Asian Journal of Chemistry; Vol. 26, No. 17 (2014), 5842-5846

ASIAN JOURNAL OF CHEMISTRY

http://dx.doi.org/10.14233/ajchem.2014.18301

Study of Aluminum Foam Sandwiched Bonnet Based on Pedestrian Protection and Orthogonal Design†

NA YANG[1], GUIFAN ZHAO[1], CONGSHENG LI[2,*], HUA LI[3] and JIANFENG WANG[1]

[1]School of Computer Science and Technology, Harbin Institute of Technology, Weihai, P.R. China
[2]School of Automotive Engineering, Harbin Institute of Technology, Weihai, P.R. China
[3]School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, P.R. China

*Corresponding author: Fax: +86 631 5672276; Tel: +86 631 5687701; E-mail: lisheng51998@163.com

AJC-15806

In order to reduce head injuries during vehicle-to-pedestrian impacts, the aluminum foam sandwiched (AFS) bonnet was designed and analyzed. Firstly, the finite element models of the pedestrian-engine bonnet were established according to the statutes of the EEVC WG17. The acceleration curve and head injury criterion (HIC) of each test point were obtained. Secondly, the original engine bonnet materials were changed to AFS materials. The parameters of the new engine bonnet were preliminarily designed. Referring to head protection, the material parameter combinations were studied by using an orthogonal experimental design method. Finally, a weight analysis was carried out. The results indicated that the new bonnet could protect a pedestrian's head effectively and also reduce the weight of the vehicle to improve fuel economy.

Keywords: Engine bonnet, Aluminum foams, Pedestrian protection, Experiment design, Range analysis.

INTRODUCTION

A survey of a large number of traffic accidents shows that the fronts of vehicles impact pedestrians and account for 70-85 % of the total number of traffic collisions. In vehicle-to-pedestrian accidents, the percentage of deaths caused by head injuries was 64 %[1,2]. In order to reduce head injuries in vehicle-to-pedestrian impacts, The European Union, Japan and Australia have enacted regulations related to pedestrian protection. In October 2009, China issued "The Protection of Motor Vehicles for Pedestrians in the Event of a Collision," which specifies the pedestrian protection regulations standard and put it into effect in July 2010.

To reduce the injuries to pedestrians and protect them effectively, not only should a relative regulation be issued, but also vehicle safety should be improved. At this time, one method is developed to improve the structure is to reduce the collision speed; another is to reduce the stiffness of the material of the engine bonnet and improve the energy absorption capability[3,4]. However, due to the limitations of the vehicle structure and weight restrictions, there is not very much potential to improve the bonnet structure. Nonetheless, studying a new bonnet material could solve the problem of pedestrian protection and at the same time work out the predicament of weight issues. Research of new materials has become the new trend in the field of vehicle passive safety.

Aluminum foam sandwiched (AFS) which has low density, high intensity, is easy to manufacture[5] and has good energy absorption capabilities. BMW, Mercedes-Benz and Honda have all applied aluminum foam material to fill components such as bumpers to achieve the goal of buffer energy absorption[6].

Models

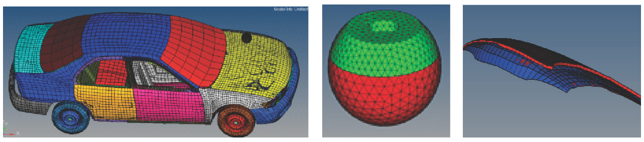
Finite element models of head form impactor-vehicle: The impact model was established according to the EEVC WG17 pedestrian protection test programme[7]. The vehicle model was an existing vehicle on the market which had 226 components which included 261,674 nodes, 250,394 elements and a total mass of 2,620kg. The free-motion head model had 2,662 nodes and 9,852 elements, the materials of which are shown in Table 1. The head-vehicle impact model is shown in Fig. 1(a). The head model is shown in Fig. 1(b).

