HEAD TOLERANCE LIMITS DERIVED FROM NUMERICAL REPLICATION OF REAL WORLD ACCIDENTS

R. Willinger, D. Baumgartner, B. Chinn*, M. Neale*

Strasbourg University, ULP-IMF-CNRS 7507 rue Boussingault 67000 Strasbourg, France
* Transport Research Laboratory, Crowthorne, UK

Abstract

The validation of the Strasbourg FE head model has been extended to include five tests by Trosseille and two tests by Yoganandan. Only one of each, however, is reported in the present paper. Results show that the model correlated well with Troseille's experiments and predicted the intra-cranial pressure accurately at sites near to the impact location; predictions became less accurate as the distance from the impact location increased. The skull stiffness and fracture force were very accurately predicted when compared with values measured by Yoganandan. The model was studied parametrically to give a better understanding of how the output varied for different values of the material characteristics such as CSF Young modulus, brain short and long term shear modulus, brain Bulk modulus and skull thickness. Helmet damage from thirteen motorcycle accidents selected from the COST 327 Action database was replicated in drop tests at TRL UK. Simulation of these accidents using the ULP FE model led to very first tentative proposals for injury criteria as follows : Intra-cerebral Von Mises stress of about 20 kPa for concussion, strain energy in the CSF layer of 4J for sub-dural haematoma and a Tsaï-Wu criterion for skull fracture.

Key words : Accident reconstruction, Biomechanics, Brain, Finite element method, Tolerance

HEAD INJURIES remain the most frequent and severe injuries in almost all types of traffic accidents, therefore, head injury reduction is a high priority for traffic safety improvement. Car safety standards rely upon criteria for human tolerance, which are based on biomedical research performed more than 30 years ago. Measures designed to improve head protection in accidents are currently evaluated against a measurement of the Head Injury Criterion (HIC). The predictive capacity of this criterion has been criticised because of its empirical derivation and limited ability to predict a probability of brain injury. It has been suggested that specific deformation of skull material and brain tissue and a measure of the relative motion of the brain and skull would be much better means of assessing head protection.
The objective of the present joint study was to construct and validate a finite element model of the human head. Finite Element Methods (FEM) were considered to be the best tool with which to investigate the response of the human head under impact condition and, in turn, would provide a model that was ideally suited to the reconstruction of accidents. To date, more than ten different 3D human head models have been described but only Zhou's model (Zhou et al. 1996) was validated and then used for accident reconstruction to investigate brain injury tolerance limits.
Most of the essential head components were incorporated in this model, which was meshed with 28,754 nodes and 37,040 elements. Recent modifications of this model (AL-Bsharat 1999 a) include the addition of a 3-layered skull and an improvement of the brain-skull interface to allow the brain to "move more freely" relative to the skull. The model was validated against the intra-cranial pressure data from impact tests onto the front of the head of cadavers and against brain-skull relative motion using data obtained from the high-speed X-ray experiments (Al-Bsharat et al. 1999 b).s
Zhou et al. 1996 simulated a fully documented road accident with this model and the shear stresses predicted by the model agreed approximately with the location of axonal injury described by the

medical report. More recently Newman et al. 1999 presented a detailed methodology for the assessment of mild traumatic brain injury based on the reconstruction of American professional football accidents, using Zhou's human head FE model. The findings suggested that mild traumatic brain injury occurred with a Von-Mises stress of 0.07 kPa and a pressure of 0.03 kPa.
Strasbourg University has developed the "ULP" human head FE model (Willinger et al.1999) and this is briefly described below. The first accident replication using a first version of this model, a head impact caused by a motorcycle accident (Kang et al. 1997), showed that it was possible to compare intracranial field parameters with neuropathological brain injury details. This study lead to the conclusion that intra-cranial pressure did not correlate well with intra-cerebral haemorrhage but that Von Mises stress distribution correlated very well with lesions. It was concluded that a value of 16 kPa was the likely tolerance limit for intra-cerebral shearing.
The research described in this paper is a more extensive validation of the model and a parametric study to provide a better understanding of the model behaviour. This is followed by a description of the use of the model to simulate 13 motorcycle accidents selected from the COST 327 Action database. The results were used to determine head tolerance limits related to brain injury mechanisms. This research was conducted jointly by Strasbourg Louis Pasteur University (ULP) and the Transport Research Laboratory (TRL) Crowthorne, UK. It is part of the research within the COST 327 Action "Motorcyclists Helmets".

THE ULP HEAD MODEL

MODEL PRESENTATION

Geometry : The geometry of the inner and outer surfaces of the skull was digitised in the Strasbourg laboratory from a human adult male skull. The data given in an anatomical atlas by Ferner et al. 1985 was used to mesh the human head using the Hypermesh code. For this study, the option was chosen to retain a given realistic human adult anatomy rather then trying to find an overage geometry, which may not exist. The effect of inter-individual geometry on head dynamic response however, has to be defined in further investigation. Figure 1 below shows the 3D-skull surface obtained by digitising external and internal surfaces of the skull as well as the meshed model. Figure 2 shows a cross section of the model and illustrates the anatomical features of the skull and the brain and the position of the brain within the skull. The main anatomical features modelled were the skull, falx, tentorium, subarachnoid space, scalp, cerebrum, cerebellum, and the brain stem.

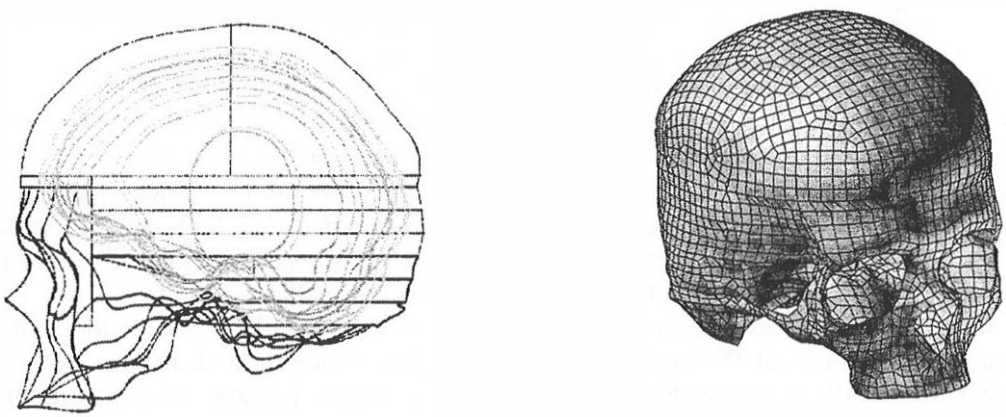

Figure 1 : 3D skull surfaces used for the model construction and skull meshing.

