The use of different CSF representations in a numerical head model and their effect on the results of FE head impact analyses

K. Baeck[1], J. Goffin[2] and J. Vander Sloten[1]

[1] Division of Biomechanics and Engineering Design, K.U.Leuven, Belgium
[2] Division of Experimental Neurosurgery & Neuroanatomy, K.U.Leuven, Belgium

Abstract

To gain better insight in the mechanopathogenesis of brain and skull lesions and to improve the design of protective devices like helmets, finite element (FE) head models are used. Current FE head models have a detailed geometrical description of the anatomical components of the head but often lack an accurate description of the behavior of the cerebrospinal fluid (CSF). Different material properties, mesh resolutions and numerical implementations are used to represent the CSF in those head models. To examine the effect of those different CSF representations on the brain mechanical responses such as strain energy, Von Mises stress, strain and intracranial pressure, this paper starts with the development of a simplified head model and small adaptations are made to the representation of the CSF, both in mesh resolution and constitutive modeling. From this study it follows that depending on which material definition is used for modeling the CSF, the mesh resolution of the CSF can have an important effect on the brain mechanical responses. The study also highlights the need for a more accurate description of CSF material, since the CSF material properties, both material definition and property values, have a significant effect on the results of a head impact analysis.

Keywords:

Finite element analysis, head impact, cerebrospinal fluid, mesh resolution, strain, Von Mises stress, strain energy

Introduction

Craniocerebral trauma is observed in 21 to 61% of the cyclists who seek medical care after an accident [1,2] and it is in 69 to 93% of all reported fatal bicycle accidents the direct cause of death [3]. In Belgium almost 10% of all traffic fatalities are cyclists [4].

To gain a better insight in the mechanopathogenesis of brain and skull lesions and to improve the design of protective devices like helmets, different research methods can be used. The golden standard is to perform head impact experiments with cadavers, but their use is limited by the limited availability of test material and ethical considerations. The cadavers also tend to be of an advanced age. Other methods used to perform head impact research, are experiments with volunteers and with animals but volunteers can only be tested at non-injurious levels and animal data needs to be scaled to be representative of human data which are drawbacks of these methods. Because of the limitations of the previous mentioned methods and due to the increase in available computing power, the method of using a computer finite element (FE) head model in head injury research has become ever more popular [5,6,7]. Detailed and controlled tests may be carried out with a high degree of repeatability.

To represent the actual human head and its behavior during impact realistically, the computer FE head models need to be as accurate as possible. Most of the current FE head models have a detailed geometrical description of the anatomical components of the head but often lack an accurate description of the cerebrospinal fluid (CSF) behavior. Different material properties, mesh resolutions and numerical implementations are used to represent the CSF in those head models. The CSF should however be modeled as accurately as possible since it plays an important role in protecting the brain against mechanical shocks and providing effective damping against sudden brain motions relative to the skull during head impacts. This paper therefore starts with the development of a simplified head model to perform impact analyses. Subsequently, small adaptations are made to the representation of the CSF in the model, both in mesh size and constitutive modeling, to examine the effect of those different CSF representations on the brain mechanical responses such as strain energy, Von Mises stress, strain and intracranial pressure.

Methodology

The simplified FE head model:

The simplified FE head model presented in this paper is built in LS-PREPOST and is based on a previous model version of the same structure [8]. Small adaptations were made to the mesh of the previous version to avoid contact definitions to be used and to ease the adaptations of the CSF mesh, described later in the text. The simplified FE model used in this paper is shown in figure 1. It consists of three components: a simplified skull that surrounds the CSF which in turn surrounds the inner part, the brain.