Finite element model of the aluminum foam sandwiched bonnet: When the finite element model of the AFS bonnet was established, the top and bottom panels made up

†Presented at 2014 Global Conference on Polymer and Composite Materials (PCM2014) held on 27-29 May 2014, Ningbo, P.R. China

TABLE-1
MATERIAL OF THE IMPACTOR

Parameter	Mass (kg)	Density (kg/m^3)		Bulk modulus of skin (GPa)	Elasticity modulus of skull (GPa)	Poisson's ratio of skull
		Skin	Skull			
Value	4.796	956	2940	0.25	30	0.33



(a) The Original Vehicle Bonnet (b) Head Form Impactor (c) AFS Material

Fig. 1. Finite element models

the shell and the filling was solid 3D elements. To simulate the contact, the 2D elements were extracted from the 3D solid elements. The model of the AFS bonnet is shown in Fig. 1(c).

Selection of the test points: The EEVC WG17 regulates that the adult head test areas should measure 1500-2100 mm wrap around distance (WAD). In the transverse direction, the middle area is divided into three parts, which is shown in Fig. 2.

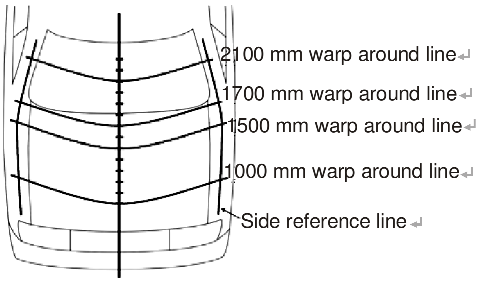


Fig. 2. Partition of adult head test areas

According to the EEVC WG17, three test points in the right, left and middle of the bonnet should be chosen, for a total of nine test points. Generally, the areas which have the potential to cause serious injuries to the head are in the sides, the upper part of the engine, the upper sides of the bonnet suspension and radiator and the upper portion of the inner bonnet structure[8]. The chosen test points are shown in Fig. 3 and Table-2.

Simulation analysis of head form impacting the original bonnet: The EEVC WG17 regulates that the impact angle be 65 ± 2° between the head form and the ground, with an impact velocity of 9.7 ± 0.2 m/s.

Head injury criterion (HIC): At present, the most widely used standard for pedestrian head injuries is the head injury criterion (HIC). The federal motor vehicle safety standards

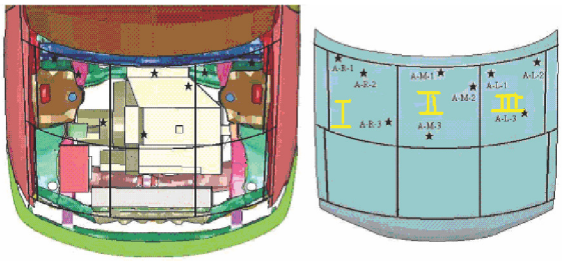


Fig. 3. Test points

(FMVSS) put forth the calculation method of the HIC as follows:

$$HIC = \left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1) \quad (1)$$

where 'a' is the resultant acceleration as a multiple of 'g' and 't_1'and 't_2' are the two time instants when the value of HIC is at maximum. Actually, the value of '$t_1 - t_2$' was 15 ms or 36 ms. When the HIC is bigger than 1000, the incidence of AIS 3+ head injuries is 20 %.

Considering the difference between the free-motion head and the Hybrid III dummy head, a linear regression equation called HIC_d was used to adjust HIC, shown as follows:

$$HIC_d = 0.75446[HIC] + 166.4 \quad (2)$$

Injury analysis of original vehicle to head: The impact of the head form to the bonnet was simulated in each test point using LS-DYNA. The HIC, HIC_d and the maximum acceleration a_{max} are shown in Table-3.

Injury analysis of AFS material vehicle to head: Initially, steel was chosen as the inner and outer panel material, with a thickness of 0.2 mm (the steel was MAT 24 in HyperMesh). As for the aluminum foam core used for the energy absorption material, the thickness should be no less than 6 mm according to literatures and manufacturers. After numerous experiments, thicknesses in the approximate range of 8mm were considered to be appropriate. The properties of each material are shown in Table-4.

The simulation results are shown in Table-5. The curves of acceleration are shown in Fig. 4 (the dotted line represents the AFS, while the solid line represents the original).