The finite element mesh is continuous and represents an adult human head. The falx and tentorium were simulated with a layer of shell elements, the skull comprised a three layered composite shell and the remaining features were modelled with brick elements. Of particular importance, and rarely modelled, is the subarachnoïd space between the brain and the skull, which in this model was represented by one layer of brick elements to simulate the cerebral-spinal fluid. This simplification hypothesis is justified by the fact that CSF flow can probably not occur in the time duration of the impacts under study and that the subarachnoïd space contains not only fluid but also bridging veins

and fibres. Eulerian formulation was, therefore, not needed and the brain-skull liaison was modelled by an elastic material validated against an in-vivo vibration analysis. For this analysis the "connective" brick elements were fixed to the skull elements at the exterior surface and to the brain or the membranes at the inner side. The tentorium separated the cerebrum and the cerebellum, and the falx separated the two hemispheres. Brick elements were used to simulate the cerebral-spinal fluid that surrounds these membranes. A layer of brick elements also modelled the scalp, which surrounds the skull and facial bone. Overall, the current head model consists of 11939 nodes and 13208 elements divided in 10395 bricks and 2813 shells and it has a total mass of 6.7 kg.

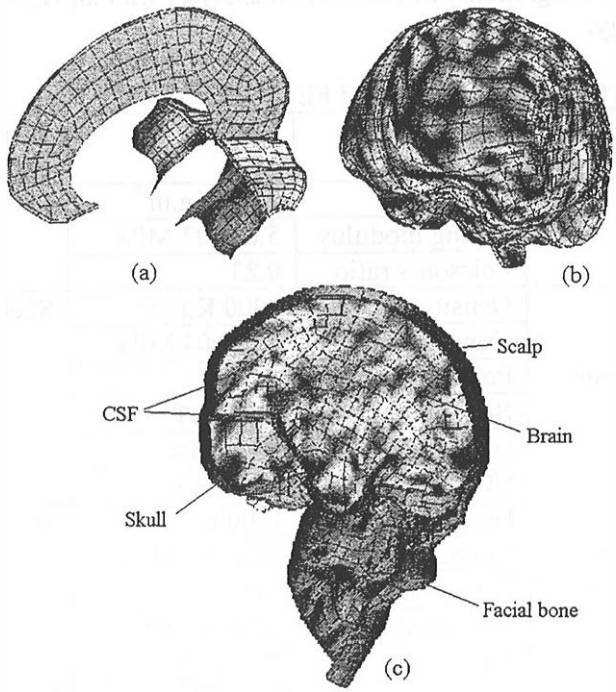

Figure 2. Meshing of the intra-cranial medium
(falx and tentorium (a), brain (b) representations and overview (c))

Material properties : Material characteristics are very important to the success of a finite element model and Table 1 below lists the properties of the materials used in the model.
Material properties of the cerebral spinal fluid, scalp, facial bones, tentorium and falx are all isotropic and homogenous. The viscoelastic properties assigned to the brain were scaled from Khalil et al 1977. The behaviour in shear was defined by: $G(t) = G_\infty + (G_0 - G_\infty)\mathrm{Exp}(-\beta\, t)$
with G_0 : Short term shear modulus, G_∞ : Long term shear modulus and β : Decay constant.
The Young's modulus of the subarachnoid space was determined by Willinger et al in 1995 using modal analysis, based on the fact that a brain-skull decoupling occurs at the first natural frequency of the human head at around 100-150 Hz. A large deformation formulation was used in order to have a realistic strain estimation in this layer of brick elements. The skull was modelled by a three layered composite shell representing the inner table, the diplöe and the external table of human cranial bone. In order to reproduce the overall compliance of cranial bone, a thickness in combination with an elastic brittle law were selected for each layer. In order to model the material discontinuity in the case of a fracture, it was necessary to use values for the limiting (ultimate) tensile and compressive stress (UTS and UTC) obtained from the literature: Piekarski 1970, for the Tsaï-Wu criterion (Tsaï-Wu 1971) (see table 1). The material properties of the intra-cerebral membranes and the scalp are similar to those used in Zhou's model and reported in table 1.

MODEL VALIDATION AND PARAMETRIC STUDY

General aspects : A total of eight instrumented cadaver impacts were reconstructed with the objective to validate the ULP model under very different impact conditions. Currently head FE models are validated against Nahum's impact (1977) and this was satisfactorily achieved with the first version

of the model, in a previous study (Kang et al.1997). The impact duration of Nahum's test was about 6 10^{-3} s . Strasbourg University devised a procedure to establish over what range the model was satisfactorily validated. The data used was taken from five highly dampened cadaver impacts with important angular components published by Trosseille et al 1992 and two extremely short cadaver impacts (to the front and to the vertex) inducing skull fracture, published by Yoganandan 1994. Only two examples are shown in this paper : The Trosseille case MS 428-2 and Yoganandan frontal case. Table 2 summarizes the main characteristics of the three classes of impact, i.e. medium, long and short duration. The RADIOSS code developed by MECALOG was used for the finite element analysis and the method of one point integration was used for all analysis with an Hourglass energy below 0.1% of the total involved energy.

