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A Numerical Investigation of a Novel Hood Design for Pedestrian Protection

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Abstract: Currently the use of new materials is becoming even more prevalent in vehicle industry for the lightweight design purpose. The design of engine hood is very important for pedestrian's safety during a vehicle-pedestrian accident. In order to improve the pedestrian protection performance of the new material engine hood, the radial stiffening rib structure and trapezium sandwich structure engine hoods were proposed in this paper. And an energy-absorbing structure has been designed on the strengthening hinge plate to reduce the pedestrian head injury further more. The simulation results indicate that with new structures, the new material engine hoods have more uniform rigidity and better energy absorbing ability, which would effectively reduce the engine hood intrusion and pedestrian head injuries.

Keywords: Engine hood, Lightweight material, New structure, Pedestrian protection, Finite element model, Headform impactor model.

1. INTRODUCTION

The pedestrian is the most vulnerable group in road traffic accidents. In 2011, U.S. pedestrian fatalities accounted for 13.6% of the total number of casualties in traffic accidents [1], In 2012, China road accidents caused 65225 deaths and 254075 injuries, pedestrians accounted for 24.96% and 17.57% respectively, which caused huge economic loss and social burden [2]. Pedestrian protection has aroused more and more attention all around the word. EC78/2009 and GTR NO.9, which are widely accepted by various countries, provide mandatory vehicle requirements for pedestrian protection; and the automotive safety certification organization EURO-NCAP also promotes more stringent requirements for pedestrian protection. The head and lower extremities are easily injured and the head injuries often result in death in a vehicle-pedestrian accident [3]. European Enhanced Vehicle Safety Committee (EEVC) proposes to use the headform impactor tests to verify the pedestrian protection performance of a vehicle engine hood; this method is referenced by various pedestrian protection regulations and vehicle safety research institutions.

To improve the vehicle pedestrian protecting performance, researchers conducted extensive researches; the research works mainly focus on improving the vehicle front structure and the study of injury mechanism [4]. The real accident reconstruction can be used to study the pedestrian injury tolerance limits and injury mechanism, as well as the relationship between the pedestrian dynamic response and the injury score [5]. Meanwhile, some researchers did parameter studies to investigate how the vehicle front structure parameters affect the pedestrian's injuries, and then optimized the significant parameters to improve vehicle's crash safety [6]. Due to the mandatory requirements of pedestrian protection regulations, vehicle research & design institutions and vehicle companies have done a lot of subsystem impact tests, and propose some effective measures to improve vehicle pedestrian protection performance [7].

At the same time, to realize vehicle lightweight design, the use of new materials becomes more and more important, but less research was done to study the pedestrian protection performance of the new materials. In this paper, the FE model of a sedan is used to study the new material engine hood and its pedestrian protection performance. Based on the simulation results, the new structure of radial stiffening ribs and trapezium sandwich is proposed to improve the pedestrian protection performance of this new material hood and simultaneously meet the static stiffness requirement.

2. DEVELOPMENT AND VALIDATION OF THE FINITE ELEMENT MODEL

2.1. Development of Finite Element Model of a Compact Sedan

The finite element model of a compact sedan front structure, which was directly related to pedestrian protection was developed. The model boundary was completely fixed with six degrees of freedom constraint and the grid size was 8 mm. The rigid parts under the hood were meshed with hexahedral solid elements, while other parts were meshed with shell elements, all parts were simulated with mat_20 material and connected based on real situation. For example, the connection between the hinge reinforcement plate and the hood was built by the way of spot welding. Fig. (**1**) showed the vehicle front structure dimensions.

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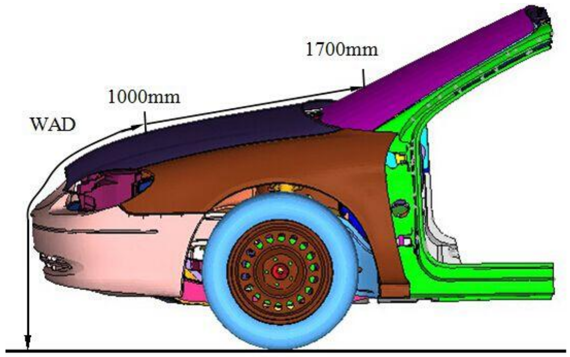


Fig. (1). Finite element model of the sedan front structure.

