MODELLING THE SHAKEN BABY SYNDROME

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Introduction

Physical child abuse is common. For the UK alone, an informed estimate is that every year more than 200 infants die from brain injuries inflicted by violent shaking ("Shaken Baby Syndrome"). Around twice this number, who actually survive such treatment, are left with severe mental and physical disability including blindness due to associated damage to the retina (the light-sensitive part of the eye). Although it is now distressingly obvious that shaking often causes debilitating brain and eye injuries, it is unclear how it happens, whilst such combined injuries are rare even in severe accidental head trauma with skull fractures.

The work involves the use of LS-DYNA to explore some of the mechanical fundamentals of these phenomena. Specifically, it addresses the difference between motions induced in the brain through the "single event" loading that is normally associated with impacts and those induced by shaking. The paper also describes a set of experiments that measured the accelerations induced by shaking an automotive dummy of a 9-month old child. The "shakers" included young men and women, and middle-aged men and women. They also ranged between small and delicate, and large and muscular. The data from this sort of experiment is essential input to the DYNA simulations.

Methodology

Figures 1 and 2 show CAT scans from a human patient. This data was digitised and used in ANSYS to generate a three-dimensional geometric model. This process was performed in layers, which were produced by the CAT scanner (e.g. figure 2). ANSYS was used to generate the finite element mesh shown in figure 3 using shell elements. This mesh was exported via HYPERMESH into LS-DYNA. The view in figure 3 shows the skull contours, which match the convolutions and folds of the brain. Viewed from the top of the brain, it is possible to observe a slight bulge close to the right temple that was the result of the scan in this particular patient (figure 1).

This process yielded a finite element model of a skull of an adult human, which was then scaled down in order to represent the skull of an infant. The brain was modelled by scaling down the skull to generate a solid model, (see figure 4) which fitted inside the skull model. The gap between the skull and brain was filled with solid elements, which were given the properties of cerebrospinal fluid (CSF). Material properties from the literature were assigned to the model as shown in Table 1; these properties were assumed to be linear elastic throughout.

The model was subjected to accelerations obtained by experiment using dummy tests (figure 5). The experiments were carried out at the Transport Research Laboratory. It was observed that the child's head started its motion with simple anterior-posterior oscillations. This quickly degenerated into rotational, forwards and backward movement suggesting a mixture of rotational and translation accelerations to a high degree. Even though the movement was extremely uncontrolled, it did not seem random or chaotic. At this stage, it is not clear whether these observations on the automotive dummy mirror effects in a real shaken infant, or whether they are a consequence of the simplicity of the dummy neck-mechanism. (This is designed to respond to impacts, and not to the reflated motions of our experiments). It was noted that the chest of the dummy had to be gripped very tightly. One of the male shakers managed to achieve an approximate 270o rotation of the head about a vertical axis down through the head, during a shake-to-exhaustion test. All of the shakers managed approximately 17 seconds during the shake-to-exhaustion. The maximum accelerations at the front and back of the head for a single female shaker ranged through 10g, 15g and 20g. Typically, outputs of velocities are shown in figure 6 and were idealised for use as loading for the DYNA model.

Discussion and Results

Maximum principal stress values induced during motion are tabulated in Tables 2 to 4, whilst contour plots are provided in figure 7. The results demonstrate that LS-DYNA is a powerful tool for complex biological simulations. The numerical data supports the hypothesis that shaking leads to larger stresses than would be induced by a single event involving similar velocities. It is too early in the study to draw any further conclusions in this socially sensitive area.

Tissue	Young's modulus (MPa)	Poisson's ratio	Density (kgm-3)	Shear modulus (MPa)	Bulk modulus (MPa)
Skull	6500	0.22	1500	/	/
CSF	0.1	0.49	1040	0.5	2.19
Brain	0.675	0.49	1040	1.68	2.19

Table 1: Physical and mechanical properties for elastic materials.

Parameter	Time Frame (secs) for ±250 mm/s velocity					
	0.007	0.017	0.008	0.018	0.010	0.020
Max. Principal stress (kPa)	1.544	1.541	1.803	1.797	0.947	1.313
Pressure (kPa)	0.978	0.974	1.391	1.399	0.	0.811
Max. Shear stress (MPa)	797.38	984.05	1.556	1.485	719.56	1,115

Table 2: a comparison of equivalent points between the first and second cycles for the model with 25 mm/s applied to the skull

Parameter	Time Frame (secs) for ±375 mm/s velocity					
	0.007	0.017	0.008	0.018	0.010	0.020
Max. Principal stress (kPa)	2.613	2.311	2.704	2.695	1.370	1.970
Pressure (kPa)	1.467	1.461	2.086	2.098	1.189	1.186
Max. Shear stress (kPa)	1.196	1.476	2.335	2.227	1.079 x	1.672

