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NUMERICAL AND EXPERIMENTAL RESULTS ON PEDESTRIAN HEAD IMPACT TESTS ON AN ALUMINIUM BONNET

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Abstract: *Nowadays, in the current vehicle development pedestrian protection is a very important topic. In Europe, a specific regulation aimed to decrease the damage to head, pelvis, and leg of pedestrian impacted by cars was adopted. It has imposed changes in the vehicles front design. In particular the bonnet is a part interested by these changes, being the more involved car body component in the impact with the pedestrian. In particular the bonnet is studied for the impact against the head of pedestrian. Usually the injuries to the head are evaluated with impact tests where a specific headform is launched on the bonnet: the acceleration signal in the centre of gravity is elaborated to obtain the HIC parameter. However, the present approach based on the HIC value only is reported to be largely unsatisfactory. In this work a lightweight design for a bonnet of a medium/large car is proposed, first by means of virtual simulations, then a new experimental methodology for the measurement of the rotational acceleration of the pedestrian head has been developed. The experimental results are reported and discussed in the work.*

Keywords: Pedestrian protection, lightweight design, triaxial rotational acceleration, head injuries evaluation

INTRODUCTION

In the last thirty years much attention of the car manufacturers, during the design process of a new vehicle, has been addressed to the safety. Road safety is a large-scale problem: for example, for what concerns the European Union, annually road crashes result in nearly 40000 fatalities and 2.4 million injuries (1). These numbers (and in particular those related to fatalities) are decreasing also thanks to the improvement in vehicle design, driven by new regulations. However it is of big concern that road traffic injuries represent the major cause of death among adolescents and young adults. Especially in the last years, the attention has been enlarged to the safety of vulnerable road users: pedestrians, cyclists and motorcyclists constitute 39% of deaths in road crashes (1). The excessively high speed of vehicles, the urban roads 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 (2).
The other important problem for the design of new vehicles concerns the polluting gas emissions. The pollution caused by vehicles is one of the most important sources of pollution for the planet (3). The gas mixture emitted by the vehicles with internal combustion engine, during their operation, creates different types of pollution (4). During the years, also thanks to the ever more stringent regulations in this field, they are progressively reduced (5) for what concern their toxic contents. Nowadays the most important problem is connected to the production of carbon dioxide which is the main greenhouse gas (6-7). This is a primary product of the combustion and its quantity is proportional to the energy required for the vehicle riding, thus in order to reduce the emission of this gas it is necessary to reduce the fuel consumption. To meet this target, the car manufacturers have worked to improve the efficiency of the vehicle in different ways: aerodynamics, engine combustion, driveline, and so on. However, one of the most effective ways to reduce the consumption is the reduction of the vehicle

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weight. This result can be obtained also by adopting innovative and smart materials, innovative at least for the automotive sector, such as aluminium and different types of plastics and composites (8).
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. In particular 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 make these tests a special equipment, developed by some of the authors, which can measure not only the linear acceleration of the headform but also the rotational ones, has been adopted.

BONNET DESIGN

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

- Thermal insulation
- Global static stiffness
- Pedestrian protection
- Local static stiffness
- Opening and closing durability
- Misuse
- Functionality
- Denting and canning
- Matching
- Acoustic insulation

Some of these criteria are evaluated first by numerical simulation and experimentally verified. In the following, the design process for the innovative concept of a pedestrian friendly bonnet is illustrated.

GEOMETRICAL 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, and 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 type of stiffness and denting resistance) have to be maintained unchanged as they were in the original solution.
The bonnet taken as reference for this work is completely made of steel. It is composed by an external skin, an internal structure, and a series of reinforcements near the hinges and near the lock device. 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.

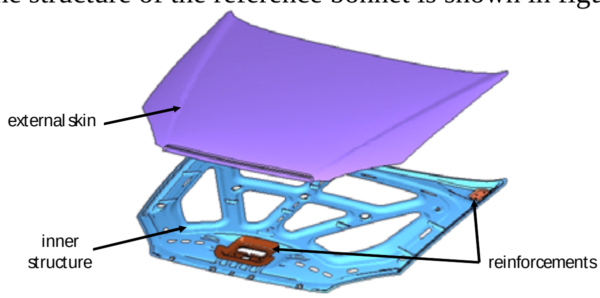

Figure 1. Structure of the reference steel bonnet

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, 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).