TABLE-2
POSITIONS OF THE TEST POINTS

Test point	X-Axis	Y-Axis	Meaning
AR1	57	-579	Bonnet side, fire-proof plate and the upper of the hinge
AR2	149	-567	Upper of inner bonnet
AR3	416	-278	Upper of inner bonnet
AM1	137	20	Bonnet side, the upper of fire-proof plate
AM2	217	220	Upper of inner bonnet
AM3	497	-40	Upper of engine
AL1	142	321	Bonnet inner, the upper of fire-proof plate
AL2	75	596	Bonnet side, fire-proof plate and the upper of the hinge
AL3	310	1099	Upper side of bonnet suspension

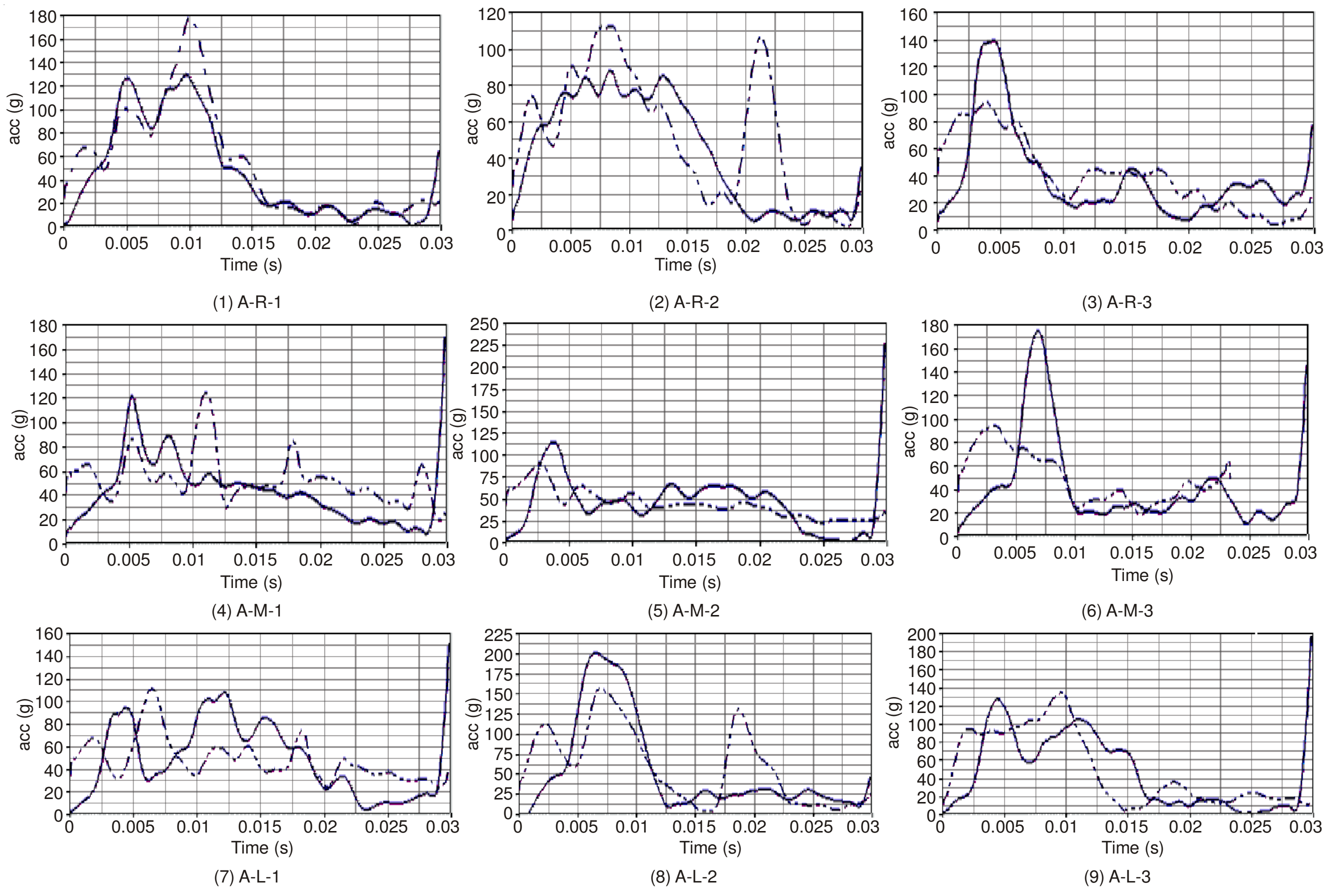


Fig. 4. Comparison of acceleration curves

TABLE-3
HIC, HIC_d AND a_{max} OF EACH TEST POINT

Test point	AR1	AR2	AR3	AM1	AM2	AM3	AL1	AL2	AL3
HIC	1047	688	549	445	432	785	698	2241	927
HIC_d	956	685	580	502	492	759	693	1857	865
a_{max} (g)	130	88	140	170	229	176	152	202	198