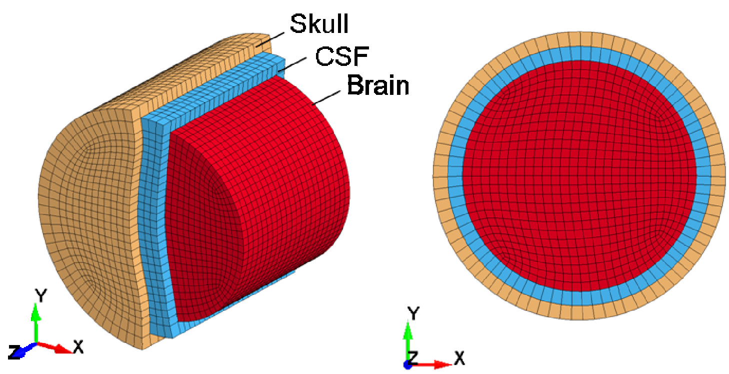

Figure 1: Simplified FE head model (left: different components of the model, right: cross section view).

The size of the FE model is comparable to the dimensions of a normal head but the geometry of the three components was however chosen to reflect the overall biomechanical behavior in head impacts. Moreover, by using this geometry, excellent element quality can be guaranteed. The average element aspect ratio is 1.4 with only 6% of all the elements (22256 in total) having an aspect ratio larger than 2. A good mesh quality will prevent badly shaped elements to occur, which can interfere with the performed study on the effect of the different CSF representation parameters on the brain mechanical responses.
All three head components (skull, CSF and brain) are tied together in a continuous mesh using linear hexahedral selective reduced integration elements. The skull is modeled as a rigid body and the CSF as a linear elastic material with a high bulk modulus and a low shear modulus to reach nearly incompressible behavior. The material properties of the CSF are based on those used in the FE head model from Horgan et al. [5,12]. The brain material is characterized as elastic in compression and viscoelastic in shear using the properties from Zhang et al. [9]. The shear modulus is expressed by:

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t}$$

where G_∞ is the long term shear modulus, G_0 is the short term shear modulus and β is the decay constant. The values of all the material properties used for this FE model, later referred to as FE model 1, are listed in table 1.

Table 1: Material properties used in FE model 1 [5,9,11,12]

Material property	Skull	CSF	Brain
Density [kg/m³]	1300	1000	1060
Bulk modulus K [GPa]		2.5	2.19
Young's modulus E [MPa]	15000	15	
Poisson's ratio ν [-]	0.22	0.499	
Short term shear modulus G_0 [Pa]			12500
Long term shear modulus G_∞ [Pa]			2500
Decay constant β [s^{-1}]			80

To perform a head impact analysis, a load needs to be applied to the simplified FE head model. For this study, a head impact from a real life accident case was used. The head impact occurred in the occipital region of the head after the victim fainted and fell straight backwards. The simulation of the accident was performed in MADYMO by Doorly et al. [10] and the head kinematics, linear and angular velocities of the head's centre of gravity, during and after impact (70ms duration) were obtained. To model this impact with the FE head model, a prescribed motion is applied to the rigid skull in correspondence to the above mentioned calculated velocity data.

Based on this model (FE model 1), small adaptations will be made to the representation of the CSF, both in mesh resolution and constitutive modeling, to examine the effect of different CSF representations on the brain mechanical responses. Slightly different FE head models will thus be created which is described below in more detail.

Alterations of the simplified head model:

In FE head models [5,6,7,9] found in literature, the CSF is modeled in many different ways, both in mesh resolution and constitutive modeling.
First of all, there is a difference in mesh resolution used for the representation of the CSF. In some FE head models, the CSF is represented as a thin layer surrounding the brain which exists of only one element through the thickness whereas other FE head models use 2 or more elements through the thickness of the CSF layer. To study the effect of the CSF mesh resolution on the FE results of a head impact, three new FE models, FE model 2-4, were built by making small adaptations to the base FE model 1. The number of CSF elements through the section thickness was increased, one element at a time, from one (base FE model 1) to four elements (FE model 4) creating those three extra FE models, shown in figure 2. An overview of the specifications of these models can be found in table 2. Based on those four FE models, a study of the CSF mesh resolution is performed.

