PEDESTRIAN SAFETY ENHANCEMENT USING NUMERICAL METHODS

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ABSTRACT

This study aims at investigating head injury mechanisms for brain injuries, subdural or subarachnoidal haematoma (SDH or SAH) and skull fractures in adult pedestrian real world accidents by in-depth accident analysis and accident numerical reconstruction. Nine accident cases were carried out using a multi-body system pedestrian and cars' models to acquire the head impact conditions such as head impact velocity, position and orientation against the car's bonnet or windscreen. These impact conditions were then imposed on a head, car's windscreen and bonnet finite element model in order to calculate different mechanical parameters that are sustained by each victim during the impact. These calculated head stresses, strains and energies were then correlated with the observed injury patterns and compared to existing and available head injury mechanisms and tolerance limits. The accident investigation reports and pedestrian kinematics before the head impact came from the University of Birmingham (United Kingdom), INSIA (Spain) and DaimlerChrysler (Germany). They were worked out in the framework of an FP6 Integrated Project on Advanced Protection Systems (APROSYS). The head, the bonnet and the windscreen FEM, the injury mechanisms and tolerance limits have been developed at the University of Strasbourg (France) in a recent past. The reconstruction results show that the numerical tools employed predicted the observed injuries well. Nevertheless, it should be pointed out that the numerical tools used can only predict injuries reliably if both the pedestrian and vehicle side are modelled appropriately, i.e. with detailed finite element structures with well validated material and contact stiffness data. Brain neurological injuries were well correlated with brain Von Mises stress. Brain contusions occurred through high brain pressures. Skull fractures and SDH or SAH were well correlated with the global strain energy of the skull and of the brain/skull interface respectively. It has been concluded that these results showed that such numerical models are good tools to predict human head injuries. They will therefore be useful to improve the head protection devices i.e. the design, the conception, the evaluation and the optimization of cars' windscreens and bonnets against well defined injury criteria.

INTRODUCTION

In road traffic accidents involving cars and pedestrians, head injuries are one of the most common injury types and the main cause of severe fatalities. Therefore, a particular attention has to be paid to the pedestrians' head protection in road traffic in order to reduce these severe fatalities. Among others, efforts can be done to improve the protection ability of the cars' windscreens and bonnets. The following described methodology, that has been led during an Integrated Project of the 6th Framework (Advanced Protective Systems: APROSYS), was designed to provide human head injuries numerical prediction tools.

METHODOLOGY

After having replicated the pedestrian's body kinematics for different real world accident cases by using MADYMO software, it will be focused in that work on the head impact against the considered part of the striking car (i.e. car's windscreen or bonnet). For that purpose we will use a finite element model (FEM) of the human head as well as one of the car's windscreen and bonnet. These different real world accidents numerical reconstructions will allow us to calculate a great deal of mechanical parameters the victims will sustain. These calculated mechanical parameters will then be compared to existing human head injury mechanisms and tolerance limits. Indeed, it will be showed that such numerical models are able to predict head injuries. In fact, it will be interesting to compare the predicted injuries to the observed injuries in order to demonstrate the ability of such numerical models to predict injuries. More generally, it will be shown how powerful such numerical tools can be in order to design, to evaluate, to validate and to optimise car structures against physiopathological injury criteria.

MATERIALS

FEM of the human head

The FEM of the human head that will be used in that part the study is the one developed at the University Louis Pasteur of Strasbourg in the past few years. That model is detailed in [KAN 97] in its first version as well as is in [WIL 03] in its more updated version. It is usually called the ULP FEM of the human head. A much more detailed description is proposed below. Such numerical methods and models have been largely used I the past few years by [LOV 75], [GEN 85], [THI 90], [MEN 92], [ZHO 96], [AND 00], [KIN 03] and [TAK 03]. The ULP FEM of the head is three dimensional with a continuous mesh. The meshing of the model has been achieved by using the HYPERMESH software. It contains 13208 elements divided in 10395 brick elements and 2813 shell elements and it weights 4800 g. This FEM includes the main anatomical components of the head which are illustrated in terms of mesh properties and mechanical behaviour in Table 1: the falx of the brain and the tentorium of the cerebellum, the brain/skull interface, the brain and the cerebellum, the skull, the face and the surrounding skin. The Table 1 gives also an illustration of each anatomical component which is modelled. The ULP FEM of the head is validated against experimental data from [NAH 77] and [TRO 92] in terms of brain accelerations and pressures and against experimental data from [YOG 94] regarding skull bones fractures. The ULP FEM of the head is especially validated in case of long duration high dampened impacts that last more than 15 ms and that usually reveal an important rotational acceleration component. This validation is refined by [BAU 01] who modelled the cerebral spinal fluid flow through the brain/skull interface and the lateral ventricles by introducing into the FEM a fluid solid coupling behaviour thanks to an arbitrary Eulerian Lagrangian formulation. That model has been developed by using the RADIOSS CRASH software. Of particular importance and rarely modelled, it must be underlined that the ULP FEM of the human head is able to predict skull fracture thanks to a Tsai Wu criterion. Such a criterion is based on the maximal tension and compression stresses that are sustained in shell elements. In terms of finite elements, if an element reaches the allowed maximal values, it is deleted. This means that it is taken out of the model from the next time step. That failure criterion is also detailed in Table 1.

