ACTIVE PEDESTRIAN HEAD PROTECTION AGAINST WINDSCREEN

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ABSTRACT

In road traffic accidents involving pedestrians or cyclists against cars, head injuries are one of the most common injury types and the main cause of fatalities. Recent in deep accident analysis demonstrates that the windscreen, pillars and bonnet are very often involved in case of severe pedestrian head injury. The present study proposes an active protection system for pedestrian or cyclist head impact against the windscreen (and in particular against the pillar) and bonnet area. In case of an automotive impact with a pedestrian, contact or non contact transducers record the impact and transfer the information to actuators which open the bonnet and eject a dampened flexible protective panel which covers the windscreen and pillars. This active protection system prevents the pedestrian's head to come into direct contact with the hard windscreen or pillar and provides a dampened surface on which the head hits, decreasing the risk of head trauma. The panel can eventually be released a few hundreds of milliseconds after head impact in order to provide visibility to the car driver. A second panel is added under the bonnet in order to decrease the risk of head injuries when the pedestrian head impacts the bonnet.

The present proposal suggests illustrating the efficiency of the proposed active and passive protection systems based on the simulation of the pedestrian kinematics and the numerical analysis of the head-protective system interaction at the time of impact. In a first step, the multibody simulation of the pedestrian kinematics showed that an activation of the protective panel within 100 ms and remaining until 250 ms after the impact is appropriate to avoid any direct head contact with the windscreen or the pillar. The multi layered flexible protective panel has then been optimised in terms of layer thickness, elastic-plastic and failure properties against both, HIC value and new biomechanical head injury criteria for adults. Simulations have also been done to evaluate the bonnet system in terms of HIC and biomechanical criteria.

INTRODUCTION

Accident statistics [1] show that more than 42.000 fatalities occur in traffic accidents in Europe per year. Among these accidents 15% are pedestrian and 10% are cyclist. 71% of the pedestrian accidents are non severe or mild, 27% are serious and 2% are fatal. In the case of pedestrian accidents the most frequent injuries concern the head (31%) and the legs (32%). 60% of all fatalities are caused by head injuries occurring when the pedestrian's head impacts the front of the vehicle (bonnet or windscreen) or the ground. As the fatal or severe head injuries are strongly correlated with car initial speed, these impacts concern most often the windscreen and pillar area.

The European Enhanced Vehicle Safety Committee (EEVC WG 10 and WG 17) has developed test procedures to assess the level of pedestrian protection for vehicle fronts. Based on the EEVC WG 17 report, legal requirements have been derived, such as European Directive 2003/102/EC [2]. In order to be conform to the legal requirements of the phase I (took effect in 2005) and phase II (will take effect in 2010) of the European Directive 2003/102/EC on pedestrian protection, passive and active protection systems must be developed. New conception solutions must be found for the bumper, the front end and especially for the bonnet and the windscreen to provide the ability of these parts to absorb kinetic energy without exceeding load limits for the pedestrian. Concerning the windscreen area, it is well known that the central area seldom causes severe injuries but, as soon as the head impact is close to the frame or against the pillar, the outcomes are quasi-systematically dramatic. A possible solution, proposed by Kuehn [3] consists in adding an airbag system under the bonnet. These airbags uplift the bonnet and cover the A-pillars and the lower windscreen frame. The bonnet is raised 40 ms after the impact of pedestrian's legs on the bumper. This system is illustrated in Figure 1 and allows an important decrease of the HIC (Head Injury Criteria) value for a velocity of 40 km/h. This solution has two main advantages: firstly, the airbags uplift the bonnet and increase thus the

deformation space under the bonnet (which enhances the kinetic energy absorption) and secondly, they protect the pedestrian against the A-pillars. However this system only protects the lower part of the A-pillars and does not take into account the upper part and the roof edge. Moreover, this protective design is known to be a quite expensive solution.

Figure 1. Passive protection system with airbags uplifting the bonnet (Kuehn, [3]).

Other solutions exist, but only for the bonnet improvement with regards to pedestrian head protection. As illustrated in Figure 2 the bonnet inner panel is traditionally designed as a rib structure supporting the bonnet outer panel.

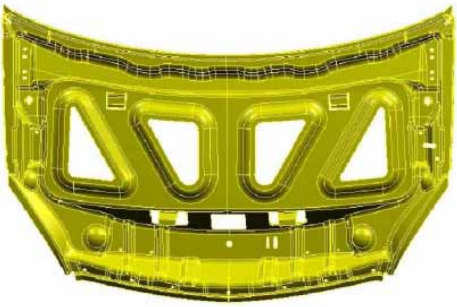


Figure 2. Traditionnal bonnet inner panel rib structure (Kerkeling, [4]).

