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Numerical and experimental investigation of a lightweight bonnet for pedestrian safety / Avalle, Massimiliano; Belingardi, Giovanni; Scattina, Alessandro. - In: INTERNATIONAL JOURNAL OF CRASHWORTHINESS. - ISSN 1358-8265. - ELETTRONICO. - (2012), pp. 29-39. [10.1080/13588265.2012.730214]

Publisher:
Taylor & Francis Limited:Rankine Road, Basingstoke RG24 8PR United Kingdom:011 44 1256 813035,

Published
DOI:10.1080/13588265.2012.730214

Numerical and experimental investigation of a lightweight bonnet for pedestrian safety

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(*Received 31 May 2012; final version received 12 September 2012*)

A topic of great consideration in current vehicle development in Europe is pedestrian protection. The enforcement of a new regulation trying to decrease the injuries to head, pelvis, and leg of pedestrian impacted by cars, is imposing great changes in vehicles' front design. In the present work a design solution for the bonnet, which is the main body part interacting with the human head during a car to pedestrian collision, is proposed. This solution meets the stiffness and safety targets, takes into account the manufacturing and recyclability requirements and gives a relevant contribution to vehicle lightweight. Thus this proposed solution puts in evidence that safety and lightweight are not incompatible targets. The amount of potential injury to the pedestrian head is evaluated, as prescribed by the standard test procedures, by means of a headform launched on the bonnet. However, the standard approach based on the head injury criterion (HIC) value only is reported to be largely unsatisfactory: therefore, a new experimental methodology for the measurement of the translational and the rotational accelerations has been developed, and the experimental results are reported. This would be a starting point for the evolution of currently adopted injury criteria to increase the safety of the vulnerable road users.

Keywords: pedestrian protection; lightweight design; tri-axial rotational acceleration; head injuries evaluation

1. Introduction

In the last thirty years car manufacturers have addressed much attention to the safety during the design process of a new vehicle. Road safety is a large-scale problem: for example, in the European Union, annually road crashes result in nearly 40,000 fatalities and 2.4 million injuries [24]. These numbers (and in particular those related to fatalities) are also decreasing thanks to the improvement in vehicle design, driven by new regulations [22]. Especially in the last few years, the attention given to the safety of vulnerable road users has been enlarged: pedestrians, cyclists and motorcyclists constitute 39% of deaths in road crashes [2,20,24,29]. The excessively high speed of vehicles, the urban road design, and the absence of a protective shell, place these road users at increased risk. For these reasons, specific pedestrian safety requirements have been established for rating and homologation of new vehicles [3].

Another important problem for the design of new vehicles concerns polluting gas emissions. The pollution caused by vehicles is one of the most important sources of pollution on the planet [9]. Nowadays the most important problem is connected to the production of carbon dioxide which is the main greenhouse gas [6,8,19,23]. This is a primary product of the combustion and its quantity is proportional to the energy spent for the vehicle riding, thus in order to reduce the emission of this gas it is necessary to reduce the fuel consumption (that is an interesting result by itself). However, one of the most effective ways to reduce the fuel consumption is the reduction of the vehicle weight. This result can be pursued adopting innovative and smart materials, innovative at least for the automotive sector, such as aluminium and different types of plastics and composites.

In this perspective, it is possible to introduce our present work, which proposes the lightweight design process for a bonnet of a medium/high-class car. The solution must meet the stiffness and safety targets, has to take into account the manufacturing and recyclability requirements while giving a relevant contribution to vehicle lightweight. Some different solutions in terms of material and shape of the inner structure have been studied by means of virtual analysis. The most interesting solution in terms of weight and performance has been prototyped. Validation has been made by a series of experimental tests, in particular to confirm the pedestrian head impact performance. To perform these tests a special equipment developed by the authors, which can measure not only the linear acceleration of the headform but also the rotational ones, has been adopted.

2. State of the art

The bonnet can be considered a standard component for a car; however there is no unique design solution widely accepted as optimal, considering the manufacturing materials

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*Corresponding author. Email: alessandro.scattina@polito.it and the production technologies. A bonnet is composed of two main parts, the external shell with style and quality requirements, usually called skin, and an inner frame or inner structure, with structural function. A bonnet is completed by a series of reinforcements, in particular for the hinges and for the lock device. The different parts of a bonnet can be joined together by means of welding, riveting, or adhesive bonding depending on the material of the bonnet and if the joining is visible or not.

Regarding the materials, about 70% of the bonnets are made of steel. Typically the mild steel for hot stamping like Fe BH 220 (Bake Hardening), FeP04 and FeP05 is used, but in some cases it is possible to use high-strength steel. The other 30% of the bonnets are made of aluminium, usually of the 5xxx or 6xxx series and in some rare cases of composite materials. The thickness of metal sheets for bonnets is quite standard, from 0.65 to 0.7 mm using steel and from 0.8 from 1.1 mm using aluminium [1].

The design requirements for a car bonnet include several types of criteria.