Table 1 Material properties of the human head FE model

Part	Material property	Material parameter	Value	Element type	Shell thickness (mm)
Face	Elastic	Density	2500 $Kg.m^{-3}$	Shell	10.0
		Young modulus	5.0E+03 MPa		
		Poisson's ratio	0.23		
Cranium (Cortical)	Elastic Plastic Orthotropic	Density	1900 $Kg.m^{-3}$	Shell	2.0
		Young modulus	1.5E+04 MPa		
		Poisson's ratio	0.21		
		Bulk modulus	6.2 E+03 MPa		
		UTS	90.0 MPa		
		UCS	145 MPa		
Cranium (Trabecular)	Elastic Plastic Orthotropic	Density	1500 $Kg.m^{-3}$	Shell	3.0
		Young modulus	4.6E+03 MPa		
		Poisson's ratio	0.05		
		Bulk modulus	2.3E+03 MPa		
		UTS	35.0 MPa		
		UCS	28.0 MPa		
Scalp	Elastic	Density	1.0E+03 $Kg.m^{-3}$	Solid	-----
		Young modulus	1.67E+01 MPa		
		Poisson's ratio	0.42		
Brain	Viscoelastic	Density	1040 $Kg.m^{-3}$	Solid	-----
		Bulk modulus	1.125E+03 MPa		
		Short time shear modulus	4.9E-02 MPa		
		Long time shear modulus	1.62E-02 MPa		
		Decay constant	145 s^{-1}		
CSF	Elastic	Density	1040 $Kg.m^{-3}$	Solid	-----
		Young modulus	0.12E-01 MPa		
		Poisson's ratio	0.49		
Falx	Elastic	Density	1140 $Kg.m^{-3}$	Shell	1.0
		Young modulus	3.15E+01 MPa		
		Poisson's ratio	0.45		
Tentorium	Elastic	Density	1140 $Kg.m^{-3}$	Shell	2.0
		Young modulus	3.15E+01 MPa		
		Poisson's ratio	0.45		

Trosseille impact : General preparation of cadavers was similar to Nahum's experiment, but the experiments were performed with a 23.4 Kg impactor at 7 m/s and the impact area, the initial impactor velocity and the head/impactor interface were varied. For all tests, an accelerometer arrangement was screwed onto the skull in the occipital area in order to measure the head acceleration in 3 dimensions. Intra-cranial pressures and frontal, ventricular occipital pressures were also measured. A free boundary

condition was used at the neck junction because the neck was not included in this model and hence there was no constraint at the head-neck joint. This hypothesis was justified for Nahum's impact which was of too short duration (6 ms in this instance) for which the neck does not influence the kinematic head response. Modelling a direct impact was, therefore, not a suitable way to replicate the Trosseille experiment because of the long pulse duration (about 15 ms). For an impact of this relatively long duration, it would be important to consider the effect of the neck response on the kinematics of the model if the direct impact had been used. However, the solution to an alternative input definition was found by deriving the head velocity from the experimental acceleration and to consider this head velocity as the model input. The skull was in this case assumed to be a rigid body and six velocities were simulated. These were calculated from the experimental acceleration data as presented in a previous study (Turquier et al. 1996).

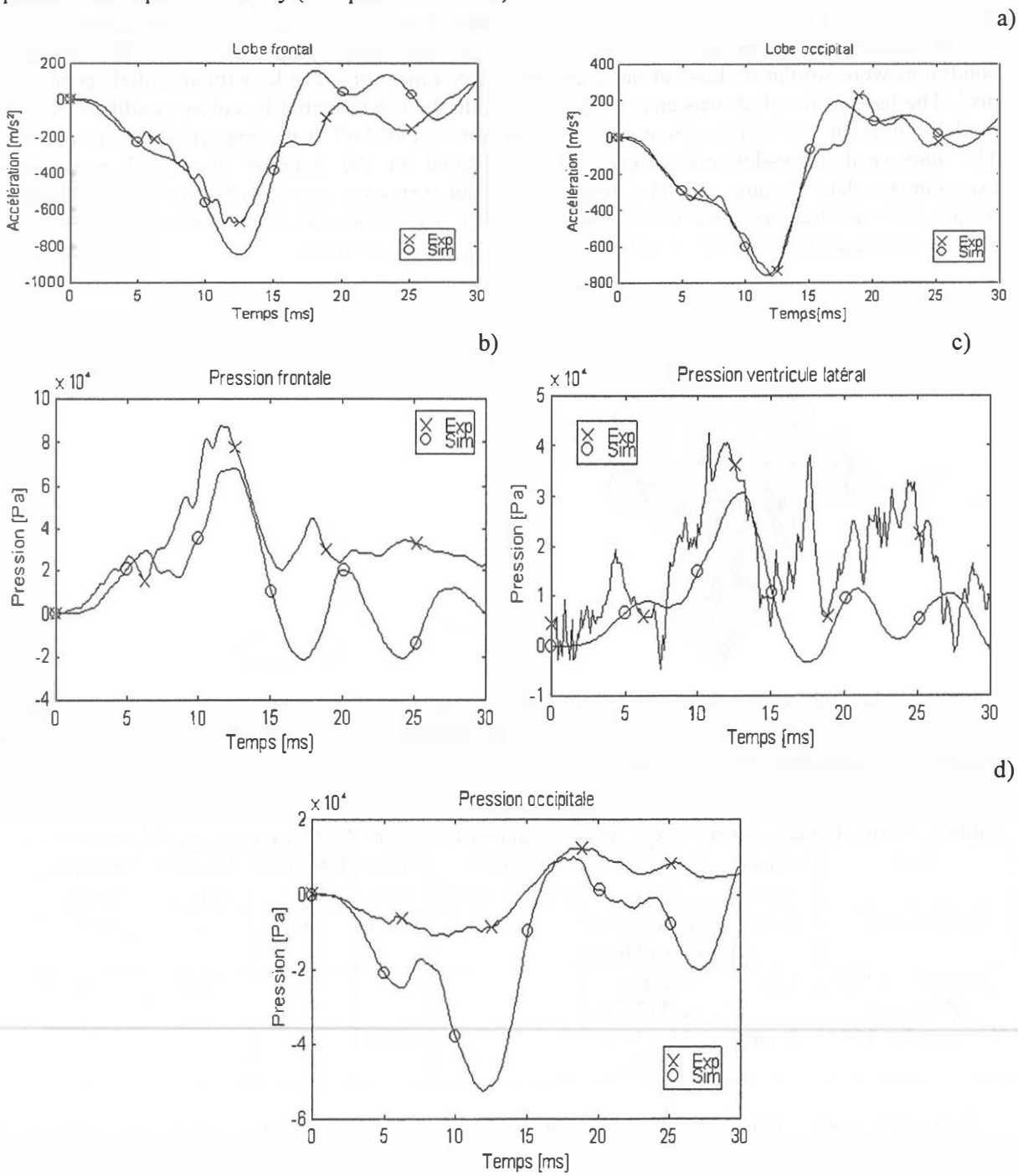

Figure 3 : Experimental and simulated head acceleration a) and intra-cranial pressure b,c,d) for a long duration impact with high angular component.