The main problem with this type of structure is the presence of stiff points: at these points the HIC (or HPC) often exceeds the limit of 1000. With regards to pedestrian protection it would be preferable to have a uniform stiffness all over the bonnet. This is the reason why many automobile manufacturers have proposed new bonnet inner panels. One solution is to increase the number of ribs in the inner panel: this makes the stiffness more homogenous even though some stiff points remain. Another solution is to change the structure of the bonnet inner panel: multi-cones are drawn in the inner panel and glued to the outer panel. The main advantage of this solution is the ability to adjust the bonnet stiffness by several parameters: geometry of cones, cut-outs of cones and glue type. The Figure 3 illustrates these two bonnet inner panel structures [4]. The both solutions yield much more homogeneous stiffness distribution.

Figure 3. New bonnet inner panel structures:

- **top: inner panel with more ribs**
- **bottom: multi-cones inner panel (Kerkeling, [4]).**

The improvement of the capability for kinetic energy absorption for the bonnet without exceeding load limits for the pedestrian requires appropriate bonnet stiffness as well as an adequate deformation space under the bonnet. To achieve these requirements a new solution consists in setting actuators under the bonnet so as to raise the bonnet after sensors have detected a collision with pedestrian legs [5]. This system is illustrated in Figure 4.

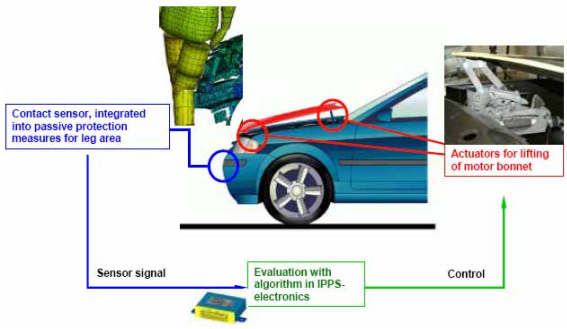


Figure 4. Passive protection system with sensors and actuators for lifting of motor bonnet (Scherf, [5]).

In the present study a solution that was designed to protect the pedestrian head against both the windscreen (with the A-pillars) and the bonnet is proposed. In the case of an automotive impact with

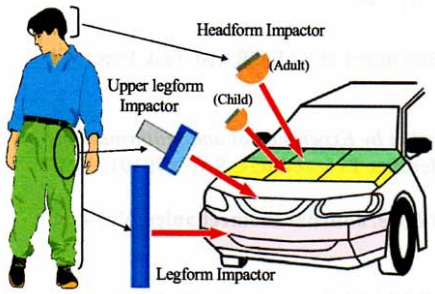
a pedestrian, contact or non-contact transducers record the impact at bumper level and transfer the information to actuators which open the bonnet and eject a dampened flexible protective panel which covers the windscreen and the pillars as shown in Figure 7. This active panel prevents the pedestrian's head to come into direct contact with the hard windscreen and provides a damping surface on which the head hits, diminishing the risk of head trauma. The plate can eventually be released a few hundreds of milliseconds after head impact in order to provide visibility to the car driver. During a vehicle-pedestrian accident the head does not always hit the windscreen: the impact point depends of several parameters, such as the vehicle speed or the pedestrian size. For this reason, a new bonnet structure with a protective panel under the upper panel of the bonnet has been designed.

The timing of this new system has first been evaluated with multibody pedestrian kinematics simulation in order to define the appropriate time for ejecting the protective panel. This new active protection system has then been modelled with finite element software and evaluated in terms of HIC and maximum acceleration (according to European Directive 2003/102/EC). Finally the new design has been evaluated numerically by modelling the head impact with an anatomical head FEM model. This permitted it to express the performance of the solution against biomechanical based head injury criteria. The same procedure has been used to evaluate the bonnet solution: first, according to European Directive, simulations with a standard pedestrian head have been carried out and secondly an anatomical head has been used to evaluate the bonnet in terms of biomechanical criteria.

REQUIREMENTS

Directive 2003/102/EC

In the Directive 2003/102/EC [2] two head forms are considered: a child head with a mass of 2.5 kg and an adult head with a mass of 4.8 kg. The impact angles of the head forms are set to 50° measured from the ground reference line for the child head and to 65° for the adult head. Both head forms should impact the bonnet with a velocity of 40 km/h.
In terms of head criteria the Directive 2003/102/EC advocates an HIC (Head Injury Criteria) lower than 1000 for both child and adult head forms, and a maximal linear acceleration of the centre of gravity of the head form (γ_{max}) between 405 and 495g for a child head form and between 337.5 and 412.5g for an adult head form. All these requirements are illustrated in Figure 5.