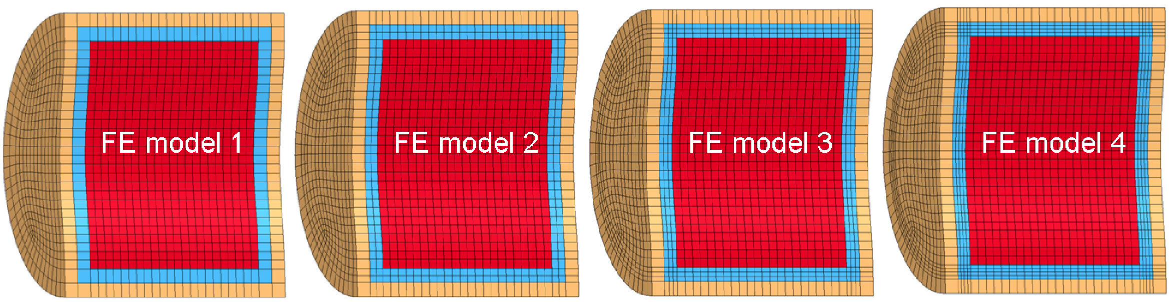

Figure 2: Four FE models with increasing number of CSF elements through the thickness of the CSF from one element (left) to four elements (right)

A complimentary study on the CSF mesh resolution is also performed with four slightly different FE models 1F to 4F, see table 2. These four models are a copy of the previous mentioned FE models 1 to 4 but only the CSF material definition is changed from an elastic material to an ELASTIC_FLUID [13] material with the same bulk modulus. This ELASTIC_FLUID material definition is especially created for modeling fluids and is used in the current FE head model from Kleiven et al. [6]

Table 2: Overview of the different FE models created to study the effect of different representations of the CSF, both in mesh resolution and constitutive modeling.

FE model	Mesh CSF: # elements through thickness	CSF material			Study
		Elastic		Fluid	
		K [Pa]	G [Pa]	K [Pa]	
1	1	2.50E+09	5.00E+06	/	effect mesh CSF
2	2	2.50E+09	5.00E+06	/	
3	3	2.50E+09	5.00E+06	/	
4	4	2.50E+09	5.00E+06	/	
1F	1	/	/	2.50E+09	effect mesh CSF fluid
2F	2	/	/	2.50E+09	
3F	3	/	/	2.50E+09	
4F	4	/	/	2.50E+09	
5	1	2.00E+05	4026	/	effect head model
6	1	/	/	2.10E+09	
7	1	/	/	2.50E+08	effect K
8	1	/	/	2.50E+07	

Apart from the differences in CSF mesh resolution used in the current FE head models, there is also a wide range of material properties used for the CSF. Some FE head models use an elastic material definition for the CSF, while others use the ELASTIC_FLUID [13] definition from LS DYNA. There is also a wide range of values used for the bulk modulus K. To investigate the effect of all these parameters, small adaptations were made again to the base FE model to create four new FE models, FE model 5 to 8.

In a first step, two new FE models, FE model 5 and 6, were created by changing the CSF material properties from FE model 1, which are the properties used in the FE head model from Horgan et al. [5], to the properties used in the FE head model from Willinger et al. [7] and from Kleiven et al. [6] respectively. The properties are listed in table 2. Mark that the CSF properties used by Kleiven et al. are ELASTIC_FLUID properties in stead of elastic properties. The FE models 1, 5 and 6 are compared to see the general effect of different CSF properties, used in current FE head models, on the brain mechanical responses.

In a second step, the effect of changing the bulk modulus K and thus changing the nearly incompressible behavior of the CSF is investigated. The value for the bulk modulus is changed within the range of values used for the CSF in the current FE head models. For this study, FE model 1F (= base FE model 1 with fluid option) is adapted by lowering the bulk modulus to 0.25 GPa and 0.025GPa, thereby creating FE model 7 and 8 respectively. A summary of all the created models can be found in table 2.

In total, twelve slightly different FE models, listed in table 2, were built all starting from FE model 1 and the results of the twelve performed impact analyses were compared to examine the effect of different CSF representations on the brain mechanical responses.