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

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

Two different designs for the inner structure have been proposed assuming the use of thermoplastic materials. They are shown in figure 2. Both are characterized by a regular structure with local ribs. They are aimed first of all to reduce the weight, and to distribute in a more efficiency 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.

Figure 2. Different designs considered for the thermoplastic inner structure

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 has been 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. The global stiffness has been evaluated by simulating two different torsion tests. The first test is made with a constraint on the side of the bonnet itself, the second test is made with a central constraint at the lock device. The results of the tests have been summarized in the following tables 2 and 3, whereas for the pedestrian impact test the HIC_{15} and the vertical deformation have been considered. 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 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, 4 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 with the reference steel solution, but at the same time there is a consistent weight reduction. 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 exam of the overall performance suggests the aluminium as the most promising. This solution has been prototyped in some samples to make a complete experimental investigation.

Table 2. 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

Table 3. 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 (inn. struct. 3.5 mm)	-31.1	-70.0	-61.5
Noryl (inn. struct. 4.0 mm)	-25.8	-66.1	-57.9
Noryl (inn. struct. 4.5 mm)	-20.5	-62.5	-55.0

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.

HEAD IMPACT EQUIPMENT

In the pedestrian head impact tests an headform made by an aluminium hemisphere covered by a layer of rubber is launched at 35-40 km/h (depending from the regulations considered) against specific points on the external surface of the bonnet fixed on the car. During the test the linear acceleration of the headform centre of gravity is measured by three triaxial accelerometers. The acceleration signals are processed to obtain the HIC parameter, which is correlated to the entity of possible head injury. However, different studies (9-10) have put in evidence that the linear acceleration is not the only cause of head injuries. The rotational accelerations also play a fundamental role in the phenomenon (9-10). For this reason a specific headform able to measure the rotational accelerations also has been developed by some of the authors.
The headform is equivalent to that used in the 2003/102/CE regulation and EuroNCAP standard (11) in terms of mass and construction, but inside the sphere, three triaxial 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 3 and 4.

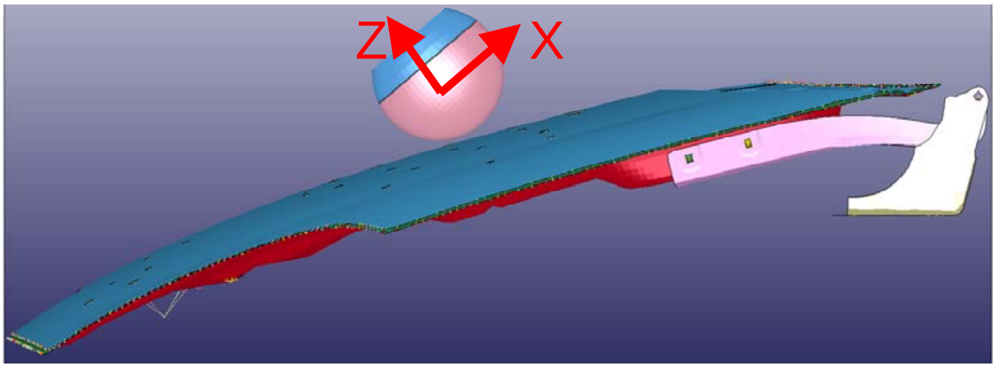

Figure 3. scheme of the impact test, the reference system of the headform is put in evidence

