EXPERIMENTAL AND THEORETICAL MODELLING OF HEAD IMPACT
- INFLUENCE OF HEAD MODELLING -

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ABSTRACT

The objective of this study is to propose an experimental and analytical method to analyse head impact which uses a more realistic model of the head than a single mass model. In the experimental components of the study, a Hybrid III dummy head and the recently published dummy head "Bimass 150" was dropped on to beams with different characteristics. The analytical component of the study consists of the mathematical construction of a lumped parameter model of the head which distinguishes the brain from other masses in the head and model of the head which use a single mass. The simulation of the impact of these models with a mathematical model of a beam are then compared to the previous experimental data. We conclude that the experimental or analytical modelling of the head mechanical behaviour has an important influence on the structure response and that this has to be taken into consideration in the analysis of structure aggressiveness.

CONSIDERATION OF THE BIOMECHANIC of head impact is important in many aspects of the study of head trauma. Often this consideration includes the analytical or physical modelling of the head. These studies also deal with injury mechanisms or with tolerance limits. These studies can be compared with epidemiological analyses. In accordance with the summary of earlier research (Patrick,1965)(Mc Elhaney, 1976), normative tests were conducted in order to evaluate the protective capacity of safety devices or more generally to get a measure of the aggressiveness of an impact.

The various aspects involved in the research of head trauma are closely linked. When we study the phenomena which occur at the time of impact, different disciplines come into play but the litterature on the subject hardly takes these various disciplines into account. Same is the case with some epidemiological studies which do not take into consideration the dynamic mechanical properties of the impacted structure. These studies which are very informative about injury mechanisms are however incomplete because all the phenomena which can occur during the shock can not be understood. The complex nature of the human head versus impacted structure interaction is not considered in all its complexity even in studies related to aggressiveness and protective aspect of a structure, not to mention that the dynamic mechanical properties of the human head are neglected.

Theoretically, the study of shocks in the previous litterature is based on the modelling of impacted structures as helmets or car accessories which use lumped parameter models like masses, springs and dashpots (Gilchrist,1994)(Ryan, 1989). In these studies, the head is always represented as a single rigid body. The same approach is adopted while conducting experiments because the real structures are impacted by a dummy head which is nothing else but another rigid body (Gilchrist, 1994)(Khalil, 1994).

This theoretical and experimental work on head impact may be criticised for two main reasons. Firstly, as suggested by some authors (Gilchrist, 1994)(Welbourne, 1994), representing the head by a rigid body rules out any realistic view of the various injury mechanisms which could occur during a shock. Moreover, it restricts the ability to predict injury risks to the study of HIC, an injury criterion widely criticised by the scientific community. Secondly, the impact parameters observed when the head is represented as a rigid body are different from those observed when a bio-faithful model of the head hits a structure. This difference modifies the force of interaction between the head and the impacted structure. This means that the response of a structure to a shock depends on the type of dummy head which impacts it.

One solution to this theoretical problem is to use the finite element method for devising models and structures close to reality (Dimasi, 1991). This numerical approach, also requires a validation of the dynamic behaviour of the impacted structure which can be a long and tricky exercise. The experimental analysis of impacts continues to be a fundamental research method given the complexity of some non linear structures and the necessity for standardization tests. As far as we know there hasn't ever been any realistic approach to this problem.

The Biomechanical Systems Laboratory of Strasbourg University and the Road Accident Reseach Unit of the University of Adelaide together studied the influence of the impacted structure on the types of injuries observed (Willinger, 1992). The aim of this joint study is to present a method for analysing head impact, theoretically and practically. It also aims at proving that it is important to have a more precise model of the head in order to evaluate injury risk and to describe the impacted structure response. Before discussing the results of this study, we will focus on the various models wich represent the head and the impacted structure. We will then give a detailed description of the theoretical and experimental simulation of the shock itself. In the last part of the present paper, we will review the difference between theoretical and experimental results and we will also discuss how a more sophisticated model of the head can throw new light on the field of head impact research.

METHOD

THEORETICAL AND EXPERIMENTAL MODELLING OF THE HEAD - The analysis of the in vivo human head's dynamic response revealed a natural frequency at about 120 Hz accompagnied by a "decoupling" of about 1 kg mass (Fig. 1). This leads to the hypothesis that it is the "decoupling" of the brain with respect to the skull. Epidemiological studies have revealed focal contusions which often appears in the frontal area what seams to confirm the hypothesis of "decoupling". These studies form the basis of lumped model which have the distinctive features of being able to distinguish between the brain mass and other masses present (Fig. 2) (Willinger, 1990).