Numerical results and discussion

For all impact analyses, performed with the 12 different FE models discussed above, the following results were obtained for the entire impact simulation of 70ms: the strain energy in the brain and CSF, the average Von Mises stress and average first principal strain in the brain and the frontal and occipital intracranial pressures. The maximum values of all those parameters during the analysis are listed in table 3, which will be discussed further in the text.

Table 3: Overview of the results (maximum values) for the 12 FE models: the strain energy (SE) in the brain and CSF, the average Von Mises stress (σvm) and average first principal strain (εI) in the brain and the frontal and occipital intracranial pressures (P).

FE model	P frontal [Pa]	P occipital [Pa]	SE CSF [J]	SE brain [J]	average σvm [Pa]	average εI [-]
1	-224749	127152	0.019	9.318	8834	0.317
2	-223474	126166	0.018	9.317	8834	0.317
3	-223801	128723	0.020	9.312	8834	0.317
4	-222980	128774	0.016	9.318	8835	0.317
1F	-227915	130159	1.523	8.402	8351	0.305
2F	-227619	130371	1.810	8.260	8274	0.303
3F	-228784	131362	2.549	7.822	8028	0.297
4F	-230390	132581	3.228	7.411	7794	0.292
5	-77424	189262	54.483	12.963	10269	0.502
6	-228062	131452	1.650	8.327	8311	0.304
7	-213201	170730	3.968	6.785	7444	0.282
8	-210006	202175	7.334	3.207	5026	0.208

The influence of the CSF mesh resolution:

To investigate the dependence of the results of a FE impact analysis on the CSF mesh resolution, FE model 1 to 4, which use the elastic CSF material definition, are first compared with each other. Afterwards, the same comparison is made for FE model 1F to 4F which have the ELASTIC_FLUID CSF material definition.

Table 3 shows almost no difference between the calculated brain response parameters during impact for FE models 1 to 4. Increasing the number of CSF elements used throughout the thickness of the CSF layer, will not have a significant effect on the behavior of the brain. This finding is however only valid when the elastic material definition with a Poisson coefficient close to 0.5 (see table 1) is used to represent the nearly incompressible CSF. When the material definition was changed from elastic (FE models 1-4) to ELASTIC_FLUID (FE models 1F-4F), an influence of the mesh resolution on the results was observed. A comparison between FE models 1F – 4F highlighted a rather small increase in frontal and occipital pressure but the CSF strain energy increases significantly from FE model 1F to 4F with a corresponding decrease in brain strain energy, Von Mises stress and first principal strain. When the mesh resolution increases, the deformation in both shear and compression of the CSF elements becomes larger together with the CSF strain energy. Due to the fact that the CSF elements will deform more, less energy is transferred to the brain which will have a decrease in energy, Von Mises stress and strain as a consequence.

An explanation for the fact that the effect of mesh resolution is visible with the ELASTIC_FLUID definition and not with the elastic definition can be found in the calculation of the deviatoric behavior of the CSF elements. In the elastic material definition, the shear modulus can not be set to zero but has usually a value between 5kPa and 5Mpa found in literature. As a consequence, there is a resistance to shear which is normally not present in a fluid. For this reason, the ELASTIC_FLUID material definition is often used to represent a fluid. In this definition, the shear modulus is zero and the deviatoric stresses are treated separately from the volumetric stresses. The volumetric stresses will be proportionate to the volumetric strains and the bulk modulus whereas the deviatoric stresses are proportional to the strain rate and the dynamic viscosity. Since there is almost no resistance to shear in the ELASTIC_FLUID option, the elements of the CSF will deform much more than with the elastic definition. This is also seen in the CSF strain energies for FE models 1-4 which are much smaller compared to the ones from FE models 1F-4F. Due to the larger deformations in the “fluid” FE models 1F-4F, the effect of altering the mesh resolution of the CSF can be clearly seen.