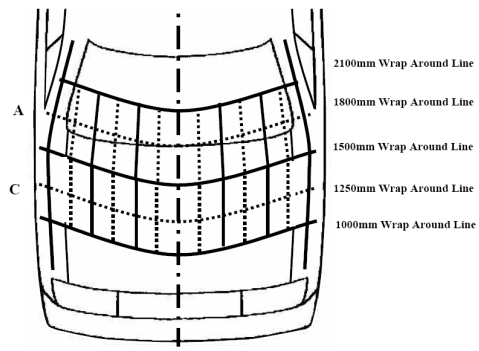


	Child head	Adult head
velocity	40 km/h	40 km/h
mass	2.5 kg	4.8 kg
HIC	1000	1000
γ_{max}	405 to 495g	337.5 to 412.5g

Figure 5. Directive 2003/102/EC requirements.

EuroNCAP

The impactor characteristics in EuroNCAP tests [3], in terms of mass and impact velocity, are the same as in Directive 2003/102/EC. Nevertheless the impact zones are more precisely defined in this protocol thanks to a splitting of the bonnet into 48 zones, as shown in Figure 6. This splitting enables the definition of two impact zones: one for the child head (C) and one for the adult head (A).
In term of injury criteria the one chosen is the HIC, the value of which must not exceed 1000.



	Child head	Adult head
velocity	40 km/h	40 km/h
mass	2.5 kg	4.8 kg
HIC	1000	1000

Figure 6. EuroNCAP Protocol requirements.

THE ACTIVE PROTECTION SYSTEM

Pedestrian Kinematics

The entire kinematics of the pedestrian was computed with a multibody approach (Madymo code) in order to fix the triggering of the system. Of particular importance was it to define the time range between bumper-leg contact and head – windscreen contact. Therefore a side impact between a pedestrian and a car has been carried out

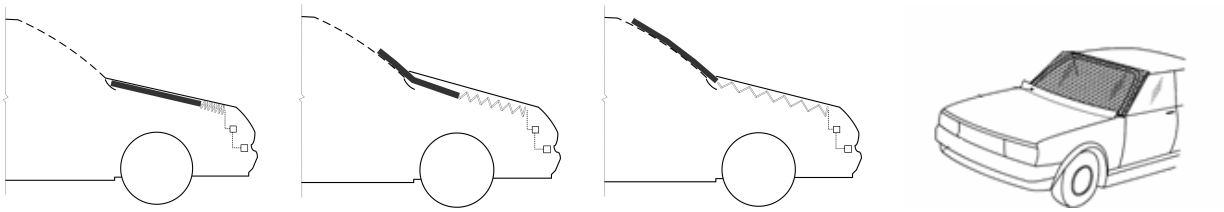
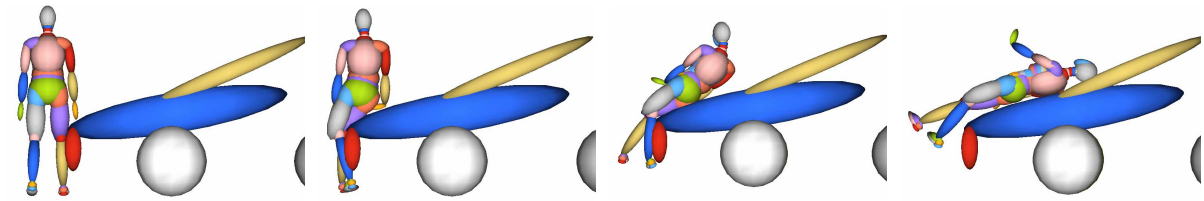


Figure 7. Illustration of the active pedestrian head protection system.



Time = 0 ms Time = 30 ms Time = 70 ms Time = 110 ms

Figure 8. Illustration of pedestrian kinematics when hit by a car for protective panel activation triggering purpose.

Figure 9. Illustration of the active pedestrian head protection system. The arrow in the picture points the active panel and its positioning over the windscreen pillar and roof rail.

with the initial velocity of the car set to 11.28 m.s^{-1}. The multi-body simulations show that an activation of the protective panel within 100 ms after the impact for approximately 150 ms is appropriate to avoid any direct head contact with the windscreen or the pillars as illustrated in Figure 8. It has been shown that this time range is efficient for typical vehicle speed, i.e. 11 m.s^{-1}.

The relevance of the proposed protective system has then been evaluated numerically with a windscreen model or panel model and two different head models, a standard pedestrian head and an anatomical head.

Head Modelling

Two head finite element models have been used for the head impact simulations: a standard pedestrian head model and an anatomical head FEM model for which injury criteria have been defined in earlier studies.

The pedestrian head model is the standard ISO model represented in Figure 10, which consists of three parts, i.e. an aluminium sphere, an aluminium plate and a rubber skin. Each of the three parts is modelled with an elastic law in conformity with values reported in Table 1. The head model is made of 3020 eight-node brick elements.