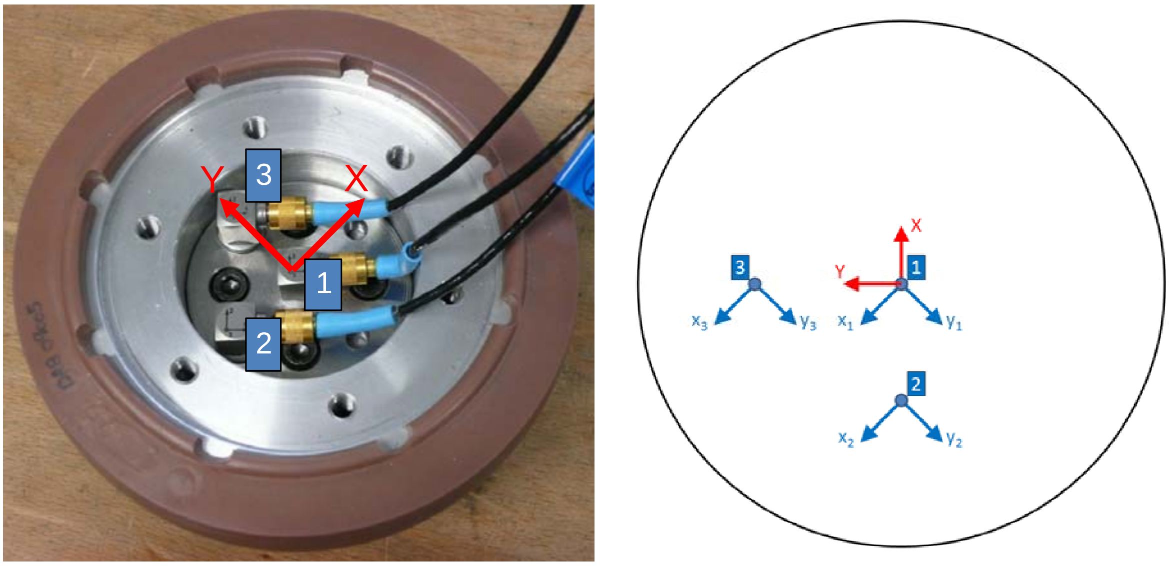

Figure 4. Picture and scheme of the arrangement of accelerometer in the used headform

Starting from this configuration, and considering the Rivals's theorem, which is a special case of the Coriolis's theorem (12), it is possible to establish the rotational accelerations. The Rival's theorem allows us to write the following equations:

$$\vec{a}_2 - \vec{a}_1 = \vec{\omega} \times \left(\vec{\omega} \times \mathbf{12} \right) + \dot{\vec{\omega}} \times \mathbf{12} = -\omega^2 \mathbf{12} + \dot{\vec{\omega}} \times \mathbf{12} \tag{1}$$

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

$$\vec{a}_3 - \vec{a}_2 = \vec{\omega} \times \left(\vec{\omega} \times \mathbf{23} \right) + \dot{\vec{\omega}} \times \mathbf{23} = -\omega^2 \mathbf{23} + \dot{\vec{\omega}} \times \mathbf{23} \tag{3}$$

By developing the equations 1, 2 and 3 it is possible to obtain the rotational accelerations:

$$\dot{\omega}_X = \frac{a_{z3} - a_{z1}}{\mathbf{13}_Y} \tag{4}$$

$$\dot{\omega}_Y = -\frac{a_{z2} - a_{z1}}{\mathbf{12}_X} \tag{5}$$

$$\dot{\omega}_Z = \frac{a_{x2} \sin\theta + a_{y2} \cos\theta - a_{x1} \sin\theta + a_{y1} \cos\theta}{\mathbf{12}_X} \tag{6}$$

The headform is launched to 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 5). In this way the launcher can slide on different positions and reach the different points of interest on the bonnet surface to perform the complete set of tests required by the regulation. The equipment 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.

Figure 5. Experimental equipment for the pedestrian head impact tests

EXPERIMENTAL HEAD IMPACT TESTS

A series of pedestrian head impact tests, according to the EuroNCAP protocol (11), 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. Seven 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 6. The selected points have been chosen in position matching the stiff component in the engine compartment: the cylinder head, the battery, the fuse box, the lock device, the light device supporting beam and the fender bracket.