When the numerical and experimental skull rotational and linear acceleration were compared, the kinematics were found to agree perfectly, as illustrated in figure 3a. Simulation results from figure 3b, 3c and 3d show that a realistic simulation of the intra-cranial pressure is possible for long duration impacts with high angular component. However, it was found that the accuracy decreased at locations far from the impact area; probably because the intra-cranial material properties are not accurately known.

Yoganandan's impact : In order to validate the ability of the ULP finite element head model to predict a skull fracture in case of very "short" impact, two impact types were simulated: a frontal shock and an impact to the vertex. The results were compared with experimental cadaver test data under the same loading conditions. However, only results relative to the frontal impact are presented in this paper. The impact configurations with the finite element model of the head are shown in figure 4. The surface of the impactor was modelled by a rigid sphere with a radius of 48 mm. Initial conditions were similar to those of the experiments i.e. a mass of 1.213 kg with an initial speed of 7.1 ms^{-1}. The base of the skull was embedded, to replicate the experimental boundary conditions. For the model validation, the contact force and the deflection of the skull at the impact site, were recorded. The numerical force-deflection curves are compared to the average dynamical response of experimental data (Figures 4). The dynamical model responses agree well with the experimental results, both the fracture force and the stiffness level. The model indicates multiple fracture located around the impact point which complies with pathological observations.

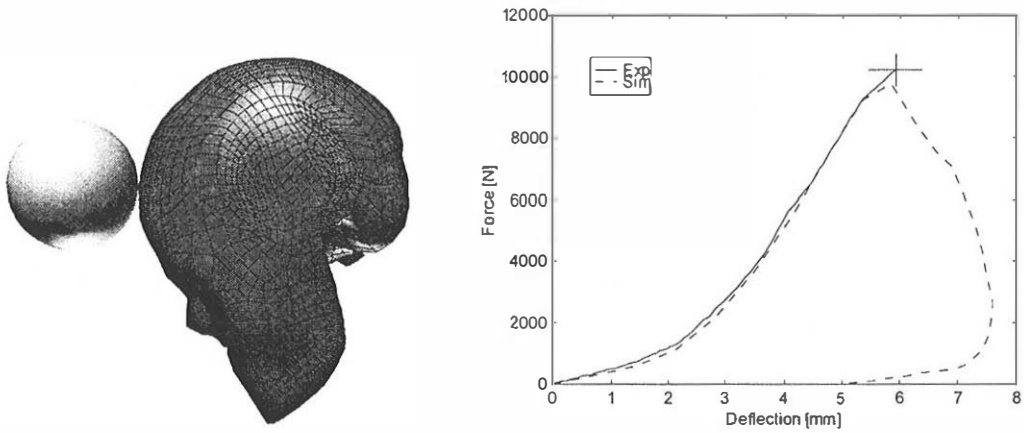

Figure 4: The 3D human head model in frontal impact configuration for Yoganandan's impact simulation and experimental vs simulated force deflection curves until fracture.(+ gives the corridor of Yoganandan's experimental results).

Table 2 : Main characteristics of experimental cadaver tests from the literature as used for validation

Test	Impact area	Impactor (kg)	Impactor velocity (m/s)	Force (N)	LA maxi (g)	RA maxi (rd/s^2)	Duration (ms)
Nahum 1977	front	cylinder (5.6) with padding	6.3	6900	198	-	6.5
Trosseille 1992 MS 428-2	face	steering wheel (23.4)	7	-	102	7602	15.8
Yoganandan 1994	front	rigid sphere (1.213)	7.1	10500	-	-	2

Parametric study : Following the validation of the head model it was concluded that further work should be completed on the model so that the output could be better understood. A parametric study was considered essential for this purpose. This parametric analysis investigated the change in the model's response (pressure and Von Mises stress) to variations in the bulk modulus and viscoelastic short and long time shear modulus of the brain, in addition to the Young's modulus of the

cerebrospinal fluid (CSF). High variations of parameters were considered in this study (up to 200%) in order to evaluate the model response for parameters defined in the literature and which can have such an order of discrepancy. These parameters were individually varied for 30 model runs in cooperation with TRL. For all these runs the model was configured to a specific set of experimental conditions. This consisted of propelling at 6 ms^{-1} a padded cylindrical impactor at the forehead of the model producing an impact similar to that of Nahum. Pressure and Von Mises stress were monitored at specific elements spread throughout the brain of the model. These included elements positioned in the anterior, posterior and base of the brain, in addition to the brain stem. The peak pressures and Von Mises stress were taken from the results and a statistical analysis performed to establish the relative importance and sensitivity of each parameter on the model's peak responses. The results from this analysis were used to summarise and support the visual observations made on the peak responses. Finally skull thickness was also modified in order to check the sensitivity of skull rigidity and fracture to this parameter.

The parametric analysis has been reported in details in the spacio-temporal domain (Neale 1999). As a summary it led to the following results. An increase of the CSF Young modulus of 100% led to an insignificant peak pressure and Von Mises stress change and hence no tendency for the brain shearing value to change. An increase of 200% of the brain short time shear modulus led typically to a decrease of the intra-cerebral pressure of approximately 10% and simultaneously an increase in the brain Von Mises stress of about 100%. The increase of 200% of the brain long time shear modulus conduced to quasi constant peak pressure and a very light shearing stress increasing of about 5%. A change in the brain Bulk modulus had a significant effect on intra-cranial response. When this modulus was factored by 10, it gave an increase in pressure of typically 25% and a decrease of the Von Mises stress of between 10% and 30%, depending upon the location. The skull was also investigated and an increase in the thickness of 50% had little effect on its rigidity but increased the contact force from about 8,500 N to 12,500 N under Yoganandan's impact. However, this did not lead to a fracture of the skull. It should be noted that the results quoted above are for a specific range of conditions and are intended only as a guide to the model response.

