3D scanned to obtain the correct profile, shape and dimension for creating a finite element model as shown in figure 3a. The model was created in LS-DYNA R7.1.3. The outer shell was made of ABS. Its behavior was described using Plastic kinematics material model [11] in LS-DYNA with a mass density of 1200 kg/m^3, Young's Modulus of 4000 MPa and Poisson's ratio of 0.37 [12]. The outer shell was modeled using shell element of 3.3 mm thickness. The foam liner was made of EPS. Its compression behavior was described using the low density foam material model in LS-DYNA with a mass density 90 kg/m^3, Young's Modulus of 25 MPa and Poisson's ratio of 0. The liner was modeled using tetrahedral solid elements with non-uniform thickness varied from 12 mm at the front to 20 mm in the vertex as shown in figure 3a. In order to simulate the interfaces between the headform-helmet and helmet-anvil, a surface-to-surface type of contact with a friction coefficient of 0.35 and 0.5 were used respectively [15].

Table 2. Material properties for outer shell and foam liner in helmet. [12]

Helmet component	Mass density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio	Thickness (mm)
Outer shell	1200	4000	0.37	3.3
Foam liner	90	8.64	0	12-20

In addition, Figure 3c shows how to set up model for the both types of Anvil. Crown and front location were against flat anvil, side and rear were against the hemisphere. The impact velocity was employed as an initial condition. Therefore, the helmet was positioned as close as possible to the anvil and known impact speed from the test was assigned to the helmet for each case. The anvil was modelled as rigid elements and restricted from movement in all directions. Two types of heads were employed which were validated child dummy head in P6 series. [13] and the other is the validated head of child human body [14], as shown respectively in figure 3. P6 made from steel covered by the rubber, to represent the skin and the equivalent weight. For deformable head, which includes skull and the brain part as shown in figures 3, were modeled with actual mechanical behaviors that are able to provide injury of the brain while the P6 can only provide kinematics responses.

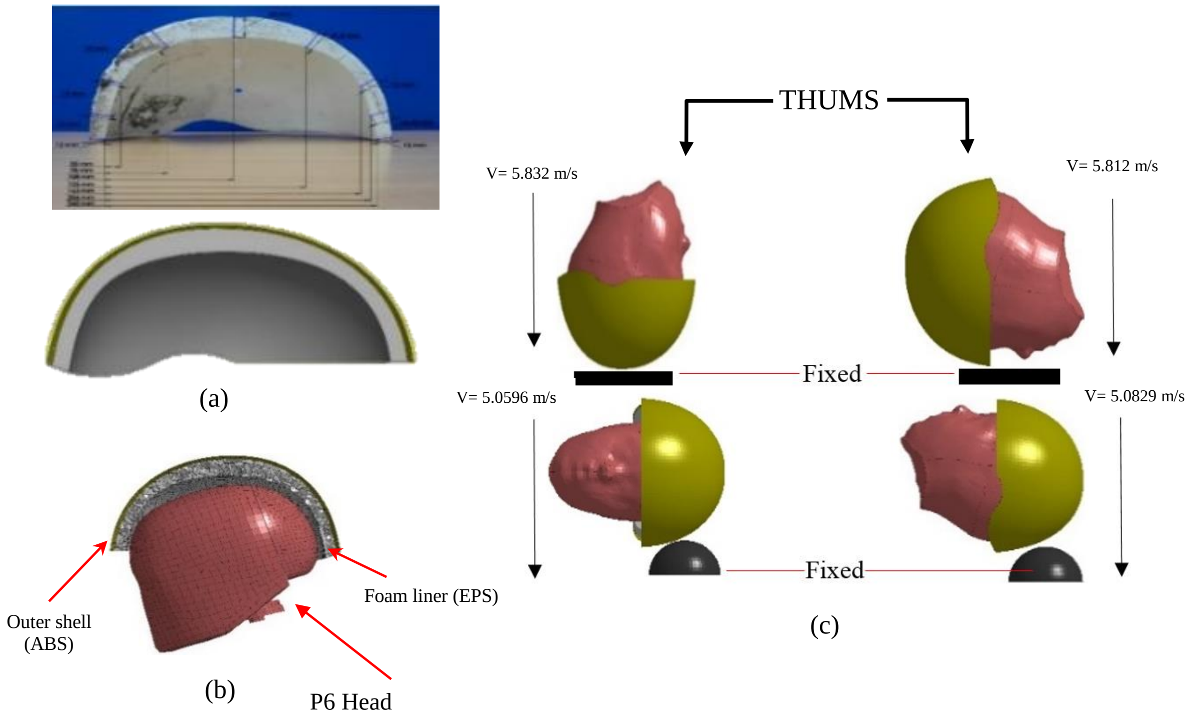


Figure 3. Shows (a) the cross section from the sagittal plane of the foam liner and CAD model (b) Finite element model for the two main parts of helmet (c) helmet impact models set up.