Table 3: a comparison of equivalent points between the first and second cycles for the model with 37.5 mm/s applied to the skull

Parameter	Time Frame (secs) for ±500 mm/s velocity					
	0.007	0.017	0.008	0.018	0.010	0.020
Max. Principal stress (kPa)	3.087	3.082	3.606	3.593	1.826	2.626
Pressure (kPa)	1.956	1.948	2.782	2.797	1.586	1.581
Max. Shear stress (kPa)	1.595	1.963	3.113	2.970	1.439	2.230

Table 4: a comparison of equivalent points between the first and second cycles for the model with 50 mm/s applied to the skull

Parameter	Time Frame (secs) for ±250 mm/s velocity					
	0.007	0.017	0.008	0.018	0.010	0.020
Max. Principal stress (kpa)	1.544	1.541	1.803	1.797	0.946	1.313
Pressure (kpa)	0.978	0.974	1.391	1.399	0.814	0.811
Max. Shear stress (kpa)	0.797	0.984	1.556	1.485	0.719	1.115

Table 5: a comparison of equivalent points between the first and second cycles for the model with 25 mm/s applied to the skull

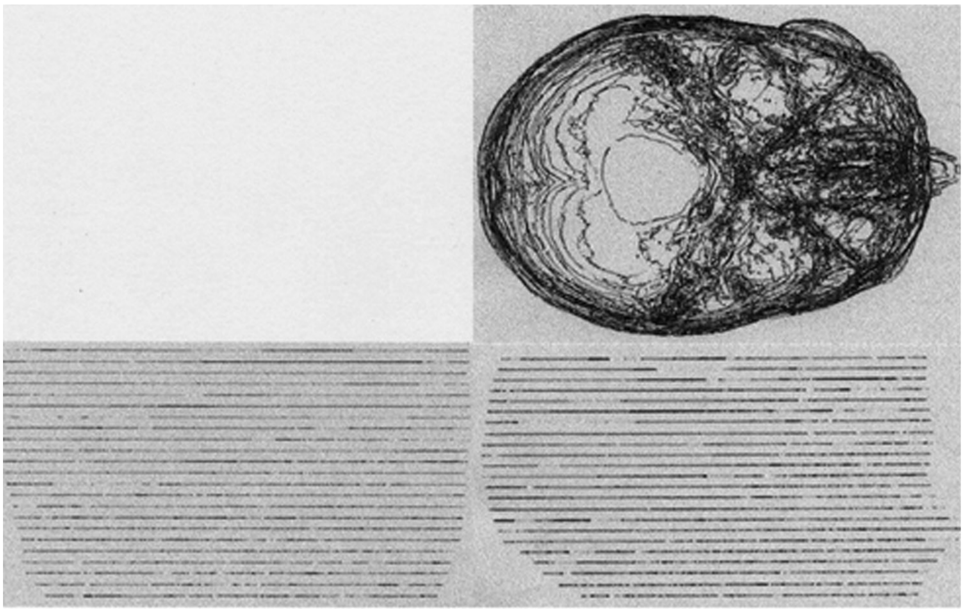

Figure 1: CAT scan used to generate geometry.

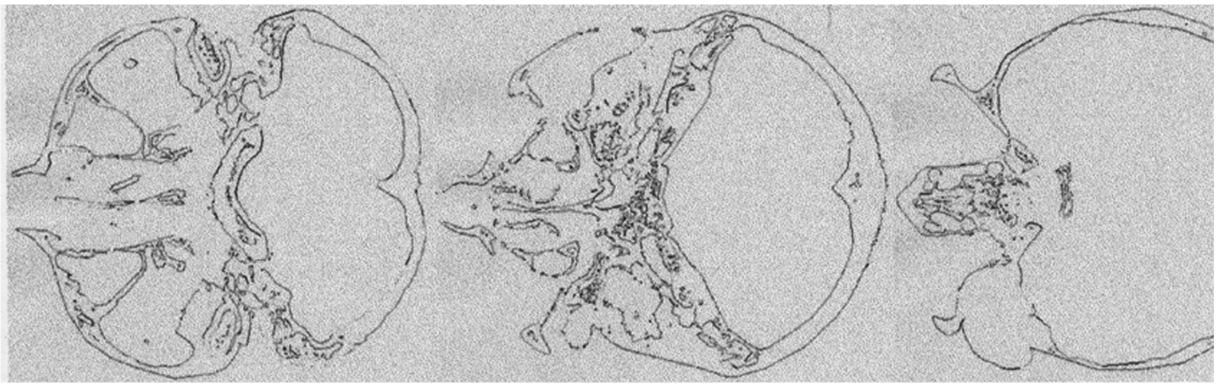

Figure 2: (from left to right) views of the 4th, 6th and 11th layers of the CAT scan.