ACCIDENT RECONSTRUCTION

As part of the work of the COST 327 Action on Motorcyclists' helmets and head injuries, data on 218 motorcycle accidents has been collected at Glasgow, Hanover and Munich. The purpose of the study was to improve the knowledge of head and neck injury mechanisms. A total of thirteen cases were replicated with drop tests of a helmeted headform at TRL. The aim of this work was to replicate head impacts sustained during real motorcycle accidents while measuring the dynamics of the head. In this experimental study (Chinn et al. 1999), TRL replicated the helmet damage using a purpose-built helmet drop test facility. The method allowed impact parameters, including impact speed, angles and targets, to be controlled and quantified. By inspection of the helmet it was possible to modify the impact parameters until the desired damage was produced. Instrumentation was used to measure the dynamics of the impact and ultimately enable the accelerations, likely to have been experienced by the casualty, to be estimated. Analysis of the damage to the shell and liner was used to identify the kinematics of the impact. Surface scratches, scuffs and paint chips often relate to the impact speed, angle and target shape. The accuracy of the replication was judged by comparing the replicated damage with the accident damage. The test helmet was an identical make and model to the accident helmet to ensure similar performance during the impact and up to five tests were sometimes necessary to obtain a satisfactory replication of the accident helmet damage. For the selected accident cases reconstructed experimentally at TRL-UK, the reconstruction report was transferred to ULP-Strasbourg. In addition ULP was provided with an electronic copy of the results of the 3D linear and angular acceleration of the dummy head and the external force measured at the target anvil.

Before accidents could be simulated numerically it was necessary to couple the human head FE model with the helmet FE model and then develop a simulation method that described the best input for a given accident. It was possible, using the data supplied by TRL, to simulate the accident in two ways: use the velocity and head-helmet orientation measured by TRL at the point of impact as initial conditions for the simulation or use the linear and rotational acceleration time histories supplied by TRL as inputs to the skull.

Both methods were applied to two accidents and there were no significant differences observed in the skull acceleration and intra-cerebral stress level. It was, therefore, decided to apply the 3D linear and angular acceleration recorded on the headform to the skull of the human head FEM. Velocity will be used as the input in further investigation and development of skull fracture.
From the 3D-acceleration time histories provided, the velocity was calculated as a function of time at three points on the skull FE model and this was used as the input to the FE accident simulation. For all cases the intra-cranial material properties used were the ones presented in table 1. Intra-cranial response was then computed with the RADIOSS FE code in order to calculate the intra-cerebral field parameters as a function of time.

Table 3 : Details of the thirteen accident cases selected for numerical replication: injury, input peak linear acceleration (PLA) and rotational acceleration (PRA), HIC and outputs in terms of maximum pressure (Pmax), Von Mises stresses (VMmax) and CSF internal energy (CSFIE).

Case	AIS	Lesions	Gr	PLA [g]	PRA [rad/s²]	HIC	Pmax [kPa]	VMmax [kPa]	CSFIE [mJ]
G196	0	None	A	105	4056	306	130	15	2751
G313	0	None	A	88	6421	254	224	20	4077
G325_1	0	None	A	118	375	578	110	14	1955
G327	0	None	A	107	5026	248	115	15	1592
G165_1	2	Obtunded on admission	B	134	11447	669	80	20	1249
G174	2	Amnesic for incident	B	152	10234	751	129	20	1698
G197_1	2	Obtunded with post traumatic amnesia	B	167	8341	771	190	20	1924
G345_1	2	Concussion	B	191	21910	667	151	22	1169
G107	5	Subdural and subarachnoid haematoma - Unconscious on admission	C	192	11482	1389	186	13,5	3904
G411	4	Subdural and small subarachnoid haematoma - Unconscious on admission	C	234	14860	2208	210	40	5221
G157	5	Base of skull and parietal bone fracture - Extradural haematoma - Unconscious	D	115	3780	154	220	26	4254
G154_2	3	Base of skull fracture - Amnesic for event	D	204	11173	1685	260	23	7365
G193	5	Base of skull fracture - Contusions - Brain swelling	D	447	32684	8918	760	45	23062

Table 3 presents the cases selected for the present numerical accident reconstruction. AIS level ranges from zero to five and this table presents simultaneously maximum values of input accelerations, computed HIC data and maximum output values such as pressure, Von Mises stresses in the brain as well as computed maximum strain energy in the CSF layer defined by the time integration of the half stress and strain tensor multiplication trace. Case number G174 is shown in more details in figure 5a) and b) concerning the linear and angular input data and in figures 5c) and d) where we show successively the calculated time evolution of pressure and Von Mises stress at the point located where this parameters reach their maximum. Finally figures 6 illustrates the field distribution of this very parameters through the brain. Spacio-temporal evolution of this parameters for the twelve other cases are detailed in COST 327 working group "Mathematical Modelling" final report (Willinger et al. 2000).