3.2. Model validation

The resultant acceleration was extracted from the accelerometer at the Center of Gravity (C.G.) of the rigid head and from the node at the C.G. of the deformable human head. Both models were validated by comparing the simulation results with the impact experimental results. Table 3 shows comparison of peak acceleration and HIC.

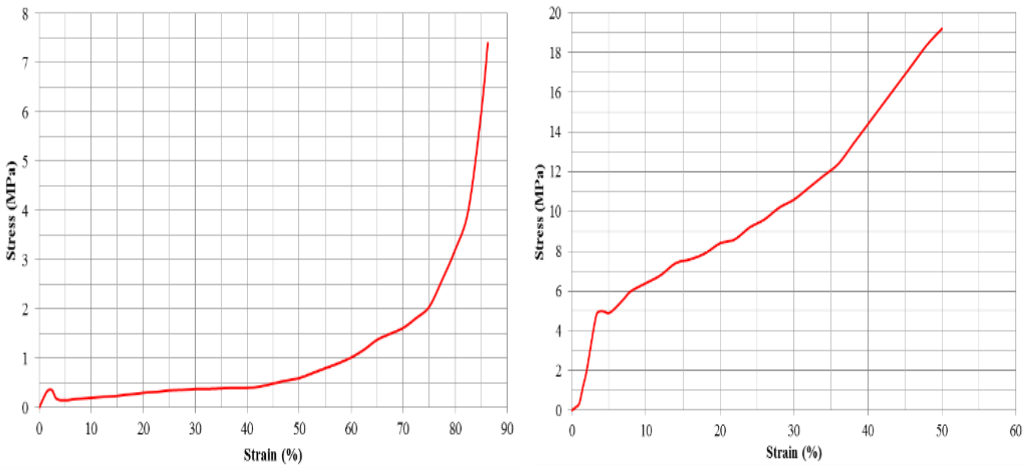
Table 3. Comparison of peak accelerations and HIC obtaining from the experiments and simulations.

Impact	Peak acceleration (g)			HIC		
Location	Experimental test	P6	THUMS	Experimental test	P6	THUMS
Crown	250.41	244.32	268.74	1473	2284	1339
Front	434.96	437.35	468.59	2206	5191	5297
Side	220.09	192.69	218.04	961	848.6	1246
Rear	212.77	223.63	198.89	859	1527	1233

The peak accelerations and HIC obtained from the experiments and the simulations with a rigid child head show small difference. Both values obtained from simulation with the rigid head are a bit lower than the experimental tests except front and rear location, the difference is less than 12.5%. Peak accelerations obtained from simulation with the deformable head shows slight discrepancy with the experiments. The highest difference in this value is at the crown location with a difference of 7.7%. Large difference of HIC value obtained at the front location is seen even though the peak linear acceleration shows little difference. This is because the impact time interval during the first peak obtained from both simulations are greater than that of the experiments. HIC is a function of both linear acceleration and contact time interval. However, the DOT FMVSS 218 standard prefer peak acceleration as passed criteria.

4. Modification of helmet model using metal foam

Implementation of metal foam as part of helmet has great ability in impact energy absorption. It also possesses low density with good shear strength and fracture strength. Since metal foam will be used in the design of child helmet, the compression test of the aluminium foam is required to obtain the material properties. The stress-strain curve obtained from compression tests are shown in figure 4. Table 4 summarizes mechanical properties of the tested aluminium foam. The aluminium foam mechanical behavior was model using crushable foam material model



(a) (b)

Figure 4. Average stress in relation to strain for aluminium foam relative densities of (a) 0.051 and (b) 0.185.

Table 4. Mechanical properties of aluminium foam.

Basic Product Specifications		Compressive Mechanical Specifications		
Density	Relative density	Densification Strain	Plateau Stress	Initial Yield Stress
140 kg/m^3	0.051	73%	0.59 MPa	0.40 MPa
510 kg/m^3	0.185	43%	0.40 MPa	5.25 MPa

4.1. Design variation

In order to discover potential benefits of metal foam, the existing helmet model was redesigned into six types with two different densities of aluminium foam as shown in table 5. Two thickness of outer shell were studied. The same impact test conditions were performed with the P6 dummy head.

Table 5. Summaries the design variation and corresponding total mass.

Model	Outer shell mat.	Inner liner mat.	Total Mass (Kg)
Baseline	ABS	EPS	0.346
1	ABS	Al foam 140 kg/m^3	0.380
2	ABS	Al foam 510 kg/m^3	0.729
3	Al foam 140 kg/m^3, 3.3 mm thick	EPS	0.115
4	Al foam 510 kg/m^3, 3.3 mm thick	EPS	0.197
5	Al foam 140 kg/m^3, 4.3 mm thick	EPS	0.131
6	Al foam 510 kg/m^3, 4.3 mm thick	EPS	0.254