TABLE-4
PROPERTIES OF EACH BONNET PANEL MATERIALS[9]

Material	Density (g/cm^3)	Elasticity modulus (GPa)	Poisson's ratio
Steel	7.89	210	0.3
Aluminum foam	0.56	69	0.3

It is observed from the above acceleration curves that the peak value of the acceleration was decreased and the wave was weakened when the bonnet was changed to AFS.

The comparison of values in Tables 3 and 5 show that most of HIC_d values of the test points decreased significantly, but the HIC_d of test points A-R-1, A-R-2 and A-L-3 still show the potential for serious head injuries. Therefore, impacts with these areas may cause death or injury and necessitate more attention when designing.

Optimization design study of aluminum foam sandwiched bonnet based on design of experiment (DOE): In order to reduce the HIC_d value and realize a lightweight product, the orthogonal test method was used to further explore the best parameter combination of the AFS bonnet based on above study.

Orthogonal experimental design: The main effect factors included the thickness, the material of the inner and outer bonnet panel and the thickness of the aluminum foam sandwiched. The orthogonal experimental design method was used to analyze these factors. Two levels for each factor were initially chosen to analyze, as shown in Table-6.

To design the experiment, $L_4(2^3)$ was chosen and the orthogonal array is shown in Table-7.

Determination for optimal combination of the bonnet parameters: Using commercial software, 36 impact simul-

TABLE-5
HIC AND a_{max} OF EACH TEST POINT

Test point	AR1	AR2	AR3	AM1	AM2	AM3	AL1	AL2	AL3
HIC	1210	720	408	434	319	413	374	1120	1048
HICd	1080	709	474	494	407	478	448	1011	957
HICd	Increase	Increase	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease	Increase
a_{max} (g)	176	111	93	123	89	93	110	155	133

TABLE-6
FACTORS AND LEVELS CONSIDERED IN THE EXPERIMENT

Factor	Code	Rank	Number
Thickness of inner and outer panel	A	0.2 mm, 0.3 mm	1, 2
Material of inner and outer panel	B	Steel, aluminum	1, 2
Thickness of the aluminum foam sandwich	C	8 mm, 12 mm	1, 2

TABLE-7
$L_4(2^3)$ ORTHOGONAL ARRAY

Experimental run	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

ations were performed according to the four experiment methods described above. The simulati on results are shown in Table-8.

The range analysis method was used to analyze the orthogonal experimental design results primarily to judge the major-minor order, the optimal level and the optimal combination.

The average values of levels 1 and 2 of the three factors were calculated and $\overline{Y}_{jk}\,(j = A, B, C,\ k = 1, 2)$ were used to represent the values. The average value can decide the optimal level of the j factor. The smaller the average value means the more superior the factor is and the smaller the HIC_d value.

Range analysis was made with the average values $\overline{Y}_{j1}$ and $\overline{Y}_{j2}$ of two levels each of factors A, B, C. The resultant expression was $R_j = |\overline{Y}_{j_1} - \overline{Y}_{j_2}|\,(j = A, B, C)$. The larger the range was, the more effective the factor and the more influential to the HIC_d. The results of the simulation are shown in Table-9. The optimal combination and the most effective factor of each point are shown in Table-10.