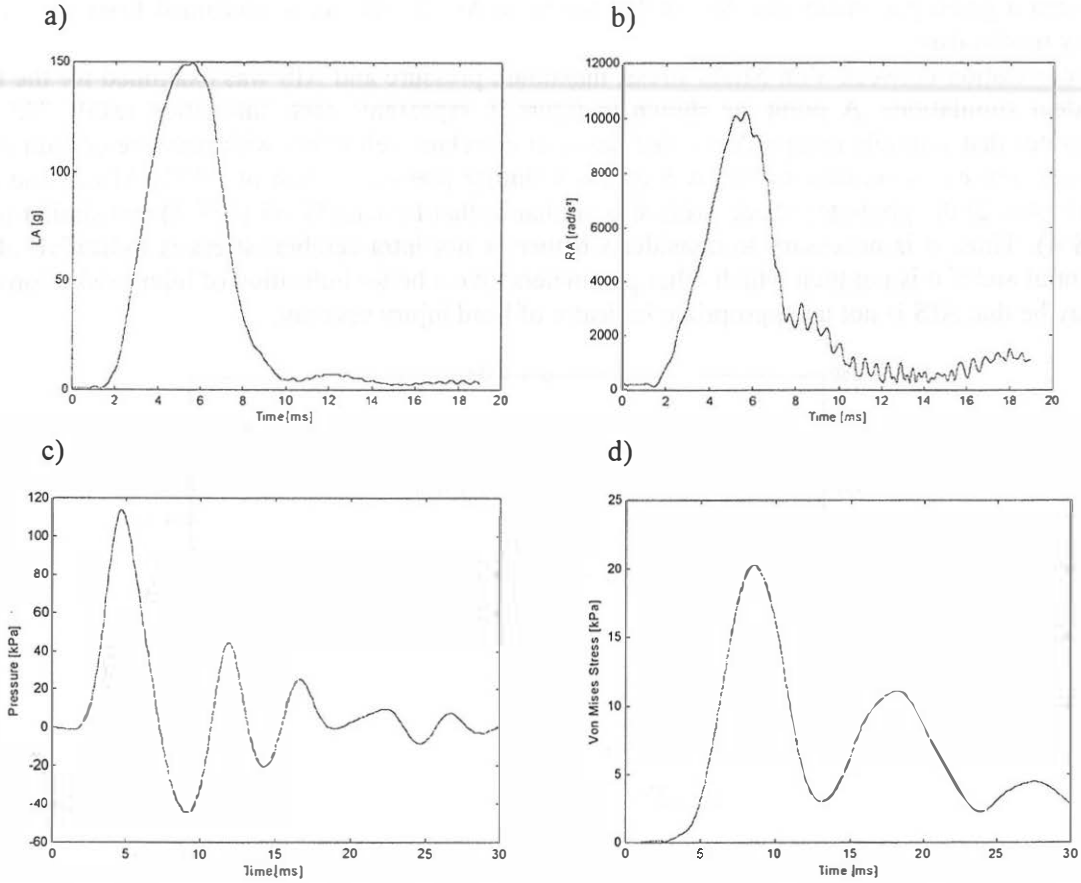

Figure 5 : Time evolution of input and output parameters for accident simulation case G174 :
5a) linear acceleration and 5b) rotational acceleration for the inputs
5c) maximum pressure and 5d) maximum Von Mises brain stress for the output.

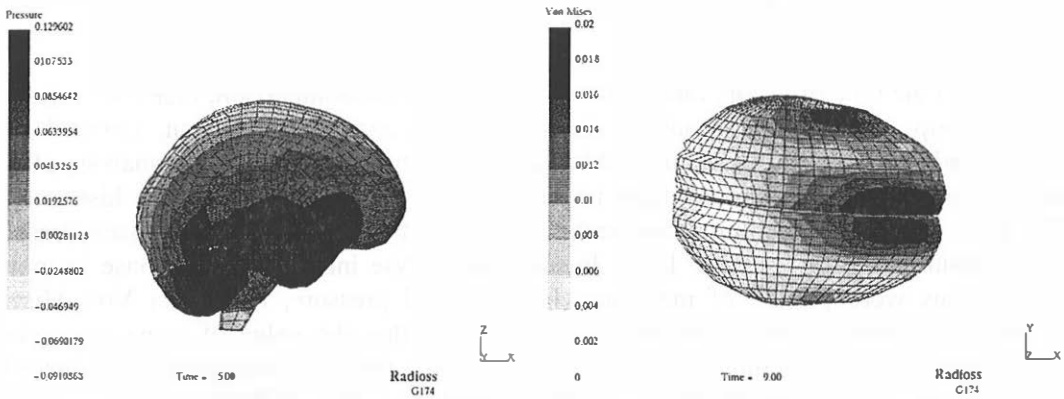

Figure 6 : Intracerebral field parameters calculated for accident simulation case G174 :
6a) Pressure and 6b) Von Mises stresses

RESULTS AND DISCUSSION

Currently, real world accident analysis is used in an attempt to correlate a known head injury parameter with the AIS value sustained. An attempt by Chinn et al (1999) to correlate, initial head impact velocity, maximum linear and rotational acceleration, HIC value and GAMBIT versus AIS gave correlation coefficients of 0.3 to 0.6, which, in the authors opinion is not satisfactory. Even if intra-cerebral mechanical parameters calculated with a head FE model were shown to give better correlation with AIS, it is considered by the authors of this paper that a much better approach is to take into account the likely head injury mechanism. In fact, the main reason for the poor correlation

between a given parameter and AIS is that the same AIS levels can be sustained from very different injury mechanisms.
The correlation between Von-Mises stress, maximum pressure and AIS was examined for the thirteen accident simulations. A point, as shown in figure 7, represents each simulation result. This figure illustrates that a simple integer AIS value does not correlate well either with pressure or with shearing stresses. For example, case G196 (AIS 0) has a similar pressure to that of G174 (AIS 2) and in case G345 (AIS 2) the predicted shear stress was similar to that for case G157 (AIS 3) and similar to G154 (AIS 4). Thus, it is necessary to consider whether or not intra-cerebral stress is indicative of injury potential and if it is not then which other parameters give a better indication of injury risk. Conversely, it may be that AIS is not an appropriate indicator of head injury severity.