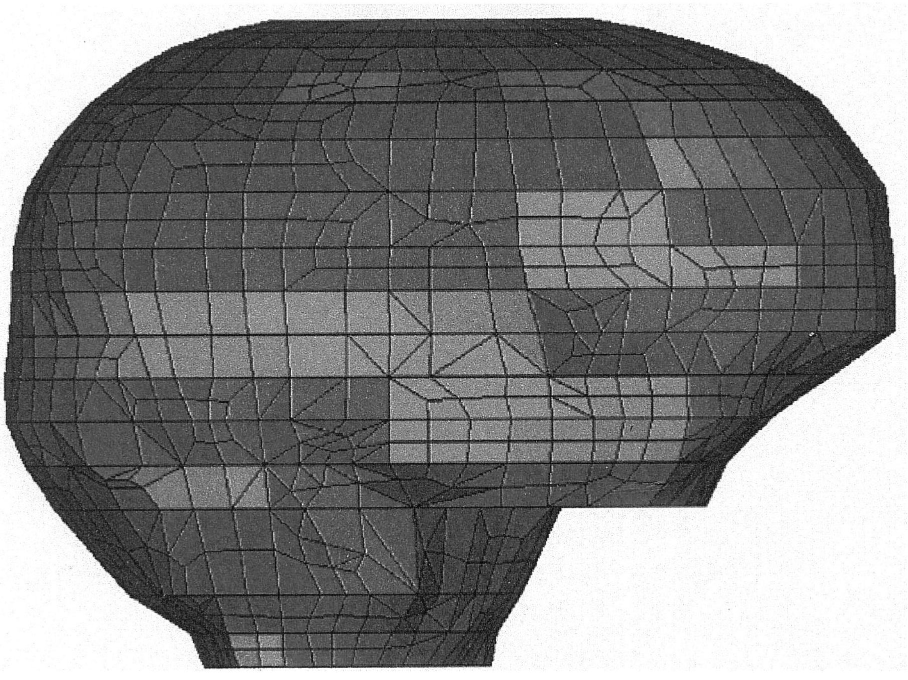

Figure 3: side view of the model of the skull

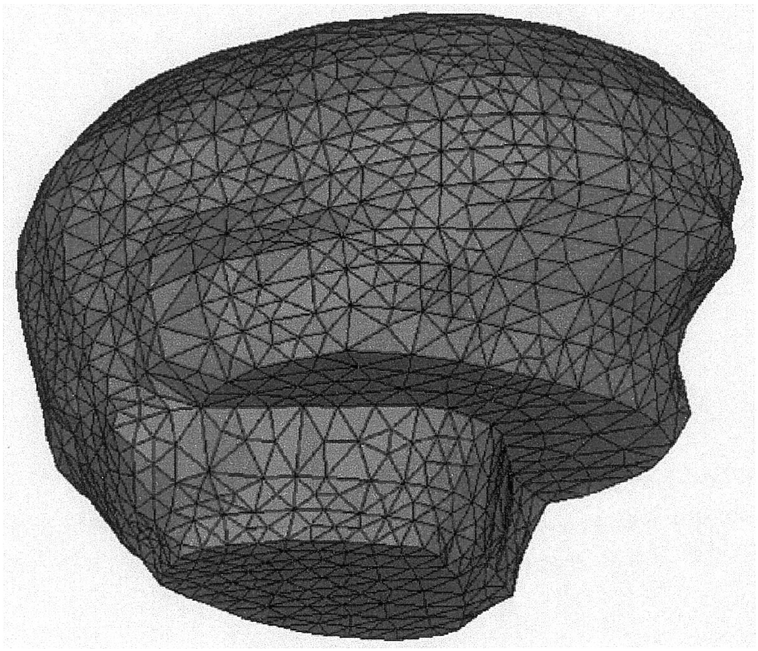

Figure 4: isometric view of the model of the brain.

Figure 5 - a view of the dummy used for the experiments.
One of the accelerometers can just be made out taped to the forehead of the dummy.