Among the others, the pedestrian protection is, in the last few years, one of the key targets in the design of a bonnet [21]. The pedestrian protection capability of a bonnet is measured by means of specific impact tests. For the homologation of a new vehicle, these testes are regulated in the European Union by the Directive 2003/102/EC of the European Parliament. Similar tests, not required for homologation, but very important for marketing strategies, are proposed by rating institutes like EuroNCAP in Europe. The impact test consists of launching a specific headform against the bonnet and the windscreen at previously defined impact points, with a prescribed velocity and in a prescribed impact direction (trajectory angles). The injury level of the pedestrian head is evaluated by means of the head injury criterion (HIC). This parameter is calculated integrating the acceleration in the centre of gravity of the headform, with the following expression:

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

where t_1 and t_2 are the initial and final times of a mobile window where the HIC is evaluated into. The mobile window has a maximum time duration, usually 15 ms. The HIC parameter should not exceed a specific value for the survival of a human: usually a reference value is 1000, but it depends on the considered regulation. The HIC takes into consideration not only the amplitude of the acceleration but also its time duration: higher values of acceleration can be tolerated for a short time, but, on the other hand, a lower acceleration with higher time duration can produce a significant displacement of the head and its internal organs and this could be much more dangerous.

However, many researchers showed serious concerns about the formulation of HIC [4,25], because it only considers the linear acceleration responsible for the injuries. The HIC neglect the head rotation as possible co-responsible of injuries. In 1943, Professor Holbourn [13], for the first time, in the authors' best knowledge, took into consideration the angular acceleration as important factor for the head injuries. Shear and tensile deformation created by the rotation can cause concussion of the brain. In 1975, Lowenheilm [15] proposed to consider angular acceleration as cause for haemorrhage of the cerebral arteries. During the years, other authors like Gennarelli *et al.* [10–12] investigated the role of the angular acceleration on brain injuries. Their conclusions were that the angular acceleration contributes more than linear ones to head injuries. From 1992, Willinger *et al.* [27,28] starting from a series of test on real accident, found that without impact the angular acceleration cannot cause any injuries. Another important problem put in evidence by Willinger *et al.* [26] was the influence of the neck on the phenomenon. The neck is the main cause of the head rotation, because it can be considered a sort of lever. It is too simple to consider only the head in the study of brain injury. As discussed by Marjoux *et al*. [16], different injury criteria have been developed to improve the measure of injuries of the head. In particular, the head impact power (HIP) criterion, proposed by Newman *et al.* [18] is based on the global kinematics of the head and takes into account the rotational acceleration fields also. As also suggested recently by King *et al.* [14], the angular acceleration are more correlated than linear accelerations to the neurological injuries. However the HIP has certain limits; for example, it does not take into consideration some types of injuries like the fracture of the skull or subdural hematoma.

3. Geometry definition and material selection

The aim of this work is to redesign and develop a bonnet for a medium/large segment car. The main target of the job was a consistent weight reduction, compared to the original solution, while maintaining a good performance for what concerns the safety in case of pedestrian head impact. At the same time, the other types of performance of the bonnet (different types of stiffness and denting resistance) have to be maintained substantially unchanged as they are in the original solution.

The bonnet taken as reference for this work is made according to the general scheme previously described in Section 2, and is completely made of steel. The different components are joined together by structural adhesive and seam crimping. The external shape of the skin could not be changed because it was defined by style. For this reason, only the material and not the shape of the skin could be changed, while for the inner structure variations of both shape and material were possible. The structure of the reference bonnet is shown in Figure 1.

Figure 1. Structure of the reference steel bonnet.

To reduce the weight of the bonnet the use of thermoplastic materials has been considered. This family of materials has been selected thanks to its low density and good recyclability. Among the wide range of available materials suitable for this application, the Noryl GTX has been selected as a possible solution. Noryl GTX, originally developed by GE Plastics (New York, USA), is a class of polymeric blends based on PPO (Polyphenilene Oxide) and PA66 (Polyamide). This material is typically used for car body applications, such as fender or bumper, thanks also to its quite good mechanical properties (Table 1).

Two different designs for the inner structure have been proposed assuming the use of thermoplastic materials. They are shown in Figure 2. Both are characterised by a regular structure with local ribs. They are aimed first of all to reduce the weight, and to distribute in a more efficient way the energy in case of impact against a pedestrian head, ensuring sufficient bending and torsional stiffness. The studied solutions have been completed by an external thermoplastic skin and reinforcements still made of steel. A third solution has been developed with the same geometry of the reference, but completely in aluminium (6016-T4 for the skin; 6181-T6 for the inner structure). Both lightweight solutions, with aluminium and thermoplastics, allow for a weight reduction of about 30% if compared to the reference solution in steel.

Table 1. Properties of the thermoplastic material Noryl GTX chosen for the design of the innovative bonnet.

Property	Value
Density (g/cm^3)	1.20
Ultimate tensile strength (MPa)	80
Yield tensile strength (MPa)	85
Elongation at break (%)	6
Elongation at yield (%)	3
Tensile modulus (GPa)	4.30
Flexural modulus (GPa)	4.00
Flexural yield strength (MPa)	135
Izod impact (unnotched, 23°C, kJ/m^2)	45
CTE linear (μm/m/°C)	55
HDT (66 psi, °C)	190
Vicat softening point (°C)	230

3.1. *Virtual analysis*

These solutions have been evaluated by means of finite element analyses. The pedestrian head impact performance and the global stiffness have been evaluated. The solver software used for simulations was PAM-CRASH®. During the simulation of the pedestrian head impact the finite element model did not include the parts of the engine compartment. In this way, it is possible to better understand the real behaviour of the bonnet. The engine head or other stiff components inside the engine compartment could affect the performance in this type of test. For the same reason, the impact point has been chosen in the middle of the bonnet, where the deflection is expected to be the highest. The global stiffness has been evaluated by simulating two different torsion tests. The first test is made with a constraint on one side of the bonnet itself, the second test is made with a central constraint at the lock device. The results of the stiffness tests have been summarised in Table 2. The results for the pedestrian impact test, the HIC$_{15}$ and the vertical deformation, have been summarised in Table 3. Figure 3 shows the acceleration measured in the centre of gravity of the headform and the time window where the HIC$_{15}$ value is evaluated, for the considered three different bonnet

Figure 2. Different designs considered for the thermoplastic inner structure.