2.2. The Headform Impactor Model

According to the pedestrian protection test procedures of GTR NO.9, child head impact tests must be done in the hood area between WAD1000 and WAD1700. Since the hood of research sedan is within the limit of WAD1700, only the child headform impactor tests need be done. The child impactor developed by Arup was used in this paper, which consists of base, core, skin and shell layer. The shell layer is simulated with shell element, while the base, core, and skin are simulated with solid element. Its total mass is 3.5 kg with the diameter of 165 mm and there is an acceleration sensor in the head center of mass. The reliability of this model is validated by drop tests according to pedestrian protection regulation and accepted extensively by research institutions, Fig. (**2**).

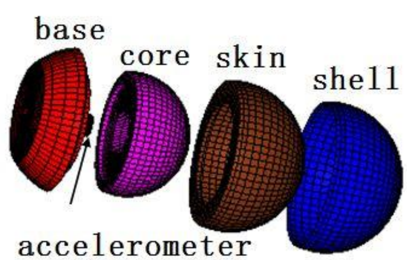


Fig. (2). Exploded view of child headform impactor.

2.3. Model Validation

The simulation of the headform impacted with engine hood was taken to evaluate the effectiveness of the impactor model and vehicle model, as shown in Fig. (**3a**). The boundary conditions of simulation were set according to the real test conditions in literature [8]. The headform impactor impacted on the point D of the engine hood with the same speed 35 km/h and impact angel 50° and with the real test and the impactor acceleration curve were compared with test result, as shown in Fig. (**3b**). The error between the simulation curve and test curve was small. The peak value in the test curve is 8.3 g bigger than the simulation curve, and the time corresponding to the peak value is 2.46 ms earlier than the simulation curve, which indicates that the definition of material properties and the connections among all parts are reliable and the whole model can be used for further research.

(**a**)

(**b**)

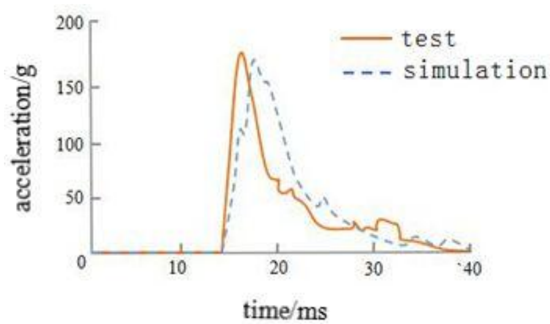


Fig. (3). Validation simulation (**a**) test setting (**b**) acceleration comparison of test and simulation.

3. RESEARCHES ON THE NEW MATERIAL HOOD

3.1. New Material Hood Contrasting with Carbon Steel Hood

Both of the inner panel and outer panel of the original engine hood were made of carbon steel; the thickness of outer panel was 0.8 mm whereas that of the inner panel was o.7 mm. In this paper the annealed magnesium aluminum alloy 5A12-O and copper aluminum alloy 2A01-T4 after quench and natural aging process were selected to replace the original material of inner panel and outer panel respectively, and the hood structure remains unchanged firstly. To ensure the sufficient rigidity of the hood assembly, the thickness of both inner panel and outer panel was increased to 1 mm. The new materials are moderate-intensity, low density and have good plasticity, which is conductive to automotive lightweight and suitable to make the hood. But, finding whether the new material hood can effectively protect the pedestrian head needs further study. Table **1** shows the mechanical properties of the original materials and new materials. σS means yield strength, ρ means density, E means young modulus, u means poisson ratio.

Table 1. Mechanical Properties of the Materials.

Material	ρ(kg/m3)	E(GPa)	μ	σS(MPa)
Carbon steel	7890	210	0.3	240
5A12-O	2610	72	0.33	220
2A01-T4	2760	71	0.31	170

3.2. Pedestrian Protection Performance Comparison of the New Materials Hood and the Carbon Steel Hood

The head injury index HIC and hood intrusion were taken as the pedestrian head injury evaluation criteria. The HIC value equals 1000 is the head injury threshold representing 15% probability of AIS4+ head injury, as shown in Formula (1). t1 and t2 are the start time and end time within the integration time interval respectively. HIC represents the maximum integration value within 15 ms; a (t) is the resultant mass center acceleration of the headform impactor.

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

When head impacts with the engine hood, if the hood intrusion is excessive in the impact direction, the head will contact with the rigid parts under the hood, and then results in a secondary collision and secondary acceleration peak that would be too large to cause big HIC.

3.3. Pedestrian Protection Simulation and Choice of Impact Testing Points

According to GTR NO. 9, the headform impactor was located above the engine hood with an axial angle of 50 degrees to the horizontal plane. The impact velocity was 35 km/h and the gravity acceleration was applied.