FEM of the car’s windscreen

In order to represent a car’s windscreen a (1200 mm x 800 mm) rectangular surface is regularly meshed by using 1536 three layered composite shell elements. Both external laminated glass layers which have a thickness of 2.2 mm are linked together through an internal poly vinyl butyl membrane which has a thickness of 1 mm. The three layered composite shell elements of the windscreen’s border are fixed to a rigid frame in order to represents the car’s mass and inertia. These border elements are free to translate but they are fixed in their three rotational degrees of freedom. Eventually added masses are set on these border elements of the windscreen in order to represent the mass and the inertia of the car. Nevertheless, that added mass has no significant influence on the dynamic response of the head during the impact as shown in a recent internal study. The mechanical behaviour adopted for both external laminated glass layers of the windscreen is an elastic plastic brittle law that allows rupture. The linking plastic membrane’s mechanical behaviour is assumed to be linear elastic. Both mechanical behaviours rely on the experimental data determined by [HAV 75] and detailed in Table 2. The validation of the windscreen FEM is based on a comparison between the damages which are observed and predicted by the FEM in a specific and standard head impact configuration. This windscreen FEM relies on the one developed by [MUK 00].

FEM of the car’s bonnet

In order to model a car’s bonnet, a (1200 mm x 1500 mm) rectangular surface has been regularly meshed by using 4500 shell elements. The thickness of each element is set to 1 mm. These shell elements’ border are fixed to a rigid frame in order to represents the car’s mass and inertia as it has been done for the windscreen. These border elements are free to translate but they are fixed in their three rotational degrees of freedom. Eventually added masses are set on these border elements of the car’s bonnet in order to represent the mass and the inertia of the car. Nevertheless, that added mass has no significant influence on the dynamic response of the head during the impact as for the windscreen. The mechanical behaviour adopted for the car’s bonnet shell elements is elastic plastic (Johnson Cook mechanical behaviour law) as detailed in Table 3 for one case. It must be underlined that the contact stiffness characteristics between the pedestrian head and the vehicle at the head impact spot were not available and were therefore roughly estimated through EuroNCAP test data on alternative impact points. Furthermore, the EuroNCAP impactor test data has not been available for the vehicles involved in the accidents GP001 and GP002 for example such that the test data of a similar vehicle was used in these cases – VW Audi A3 instead of VW Golf 3 and VW Polo respectively.

Table 1.
ULP FEM of the human head. Mesh properties and mechanical behaviour.