Table 2. Numerical results of the stiffness tests. The values are compared with the reference steel solution.

Solution	Weight (%)	K_t side constraint (%)	K central constraint (%)
Aluminium	−32.5	26.1	20.1
Noryl (inner structure 3.5 mm)	−31.1	−70.0	−61.5
Noryl (inner structure 4.0 mm)	−25.8	−66.1	−57.9
Noryl (inner structure 4.5 mm)	−20.5	−62.5	−55.0

Table 3. Numerical results of the pedestrian head impact test. The values are compared with the reference steel solution.

Solution	Weight (%)	HIC_{15} (%)	Deformation (%)
Aluminium	−32.5	−10.0	14.7
Noryl (skin 2 mm)	−31.1	−11.8	4.2
Noryl (skin 2.5 mm)	−27.8	0.5	−3.8

configurations. For the thermoplastic solution, different thicknesses for the inner structure and for the skin have been studied. In particular, in the pedestrian impact test, two different thickness values for the external skin have been examined (2 mm and 2.5 mm), while for the inner structure a unique value of thickness of 3.5 mm has been maintained. For the global stiffness evaluation, three different thickness values for the inner structure (3.5 mm, 4 mm and 4.5 mm) have been considered.

Both the aluminium and the Noryl solutions show good potential to obtain the same improved performance for the pedestrian head impact. The values of HIC_{15} and the vertical deformation are comparable and even better than the reference steel solution, but at the same time there is a consistent weight reduction. These results are confirmed examining the acceleration signals (Figure 3). The plastic solution is the best from the pedestrian safety point of view. The reached levels of acceleration are the lowest and the acceleration trend is quite flat, it looks like an ideal absorber. The mobile window where the HIC is evaluated is the largest. The aluminium bonnet gives intermediate results: the acceleration values are higher than plastic solution ones and with more fluctuation. The worst solution is the steel one, which gives the highest values of acceleration with a more pronounced first peak that increases the HIC value. However, when evaluating the stiffness, due to the low ratio between the elastic modulus and the density of Noryl, it is difficult to obtain a performance comparable with the whole steel or aluminium solutions. To increase the stiffness of the Noryl bonnet, a possible solution could be to increase the inertia moment in the transverse and longitudinal sections, growing the distance between the inner structure and the external skin and inserting a series of ribs. Therefore, even if the plastic solutions could give good results in terms of weight reduction, the evaluation of the overall performance suggests the whole aluminium solution as the most promising. This solution has been prototyped in some samples to make a complete experimental investigation.

4. Pedestrian safety experimental tests

On the prototyped aluminium bonnet, the complete experimental verification and validation has been made. Among the others, of particular interest is the pedestrian head impact test, which is reported in this work. Moreover, the tests have been made with an innovative equipment and specially designed measurement system, which is illustrated in details in the following paragraphs.

4.1. Head impact equipment

Starting from the reported discussion about the contribution of the rotational acceleration in the brain injuries, a specific headform able to also measure the rotational accelerations

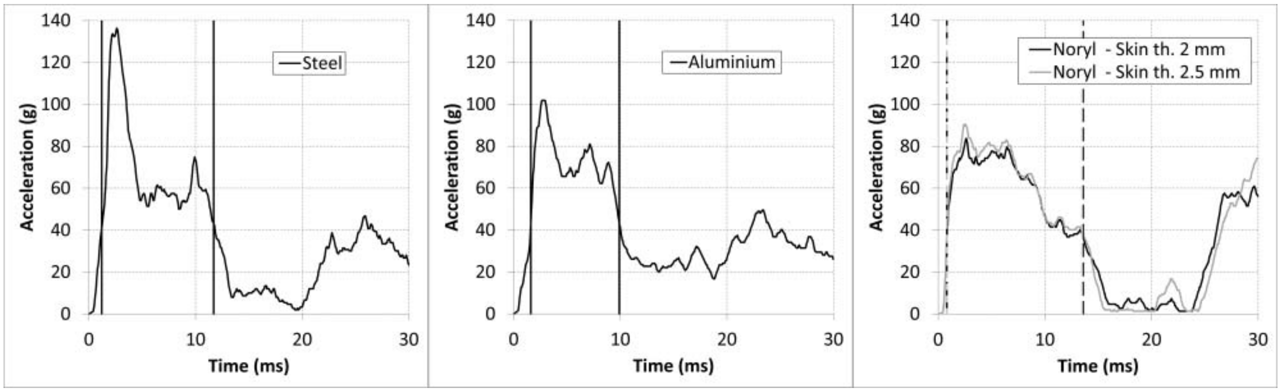

Figure 3. Acceleration signals and HIC_{15} windows for the three main bonnet configuration considered (a: steel; b: aluminium; c: plastic).

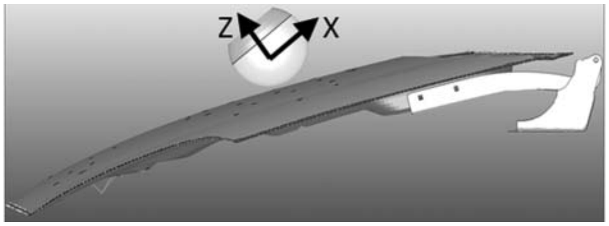

Figure 4. Scheme of the impact test, the reference system of the headform is put in evidence.

and not only the linear accelerations has been developed by the authors.