Depending on which material definition is used for modeling the CSF, the mesh resolution of the CSF could have an important effect on the brain mechanical responses. A mesh conversion analysis is therefore always recommended.

The influence of the CSF material modeling:

The effect of different material properties for the CSF on the impact response of the head was investigated through FE model 1 and 5-8 and the results are summarized in table 3.
In a first step, a comparison is made between FE model 1, 5 and 6 where the CSF material properties from the FE head models of Horgan et al. [5], Willinger et al. [7] and Kleiven et al. [6] are used respectively. Figure 3 shows for all three FE models the evolution of the average brain Von Mises stress and first principal strain with impact around 0.05s. Based on figure 3 and the results in table 3, it is clear that FE model 5, with the properties used by Willinger et al. [7], give rise to significant differences in the results compared to FE model 1 and 6. This is due to the fact that FE model 5 uses a very low bulk modulus compared to the other FE models 1 and 6, who have a similar bulk modulus. Therefore the CSF is no longer modeled as a nearly incompressible material in FE model 5, which leads to large, unrealistic deformations, both shear and compression, of the CSF and the brain. This also gives rise to a reciprocating motion of the brain with respect to the skull which can be seen as small vibrations superimposed on the brain Von Mises stress and strain in figure 3 for FE model 5.
For FE models 1 and 6, the results are quite similar except for the strain energy of the CSF which is higher for FE model 6. The reason for this difference in CSF strain energy is because in FE model 6, the ELASTIC_FLUID option is used compared to FE model 1 where the elastic definition is used, see table 2. Due to the use of the fluid option, as explained in the previous section, the deformation of the CSF elements is bigger in FE model 6 and thus a larger CSF strain energy is observed. Because less energy is then transferred to the brain in FE model 6, the brain Von Mises stress and strain will be slightly lower than in FE model 1 which is clearly seen in figure 3.

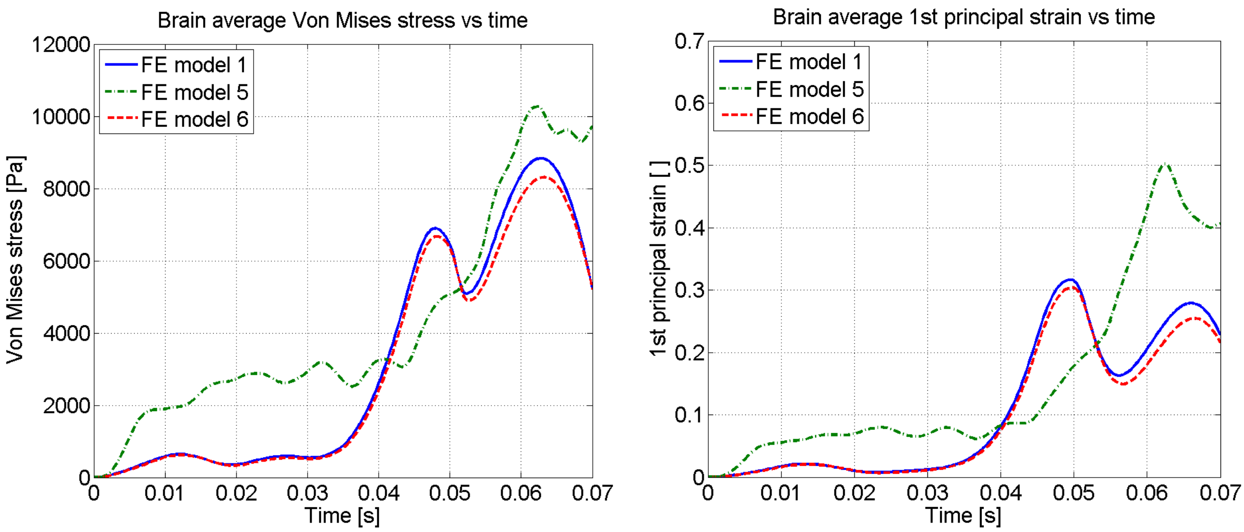

Figure 3: The evolution of the brain Von Mises stress and first principal strain for FE models 1, 5 and 6. The head impact occurs around 0.05s.