From Table-10, some conclusions about HIC_d can be drawn: For the reason that the optimal level of all test points was A1, so the level 1 of the A factor was the optimal level. Level B1 was the optimal level of A-R-1, A-M-2, A-L-2 and A-L-3 test points. The range value of levels 1 and 2 was 90.0, 24.2, 9.2 and 21.8, respectively. The difference was small between the four test points. Level B2 was the optimal level of A-R-2, A-R-3, A-M-1, A-M-3 and A-L-1 test points. The range value of Level 1 and 2 was 120.4, 81.8, 50.2, 68.6 and 24.4, respectively. Therefore, the optimal level of B was level 2. Level C1 was the optimal level of six test points, C2 was the optimal level of three test points. The range value of levels 1and 2 of the A-R-1, A-L-2, A-L-3 was 33.6, 17.4, 48.4, respectively and the difference of the HIC_d value was small. So the

TABLE-8
HIC_d OF EACH TEST POINT

Number	AR1	AR2	AR3	AM1	AM2	AM3	AL1	AL2	AL3
1	1080	709	474	494	407	478	448	1011	957
2	1136	637	513	488	501	461	469	1003	930
3	1161	825	630	713	489	551	514	1039	959
4	1285	656	427	618	443	430	444	1066	1029

TABLE-9
RANGE ANALYSIS

Test point	Factor A			Factor B			Factor C			Optimal combination	Most effective factor
	$\overline{Y}_{A1}$	$\overline{Y}_{A2}$	R_A	$\overline{Y}_{A1}$	$\overline{Y}_{A2}$	R_A	$\overline{Y}_{A1}$	$\overline{Y}_{A2}$	R_A		
AR1	1108	1223	115	1120	1210	90	1182	1149	33	A1B1C2	A
AR2	673	740	67	767	647	120	683	731	48	A1B2C1	B
AR3	494	528	34	552	470	81	450	572	121	A1B2C1	C
AM1	491	666	174	603	553	50	556	601	44	A1B2C1	A
AM2	454	466	12	448	472	24	425	495	69	A1B1C1	C
AM3	470	491	21	514	446	68	454	506	51	A1B2C1	B
AL1	459	479	20	481	457	24	446	492	45	A1B2C1	C
AL2	1007	1053	45	1025	1034	9	1038	1021	17	A1B1C2	A
AL3	944	994	50	958	980	21	993	944	48	A1B1C2	A

TABLE-10
RESULTS ANALYSIS

Test point	A1	A2	B1	B2	C1	C2	Most effective factor
A-R-1	√	–	√	–	–	√	A
A-R-2	√	–	–	√	√	–	B
A-R-3	√	–	–	√	√	–	C
A-M-1	√	–	–	√	√	–	A
A-M-2	√	–	√	–	√	–	C
A-M-3	√	–	–	√	√	–	B
A-L-1	√	–	–	√	√	–	C
A-L-2	√	–	√	–	–	√	A
A-L-3	√	–	√	–	–	√	A
Total times	9	0	4	5	6	3	A-4 times, B-2 times, C-3 times

TABLE-11
COMPARISON OF IMPACT RESULTS OF THE ADULT HEAD FORM TO THE ORIGINAL AND MODIFIED VEHICLES

Test point	AR1	AR2	AR3	AM1	AM2	AM3	AL1	AL2	AL3
HIC of original car	1047	688	549	445	432	785	698	2241	927
HIC_d of original car	956	685	580	502	492	759	693	1857	865
HIC of new car	1001	609	310	239	307	329	381	1168	987
HIC_d of new car	937	626	400	347	398	415	456	1048	920
Change of HIC_d	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease	Increase