The headform is equivalent to that used in the 2003/102/CE regulation and EuroNCAP standard [7] in terms of mass and construction, but inside the sphere, three tri-axial accelerometers have been positioned. One of them is in the centre of gravity, as requested by the regulation. Knowing the orientation and the relative position of the three accelerometers, it is possible to evaluate also the rotational accelerations. In particular the scheme of the developed headform is shown in Figures 4 and 5.

Starting from this configuration, and considering the Rivals's theorem, which is a special case of the Coriolis's theorem [5] it is possible to establish the rotational accelerations. The Rival's theorem allows us to write the following equations:

$$\vec{a}_2 - \vec{a}_1 = \vec{\omega} \times (\vec{\omega} \times \mathbf{12}) + \dot{\vec{\omega}} \times \mathbf{12} = -\omega^2 \mathbf{12} + \dot{\vec{\omega}} \times \mathbf{12} \tag{2}$$

$$\vec{a}_3 - \vec{a}_1 = \vec{\omega} \times (\vec{\omega} \times \mathbf{13}) + \dot{\vec{\omega}} \times \mathbf{13} = -\omega^2 \mathbf{13} + \dot{\vec{\omega}} \times \mathbf{13} \tag{3}$$

$$\vec{a}_3 - \vec{a}_2 = \vec{\omega} \times (\vec{\omega} \times \mathbf{23}) + \dot{\vec{\omega}} \times \mathbf{23} = -\omega^2 \mathbf{23} + \dot{\vec{\omega}} \times \mathbf{23}. \tag{4}$$

Figure 6. Experimental equipment for the pedestrian head impact tests.

By developing Equations (2), (3) and (4), it is possible to obtain the rotational accelerations:

$$\dot{\omega}_X = \frac{a_{z3} - a_{z1}}{\mathbf{13}_Y} \tag{5}$$

$$\dot{\omega}_Y = -\frac{a_{z2} - a_{z1}}{\mathbf{12}_X} \tag{6}$$

$$\dot{\omega}_Z = \frac{a_{x2}\sin\theta + a_{y2}\cos\theta - a_{x1}\sin\theta + a_{y1}\cos\theta}{\mathbf{12}_X}. \tag{7}$$

The headform is launched towards the bonnet by means of a pneumatic cylinder and a specific release system. This launcher is positioned on a specific structure made of beams with groove profile (Figure 6). In this way, the launcher can slide on different positions and reach the different impact points of interest on the bonnet surface to perform the complete set of tests required by the regulation. The equipment

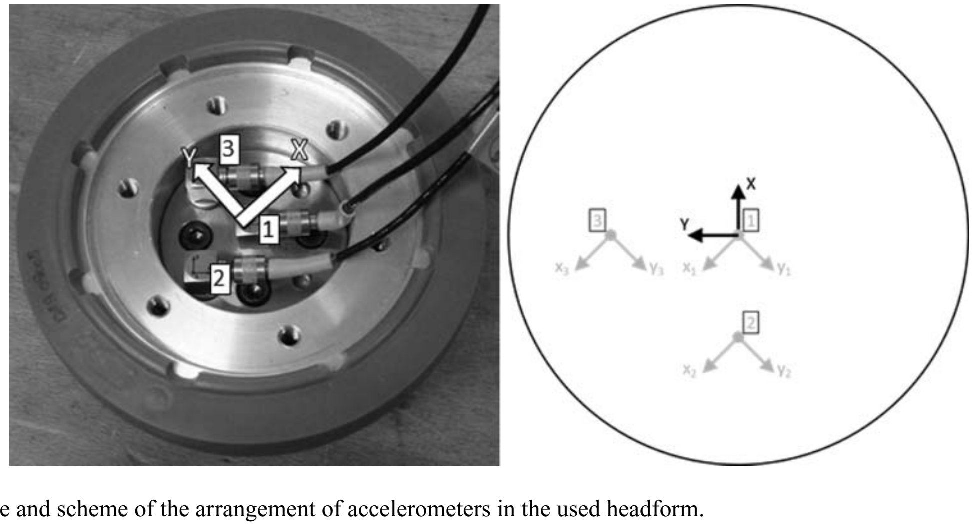

Figure 5. Picture and scheme of the arrangement of accelerometers in the used headform.

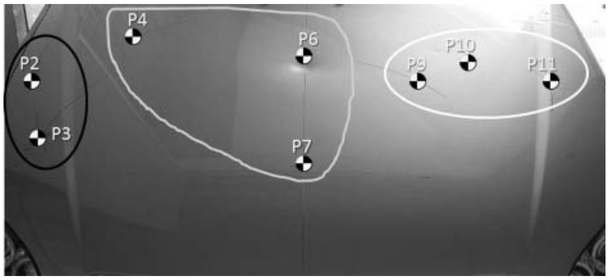

Figure 7. Arrangement of the impact points on the bonnet, the points are grouped in three families.

can be adapted for vehicles with different dimensions. The structure is fixed to two concrete blocks to contrast the reaction forces due to the shot. The speed of the headform is measured in two different ways. In the first one, a laser head for triangulation systems is used to measure the displacement during the headform acceleration stroke. It is fixed to the supporting structure and pointed to the rear part of the headform. The impact tests have also been recorded with a high-speed movie camera from a side point of view. Elaborating the movies obtained during the tests, it is possible to evaluate the speed of the headform.