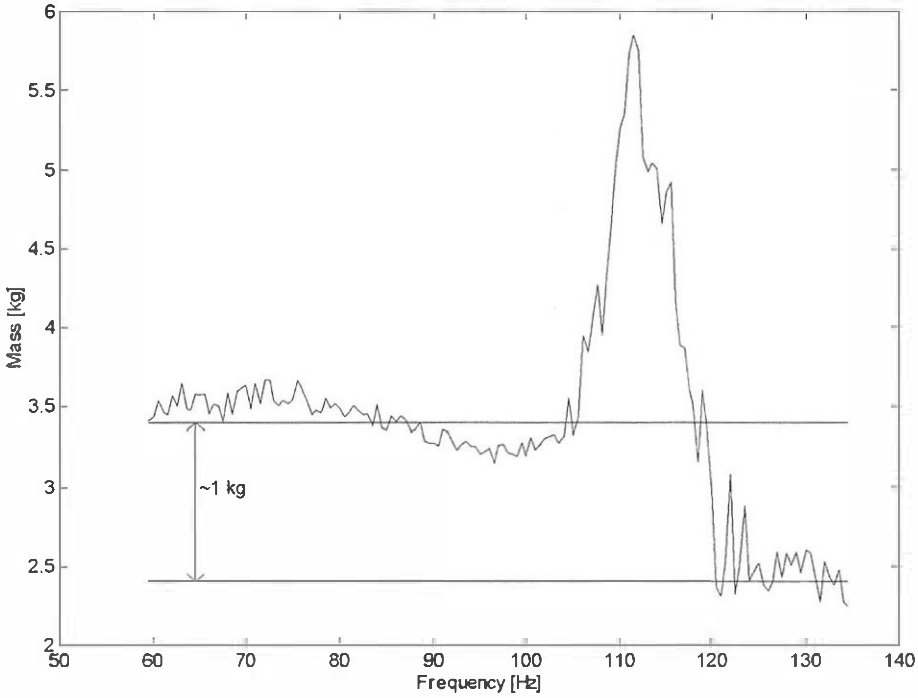

Fig. 1 - In vivo head apparent mass

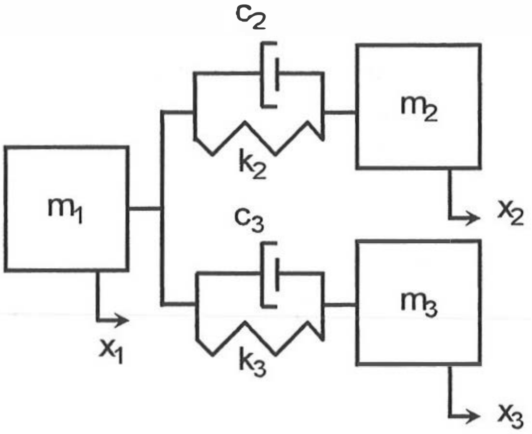

Fig. 2 - Trimass Model

In this study, we are interested in the brain - skull relative displacements during an impact, assuming a non deformable skull. In this case, the stiffness between m_1 and m_3 can be considered to be infinity and the general model in figure 2 (Trimass) can therefore be considered as a two mass model - the skull $m_1 + m_3$ on the one hand and the brain m_2 on the other. Dummy heads such as Hybrid III used till now for standardizing safety systems consider the head as a rigid body. With the intention of improving their biofidelity we designed a new physical model of the head called Bimass 150 which can simulate the brain - skull relative displacement (Willinger, 1995).

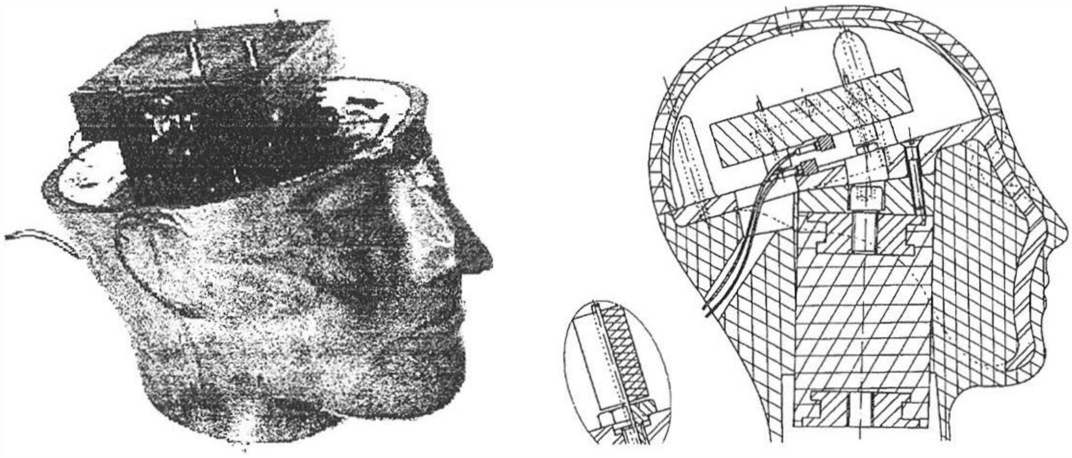

Fig. 3 - The Bimass 150 : photography and detailed view

The Bimass 150 is in fact a dummy head with a mass representing the brain mass inside. Four metal rods sealed in four plastic cylinders maintain the links between the two. This combination simulates the stiffness and the damping involved in the brain - skull contact, respectively. Two accelerometers, one fixed to the skull and the other to the brain give the kinematic readings of these two masses along the "front-to-back" axis. It is also possible to prevent the brain motion and thus to transform the Bimass 150 into a Hybrid III like dummy head but with a mass of 5.285 kg instead of the 4.5 kg standart Hybrid III head.