The anatomical head model is the ULP finite element head model [6]. This model, which is described more in details in the literature, includes the face, the dura matter (falx and tentorium), the subarachnoidal space, the brain and the cerebellum as shown on the Figure 11.

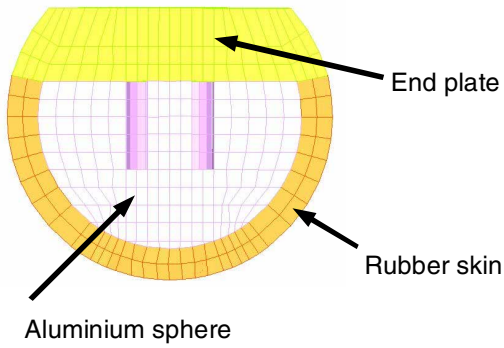


Figure 10. Standard ISO pedestrian head model.

Table 1. Mechanical properties of the different parts of the pedestrian head finite element model.

	ρ (kg.m^{-3})	E (MPa)	υ
Aluminium sphere	2800	200000	0.29
Rubber skin	1950	7	0.4
End plate	2800	200000	0.29

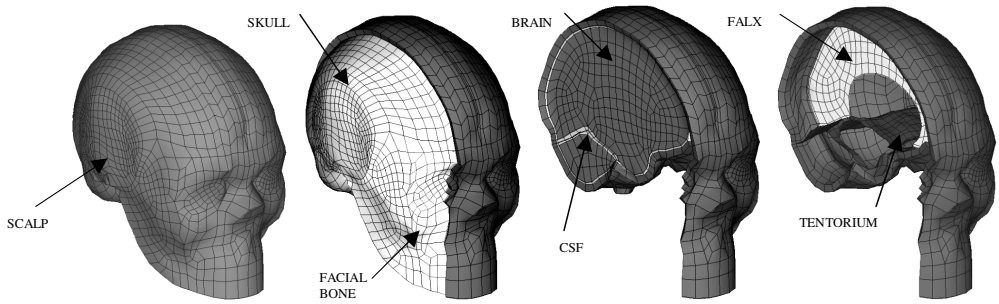


Figure 11. Illustration of the ULP finite element head model.

Tolerance limits for this model have been established by reconstructing 64 real world accident cases [7, 8] and summarized in Table 2. In order to evaluate the relevance of active protective panel on the windscreen, these limits will be used to predict the severity of head injuries and will be considered for further panel optimisation.

Table 2. Tolerance limits related to the ULP head FE model [8].

Mechanical parameter	Maximum strain energy in the CSF layer	Maximum Von Mises stress		Maximum strain energy in the skull
Injury	Subdural or Subarachnoid haematoma	Moderate DAI	Severe DAI	Skull fractures
Tolerance limit	4211 mJ	27 kPa	39 kPa	833 mJ

Windscreen Modelling

FEM Model

The windscreen consists of three layers (two glass layers and a PVB layer) whose characteristics are given in Table 3. Each material is supposed to have an elastic brittle behaviour [9]. The A-pillars have been considered as rigid bodies.
The damping material is represented by four layers of eight-node bricks (11.740 bricks with a total thickness of 30 mm). The chosen damping material is expanded polystyrene with an 85 kg.m^{-3} density whose behaviour law has been established through experimental compression tests. The stress strain behaviour in compression is illustrated Figure 12.

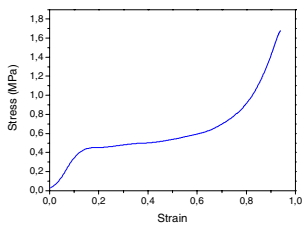


Figure 12. Stress strain curve of expanded polystyrene.

Table 3.Mechanical properties of the windscreen.

	ρ (kg.m^{-3})	E (GPa)	ν	ε_{t1}	ε_{m1}	t (mm)
Glass	2400	65	0.22	6.15e-4	1.23e-3	2.2
PVB	950	50	0.21	0	0	2

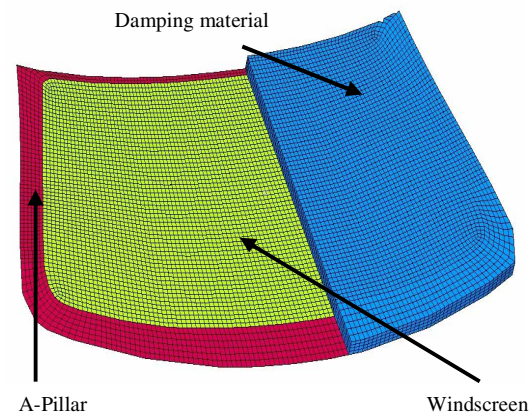


Figure 13. General view of pillar, windscreen and protective panel mode. Protective panel is only partially represented.