4.2. *Experimental head impact tests*

A series of pedestrian head impact tests, according to the EuroNCAP protocol [7] have been performed on the aluminium bonnet. The same tests have been done also on the reference steel bonnet in order to compare the results.

Table 4. Results of the pedestrian head impact points in term of HIC_{15}.

	HIC_{15}		
	Aluminium	Steel	ΔHIC_{15} %
P2	2613	1909	36.9
P3	2324	1989	16.8
P4	1095	1250	−12.4
P6	955	895	6.7
P7	1529	1194	28.1
P9	644	679	−5.2
P10	1015	875	16.0
P11	1582	1439	10.0

Eight different points have been evaluated. The choice of the impact points has been made considering the layout of the engine compartment. The arrangement of the impact points is shown in Figure 7. The selected points have been chosen in some particular positions in order to match the stiff components in the engine compartment: the cylinder head, the battery, the fuse box, the lock device, the light device supporting beam and the fender bracket. The eight impact points can be subdivided into three groups, as it is shown in Figure 7. The points of the group outlined by the black line on the left are positioned on stiff component like lighting group and fender rail. The points inside the blue line are in the central part of the bonnet, where, at least for points P4 and P6, there is more space between the bonnet and the stiff component in the engine compartment (engine head, engine air filter). The three points inside the red line on the right are in the zone of the battery and the fuse box.

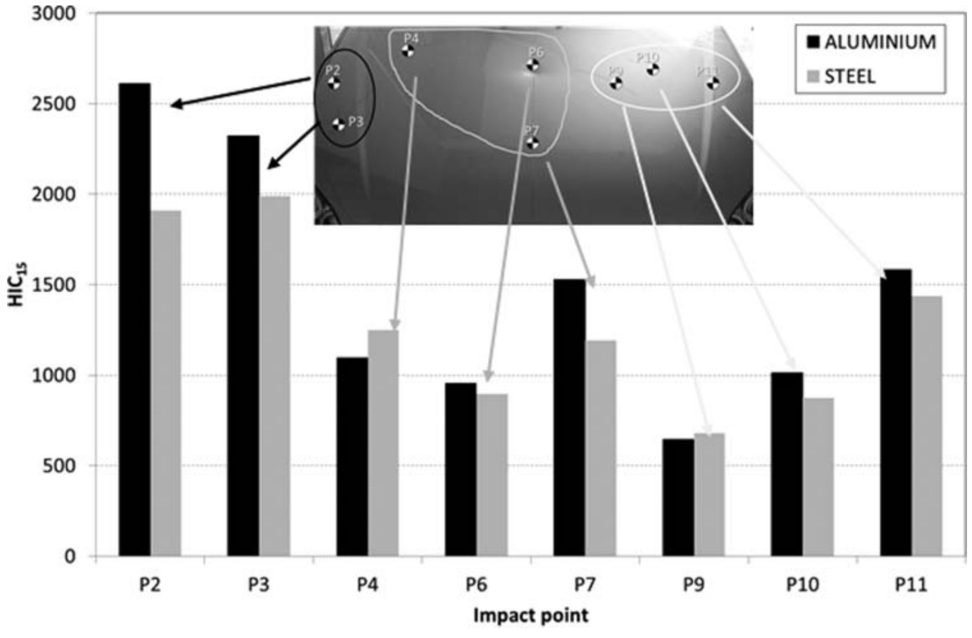

Figure 8. Comparison of HIC_{15} values for the different impact points.

For each impact point the linear acceleration of the centre of gravity and, moreover in order to investigate in depth the comparison between metal bonnets behaviour and in particular to develop the experimental equipment, the rotational acceleration of the head in the three main directions have been measured. The measure of this entity is not conventional in the pedestrian head impact test but, as demonstrated before, it is quite important for the pedestrian head injuries.

With the measured linear acceleration, the value of the HIC_{15} is evaluated on each point and also the speed of the headform is verified at each test. The results of these tests are summarised in Table 4 and Figure 8.

For what concerns the HIC_{15}, the values obtained for each impact point, both for the aluminium and steel solutions are compared. These results do not indicate undoubtedly the superiority of one solution over the other. In some points the difference between the values of the HIC_{15} for the aluminium and the steel solutions is quite high, in other points the two solutions are nearly equivalent. Only in two points is the aluminium bonnet better than the reference steel solution. The results are heavily influenced by