ANALYTICAL ANALYSIS OF THE IMPACTS - The head - structure interaction during the shock is studied in an analytical fashion with the help of lumped parameter models of the head and the impacted structure. The first step is to represent the head as a two masses structure as in figure 4. The second step is to represent the head as a single non deformable mass in order to simulate a Hybrid III dummy head (Fig. 4). These models were chosen to study the importance of the head response on the resulting impact .

The impacted structure is also represented as a lumped parameter model. As far as this study is concerned, the beams are modelled by a simple mass - spring system (Fig. 4). This model is a reproduction of the first mode of vibration of the beam simply supported. Its natural frequency is given by the following formula (Press, 1992)

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{m_3}}$$

where

$$K = \frac{48EI}{L^3}$$

and

$$m_3 = 0.5m$$

where E is the Young's modulus of the beam, I its moment of inertia, m its mass and L its length. To avoid any discontinuity at the time of contact, the modal stiffness of the beam is split into two, as in figure 4. This allows us to deal with the contact without modifying the natural frequency of the beam.

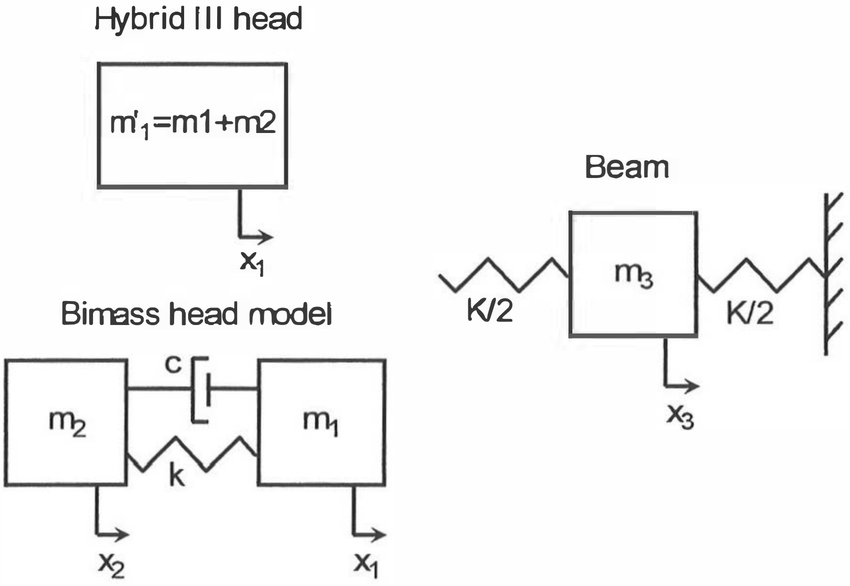

Fig. 4 - Lumped parameters models

with : m'_1 : head mass (5.285 kg non-standard Hybrid III head)
m_1 : skull mass (4 kg)
m_2 : brain mass (1.285 kg)
k : brain - skull stiffness factor ($36*10^{0.4}$ N/m)
c : brain - skull damping factor (22 Ns/m)
m_3 : modal mass of the beam (Beam 1 : 1.15 kg)
(Beam 2 : 0.47 kg)
K : modal stiffness of the beam (Beam 1 : $6.82*10^4$ N/m)
(Beam 2 : $14.3*10^4$ N/m)

The equations which describe the one mass model of the head and the beam are as follow

$$\text{Out of contact} \begin{cases} m'_1\,\ddot{x}_1 = 0 \\ m_3\,\ddot{x}_3 = -\dfrac{K}{2}x_3 \end{cases} \qquad (1)$$

In contact
$$\begin{cases} m'_1\,\ddot{x}_1 = -\dfrac{K}{2}(x_1 - x_3) \\ m_3\,\ddot{x}_3 = \dfrac{K}{2}(x_1 - x_3) - \dfrac{K}{2}x_3 \end{cases} \tag{2}$$

If the head is considered as the two masses model, these equations are expand to

Out of contact
$$\begin{cases} m_1\,\ddot{x}_1 = -k(x_1 - x_2) - c(\dot{x}_1 - \dot{x}_2) \\ m_2\,\ddot{x}_2 = k(x_1 - x_2) + c(\dot{x}_1 - \dot{x}_2) \\ m_3\,\ddot{x}_3 = -\dfrac{K}{2}x_3 \end{cases} \tag{3}$$

In contact
$$\begin{cases} m_1\,\ddot{x}_1 = -k(x_1 - x_2) - c(\dot{x}_1 - \dot{x}_2) - \dfrac{K}{2}(x_1 - x_3) \\ m_2\,\ddot{x}_2 = k(x_1 - x_2) + c(\dot{x}_1 - \dot{x}_2) \\ m_3\,\ddot{x}_3 = \dfrac{K}{2}(x_1 - x_3) - \dfrac{K}{2}x_3 \end{cases} \tag{4}$$

These set of equations are then solved with a Runge - Kutta algorithm of order 2 and 3 (Press, 1992).