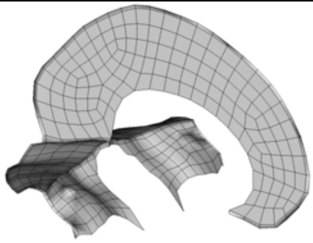
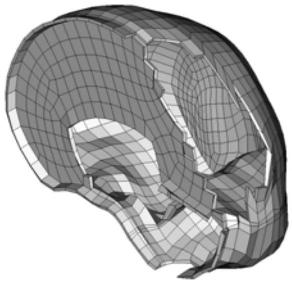
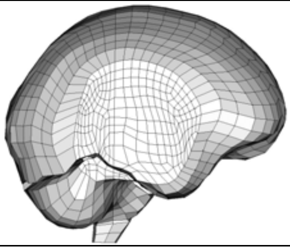
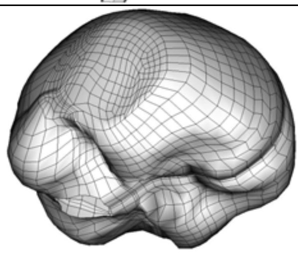
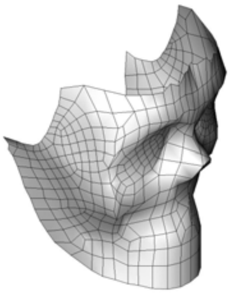
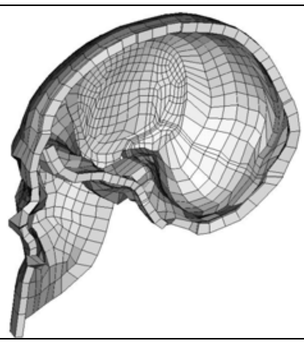
Anatomical Segment	Illustration	Mesh	Mechanical Behaviour	Mechanical Characteristics	Mechanical Characteristics
Falx of the Brain and Tentorium of the Cerebellum		471 shell elements	Linear Elastic	e = 1 mm ρ = 1140 kg/m^3 E = 31.5 MPa ν = 0.45	/
Brain/skull Interface		2591 brick elements	Linear Elastic	ρ = 1040 kg/m^3 E = 0.012 MPa ν = 0.49	/
Brain and Cerebellum		5508 brick elements	Elastic Plastic	ρ = 1040 kg/m3 K = 1125 MPa G_0 = 0.049 MPa G_{inf} = 0.0167 β = 145 s^{-1}	/
Skull		1813 three layered composite shell elements	Elastic Plastic Brittle	**Cortical** e = 2 mm ρ = 1900 kg/m^3 E = 15000 MPa ν = 0.21 K = 6200 MPa UTS = 90 MPa UTC = 145 MPa	**Trabecular** e = 3mm ρ = 1500 kg/m^3 E = 4600 MPa ν = 0.05 K = 2300 MPa UTS = 35 MPa UTC = 28 MPa
Face		529 shell elements	Linear Elastic	e = 10 mm ρ = 2500 kg/m^3 E = 5000 MPa ν = 0.23	/
Skin		2296 brick elements	Linear Elastic	ρ = 1000 kg/m^3 E = 16.7 MPa ν = 0.42	/

Table 2.
FEM of the car’s windscreen. Mechanical behaviour.

Structure	ρ [kg/m3]	E [mm]	E [GPa]	ν	ε_{rt}	ε_{mt}	σ_{el} [MPa]
Glass	2400	2.2	65	0.22	0.000615	0.00123	3.8
PVB	950	1	50000	0.22	/	/	/

Table 3.
FEM of the car’s bonnet example. Mechanical behaviour.

Structure	ρ [kg/m3]	E [mm]	E [GPa]	ν	a	b	n	σ_{max} [MPa]
Bonnet	2700	1	69	0.3	120	567	0.623	345

Human head injury mechanisms and tolerance limits

Introduction

A first step would be to define the injury types. Even this classification is not definitive due to terminology differences which may exist. The second step will be to define the injury parameters, i.e. the mechanical parameters which lead a type of injury. At this level several assumptions exist in the literature. Finally a threshold value for each injury parameter must be defined in order to become a tolerance limit to a specific injury. This difficult exercise is based either on cadaver tests, animal tests or more recently on accident reconstruction. Tolerance limits estimation on cadaver is restricted to skull fracture. Injury analysis based on animal tests is a critical issue because animal acceleration field, even scaled to the human dimension and mass will not lead to similar brain loading conditions due to the shape difference. Finally real world accident simulation is some times critical because of the lack of accident data accuracy.

Human head injuries criteria

In order to demonstrate the ability of the previously described numerical tools to predict human head injuries, the calculated mechanical parameters can be compared to existing human head tolerance limits. In fact, human head injury mechanisms and tolerance limits can be obtained by using FEM as detailed in a great variety of past studies. In our specific study, the FEM of the human head developed at the University Louis Pasteur of Strasbourg and described previously has been used. That model has allowed us, in previous studies achieved by [WIL 03] and [WAR 80], to establish human head injury mechanisms and tolerance limits as follows:

- Brain contusions (CONT) occur when brain pressure reaches values of 200 kPa according to [WAR 80].
- Brain neurological injuries such as diffuse axonal injuries or haemorrhagic injuries (DAI) occur when brain Von Mises shearing stress reaches values of 18 kPa (for moderate injuries (MOD DAI)) and 38 kPa (for severe injuries (SEV DAI)) according to [WIL 03].
- Subdural haematoma (SDH) or subarachnoidal haematoma (SAH) occur when the global strain energy of the brain/skull interface reaches values of 5500 mJ according to [WIL 03].
- Skull fractures (SF) occur when the global strain energy of the skull reaches values of 2200 mJ according to [WIL 03].