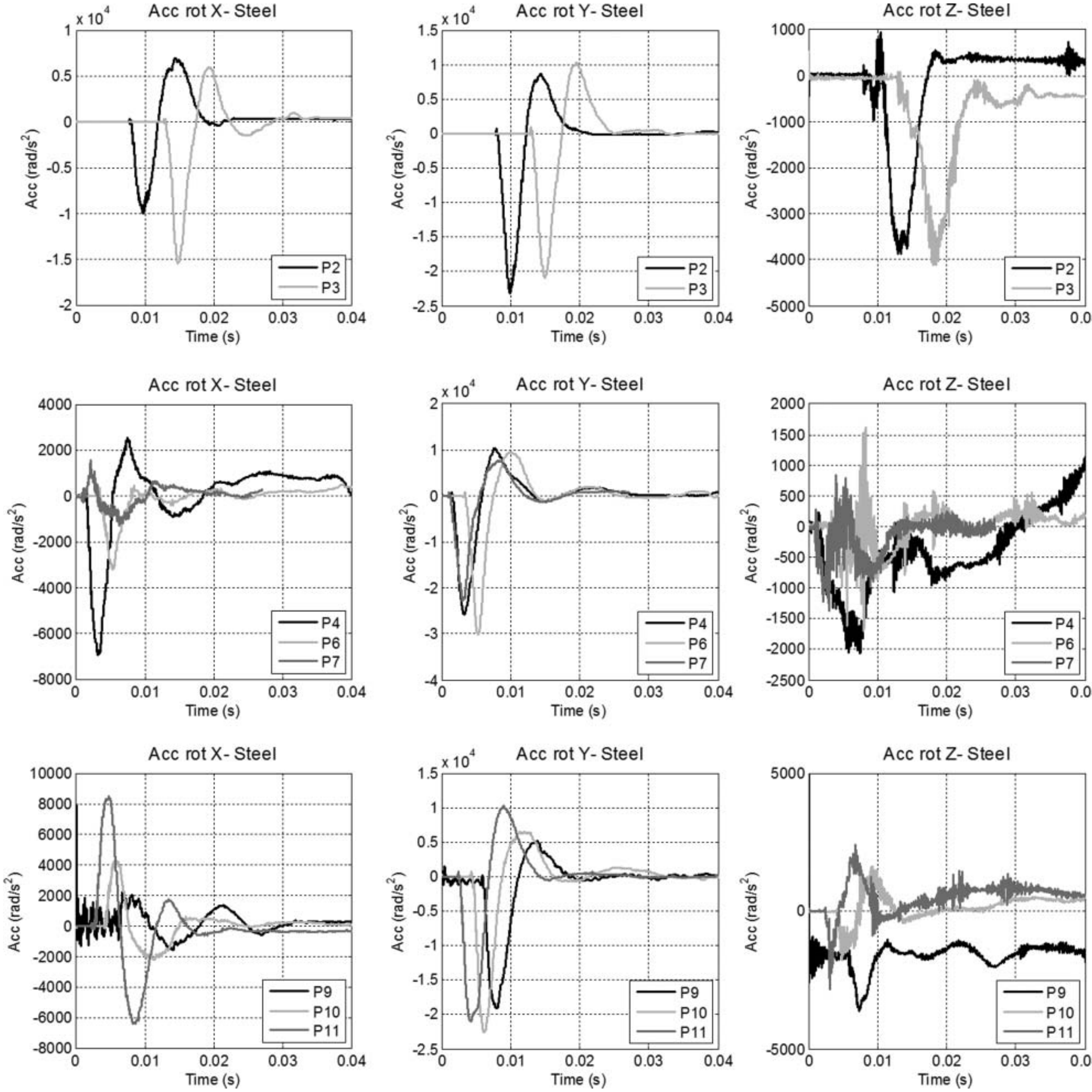

Figure 9. Rotational acceleration signals for the steel bonnet; the impact points are gathered in the three different groups.