Head Impact Conditions

Head impacts have been carried out to evaluate the new protective system first in terms of HIC with the pedestrian head model and then in terms of biomechanical criteria with the ULP head model. The chosen initial conditions for the simulations are close to a typical pedestrian head impact condition as defined here after. The model was impacted at the junction between the windscreen and the A-pillar, with an impact angle of 65° and an initial velocity of 5 m.s^{-1}. Figure 14 represents the head before the impact. This impact condition is considered to be the most significant as it considers a quite critical situation.

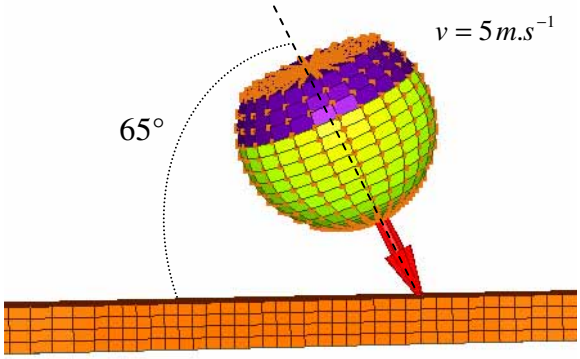


Figure 14. Illustration of the pedestrian standard head impact initial condition on the windscreen or protective panel: the standard head has an initial velocity of 5 m.s^{-1} with an impact angle of 65° with the windscreen.

Bonnet Modelling

FEM Model

The numerical model of the bonnet is characterised by the following components: the upper panel represented by 4032 four nodes shell, the protective panel represented by three layers of eight-nodes brick (12 096 bricks with a total thickness of 30 mm) and the engine block modelled with 4019 four nodes shell elements and 2664 eight-nodes brick elements. The different parts of the bonnet model are illustrated in Figure 15.

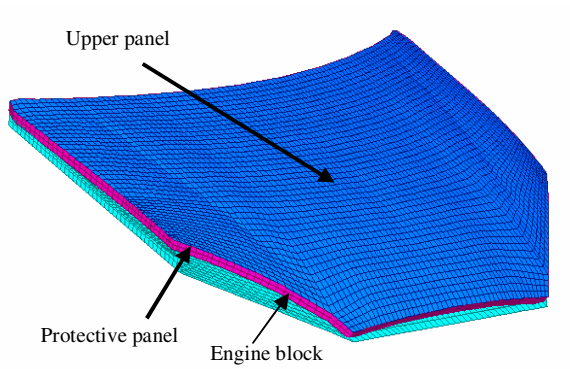


Figure 15. General view of upper panel (blue), protective panel (magenta) and engine block (green).

The chosen material for the upper panel is aluminium which is supposed to have an elastic plastic behaviour, the characteristics of which are given in Table 4. The protective panel material is expanded polystyrene, the characteristics of which are the same as those used for the windscreen model. The engine block has been considered as rigid body.

The boundary conditions are one of the most important parameters that influence the behaviour of the bonnet. The upper panel of the bonnet FEM model is fixed in two points in the front of the bonnet and the engine block is fixed.

Table 4. Mechanical properties of the bonnet upper panel.

ρ (kg.m^{-3})	E (MPa)	υ	σ_e (MPa)	b (MPa)	n	σ_m (MPa)
2700	65000	0.3		567	0.623	345

Head Impact Conditions

The chosen initial conditions for the simulations are those prescribed by the EuroNCAP Pedestrian Testing Protocol. The head was impacted in the middle of the bonnet, with an initial velocity equal to 11.1 m.s^{-1} and an impact angle measured from the ground reference equal to 65°. The position of the head before the impact is represented in Figure 16.

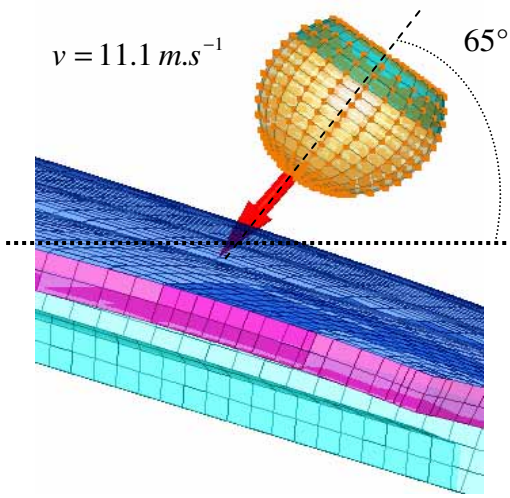


Figure 16. Illustration of the initial impact conditions of the standard head model on the bonnet: the initial velocity is equal to 11.1 m.s^{-1} and the impact angle is 65° measured from the ground reference.