In a second step, the effect of changing the bulk modulus K in the ELASTIC_FLUID material definition is investigated using FE models 1F, 7 and 8 where the bulk modulus was lowered from 2.5GPa to 0.025GPa respectively. Lowering the bulk modulus further to the values used by Willinger et al. [7], around 0.2 MPa, gave unstable results for the ELASTIC_FLUID definition, so a lower limit of 0.025GPa was used. Figure 4 shows the evolution of the average Von Mises stress and first principal strain in the brain for all three FE models. The results in table 3 and figure 4 show that a decrease in bulk modulus leads to an increase in CSF strain energy and a corresponding decrease in brain strain energy, Von Mises stress and first principal strain. It is known that when the bulk modulus decreases, the nearly incompressible behavior of the CSF is compromised and the deformations, both compression and shear, of the CSF elements will increase. This rise in deformations is seen in the increase in CSF strain energy. Since the CSF deforms more, less energy is transferred to the brain, with the mentioned decrease in Von Mises stress, strain and strain energy of the brain as a consequence.

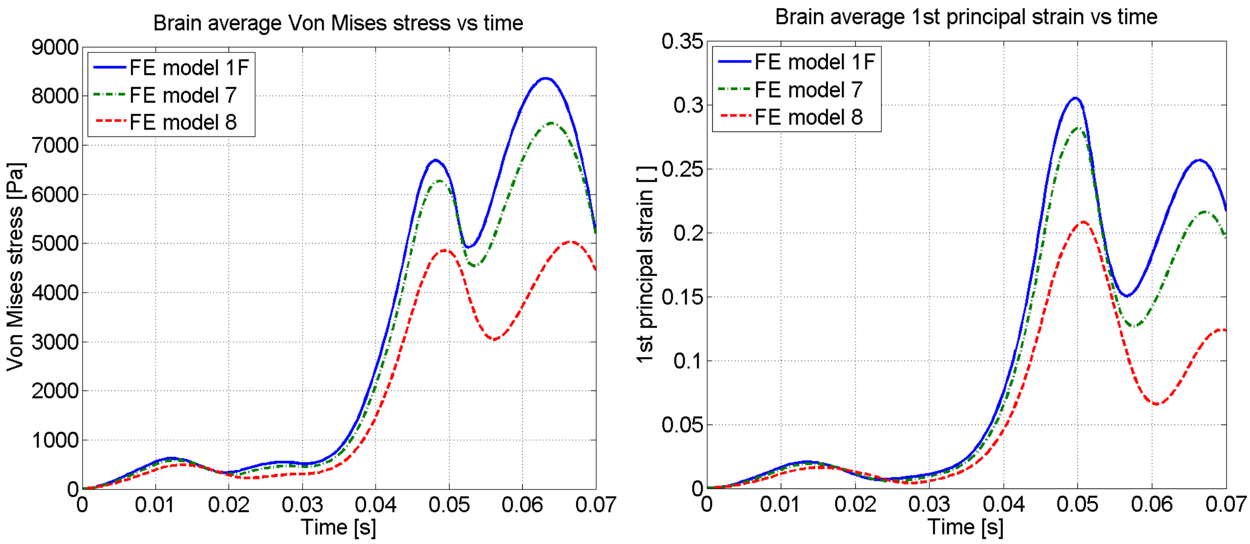

Figure 4: The evolution of the brain Von Mises stress and first principal strain for FE models 1F, 7 and 8. The head impact occurs around 0.05s.

The presented study on different CSF constitutive modeling highlighted the large influence of the CSF material properties, both material definition and property values, on the results of a head impact analysis. It is therefore important to narrow the range of currently used CSF material properties to obtain an accurate description of the CSF and brain behavior during impact.