It must be kept in mind and strongly underlined that these injury mechanisms and tolerance limits are linked to a specific head FEM which is the one of ULP. It is common for other FEM to predict injuries thanks to other mechanical parameters like strains, displacements, or strain rates. It also usual for other FEM to use the same mechanical parameters as the ones proposed by ULP but with other values relatively to the tolerance limits. Indeed, the inferred tolerance limits are very sensible to the geometry of the model as well as to the mechanical behaviour of each anatomical feature which is modelled. The Table 4 reminds the different human head injuries mechanisms and tolerance limits. Indeed, it has been previously showed that FEM of the human head are able to predict injuries thanks to a correlation between calculated mechanical parameters on the one hand and injuries occurrence on the other hand ([WIL 03]). For each calculated mechanical parameters (which is a specific injury indicator) there exists a range of values for which:

- No specific injury is predicted.
- A specific injury is possible (but the victim can also remain uninjured).
- A specific injury is clearly predicted.

These different ranges are detailed in the Table 4. For example, if the calculated brain pressure remains under 160 kPa, no injury is predicted. If that calculated brain pressure is between 160 kPa and 240 kPa, it will not be possible to indicate if brain contusions will occur or not. Eventually, if the calculated brain pressure exceeds 240 kPa, brain contusions will be predicted without any doubt.

Table 4.
Human head tolerance limits ranges

Calculated mechanical parameter and injury indicator	Injuries	Uninjured	Possibly injured	Injured
Brain pressure [kPa]	Brain contusions (CONT)	< 160	> 160 < 240	> 240
Brain Von Mises stress [kPa]	Brain moderate neurological injuries (MOD DAI)	< 14	> 14 < 22	> 22
Brain Von Mises stress [kPa]	Brain severe neurological injuries (SEV DAI)	< 30	> 30 < 46	> 46
Global strain energy of the brain/skull interface [mJ]	Subdural or subarachnoidal haematoma (SDH or SAH)	< 4300	> 4300 < 6500	> 6500
Global strain energy of the skull [mJ]	Skull fracture (SF)	< 1700	> 1700 < 2700	> 2700

Real world accidents reconstruction

Nine real world accidents are considered in that study:

- One cyclist accident that has been collected and worked out at the University of Birmingham (BASC – United Kingdom) : BASC cyclist 001 (BC001). It has to be underlined that the cyclist did not wear any helmet. It is therefore possible to include such a vulnerable road user in that study and consider him as a pedestrian. In fact, from a head injury point of view, it is not critical to be a real pedestrian or another road traffic user. Nevertheless, if that cyclist would have worn a helmet, a helmet FEM would have been developed is order to reconstruct numerically that accident.
- Eight pedestrians' accidents that has been collected and worked out at the University of Birmingham (BASC – United Kingdom), DaimlerChrysler (GIDAS – Germany) and the Institute for Automobile Safety (INSIA – Spain) respectively:
  - BASC:
    - BASC pedestrian 002 (BP002)
    - BASC pedestrian 022 (BP022)
    - BASC pedestrian 023 (BP023)
  - GIDAS:
    - GIDAS pedestrian 001 (GP001)
    - GIDAS pedestrian 002 (GP002)
  - INSIA:
    - INSIA pedestrian 002 (IP002)
    - INSIA pedestrian 003 (IP003)
    - INSIA pedestrian 006 (IP006)

For each of these accident cases, one of the aims of the MADYMO software replication was to establish the relative position and velocity between the head and the windscreen or the bonnet of the striking car at the time of the head impact. The ULP FEM of the head is then positioned towards the windscreen or the bonnet in respect to the MADYMO software calculated position just before the head impact. The initial relative velocity between the head and the windscreen or the bonnet is then set on the nodes of the head on the hand and on the nodes of the windscreen or the bonnet on the other hand. That numerical analysis is done thanks to the RADIOSS CRASH finite element code. The pre processing and the post processing is achieved on a SUN SUNBLADE 150 workstation. The engine is running on a DEC ALPHA SERVER. Each accident case is run over a duration of thirty milliseconds. Such a running duration corresponds to a CPU time of eight hours approximately. The different mechanical parameters that are calculated during the head impact are the following:

- Brain pressure.
- Brain Von Mises shearing stress.
- Global strain energy of the brain/skull interface.
- Global strain energy of the skull.
- Deleted elements of the skull (in order to check the ability of the model to predict skull fractures).