Bonnet Evaluation Method

Based on 425 EuroNCAP tests, procedures have been defined to built stiffness corridors for the different vehicle front parts area (bumper, bonnet and windscreen). These corridors have been obtained by recording the normal acceleration of the centre of gravity of the head: this acceleration is integrated twice to get the displacement and multiplied with the impactor mass to get the normal impact force. All the obtained force-displacement curves have been classified into three categories defined by EuroNCAP [11]. The bonnet FEM model is considered as "yellow bonnet", i.e. its HIC is between 1000 and 1350 and its force-displacement curve is inside the corridor represented in Figure 17.

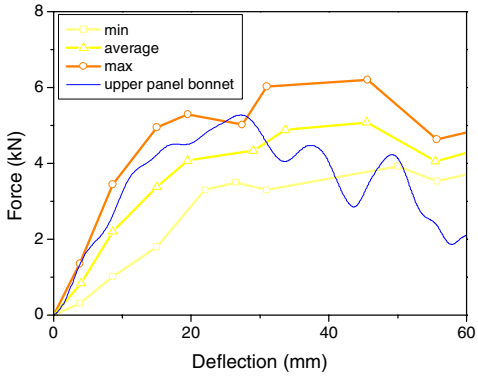


Figure 17. Simplified stiffness corridor for a "yellow bonnet" (HIC between 1000 and 1350) and proposed upper panel stiffness.

RESULTS

Windscreen Results

In order to demonstrate the improvement brought by this new system all simulations have been done with and without the protective panel. Radioss code has been used for this purpose. The simulations have been carried out first with regards to standards in terms of HIC and maximal linear acceleration. The results are given in Figure 18 and Figure 20. T +hese results demonstrate the real improvement brought by the proposed system: as the HIC value decreases significantly when a protective panel is added to the windscreen and the A-pillars. The same improvement can be observed in terms of maximal linear acceleration of the centre of gravity as a whole HIC value has been divided by about 8 and remains under tolerance level when the protective panel is activated.

Same simulations have been carried out with the ULP model in order to predict the potential injuries during the impact of the head against the windscreen alone and the windscreen with the protective panel. The results are reported in Figure 21 in terms of maximum strain energy in the skull and in terms of maximum strain energy in the CSF layer and intracranial Von Mises shearing stress. The recommended tolerance limit for the maximum strain in the CSF layer is 4211 mJ, which is equivalent to an injury risk of 50% of subdural haematoma.

The results show that, without damping material, the maximum strain energy in the CSF layer reaches 7370 mJ (this implies a significant risk of subarachnoid or subdural haematoma) whereas this value decrease to 755 mJ with the protective panel, eliminating the SDH risk.

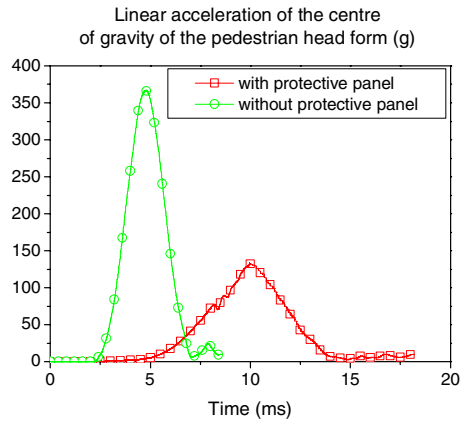


Figure 18. Evolution of the linear acceleration of the standard head form centre of gravity during impact with and without protective panel over the windscreen.

The same trend can be observed for the maximum strain energy in the skull as the initial value of 2038 mJ without damping material decreases to 95 mJ when adding the panel, eliminating thus the skull fracture risk.

The results in terms of Von Mises stress are given Figure 21 (c). Here again the risk of moderate neurological injury has been eliminated by the protective system.

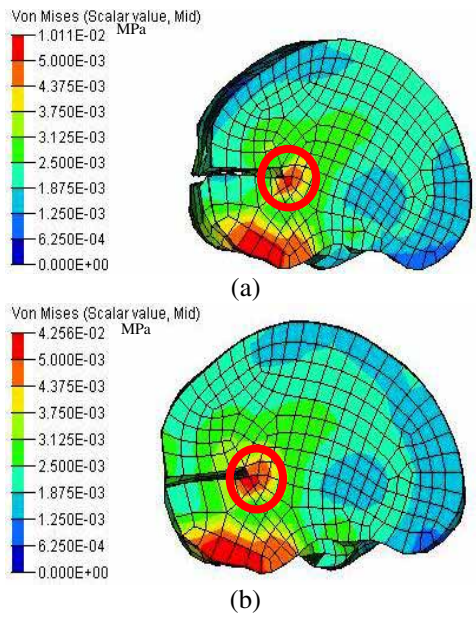


Figure 19. Localisation in sagittal section of the maximum Von Mises stress response computed with the ULP head model impacting the windscreen (a) and the windscreen with protective panel (b).