Limitations of the presented study

The presented study evaluated the different CSF representations used in literature and it was seen that both CSF mesh resolution and CSF material properties can have a significant effect on the brain mechanical responses. It was concluded that the large range of values for the CSF material properties available in literature should be narrowed. One important question remains unanswered in this study: whether it is possible to obtain a realistic representation of the CSF when a finite element representation is used to represent a fluid material. The main drawbacks of the finite element method are that no fluid flow is possible and shear stresses in the elements exist whereas this is not realistic for a fluid. A first attempt to approach a realistic fluid behavior with finite elements was made with the use of an ELASTIC_FLUID definition for the CSF where the shear modulus is set to zero. For this definition, fluid flow still remains impossible. A suggestion for future studies could add the use of smoothed particles to represent the CSF using the Smoothed Particle Hydrodynamics (SPH) technique since this technique allows for a fluid to flow. Some first attempts were made to model the CSF with smoothed particles in the presented simplified FE head model but they failed due to interaction problems between the finite elements of the brain and skull and the smoothed particles of the CSF. Further research is therefore necessary.

Conclusions

This paper highlighted the need for and importance of a more accurate description of the CSF material properties for predicting head injuries, because these properties have a large influence on the CSF and brain impact behavior. The mesh resolution of the CSF can also have an important effect on the CSF and brain mechanical responses depending on which material definition is used for modeling the CSF. A mesh conversion analysis is therefore always recommended.

Acknowledgment

This research is funded by a PhD grant of the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen SB071092).

References

[1] Eilert-Petersson E., Schelp L., An epidemiological study of bicycle-related injuries. Accid Anal and Prev. 1997, 29:363-372

[2] Elsen M., Janzing H., Broos P., Delooz H., Hoofdletsels bij fietsongevallen. Tijdschr. voor Geneeskunde. 1997, 53:945-952

[3] Oström M., Björnstig U, Näslund K, Eriksson A., Pedal cycling fatalities in Northern Sweden. Int J Epidemiol. 1993, 22:483-488

[4] NIS. Toename van de verkeersdoden - verkeersongevallen in 2008. Brussels: NIS (Statistics Belgium); 2008

[5] Horgan, T.J. & Gilchrist, M.D., The creation of three-dimensional finite element models for simulating head impact biomechanics. Int. J. of Crashwothiness, 2003, 8 (4): 353-366

[6] Kleiven, S., Finite Element Modeling of the Human Head. *Doctoral Thesis.* Technical Report 2002-9, Department of Aeronautics, Royal Institute of Technology, Stockholm, Sweden, 2002

[7] Willinger R., Baumgartner D., Human head tolerance limits to specific injury mechanisms. Int. J. of Crashw, 2003, 8/6: 605-617

[8] Baeck, K., Goffin, J., Vander Sloten, J. The effects of different brain material properties, FE mesh size and hourglass modes on the results of FE head impact analyses. IFMBE Proceedings Vol. 25/IV. World Congress: Medical physics and biomedical engineering. Munich, Germany, 2009, pp. 902-905

[9] Zhang, L.; Yang, K.H.; Dwarampudi, R.; Omori, K.; Li, T.; Chang, K.; Hardy, W.N.; Khalil, T.B. and King, A.I., “Recent Advances in brain Injury Research: A New Human Head Model Development and Validation” *Stapp Car Crash Journal* 2001, 45:369-393

[10] Doorly, M.C., Gilchrist, M.D., The analysis of traumatic brain injury due to head impacts arising from falls using accident reconstruction. Comp Meth Biomech Biomed Eng, 2006, 9 (6):371-377

[11] McElhaney, J.H., Fogle, J.L., Melvin, J.W., Haynes, R.R., Roberts, V.L., Alem, N.M., Mechanical properties of cranial bone. J. Biomech. 1970, 3:495-496

[12] Goldsmith, W., Biomechanics of head injury. Biomechanics: Its Foundations and Objectives, 1972, 585-634

[13] Hallquist, J.O. LS-DYNA User’s Manual, Version 971