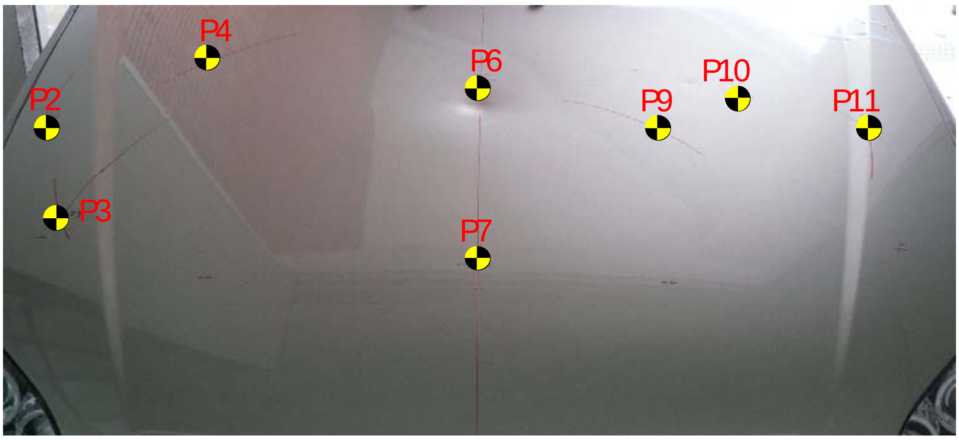

Figure 6. Arrangement of the impact points on the bonnet

For each impact point the linear acceleration of the centre of gravity and the rotational accelerations of the head in the three main directions have been measured. 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 summarized in the following figure 7.
For what concerns the HIC_{15}, the values obtained for each impact point, both for the aluminium and steel solution are compared. These results do not indicate undoubtedly the superiority of a solution

over the other. In some points the difference between the value of the HIC_{15} for the aluminium and the steel solutions is quite high, in other points the two solutions are more or less equivalent. In two points only the aluminium bonnet is better than the reference steel solution. The results are heavily influenced by the layout of the engine compartment. During the tests, the aluminium bonnets experienced higher deformation, 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. The amount of energy absorbed with elastic (reversible) deformations increases with the thickness of the sheet and the yield limit and is inversely proportional to Young's modulus. 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 (13). 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.

	HIC_{15}		ΔHIC_{15}
	ALUMINIUM	STEEL	%
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

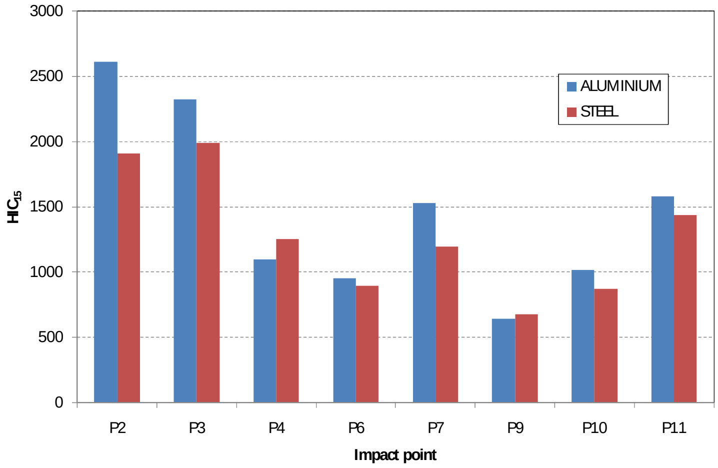

Figure 7. On the left results of the pedestrian head impact points in term of HIC_{15}; on the right comparison of HIC_{15} values for the different impact points

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 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 first to the shape of the external surface and then to the presence of stiff body, under the bonnet surface, during the impact. An example of the rotational acceleration diagrams as a function of the time obtained during the tests is shown in figure 8 for the impact point P9.