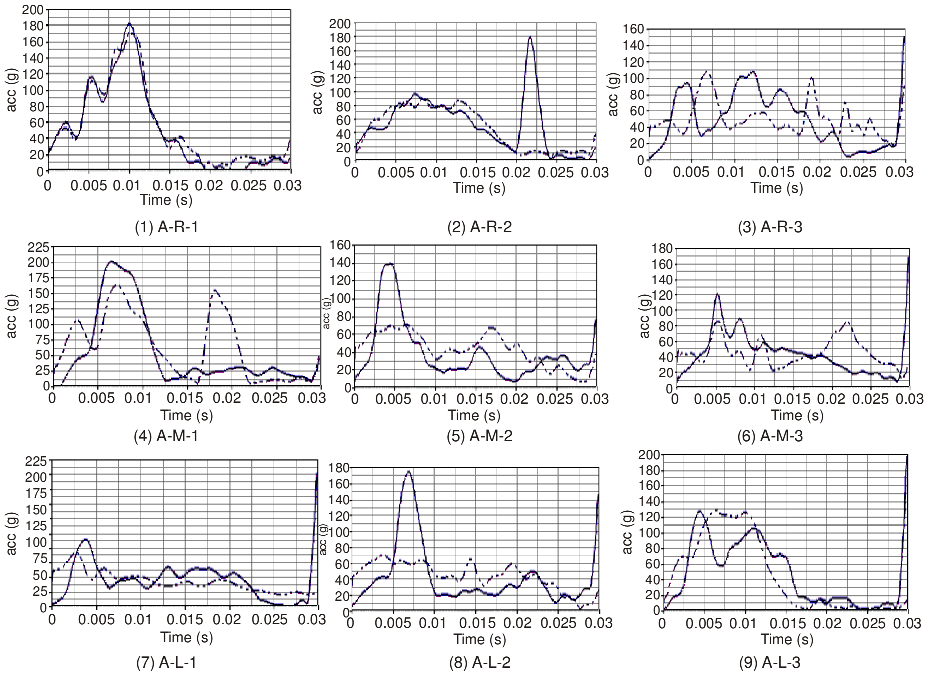


Fig. 5. Comparison of original car and modified car acceleration curves

optimal level of the C factor was level 1. To sum up, the optimal combination of bonnet parameters was A1B2C1.

Verification: From the above information, it can be confirmed that the optimal combination is A1B2C1 and this combination did not belong to the four cases in the orthogonal experimental design. This showed that the optimal results represented the information obtained in the experiments and the orthogonal design method can be adopted to optimize the bonnet.

The thickness of the outer panel was changed to 0.2 mm and it was simulated again. The results are shown in Table-11. The comparison of the acceleration curves are shown in Fig. 5.

From Table-11 and Fig. 5, it can be seen that parameters A1B2C1 decreased the HIC_d significantly and the wave of acceleration was also weakened. This optimal combination was proved effective.

Weight analysis of the aluminum foam sandwiched bonnet: The HyperMesh has a function that counts component mass. Compared to the original bonnet, the mass of the AFS bonnet decreased from 21.42-8.524 kg because of the low density of the aluminum foam, therefore achieving the goal of being lightweight. It can also improve fuel efficiency and decrease energy consumption.

Conclusion

Using HyperMesh, the original bonnet material was changed to aluminum foam sandwiched and LS-DYNA was used to simulate the impact progress. The pedestrian head protection effect of the new bonnet was studied. Compared to the original bonnet, the simulation results showed that the aluminum foam sandwiched bonnet had a better effect on pedestrian protection. The optimal combination of the aluminum foam sandwiched bonnet was attained for pedestrian head protection through orthogonal experimental design methods. And by mass analysis, the low-weight effect was improved effectively. The research results in this paper can provide a certain theoretical basis for the application of new materials in vehicles, especially in terms of pedestrian protection and reducing vehicle weight.

REFERENCES

1. D. Liu, Y.D. Li and H. Zhao, *Trans. Chinese Soc. Agric. Machinery*, 34 (2003).
2. W.G. Qiao, X.C. Zhu and Z.F. Wang, *Trans. Chinese Soc. Agric. Machinery*, 36 (2005).
3. S.I. Farooq and P.J. Schuster, SAE paper, 2003-01-1300 (2003).
4. D. de Melo Baleki and A. Ferreira, *SAE Technical Papers*, 2009-36-0093 (2009).
5. Z.L. Wu, X.X. Xu and L. Liu, *Transport. Sci. Technol.*, 4 (2008).
6. P.P. Wang and Y.H. Yu, *Coal Mine Machinery*, 11 (2003).
7. European Enhanced Vehicle-safety Committee (EEVC) Working Group 17 Report, Improved Test Methods to Evaluate Pedestrian Protection Afforded by Passenger Cars (2002).
8. European Enhanced Vehicle-Safety Committee, EEVC Working Group 10 Reports-Proposals for Methods to Evaluate Pedestrian Protection Afforded by Passengers Cars, Delft, the Netherlands: TNO Crash-Safety Research Centre (1994).
9. P. Wei, Doctoral Thesis, Huazhong University of Science and Technology (2006).