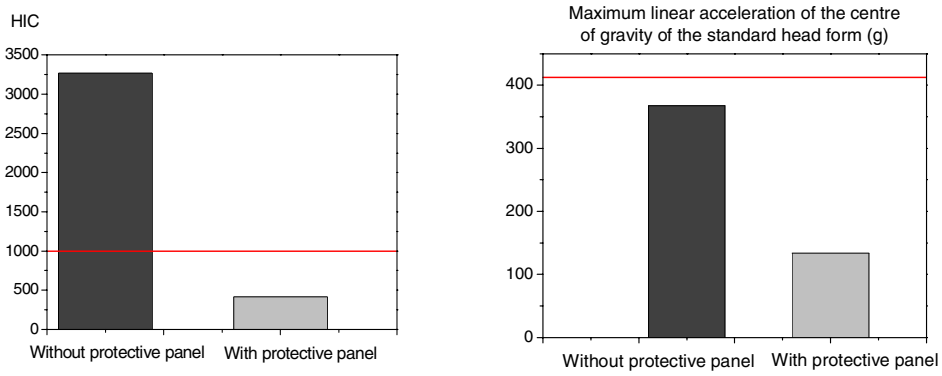


Figure 20. HIC and γ_{max} results for the two cases (with and without damping material).

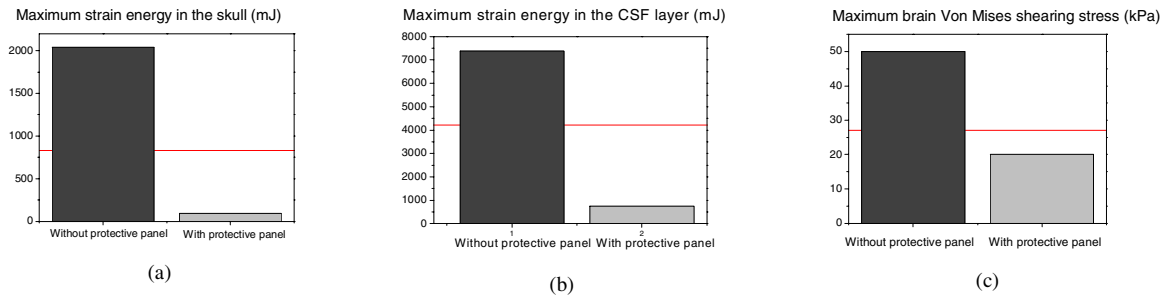


Figure 21. Intracranial head response computed with the ULP head model impact against the windscreen (black) and the windscreen with the protective panel (grey) in terms of strain energy in the skull (a), strain energy in the CSF layer (b) and in term of maximum brain Von Mises shear stress (c).

In Figure 19 the distribution of the intracranial Von Mises stress is shown. The maximum area is situated at the same place and only the maximum values vary.

Bonnet Results

In the same way as for the windscreen, all the simulations have been done with and without the protective panel. The bonnet has first been evaluated with regards to standards in terms of HIC and maximal linear acceleration. The results are given in Figure 22. The results in terms of HIC show the improvement due to the adding of a protective panel under the bonnet: with the panel the HIC value is 989 and is under the recommended limit of 1000. The same trend can be observed in terms of maximal linear acceleration of the centre of gravity of the head.

The two situations (with and without protective panel) have always been simulated with regards to biomechanical criteria. The results are reported in Figure 23 in terms of maximal strain energy in the skull, maximal strain energy in the CSF layer and in terms of maximum brain Von Mises shear stress. In the case of an upper panel without the protective panel, all the results are over the tolerance limits. The maximum strain energy in the skull reaches 13667 mJ, the limit being 833 mJ (Figure 23 (a)), so there is a very high risk of skull fracture. The maximum strain energy in the CSF layer is 6282 mJ whereas the limit is 4211 mJ (Figure 23 (b)) which corresponds to a high risk of subdural or subarachnoidal haematoma. Finally the maximum brain Von Mises shear stress reaches the value of 42 kPa (limit being 39 kPa) for severe neurological injuries (Figure 23 (c)). All these values decrease significantly when adding the protective panel under the bonnet: the maximum strain energy in the shull and in the CSF layer stays under the tolerance limits, and in the skull, even though the value of the maximum strain energy has significantly decreased, it remains slightly above the limit. Figure 24 shows the distribution of the intracranial Von Mises stress. The area of the maximum Von Mises stress varies when adding the protective panel: this area is situated on the top of the brain for simulations without the protective panel and inside the brain with the protective panel.