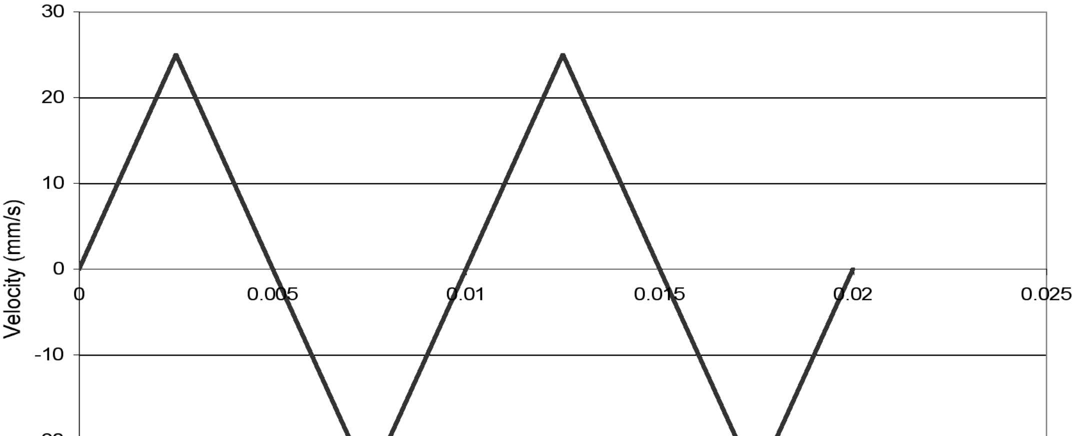

Figure 6: a graph showing one of the velocity load curves applied to the model of the head. The other velocity load curves varied from this one in that the maximum and minimum velocities applied were ±3.5 mm/s and ±500 mm/s.

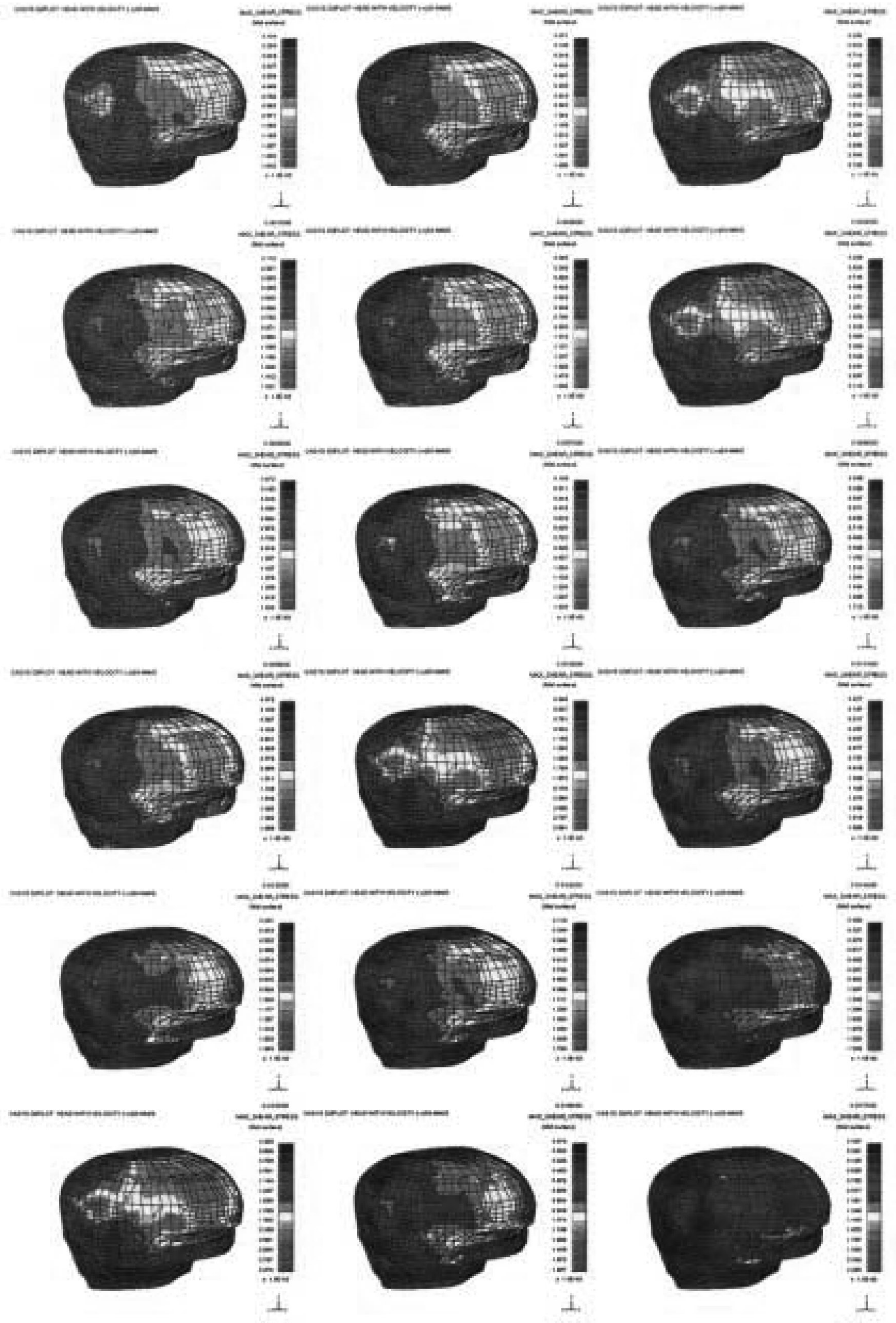

Figure 7 - Development of maximum principal shear stress during the most violent shaking studied.