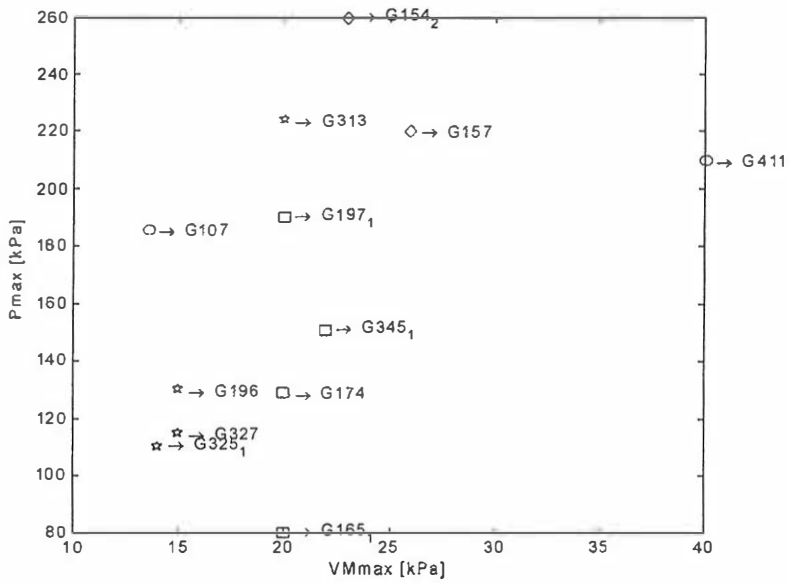

Figure 7: Results of the 13 simulated accident cases showing the maximum pressure vs Von Mises stress. Key: stars for group 1, squares for group 2, circles for group 3 and diamonds for group 4 (diamond for case G193 is out of figure)

However, when the type of lesion, rather than AIS, was used for comparison, then four distinct groups emerged : group 1, uninjured, group 2, concussed, long and short duartion, group 3, sub-dural haematoma and group 4, skull fracture (table 3). In order to go further in the analysis of the intra-cranial responses relative to the accidents under study we plot successively three histograms which give for each case the maximum intra-cerebral pressure, the maximum Von Mises stress and the maximum strain energy in the CSF layer. In order to analyse intra-cranial response in more detail, three histograms were plotted of maximum intra-cerebral pressure, maximum Von Mises stress, maximum strain energy. After examination it was found that the value of some parameters for a specific group of accident victims was found to be valid as a means of estimating a tolerance limit for the injury sustained by that group. For example the histogram given in figure 8a shows that pressure, because of the wide variation was not responsible for the injury in groups 1 to 3. Only group four shows a correlation of injury with pressure and it was concluded that pressure was not a good indicator of injury potentail. Maximum tensile stress was also considered but led to similar conslusions
The maximum Von Mises stress and strain energy, see figures 8b and 8c, are of greater interest and show better correlation. Group 1, uninjured, sustained low values whereas group 2, concussed, sustained values typically 30% greater than those of group one. However, for groups 3 and 4, haematoma and fracture, the Von-Mises stress and strain energy varied greatly. The third histogram figure 8c is related to maximum strain energy in the CSF layer and shows that for group 3, subdural haetoma, the values were consistently, substantially greater than for the other groups.

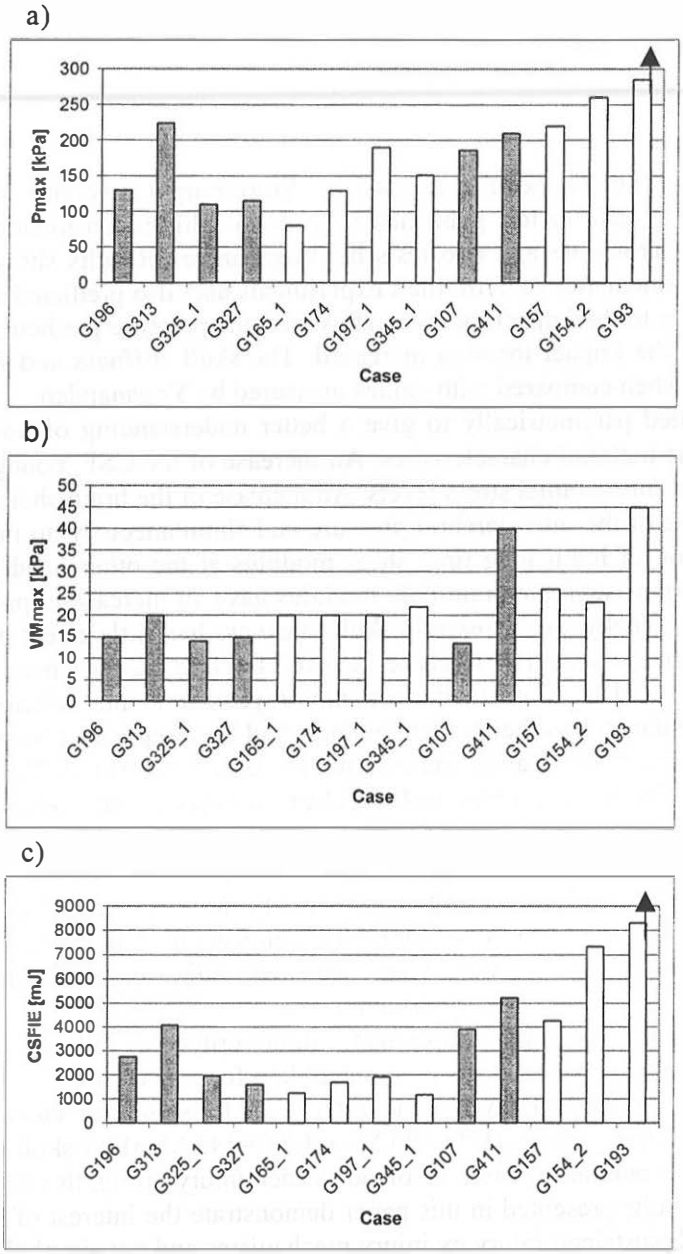

Figure 8 : Histograms of intra-cranial parameters relative to the 13 accident simulations : a) Maximum brain pressure, b) maxi. Von Mises stress in the brain and c) maximum strain energy in the CSF layer. (Spacio-temporal data are given in figures 5 & 6 for case G174. Other cases are reported by Willinger et al 2000)

The above analysis led to the following tentative conclusions. Intra-cerebral Von Mises stresses is a good indicator of concussion, with an upper limit of approximately 20kPa (figure 8b) for longer duration concussion. It is well known that SDH, group 3 are related to brain –skull relative motion which in the above analysis is expressed in terms of maximum strain energy in the CSF layer. Figure 8c shows that there is an upper limit of this parameter of the order of 4J. Finally the skull fracture cases from group 4 are obviously due to skull stress which were not calculated in this study. It is worth noting that the pressure histogram of figure 8a shows the highest but somewhat inconsistent values for the cases in group 4 and this illustrates the high energy of these impacts. Thresholds for this kind of lesion could be obtained by a new simulation of these accidents whereby the helmet-head velocity and impact position, as specified by the experimental reconstruction, are used as the initial conditions of the simulation. In addition, it may be possible to determine the tolerance limits for skull fracture by considering Yoganandan's impacts simulated in the model validation phase. This would lead to the

Tsaï-Wu failure criteria for the specified UTS and UTC (ultimate tensile and compression strength of bone material) as given in table 1.