It is important to notice that for some of these cases, a secondary ground impact occurred (BP002, BP022, BP023, GP001 and GP002). It is possible for that secondary ground impact to generate injuries too. In the undergoing study, that impact is not presented. It remains a perspective for ongoing studies. Thus, an observed injury that may not be predicted by the numerical tools that are developed in that study may occur in the secondary ground impact. This has obviously to be check in future studies and compared to the first impact on the vehicle's windscreen or bonnet.

RESULTS

Introduction

For each accident case, a table shows the calculated mechanical parameters that lead to the predicted injuries as well as the observed injuries. If the observed injury is indeed predicted, a green square appears. And if the observed is not predicted, a red square appears. Moreover, if a star appears in the predicted injury column, this means that it is not really possible to decide whether or not the injury is predicted: there could be an injury but there could also not be an injury

BASC cyclist 001 (BC001)

Table 5.
BC001 numerical simulation results.

Calculated mechanical parameter	Maximal value	Observed injury	Predicted injury
Brain pressure [kPa]	150	NO CONT	NO CONT
Brain Von Mises stress [kPa]	55	SEV DAI	SEV DAI
Global strain energy of the brain/skull interface [mJ]	2923	SAH	NO SAH
Global strain energy of the skull [mJ]	790	SF	NO SF

The Table 5 shows the results of the numerical accident reconstruction of case BC001. In that cyclist accident case, the numerical model predicts well the brain neurological injuries (which are severe) but is unable to predict the subarachnoidal haematoma as well as the skull fracture. Both these injuries can not occur in the secondary ground impact since such an impact is not mentioned in the accident report. Moreover, the model represents well the absence of injuries as brain contusion in that case.

BASC Pedestrian 002 (BP002)

Table 6.
BP002 numerical simulation results.

Calculated mechanical parameter	Maximal value	Observed injury	Predicted injuryt
Brain pressure [kPa]	130	CONT	NO CONT
Brain Von Mises stress [kPa]	25	SEV DAI	MOD DAI
Global strain energy of the brain/skull interface [mJ]	2261	SAH	NO SAH
Global strain energy of the skull [mJ]	2167	SF	SF*

The Table 6 shows the results of the numerical accident reconstruction of case BP002. In that pedestrian accident case, it seems that the brain contusions and severe neurological injuries as well as the subarachnoidal haematoma are linked to the secondary ground impact since the first impact simulation does not predict these injuries. In fact, such a secondary ground impact is mentioned in the accident report. Nevertheless, the observed skull fracture is well predicted by the simulation even if it could be possible for the victim not to sustain skull fractures according to the prediction criterion.

BASC pedestrian 022 (BP022)

The Table 7 shows the results of the numerical accident reconstruction of case BP022. In that pedestrian accident case, the victim sustained brain contusions, brain severe neurological injuries, a subdural haematoma and a skull fracture. Nevertheless, none of these injuries is predicted by the model. Brain moderate neurological injuries are possible but not sure. Therefore, it seems clear that the whole injuries sustained by that victim may be linked to the secondary ground impact which is mentioned in the accident report. Another hypothesis could be that the complete accident reconstruction process is wrong and led to wrong inputs for the FEM of the human head, the car's windscreen and the car's bonnet. In fact, wrong data may have been collected on the accident scene or badly interpreted.

Table 7.
BP022 numerical simulation results.

Calculated mechanical parameter	Maximal value	Observed injury	Predicted injury
Brain pressure [kPa]	110	CONT	NO CONT
Brain Von Mises stress [kPa]	18	SEV DAI	MOD DAI*
Global strain energy of the brain/skull interface [mJ]	1601	SDH	NO SDH
Global strain energy of the skull [mJ]	461	SF	NO SF

BASC pedestrian 023 (BP023)

Table 8.
BP023 numerical simulation results.