4.2. Simulation results

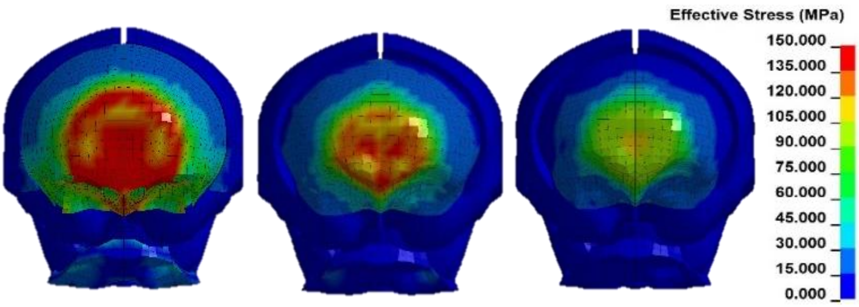
Table 6 shows comparison of peak acceleration and HIC for each simulation cases. Introducing metal foam to 5 helmet models led to reduction in the peak acceleration for all impact locations except the rear location. The peak accelerations obtained from all six model at the front location are less than the baseline model and below the maximum allowable value of 400g of TISI standard. Model no. 3 shows the acceleration of 303.58 g. For the rear location, the peak acceleration is more than the baseline model. However, they are all still lower than the allowable value. The HIC values also followed the same trend as the peak accelerations. Model no. 3 with aluminium foam outer shell of 140 kg/m^3 density and 3.3 mm thickness exhibit optimum performance when taking mass of the helmet into consideration. The mass can be reduced by 66.76%.

Table 6. Peak acceleration and HIC results from P6.

Model	Peak acceleration(G)				HIC			
	Impact Location				Impact Location			
	Crown	Front	Side	Rear	Crown	Front	Side	Rear
Baseline	244.32	437.35	192.69	223.63	2284	5191	848.6	1527
Model No.1	192.16	333.22	173.68	271.94	1188	3409	776.2	2086
Model No.2	290.44	341.53	195.63	287.66	2674	3568	1065	2268
Model No.3	203.25	303.58	200.96	266.35	1744	3056	1084	2166
Model No.4	207.78	311.32	208.61	260.92	1846	3270	1197	2096
Model No.5	197.94	370.12	186.49	328.53	1647	3697	1009	3317
Model No.6	227.99	311.35	181.71	323.19	1836	3266	999.7	3335

4.3. Injury analysis

The helmet model no. 3 was employed to simulate the impact test with deformable head to investigate the brain injury as shown in figure 5 and figure 6. The skull stress is above 80 MPa for the cases without helmet and with the baseline helmet, this indicate high risk of skull fracture [16]. However, the simulation with model No.3 shows large reduction in brain pressure that is much lower than 80 MPa. Very high strain occurred at the brain stem for the case without helmet. The maximum brain strain value of this case is 0.98 which is much larger than the 0.2 threshold [17] It implies severe brain contusion. The head with helmet shows reduction in brain strain especially with the redesigned helmet models where the maximum brain strain is lower than 0.2. Low risk of brain injury is observed for the case with the redesigned helmet model no. 3.



(a) (b) (c)

Figure 5. Shows the Von Mises stress distribution on the skull at the front impact location from (a) deformable head, (b) baseline model, (c) re-design model No.3

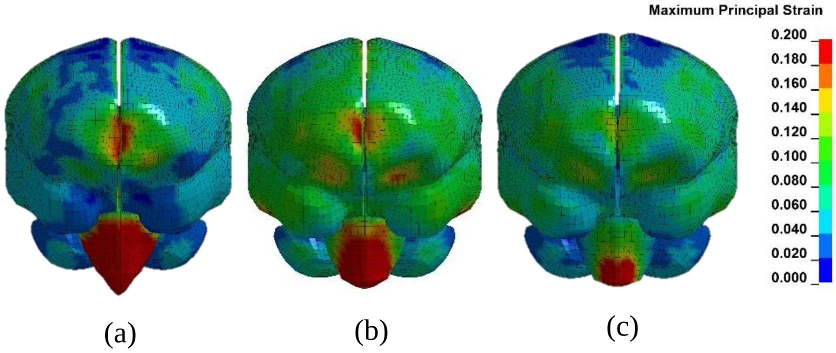


Figure 6. Shows strain distribution that occur in the brain at the front impact location form (a) deformable head, (b)baseline model (c) re-design model No.3.

5. Conclusion

Finite element model of the child helmet was developed and validated with the experimental results. The existing helmet failed the impact test at the front location. The modification of the helmet was done by introducing metal foam with two densities and two shell thickness for both outer shell and liner. Different designs of child helmet were evaluated by their performances and weight. Introducing aluminium foam to the helmet mitigated the peak acceleration experienced by child's head. The optimum design was with low density aluminium foam as outer shell of 3.3 mm thickness. It improved the head linear acceleration, HIC while reducing the mass. This modified child helmet with a mass reduction of 66.76 % passed impact tests for all locations. The skull stress is lower than the fracture limit whereas the brain strain is also lower than the brain injury criteria. The modified helmet can mitigate brain injury.

6. Acknowledgements

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