The numerical study of the proposed solution showed a real improvement when adding a damping panel on the windscreen or under the bonnet, in terms of HIC and maximum linear acceleration as well as in terms of biomechanical criteria.

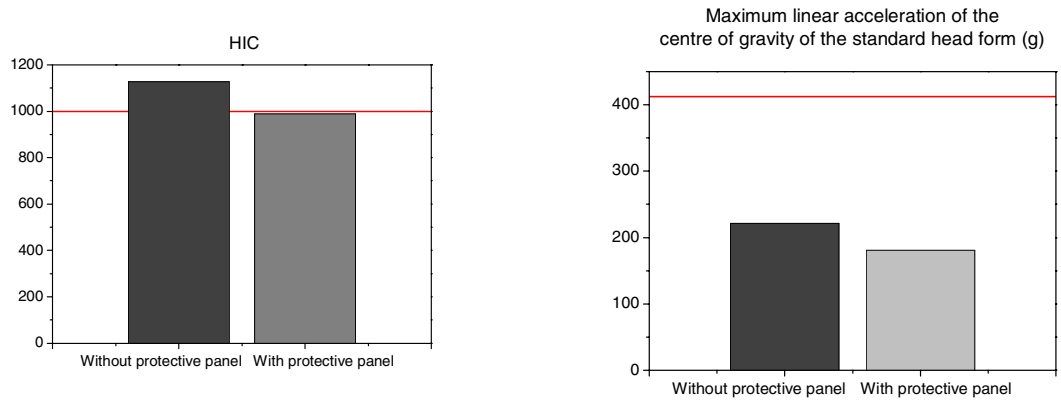
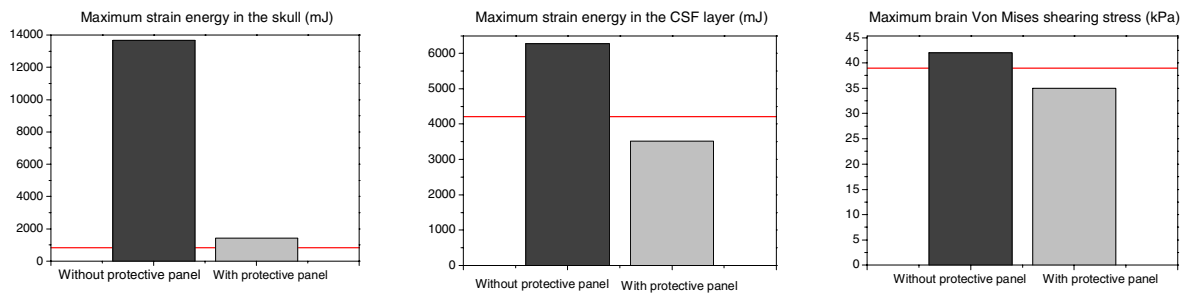
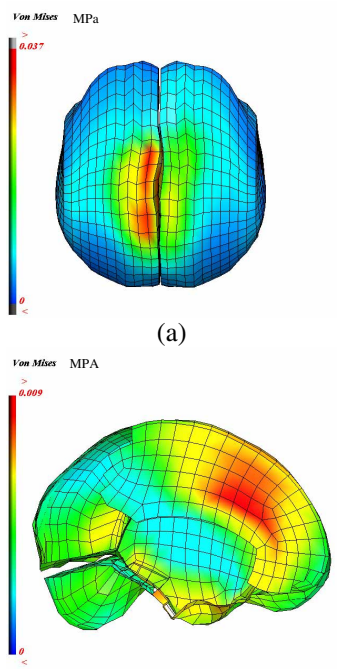


Figure 22. HIC and γ_{max} results for the two cases (with and without damping material).



(a) (b) (c)

Figure 23. Intracranial head response computed with the ULP head model impact against the bonnet (black) and the bonnet with the protective panel (grey) in terms of strain energy in the skull (a), strain energy in the CSF layer (b) and in term of maximum brain Von Mises shearing stress (c).



(a)

(b)

Figure 24. Localisation of the maximum Von Mises stress response computed with the ULP head model against the bonnet (a) and the bonnet with protective panel (b).

CONCLUSION AND DISCUSSION

The proposed innovative solution for protection of the pedestrian head during impacts on the windscreen or the pillars has been shown to be efficient if propelled in the 100 – 250 ms time frame. It decreases significantly the risk of head trauma for these pedestrians, in terms of HIC criteria as well as with regards to biomechanical criteria. The same improvements have been obtained with the new bonnet solution: when adding a protective panel under the bonnet, the risk of head injuries decreases importantly. Moreover these inventions have a huge economical and social interest as safety is a society priority but also an important sale argument.

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