Because the rigid parts under the hood are easy to bring about secondary collision and cause serious head injuries to pedestrians, the impact testing points were chosen on these places. As shown in Fig. (**4**), C1-C6 six impact testing points were set to represent the corresponding place of following rigid parts: C1-air filter, C2-battery, C3-intake manifold assembly, C4- engine support, C5-shock absorber, and C6-cooling liquid tank.

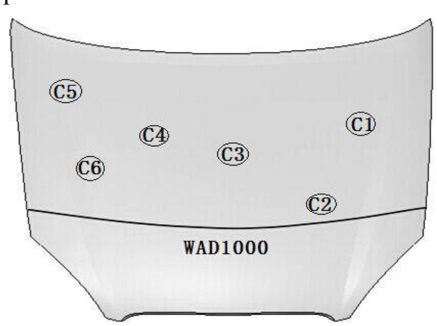


Fig. (4). The impact testing points of C1-C6.

3.4. Results

The simulation results of HIC value and hood intrusion when headform impactor impacted on C1-C6 six testing points of the new materials hood and carbon steel hood were shown in Table **2**. L represented the maximum hood intrusion in the impact direction and L0 represented the distance between the hood and the rigid parts under the hood.

Table **2** indicates that the intrusions of the new material hood and carbon steel hood were equal with L0 at point C3, which mean there were secondary collision at point C3 in both two types of material hoods. While in other five testing points, the new material hood intrusions were bigger than carbon steel hood, and the new material hood intrusion at point C6 even reached L0, which indicates the secondary collision occurred at point C6 if using new material hood. As for the HIC, when using the new material hood, the HIC at point C3 and C6 was bigger than original hood, while smaller than original hood in other four testing points. Point C5 gets the best HIC value i.e. 752 and point C3 gets the worst HIC value i.e. 1673. To better understand the pedestrian protection performance of these two different material hoods, the head centric acceleration curves of the point C3 and C6 were analyzed, as shown in Fig. (**5**).

Table 2. Simulation Results.

Point	Carbon Steel		New Material		L_0/mm
	HIC	L/mm	HIC	L/mm	
C1	1086	51.4	887	64.5	77.5
C2	1257	48.2	1055	67.4	82.4
C3	1525	53.8	1673	53.8	53.8
C4	1123	47.5	995	71.5	79.2
C5	1372	41.3	752	65.1	68.9
C6	984	55.6	1339	59.3	59.3

In Fig. (**5**), at the testing point C3, the curves of both the material hoods appeared as two obvious peaks, which indicated the occurrence of secondary collisions at that point. It matched the intrusion deduction. For original carbon steel hood, the first peak was 231 g, the second peak was 212 g, and the corresponding HIC was 1525. For the new material hood, the first peak was 189 g, the second peak was 264 g, and the HIC was 1673.

At the testing point C6, only the new material hood curve appeared as two obvious peaks, which indicated that the secondary collision occurred only when using new material hood. For original carbon steel hood, the acceleration peak was 229 g and the HIC was 984. For the new materials hood, the first peak was 176 g, the second peak was 206 g, and the corresponding HIC was 1339.

At both the testing points, the first acceleration peak of the carbon steel hood was larger and appeared earlier than the new material hood; it was because of the larger density and elastic modulus of carbon steel which resulted in the larger inertial mass as well as greater local stiffness in the collision region. At testing point C3, the second acceleration peak of the new materials hood was larger than carbon steel hood due to its smaller elastic modulus, yield strength and less energy absorption, which then caused larger HIC. At testing point C6, the secondary collision occurred when using new material hood and resulted in the second acceleration peak and severe head injury. According to above analysis, if using new material hood, the intrusion would be larger due to its lower density. Then there would be two conditions: when the distance between the hood and rigid parts was small, and the pedestrian head would have a secondary collision with the rigid parts under the hood and get more severe head injuries than the carbon steel hood due to the lack of energy-absorbing space; when no secondary