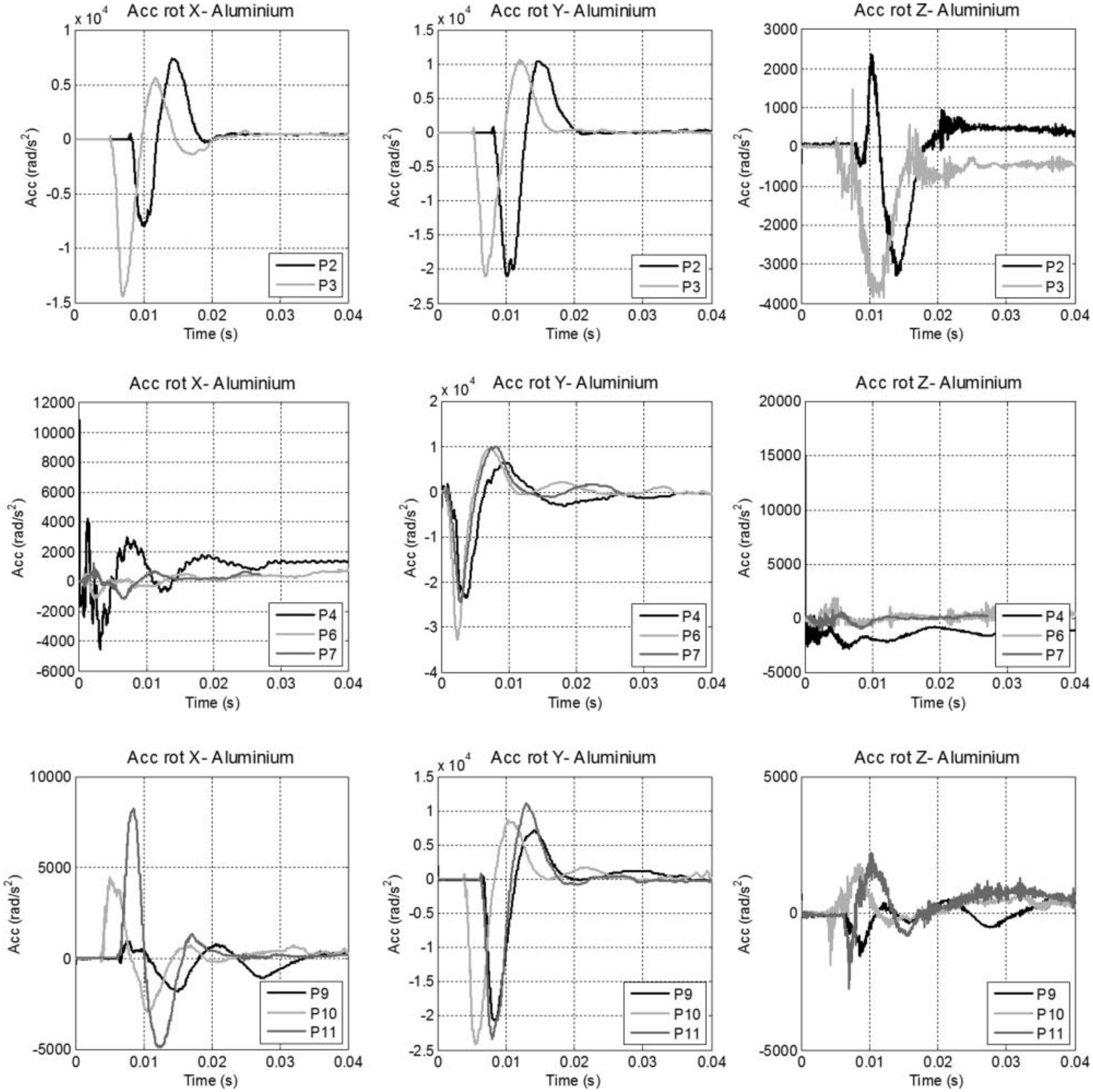

Figure 10. Rotational acceleration signals for the aluminium bonnet; the impact points are gathered in the three different groups.

the layout of the engine compartment. During the tests, the aluminium bonnets experienced higher deformations, but, after the tests, the permanent deformations have been always higher for the steel bonnet. This behaviour is due to the difference between yield stress and elastic modulus of the two considered materials. According to the classical theory of elasticity, the amount of energy absorbed with elastic (reversible) deformations increases with the thickness of the sheet and the yield limit is inversely proportional to Young's modulus. For example, considering a circular panel, the elastic amount of energy is given by the following expression [17]:

$$W_{el} = \frac{c_2}{2c_1^2} \frac{tR^2\sigma_y^2}{E}, \tag{8}$$

where W_{el} is the elastic energy, c_1 and c_2 two coefficients depending on boundary conditions [17], E the elastic modulus, t the thickness of the panel, R the radius and σ_y the yield stress.

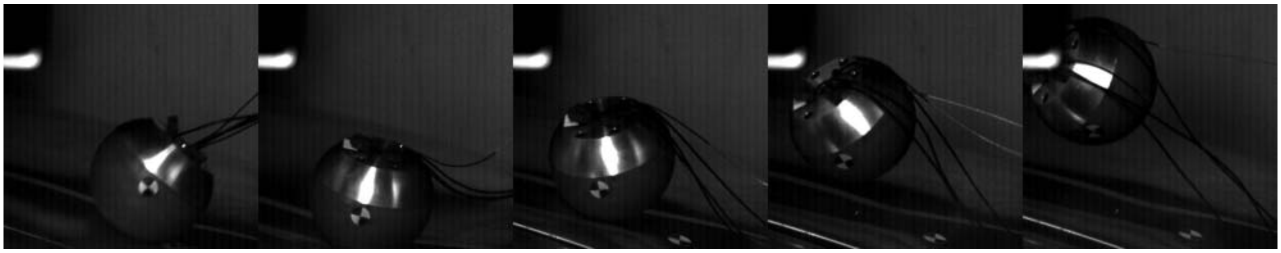

Figure 11. Head impact test on aluminium bonnet at P3 impact point.

In comparison with a steel plate, an aluminium plate can absorb more energy if the product of the thickness multiplied by the square of the yield strength is at least one-third of the corresponding steel value, being the steel elastic modulus about three times aluminium one. For this reason, today, steel is likely to be replaced by aluminium for bonnet and fender. For what concerns the plastic deformations, the permanent mark is the same even considering different materials, if the plates used have the same value of thickness times yield strength [17]. The values of the HIC_{15} are strictly influenced by the layout of the engine compartment. The highest values of the parameters have been obtained in the points P2, P3 and P11, where there are the body structure of the fender, the supporting beam for the light group and the fuse box, respectively. Also the values in the point P7 have been influenced by the front supporting beam for light groups. In the other impact points, there is more free space between the internal surface of the bonnet and stiff components in the engine compartment and, therefore, the HIC resulting values are lower.

For what concerns the angular accelerations both the trend of the curves along the time and the maximum value reached have been taken into consideration. The rotational acceleration signals are shown in Figures 9 and 10. The tests show that the most important rotation is around the Y axis of the head, then, in some impact points, the rotation around X axis of the head can be also relevant, while the rotation around the Z axis is not very significant. The rotations are due firstly to the shape of the external surface and then to the presence of stiff body, under the bonnet surface, that are reached during the impact.

Generally, the curves of the rotational accelerations around the X and Z axis measured at different impact points are variable and without a specific trend. Instead,