EXPERIMENTAL IMPACT ANALYSIS - In order to confirm the results of the mathematical simulations, experiments were conducted to determine the impact between the physical model and two beams resting on a simple fulcrum. The properties of these two beams are reported in the table 1 below. Tests were conducted with Bimass 150 and Hybrid III on a vertical impact test system for drop height of 0.1 and 0.15 metres.

Table 1 : Beams properties

	Young Modulus [Pa]	**L x W x H [m]**	**Inertia [m^4]**
Beam 1	$2.2685{*}10^{11}$	0.66 x 0.1 x 0.006	$1.8{*}10^{-09}$
Beam 2	$2.0685{*}10^{11}$	0.5 x 0.1 x 0.006	$1.8{*}10^{-09}$

RESULTS AND DISCUSSION

We present hereafter the results of impacts for both the beams we used and for the drop heigth of 0.1 and 0.15 metres.

The method used to analytically solve the head - structure interaction is first validated with the one mass head model or the Hybrid III headform. Figures 5 and 6 present the acceleration of the centre of gravity of the mass versus time as a result of the numerical solution of the differential equations (1)&(2) on one hand and experimental measurements on the other, for impact on the first beam, for drop height of 0.1 and 0.15, respectively.A second beam, with a higher stiffness, is then hit in the same conditions with the same analytical and experimental models. Results are presented in figure 7 for a drop height of 0.1 m and in figure 8 for a drop height of 0.15 m.

All shocks considered above show reasonable agreement between theoretical and experimental data. The method is thus validated for this type of simple head model. We can notice that the simulated curves are slithtly higher in amplitude and the oscillations a little bit stronger than for the experimental data especially for the stiffest beam (Fig. 7 and 8). This phenomena may be explained by the dummy head rubber scalp, a parameter not taken in account in the present state of this theoretical approach.

These analytical and experimental impacts were repeated using models of the head built with two masses. The acceleration of the centre of gravity of the head is here no longer meaningful. Hence the results now show two curves of accelerations, one related to the "skull" and the other to the "brain". Data are reported in figures 9 and 10 for the first beam and in figures 11 et 12 for the second. They also show a quiet good agreement between simulations and experiments. Once again, we notice the damping of the theoretical skull acceleration compared to the experimental one. The larger oscillations of the brain for experimental data in figures 9 and 10 are probably caused by a over-estimate of the skull - head damping factor. This phenomena is however less evident in figures 11 and 12. This effect is probably due to the external rubber scalp whose shock filtering effect is more important for the second (more rigid) beam as mentionned with the mono mass model.

The influence of head modelling on the dynamic response of the impacted structure is illustrated by the difference in the interaction forces calculated with different head models.

Figure 13 shows the forces of interation for both the single mass head model and the trimass head model impacting the first beam from a drop height of 0.1 m.

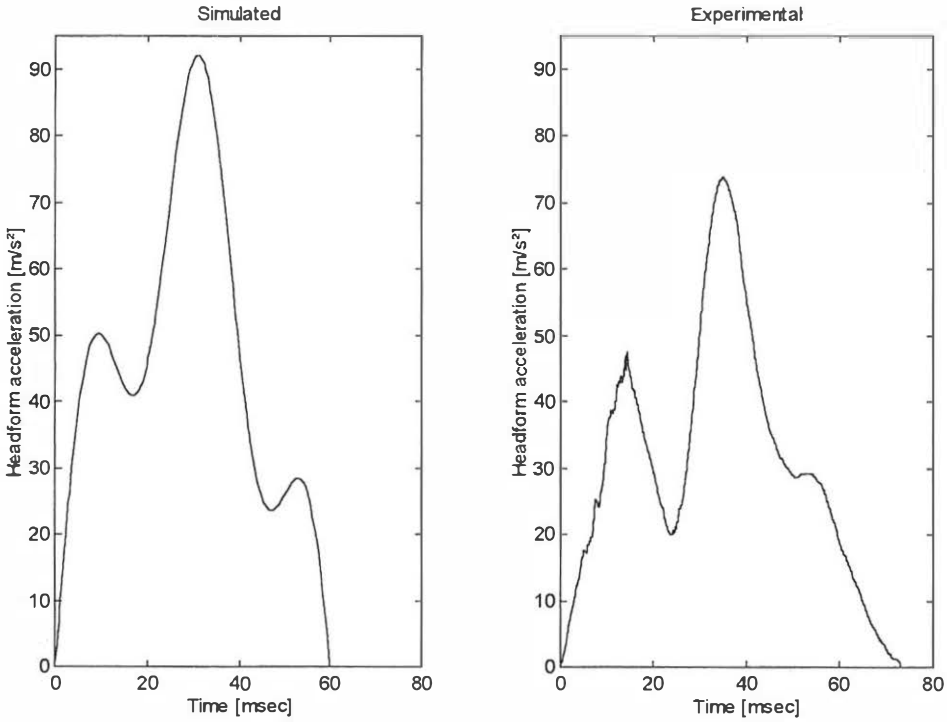

Fig. 5 - One mass head acceleration (Beam 1, drop height : 0.1m)