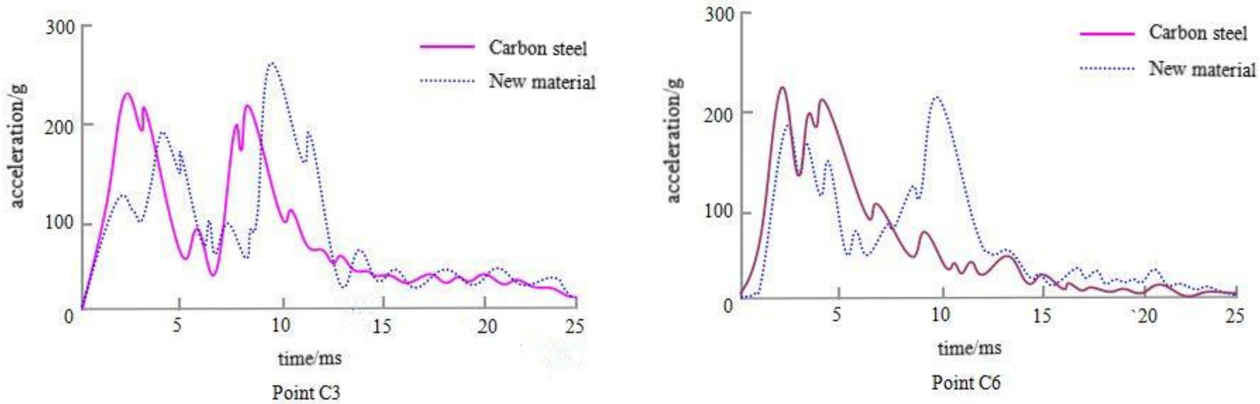


Fig. (5). The acceleration curves of the impactors.

collision occurred, the head injury would be smaller, for example, the HIC values were all below 1000 at points C1, C4 and C5 even the hood intrusion were bigger. Therefore, it was necessary to further study and improve the hood structure if using new material to provide better protection for the pedestrian head.

4. THE STRUCTURE DESIGN OF NEW MATERIAL HOOD

4.1. The Structure of Radial Stiffener Hood and Trapezium Sandwich Hood

From formula (1), it can be seen that a feasible method to minimize the HIC is to reduce the acceleration peak as possible and make the time interval between two peaks longer than 15 ms. And the literature [9] pointed out that the needed energy absorption space would be lowest and the energy absorption amount would be most when the head acceleration curve was high in front and low in back, so it would be helpful to try to make the acceleration peak appears earlier.

The stiffness of the conventional structure hood is not equally distributed and cannot prevent the pedestrian from suffering from a second collision against the rigid parts under the hood. The situation is worse when using the new materials hood with lower modulus of elasticity and yield strength. To improve the pedestrian protecting performance of the new material hood, it is necessary to redesign the hood structure to ensure that the hood could absorb the maximum energy in limited deformation and maintain appropriate stiffness at the same time. In this paper, the radial stiffening rib structure and trapezium sandwich structure were proposed to replace the conventional ribbed slab structure inner panel, and the pedestrian protecting performance of these two new structure hoods were discussed.

The radial stiffening rib structure inner panel and its cross-section view are shown in Fig. (**6**). In this structure, the radial stiffener and central stiffeners are distributed in a certain rule, the central stiffener is located in the middle of the hood impact area and the radial stiffeners are evenly distributed along the diagonal direction around the central stiffener. Each stiffener consists of two quarter arcs with radius of 17 mm and a straight line of 8 mm, and the hemispherical structure is punched out on the clear planar area which has no stiffener to increase the overall stiffness. The thickness of the inner panel and outer panel were 1 mm, the outer panel is connected with inner panel's stiffeners by adhesive.

The new material hood with this kind of structure inner panel could protect the pedestrian head effectively by improving the distributing stiffness, then would disperse the head impact load and change the hood deformation mode, which can help the hood to deform in a larger area and absorb more kinetic energy and then reduce pedestrian head injury.

Another new structure hood was the trapezium sandwich hood. In this structure a middle layer was added between the inner panel and outer panel, as shown in Fig. (**7a**), which shows the view of middle layer with the inner panel structure, and Fig. (**7b**) shows the middle layer section dimensions. The industrial aluminum was used to make the middle layer. Its density is 2700 kg/m3 and yield strength is 30 MPa. The thickness of the middle layer is 0.6 mm, while the thickness of the inner panel and outer panel is 1 mm. The middle layer of the trapezium sandwich can fully absorb the impact energy by plastic deformation when the pedestrian head impact on the hood. The inner panel is parallel with the outer panel; the middle layer is connected with the outer panel by glue and connected with the inner hood by spot welding.