Calculated Mechanical parameter	Maximal value	Observed injury	Predicted injury
Brain pressure [kPa]	1590	CONT	CONT
Brain Von Mises stress [kPa]	80	SEV DAI	SEV DAI
Global strain energy of the brain/skull interface [mJ]	21737	NO SDH	SDH
Global strain energy of the skull [mJ]	25642	SF	SF

The Table 8 shows the results of the numerical accident reconstruction of case BP023. In that pedestrian accident case, each specific observed injury is predicted by the simulation shall it be brain contusions, severe brain neurological injuries or skull fractures. Besides, the model predicts a subarachnoidal or subdural haematoma whereas such a vascular injury is not observed.

GIDAS pedestrian 001 (GP001)

Table 9.
GP001 numerical simulation results.

Calculated mechanical parameter	Maximal value	Observed injury	Predicted injury
Brain pressure [kPa]	65	NO CONT	NO CONT
Brain Von Mises stress [kPa]	10	NO DAI	NO DAI
Global strain energy of the brain/skull interface [mJ]	651	NO SDH	NO SDH
Global strain energy of the skull [mJ]	1618	NO SF	NO SF

The Table 9 shows the results of the numerical accident reconstruction of case GP001. In that pedestrian accident case, no injuries are observed. That fact is well represented by the impact simulation. It has to be noticed that a secondary ground impact is mentioned in the accident report. It will therefore be important to check whether or not that secondary ground impact generates injuries even if the victim did not sustain any injury.

GIDAS pedestrian 002 (GP002)

Table 10.
GP002 numerical simulation results.

Calculated mechanical parameter	Maximal value	Observed injury	Predicted injury
Brain pressure [kPa]	126	NO CONT	NO CONT
Brain Von Mises stress [kPa]	16	MOD DAI	MOD DAI*
Global strain energy of the brain/skull interface [mJ]	2305	NO SDH	NO SDH
Global strain energy of the skull [mJ]	4818	NO SF	SF

The Table 10 shows the results of the numerical accident reconstruction of case GP002. In that pedestrian accident case, the model predicts well the absence of brain contusions and subarachnoidal or subdural haematoma. None skull fracture is observed but this is not predicted in the impact simulation since the impact simulation predicts a skull fracture which is not observed in reality. Moreover, the moderate brain neurological injuries are well predicted by the simulation even if it could be possible for the victim to not sustain such an injury.

INSIA pedestrian 002 (IP002)

Table 11.
IP002 numerical simulation results.

Calculated mechanical parameter	Maximal value	Observed injury	Predicted injury
Brain pressure [kPa]	100	NO CONT	NO CONT
Brain Von Mises stress [kPa]	18	MOD DAI	MOD DAI*
Global strain energy of the brain/skull interface [mJ]	225	NO SDH	NO SDH
Global strain energy of the skull [mJ]	1258	NO SF	NO SF

The Table 11 shows the results of the numerical accident reconstruction of case IP002. In that pedestrian accident case, the only injury that is sustained by the victim (i.e. moderate brain neurological injuries) is well predicted by the model. Moreover, the model predicts well the absence of brain contusions, subarachnoidal or subdural haematoma as well as skull fractures. None secondary ground impact is mentioned in the accident report.

INSIA pedestrian 003 (IP003)

The Table 12 shows the results of the numerical accident reconstruction of case IP003. In that pedestrian accident case, the only injury that is sustained by the victim (i.e. moderate brain neurological injuries) is predicted by the model but is only predicted in a severe range (which is possible but not yet sure). Moreover, the model predicts well the absence of brain contusions, subarachnoidal or subdural haematoma as well as skull fractures. None secondary ground impact is mentioned in the accident report.

Table 12.
IP003 numerical simulation results.

Calculated mechanical parameter	Maximal value	Observed injury	Predicted injury
Brain pressure [kPa]	88	NO CONT	NO CONT
Brain Von Mises stress [kPa]	35	MOD DAI	SEV DAI*
Global strain energy of the brain/skull interface [mJ]	1176	NO SDH	NO SDH
Global strain energy of the skull [mJ]	233	NO SF	NO SF

INSIA pedestrian 006 (IP006)

Table 13.
IP006 numerical simulation results.