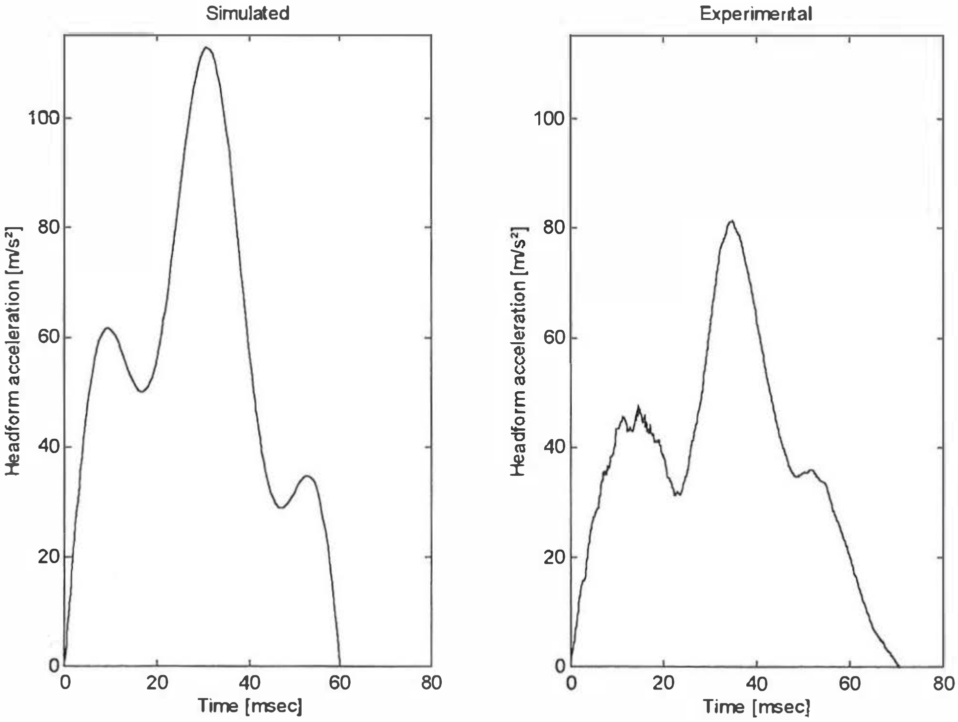

Fig. 6 - One mass head acceleration (beam 1, drop height : 0.15m)

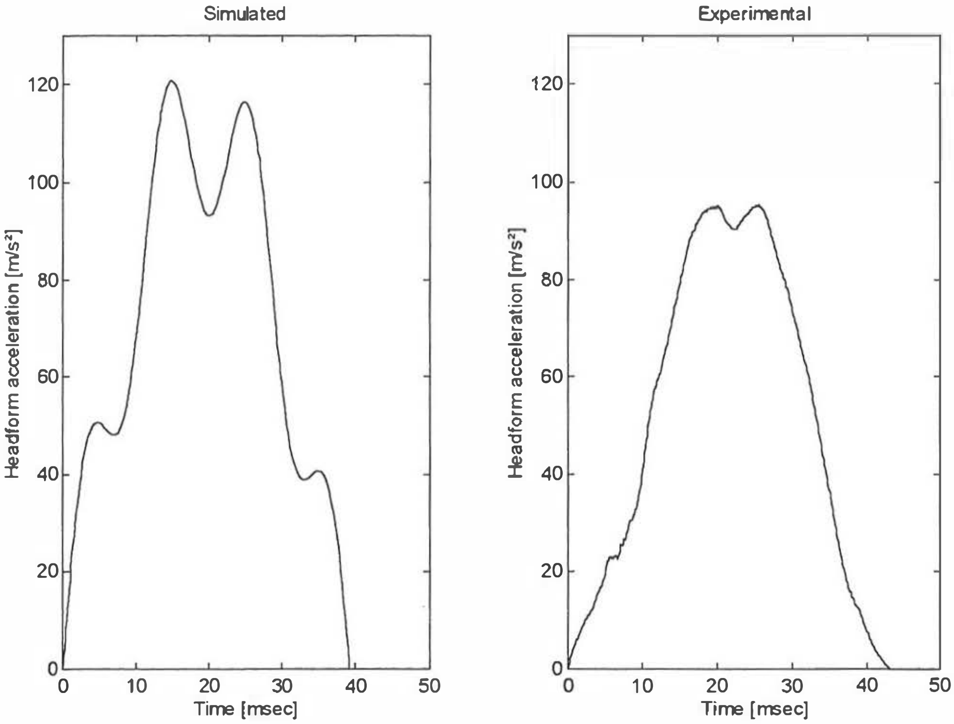

Fig. 7 - One mass head acceleration (beam 2, drop height : 0.1 m)