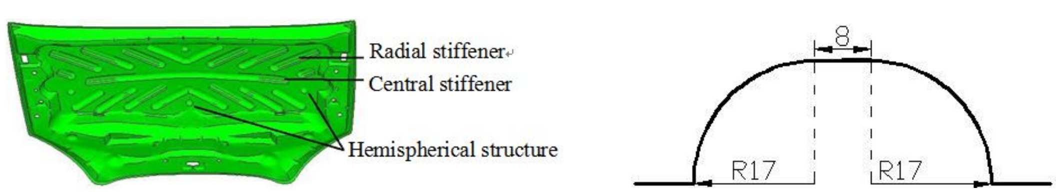


Fig. (6). The radial stiffener structure.

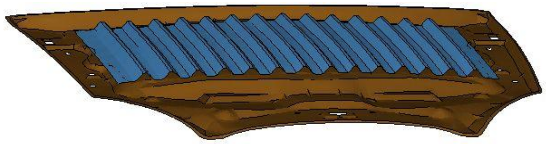
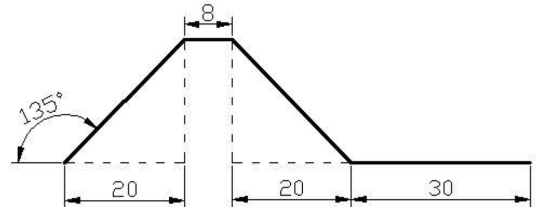


Fig. (7). The trapezium sandwich structure.



4.2 Pedestrian Protection Performance Evaluation of Two Kinds of Structure Hoods

The same simulation tests were performed with 2.3 using these two new material hoods with new structure; the simulation results at six testing points are shown in Table **3**.

Table 3. The Simulation Results of Two New Structure Hoods.

Point	Radiative Stiffener		Trapezium Sandwich	
	HIC	L/mm	HIC	L/mm
C1	745	56.4	847	53.2
C2	947	55.1	836	61.5
C3	821	52.2	1137	53.8
C4	576	62.9	884	59.7
C5	833	49.6	656	60.3
C6	907	54.5	955	57.3

It can be seen that the HIC value and the hood intrusion were obviously reduced. When using the new material hood with radial stiffening rib inner panel, the HIC values were lower than 1000 at all testing points and the intrusion amounts were smaller with the average 55.1 mm, but the HIC increased to 833 from 752 at the point C5. It maybe because the impactor impacted on the connection region causing larger inertial mass and local stiffness. When use the new material hood with trapezium sandwich structure, the HIC was over 1000 at the testing point C3; there must be a second collision occurred, but the HIC reduced by 32% relatively to original structure. The HIC was lower than 1000 and the hood intrusions were smaller with the average of 57.6 mm at other testing points.

Fig. (**8a**, **b**) showed the headform contacted with the trapezium sandwich hood at beginning and at 0.08 s respectively, from which it can be seen that the middle layer of the trapezium sandwich hood had a wide range of plastic deformation and could absorb the collision energy fully, and then greatly reduced the energy needed to be absorbed by the inner panel and outer panel; the HIC and the intrusion were largely reduced.

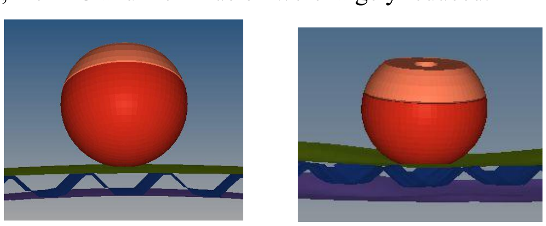


Fig. (8). The deformation view of the trapezium sandwich hood at collision point C3.

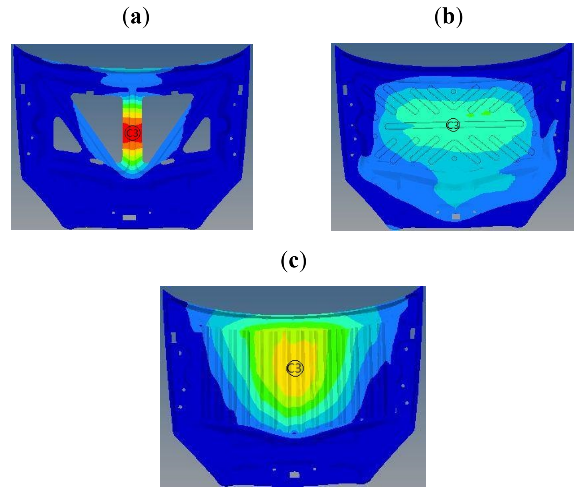


Fig. (9). The energy contours at collision point C3 (**a**) original structure (**b**) radial stiffener structure (**c**) trapezium sandwich.