Calculated mechanical parameter	Maximal value	Observed injury	Predicted injury
Brain pressure [kPa]	110	NO CONT	NO CONT
Brain Von Mises stress [kPa]	15	MOD DAI	MOD DAI*
Global strain energy of the brain/skull interface [mJ]	1270	NO SDH	NO SDH
Global strain energy of the skull [mJ]	530	NO SF	NO SF

The Table 13 shows the results of the numerical accident reconstruction of case IP006. In that pedestrian accident case, the only injury that is sustained by the victim (i.e. moderate neurological injuries) is well predicted by the model. The prediction is possible but not yet sure. Moreover, the model predicts well the absence of brain contusions, subarachnoidal or subdural haematoma as well as skull fractures. None secondary ground impact is mentioned in the accident report.

DISCUSSION

Brain contusions

Three accident victims sustained brain contusions. One of these contusions was well predicted by the accident numerical simulation whereas two of them were not predicted. Nevertheless in both cases where the simulation did not predict brain injuries, a secondary ground impact occurred. It is therefore possible that the secondary ground impact was responsible for that kind of injury. Besides, six victims did not suffer from brain contusions and this was very well predicted by the accident numerical reconstruction for each of these six cases.

Brain neurological injuries

Only one victim did not suffer from brain neurological injuries shall they be moderate or severe. The accident numerical reconstruction predicted well the lack of injury in that specific case. Four accident victims sustained some moderate brain neurological injuries. For all these cases, the accident numerical reconstruction predicted moderate brain neurological injuries. Four victims suffered from brain severe neurological injuries. For two of them the model predicted well the injury patterns. Nevertheless for both remaining victims, the accident numerical simulation predicted brain moderate neurological injuries. Thus, the right injury pattern was predicted but not in the right range.

Subdural or subarachnoidal haematoma

Three victims sustained a subarachnoidal or a subdural haematoma consecutively to their accident. For all these three accident cases, the model was not able to predict that specific injury. Nevertheless, in two cases the accident report mentioned a secondary ground impact that may be responsible for the observed injury. Besides, six accident victims did not sustain any subarachnoidal or subdural haematoma. Only for of these six victims the accident numerical reconstruction predicted such an injury. Thus, for the five other accident cases, none subarachnoidal or subdural haematoma was predicted.

Skull fractures

Four accident victims revealed a skull fracture. For two of them, the model predicted well that specific injury. Nevertheless, for the two remaining victims, the accident numerical reconstruction was not able to predict any skull fracture. It can be noticed that for one of these two cases, the accident report mentioned a secondary ground impact that might be responsible for that observed injury. Moreover, five victims did not suffer from skull fractures. The model predicted that none occurrence of injury well for four victims. Thus the model predicted a skull fracture only for one victim that did not reveal any skull fracture.

CONCLUSIONS AND PERSPECTIVES

From an injury prediction point of view it can be concluded that the numerical tools that have used to reconstruct the real world accident cases under study are pretty good (i.e. the FEM of the human head, of the car's windscreen and bonnet). Moreover, they are much more powerful to predict the absence of injury. It has to be underlined that statistical results have not been derived from that study since the number of accidents considered is to low at that level. Nevertheless, in some cases, the observed injuries were not predicted at all. But in the majority of these accident cases, a secondary ground impact was mentioned in the accident report. It is therefore desirable to reconstruct numerically the second part of the accident in order to evaluate the mechanical field parameters that are sustained by each victim at that level. It could therefore be useful to compare the outcomes of both impact numerical reconstructions to infer which impact is responsible for which injury. A further step would be to increase the numbers of accident cases in the database. In fact, the numerical reconstruction of a great number of different cases would allow leading a statistical approach in that framework. Another perspective lies in the improvement of the numerical models that are used for the reconstructions. In fact, efforts have still to be made to access to more accurate geometries as well as mechanical behaviour of the car's bonnet and windscreen and of the human head. Nevertheless, even if models are powerful and reliable, the complete accident reconstruction process has to be controlled very accurately. Indeed, the initial conditions of the head impact against the striking structure have to be known with a great precision if conclusions should be inferred from such numerical tools. Therefore the kinematics of the whole pedestrians – and thus the whole pedestrian and car model – have to be calculated with a high accuracy. This has been possible in the framework of that cooperation work between different European Institutes but asked for tremendous efforts. It can be concluded that these results showed that such numerical models are good tools to predict human head injuries. However, the numerical tools used can only predict injuries reliably if both the pedestrian and vehicle side are modelled appropriately, i.e. with detailed FE structures with well validated material and contact stiffness data. They will therefore be useful to improve the head protection devices i.e. the design, the conception, the evaluation and the optimization of cars' windscreens and bonnets against well defined injury criteria.

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