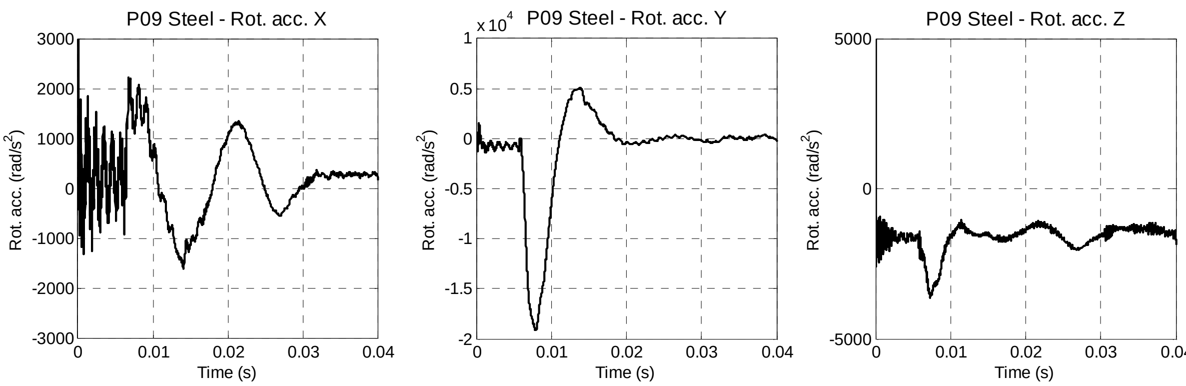

Figure 8. Rotational acceleration in the three main directions obtained in the impact point P9