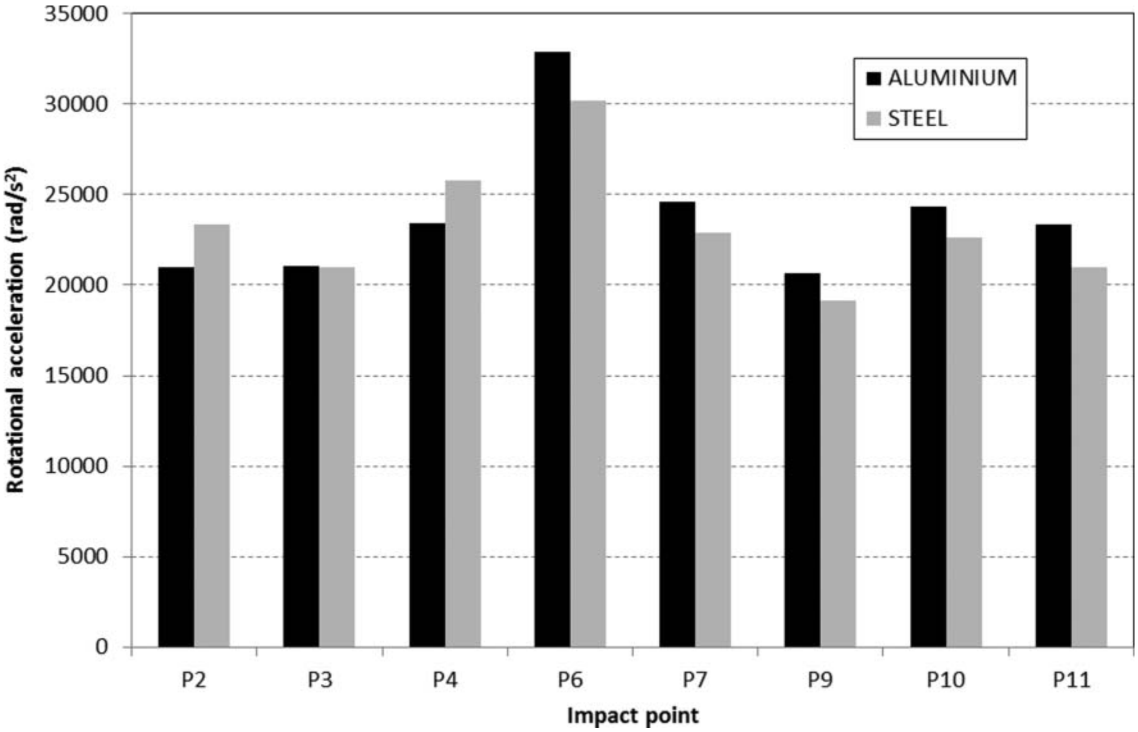

Figure 12. Comparison of the rotational acceleration around Y axis for the different impact points.

the rotational acceleration around the Y axis has shown the same trend for all the impact points.

Only the rotational acceleration around the X axis at the impact points P2 and P3, shows a curve similar to those around Y axis; this is due to the bonnet external shape, that is not completely flat but with a certain curvature toward the fender and to the presence, very near under the bonnet, of the upper rail where also the fender is fixed.

During the test, there is also an important rotation around the X axis as is possible to see in Figure 11, where there is a slideshow of the test at the impact point P3. The pictures have been obtained recording the test with a high-speed camera. However, the acceleration values reached around X axis are lower than that around Y axis.

The trend of the curves of the rotational acceleration around the Y axis is due to the rotation which occurs during the rebound phase of the headform after the impact on the bonnet surface. The maximum acceleration values for all the impact points were obtained by the rotation around the Y axis, so the attention has been focused on this acceleration component. The maximum acceleration values are summarised in Figure 12.

The values are not very scattered; only for the point P6 dispersed values were measured. Being the impact point in the middle of the bonnet and due to the larger distance between the inner structure of the bonnet and the stiff components of the engine, the deformations have been higher and consequently there is higher rebound and higher rotational acceleration. Only in two points the use of aluminium has brought to lower acceleration value.

5. Conclusions

Safety (with special attention to the so called Vulnerable Road Users) and green design (with particular attention to the vehicle weight reduction) are nowadays leading points in the development of new vehicles. The trend exhibited by the vehicle weights in the years is a growing trend and this is mainly due to the enforcement of more stringent safety regulations. So it seems that to have safer vehicle we must have heavier vehicle. This perspective is not completely acceptable and design solutions that make it possible to have lighter vehicle at the same safety performance, at least, should be explored.

In this work, the lightweight design of a bonnet of a medium/large car has been proposed. Different design solutions in terms of shape for the inner structure and materials (aluminium and a thermoplastic) have been considered by means of virtual analysis.

The thermoplastic solution gives excellent numerical results in terms of weight reduction and performance in the pedestrian head impact; however, the stiffness performance is unsatisfactory especially if compared with the reference steel solution.

The most promising solution, completely made of aluminium, led to a weight reduction of 32%. This solution has been prototyped and a series of experimental tests have been performed. In particular, the standard pedestrian head impact tests have been made. To perform these tests, a special equipment that allows to measure not only the translational acceleration components of the headform but also the rotational ones has been developed. These experimental tests have given the expected confirmation of the results achieved through the numerical simulations.

The pedestrian head impact tests have shown that to improve the safety performance, it is not sufficient to redesign the structure of the bonnet, working on interior structure shape and materials, but it is also necessary for a concurrent design that takes into account the arrangement of the stiff bodies into the engine compartment. The results are heavily influenced by the zone of the impact point and by the under bonnet components.

The use of more complex measurement techniques for the evaluation of real head loading conditions by means of the joint analysis of both the translational and the rotational acceleration components, can give way to advanced injury criteria for the head improving the ability to forecast potential injuries. This is certainly a starting point for the evolution of the head injury criteria beyond the currently adopted HIC parameter in order to increase the safety of road users.

Acknowledgements

The financial support of the Piemonte Regional Government made this work possible, within the project 'TREES – The 5 stars of sustainable mobility', through grant No. RIJ08PA01, Regional Call for Industrial Research and Pre-competitive Development 2006, Area: 'Sustainable Mobility'. This financial support is gratefully acknowledged. The authors wish also to acknowledge the contribution of Mrs. Katia Bianciotto and Mr. Antonio Casu of Italdesign-Giugiaro for the part related to numerical investigation.

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