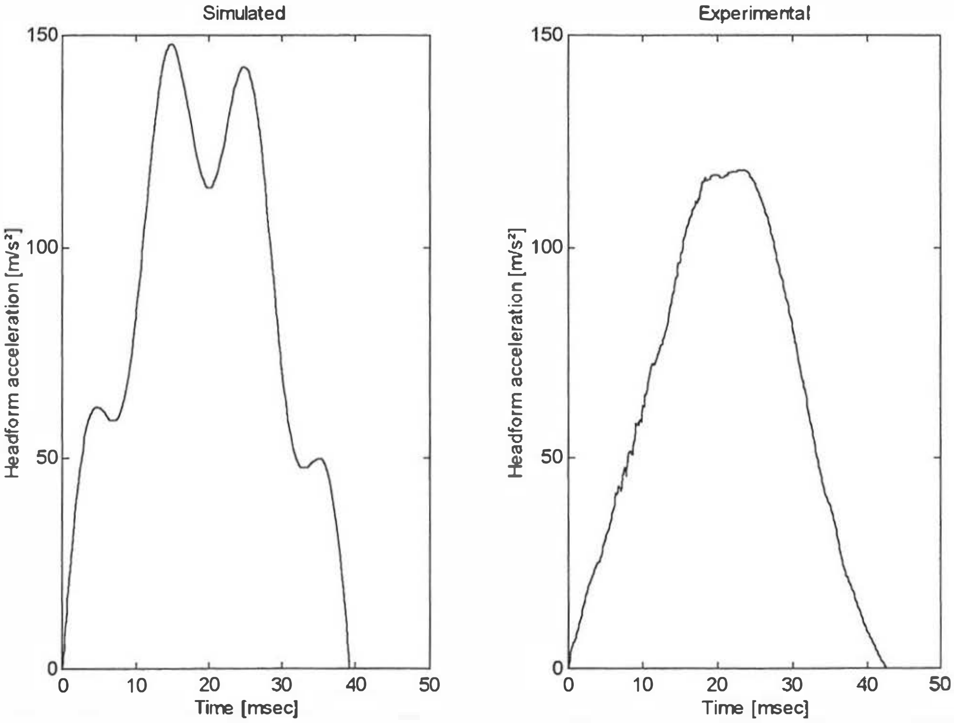

Fig. 8 - One mass head acceleration (beam 2, drop height : 0.15 m)

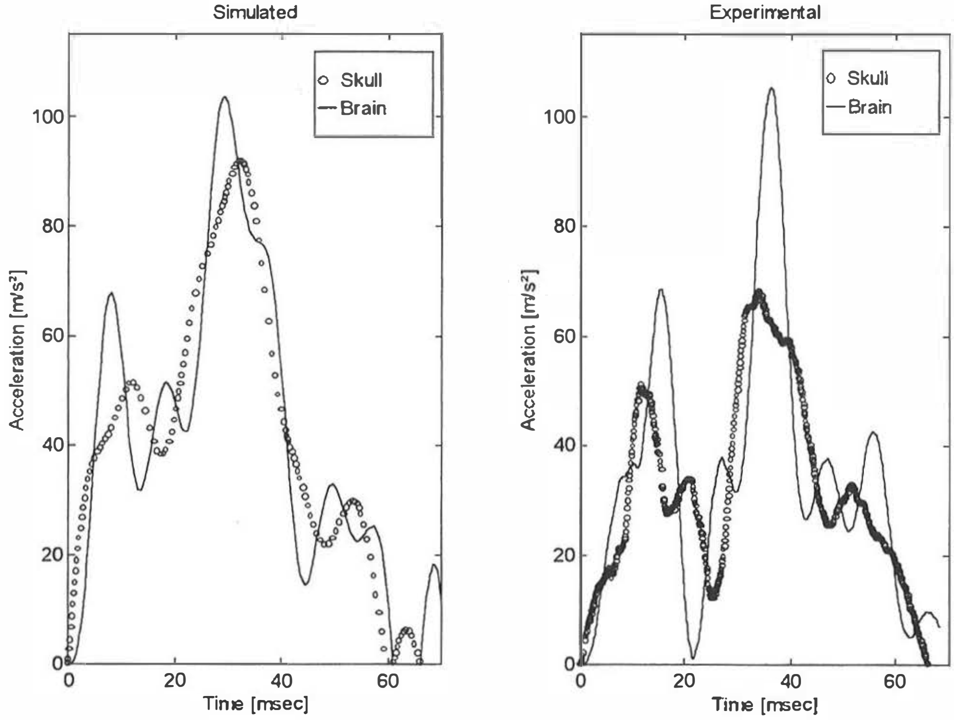

Fig. 9 -Bimass head accelerations (beam 1, drop height : 0.1m)