Fig. (**9**) showed the energy contours of the inner panel with the original structure and the two new structures at 0.08 s when impactor impacted at point C3. The original structure inner panel only absorbed energy locally and resulted stress concentration due to the irrational inner hood structure, while two new structure hoods can evenly disperse the impact energy to the surrounding area and absorbed the impact energy in a larger area and then could reduce the pedestrian head injuries.

4.3. The Energy-Absorbing Structure at the Stiffening Hinge

The high rigidity stiffening hinge plate is welded on the inner panel to connect the hood with the vehicle body. Because of the small distance between the inner panel and the outer panel, the second collision is inevitable when the head impact on the stiffening plate mounting area, which can cause severe head injuries. Therefore, the energy-absorbing structure on the stiffening hinge plate was added, as shown in Fig. (**10**).

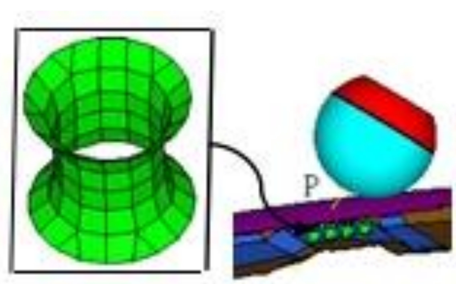


Fig. (10). The energy-absorbing structure.

To evaluate the energy-absorption performance of this structure, some simulation tests were taken at the point P which was at the stiffening plate mounting area according to the regulatory requirements. Also the pedestrian protection performance of the radial stiffener hood with and without the energy-absorption structure was compared. The simulation results are shown in Table **4**. From Table **4** it can be seen that the maximum head acceleration reduced from 235 g to 182 g and the HIC reduced from 1534 to 1121 upon adding this energy-absorption structure. The energy absorbed by the energy-absorption structure was 40.2 J, accounting for 23% of the total impact energy. In summary, the energy-absorption structure can help to improve the pedestrian protection performance.

Table 4. The simulation results of the hood with and without the energy-absorbing structure.

Energy-Absorption Structure	HIC	Acceleration Peak	Energy Absorbed/J
Have	1121	182	40.2
None	1534	235	None

Table 5. The Simulation Results of the Stiffness Check.

Structure	Local		Global		Torsional		Mass/kg
	Deformation (mm)	Rigidity (N/mm)	Deformation (mm)	Rigidity (N/mm)	Deformation (mm)	Rigidity (N/mm)	
Original	1.03	97.1	3.59	49.6	1.21	82.6	17.8
Radial stiffener	1.45	68.9	1.37	81.8	0.84	119.1	11.2
Trapezium sandwich	1.76	56.8	2.17	48.4	0.95	1.5.3	10.5

4.4. The Static Stiffness Check of the New Structure Hood

Engine hood design can not only consider the pedestrian protection performance but also the sufficient static stiffness. The hood static stiffness includes local stiffness, global stiffness and torsion stiffness. The hood should be designed with low local stiffness to fully protect the pedestrian and with high global stiffness and torsion stiffness to improve its crashworthiness. In order to increase the global stiffness and torsion stiffness, the thickness of the hood folded edge increased from 1.2 mm to 2 mm. Then the static stiffness of these two structure hoods were checked according to the boundary conditions set in literature [10]. The simulation results are shown in Table **5**. Compared with the original structure hood, the local stiffness of new hoods reduced obviously, and at the same time, the torsion stiffness improved. The global stiffness of the trapezium sandwich hood reduced by 2.4%, while the radial stiffener structure increased by 39.3%. In addition, the mass of the radial stiffener hood and the trapezium sandwich reduced 37.1% and 41% respectively.

CONCLUSION

To realize the vehicle lightweight design, the new material was used to replace the carbon steel for vehicle body manufacture. But due to its smaller elastic modulus and yield strength, when the pedestrian impacts with the new material vehicle engine hood, the hood will have larger intrusion and the pedestrian head may suffer a secondary collision with the rigid parts under the hood and cause even more severe head injuries. In order to solve this problem, two new structures were proposed to improve the new material hood's pedestrian protection performance. The simulation results show that with new structures the new material engine hoods have more uniform rigidity and better energy absorbing effect, which will effectively reduce the engine hood intrusion and pedestrian head injuries during the collision. And at the same time, the local stiffness of the new radial stiffener structure hoods reduced obviously, and the torsion stiffness and global stiffness improved much. The mass reduced by 37.1%, which would be helpful for the development of the lightweight vehicle.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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