CONCLUSIONS

The FE model of the human head developed by Strasbourg University was previously validated against the results of a cadaver test published by Nahum. This first validation has been extended to include five tests by Trosseille and two tests by Yoganandan. Results show that it was possible to reconstruct the head kinematics of Troseille's experiments and also predicted the intra-cranial pressure accurately at sites near to the impact location. However, the pressure predictions became less accurate as the distance from the impact location increased. The skull stiffness and fracture force were very accurately predicted when compared with values measured by Yoganandan.

The model was studied parametrically to give a better understanding of how the output varied for different values of the material characteristics. An increase of the CSF Young modulus was found to have low influence on intra-cranial stress levels. An increase of the brain short time shear modulus led typically to a decrease of the intra-cerebral pressure and simultaneously an increase in the brain Von Mises stress. Variation of brain long time shear modulus at the other hand had very low effect on model response. An increase in the brain bulk modulus gave an increase in pressure and a decrease in the Von Mises stress. Finally, an increase in skull thickness had little effect on rigidity but increased the contact force and had substantial effects on the skull fracture phenomenon.

The model was then used to simulate thirteen motorcycle accidents selected from the COST 327 Action data base. The damage to the accident helmets had been replicated by drop tests at TRL during which rotational and linear acceleration and external force were measured. These data were transferred to Strasbourg University for the numerical accident simulation. The output from the model was compared with the head injuries recorded for each case. It was concluded that AIS does not correlate well either with the conventional test criteria such as acceleration, HIC and GAMBIT or with intra-cerebral maximum stresses. However, when head injury was examined the following four distinct groups emerged: uninjured, concussed, sub-dural haematoma and skull fracture. Histograms of several intra-cranial mechanical parameters were then correlated with injury types in order to derive a first tentative tolerance limit for specific injury mechanisms.

The foregoing analysis led to tentative proposals for injury criteria as follows:

1) Intra-cerebral Von Mises stress of about 20 kPa for concussion
2) Strain energy in the CSF layer of the order of 4 J for sub-dural haematoma
3) A Tsaï-Wu failure criteria (UTS=90 Mpa, UTC=145 Mpa) for skull fracture

However, given the low number of cases involved in each injury group, this accident analysis must be continued. The first results presented in this paper demonstrate the interest of the proposed approach, and the need to analyse sustained injury by injury mechanisms and not simply by AIS value. This very first conclusion shows that the final target, which is the definition of a threshold value for a given head injury mechanism, can be reached.

REFERENCES

Al-Bsharat A.S., Zhou C., Yang KH., Khalil TB., King AI.: Intracranial Pressure in the human head due to frontal impact based on a FE model. Proceedings of ASME 1999a summer meeting, Big Sky, Montana.

Al-Bsharat A.S., Yang KH., Khalil TB., King AI. : Some critical issues in the modelling of human head impact. Submitted to J of Biomech. Eng. 1999b

Chinn BP., Doyle D., Otte D., Schuller E. : Motorcyclists head injury : Mechanisms identified from accident reconstruction and helmet damage replication. Proceed. of IRCOBI Conf.1999, p53-71.

Ferner H., Staubesand J., Atlas d'anatomie humaine-tête, cou, membre thoracique, Edition Médicales internationales Paris, 1985

Kang HS., Willinger R., Diaw B., Chinn B. : Validation of a 3D Anatomic Human Head Model and Replication of Head Impact in Motorcycle Accident by Finite Element Modeling, Proc. 41th Stapp Car Crash Conf., 1997, pp 329-338.

Khalil T.B., Hubbard R.P., Parametric study of head response by finite element modelling, Journal of Biomechanics, Vol. 10, 1977, p119-132.
Nahum A.M., Smith R., Ward C.C. : Intracranial pressure dynamics during head impact, Proceed. of the 21st Stapp Car Crash Conf., SAE Paper 770922, 1977, p339-366.
Neal M : Parametric study of ULP head FE model. Short term scientific mission 1999,COST 327
Newman J., Beusenberg M., Fournier E. Shewchenko N., King A., Yang K., Zhang L., MCElhaney, Thibault L., McGinnis G. : A new biomechanical assessment of mild traumatic brain injury-Part 1 : Methodology. Proceed. of IRCOBI Conf. 1999, p17-36
Piekarski, Fracture of bone. J. Appl. Phys. 14, N°1, 215-223 (1970).
Trosseille X., Tarrière C., Lavaste F., Guillon F., Domont A. ,Development of a F.E.M. of the human head according to a specific test protocol, Proceed. of the 36th Stapp Car Crash Conf., 1992, p235-253.
Tsaï-Wu, Composite failure criterion, Journal of Composite material, (1971).
Turquier F., Kang H.S.-Troseille X.-Willinger R.-Tarriere C.-Lavaste F., Validation study of a 3D finite element head model against experimental data, Proceed. of the 40 st Stapp Car Crash Conference, Albuquerque, 1996, pp283-294
Willinger R., Taleb L., Kopp C. M., Modal and temporal analysis of head mathematical models, Journal of Neurotrauma, Vol. 12, N° 4, pp. 743-754, 1995.
Willinger R., Kang HS., DIAW BM. : Développement et validation d'un modèle mécanique de la tête humaine. C. R. Acad. Sci. Paris, t.326, Série II b, pp 125-131, 1999
Willinger R, Chinn B., Giavotto V., Mathematical modelling of the head neck compex. Working Group Final Report , 2000, COST 327.
Yogonandan N., Biomechanics of Skull Fracture, Proceed. of Head Injury 94 Symposium, Washington DC, Oct. 1994
Zhou C., Khalil T.B., Dragovic L.J., Head injury assesment of a real world crash by finite element modeling, AGARD, 1996