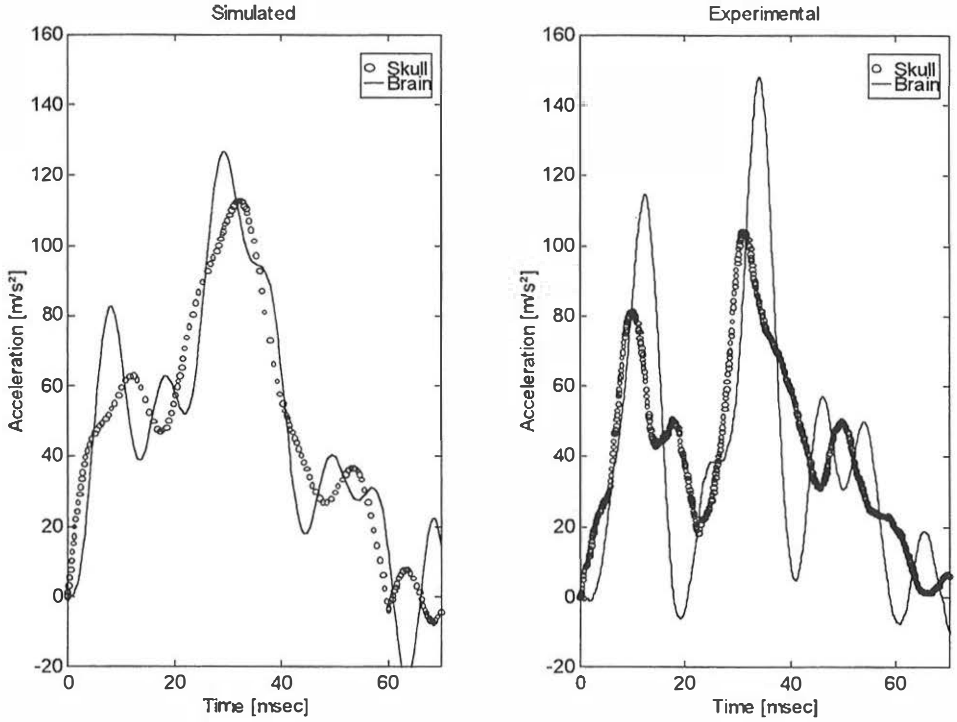

Fig. 10 -Bimass head accelerations (beam 1, drop height : 0.15m)

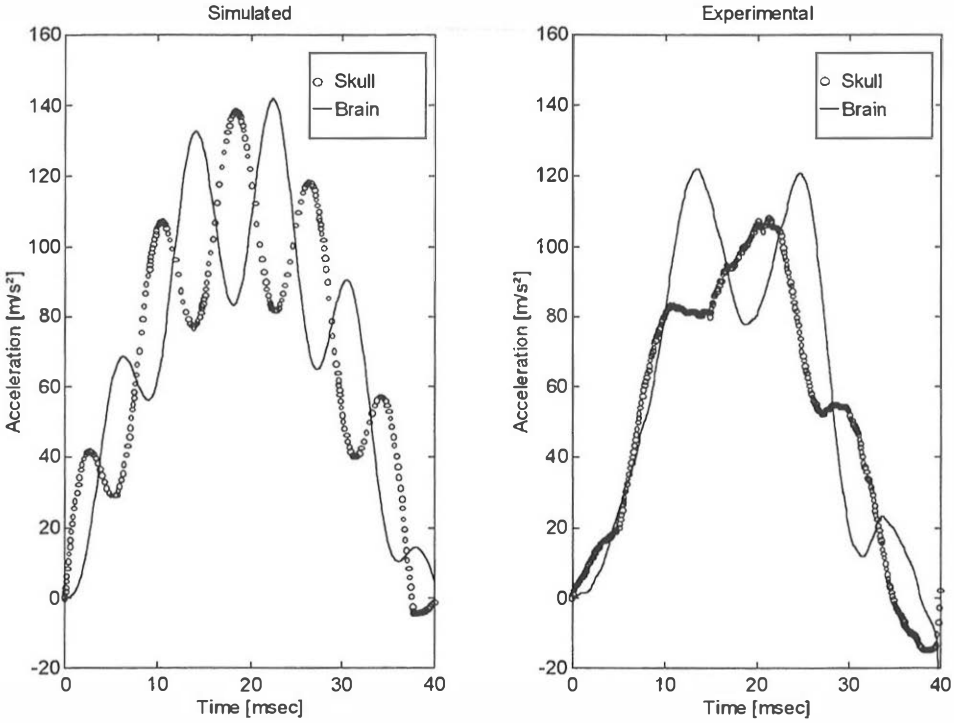

Fig. 11 - Bimass head accelerations (beam 2, drop height : 0.1m)