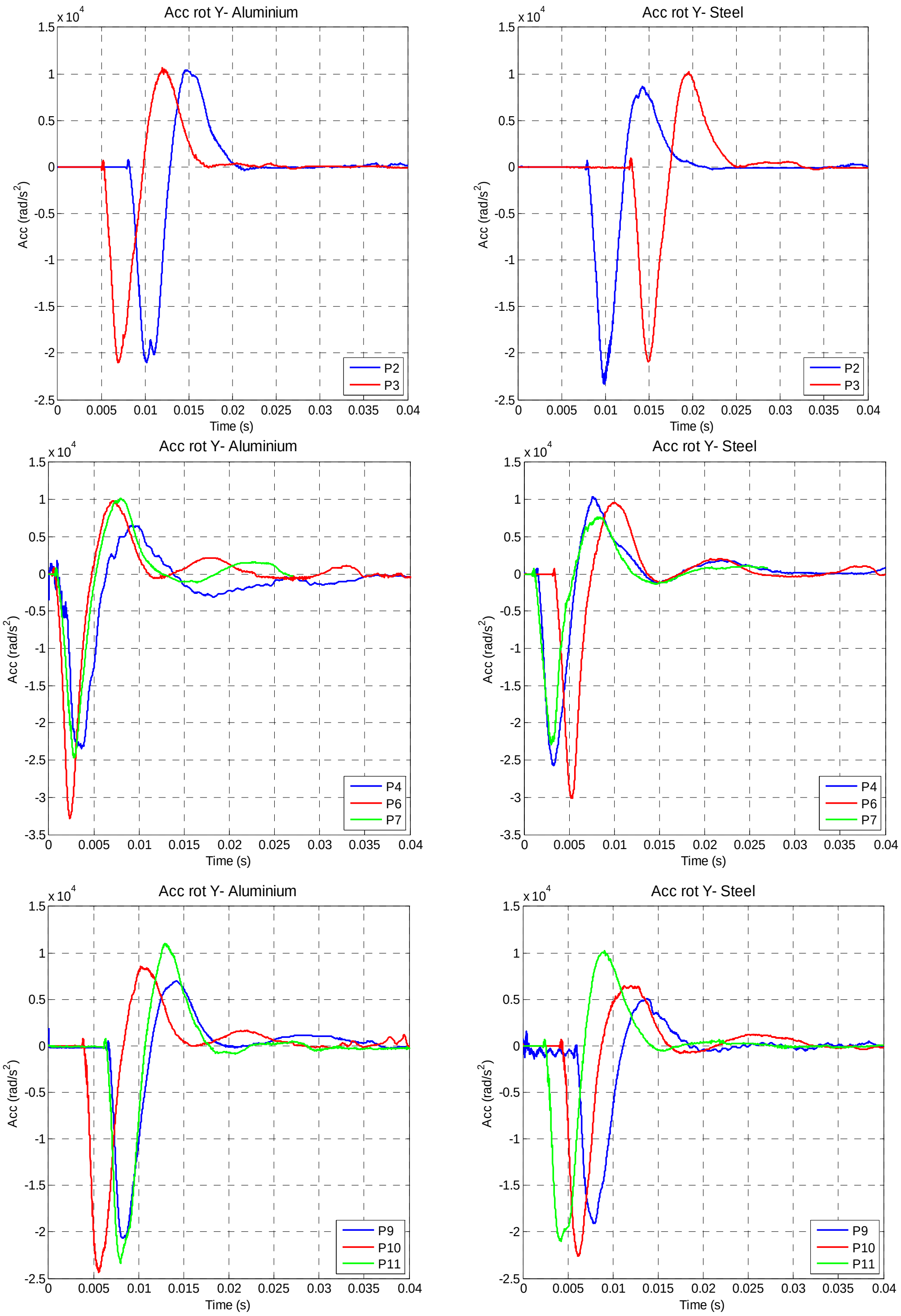

Figure 9. Rotational accelerations signals for the aluminium bonnet on the left, and for the steel bonnet on the right, the impact points are gathered in three different groups

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, the rotational acceleration around the Y axis has shown the same trend for all the impact points. This 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 from the rotation around the Y axis, so the attention has been focused on this acceleration component.

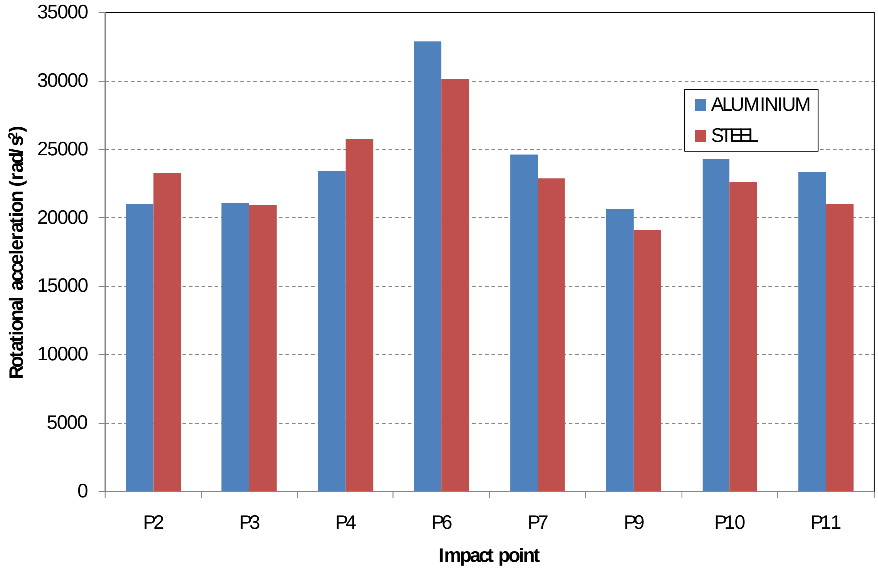

Figure 10. Comparison of the rotational acceleration around Y axis for the different impact points

The acceleration signals obtained during the tests for each impact points, both for the aluminium and the steel bonnet are shown in figure 9, while a summary of the maximum acceleration values are shown in figure 10.

For what concerns the curves of the rotational acceleration around the Y axis that specific trend is due to the rotation which occurs during the rebound phase of the headform after the impact on the bonnet surface. Speaking about the maximum values of the curves, they are not very scattered, only in the point P6 values out of trend were measured. Being the impact point in the middle of the bonnet, 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.

CONCLUSIONS

Nowadays the key points in the automotive design are the safety, with special attention for the safety of Vulnerable Road Users, and the green design, that means attention to the reduction of pollutant emissions and consequently reduction of the weight.

In this work the lightweight design of a bonnet of a medium/large car has been discussed. Different designs 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 results in terms of weight reduction and performance in the pedestrian head impact; however the stiffness performance are too low in particular if compared with the reference steel solution. The aluminium solution appears as the most promising one, leading to a consistent weight reduction (32%) and having good performance for pedestrian safety and stiffness. This solution has been prototyped and a series of experimental tests have been performed.

In particular, for the pedestrian head impact tests, a special equipment, that allows to measure also the rotational accelerations of the headform, has been developed. The experimental results substantially confirmed what expected through the numerical simulations. Moreover, the rotational acceleration evaluation is a more complex measurement technique which can contribute to improve the injury criteria adopted to forecast the damage of the head during impact.

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

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