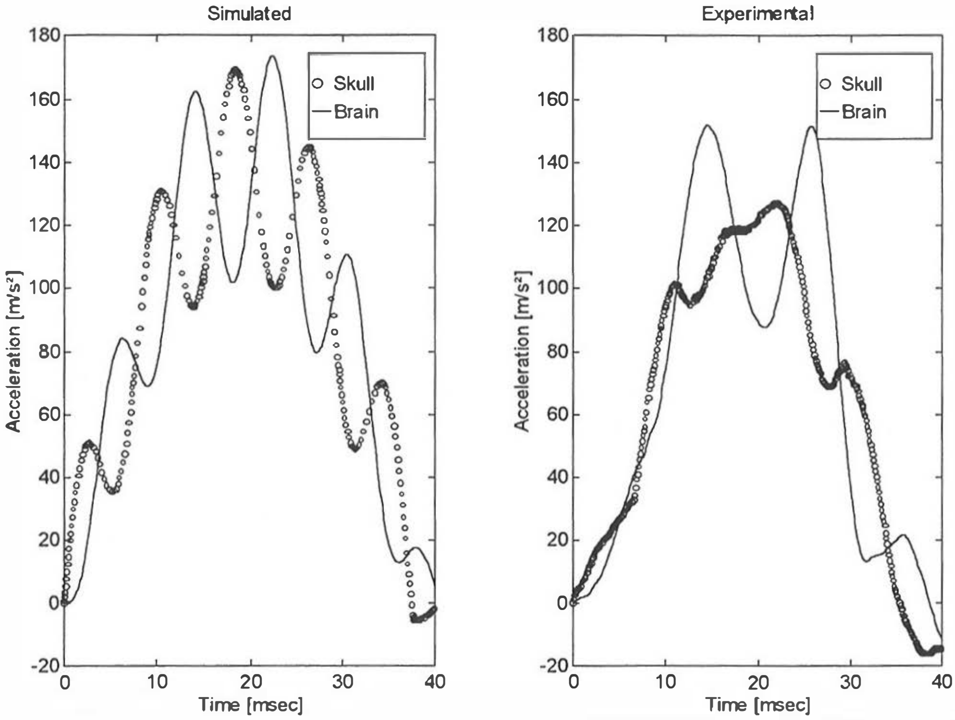

Fig. 12 - Bimass head accelerations (beam 2, drop height : 0.15 m)

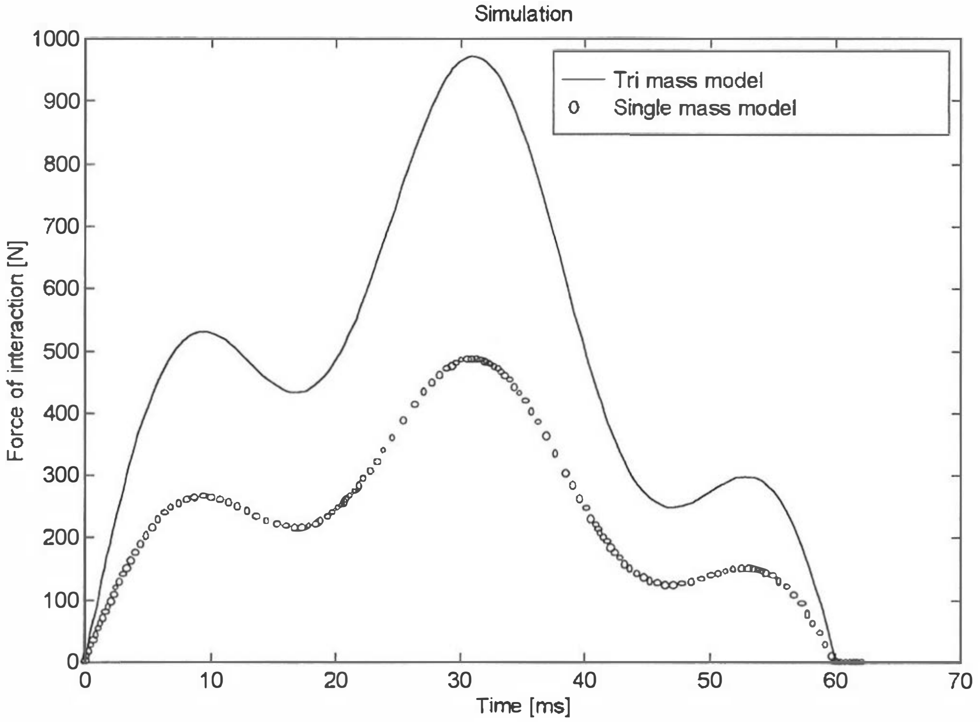

Fig. 13 - Forces of interaction of the one mass model and the tri mass model against the first beam from a drop height of 0.1 m

CONCLUSION

The aim of this joint study was to propose an theoretical and experimental method of analysis for head impact using a more realistic model of the human head.

From an analytical point of view, the head is modelled by a lumped parameter model which distinguishes the brain and the other parts of the head. The physical approach considers a new dummy head designed with a mass to simulate the brain within a dummy skull. This study considers shocks of quiet low energy level. The impacted structures are beams for the physical impact and are modelled as lumped parameter models for the theoretical approach.

The analytical solution of the head - structure interaction is based on a Runge - Kutta algorithm. In order to bring to the fore the influence of the choice of head modelling on the phenomena which can occur during a shock, all the theoretical and experimental impacts have also been carried out with a single mass head.

The results showed that

i) Despite some damping problems with the dummy head, simulations and experiments show good agreement for the two mass head model as well as for the single mass head one. This valids the theoretical approach.

ii) The choice of head modelling greatly influences the nature of the shock, i. e. the forces of interaction are different according to the type of head model for a same impacted structure.
iii) The two mass model gives information about the intracranial dynamics and thus permits to have some information about the injury mechanisms that could occur during a shock.

Even if this work is just a step towards the comprehension of head trauma and although it is still making a simple hypothesis, it nevertheless clearly shows the importance of a more realistic modelling of the head in the theoretical and experimental study of shock agressiveness.

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