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Dynamic Mechanical Properties of Cranial Bone

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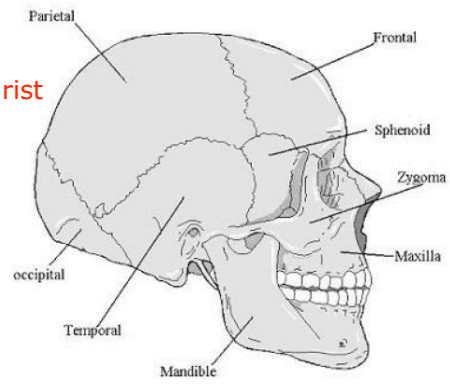

Introduction

The dynamic behaviour of the head and the underlying mechanisms at work as a result of excessive kinematics are so complex that it is unlikely that a single tolerance criterion could be applied to all types of head injuries. One of the mechanisms at work during head injury is fracture of the skull. It has been found that the deformation of the skull as a result of an impact is directly responsible for certain brain injuries. Therefore, it is likely that if the mechanism of skull fracture could be better understood and thus, more effectively prevented, this would also result in the prevention of brain injuries. Furthermore, if a failure criterion for the mechanism of the fracture of cranial bone could be established it would aid the designs of safety devices, such as helmets, to prevent injury and it would be a significant step towards understanding head injuries as a whole.

Objectives

(1) To carry out dynamic bending tests on sections of cranial bone, (2) to evaluate the mechanical properties of the cranial bone 'sandwich' structure (3) to analyse the structural characteristics and their variation in cranial bone and (4) to create and validate structurally accurate FE models of the cranial specimens.

Method

To date mechanical testing of cranial bone has been carried out predominately at quasi-static speeds. However, to investigate the mechanical properties of cranial bone under more realistic accident conditions the current tests were carried out at dynamic speeds.

Cranial bone specimens (6cm x 1cm) were extracted from 8 fresh-frozen cadavers (F=4, M=4; 81±11 yrs old; max=97 yrs old; min=62 yrs old). 63 specimens were obtained from the parietal and frontal cranial bones. Prior to testing all specimens were scanned using a microCT scanner at a resolution of 56.9 µm.

Position \ Speed	0.5 m/s	1 m/s	2.5 m/s
Right parietal	8	9	9
Left parietal	6	6	8
Frontal	4	5	5

Table 1. Testing speed and cranial position of the specimens

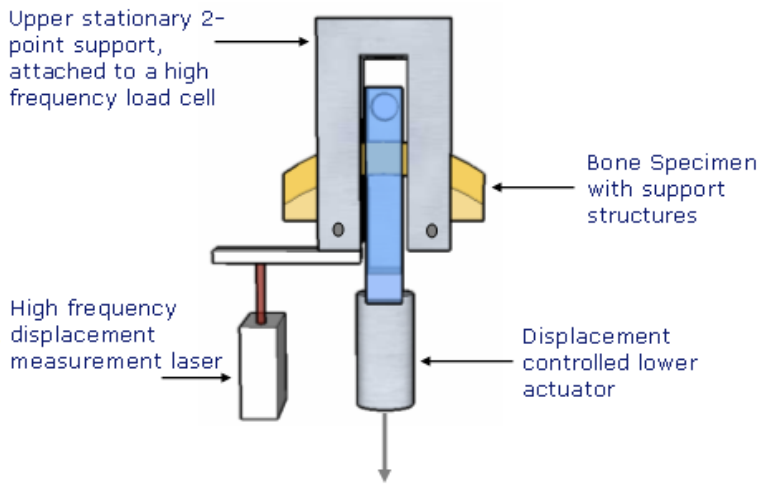

Fig.1. Experimental Setup

Results

From the measured force-displacement curves (Fig.3) and the structural information obtained from the µCT images it was possible to calculate the mechanical parameters shown in Table 2.

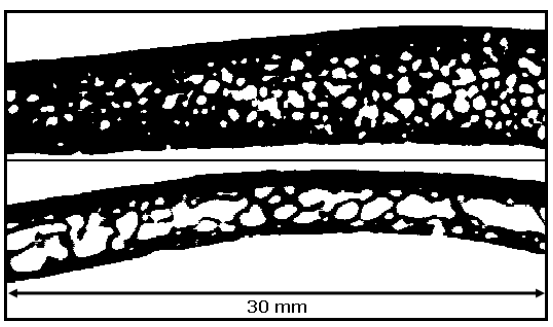

Fig. 2. A binarised µCT slice, longitudinally cut through the centre of two of the tested specimens, to illustrate the structural variation seen within the eight calvaria sampled.

The test loading rates had a significant effect on the resulting values for the maximum force to failure ($p=0.0007$), the elastic modulus ($p=0.025$) and the max bending stress ($p=0.0009$). The cranial sampling position (parietal/frontal) was a significant factor in the resulting values for the max force to failure ($p=0.0309$), the 2nd moment of inertia ($p=0.0230$) and energy absorbed until failure ($p=0.0383$).

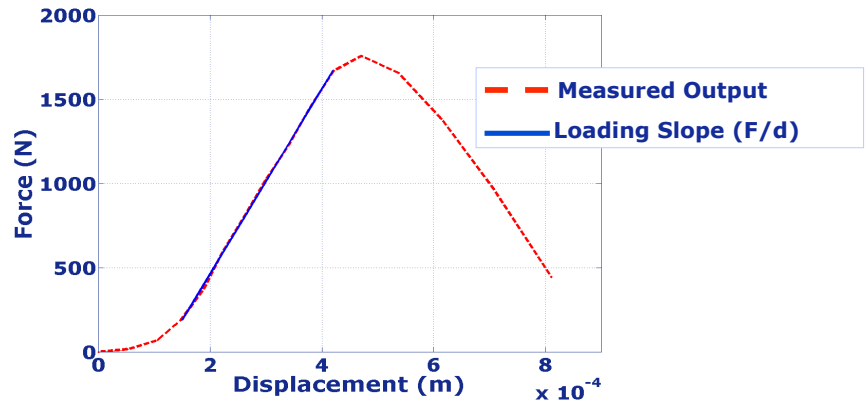

Fig. 3. Measured force versus displacement: Frontal specimen; 2.5 m/s

Mechanical Property	0.5 m/s	1.0 m/s	2.5 m/s
Elastic Modulus (GPa)	7.46 ±5.39	10.77 ±9.38	15.54 ±10.29
Max. Force at Failure (N)	803.08 ±345.08	791.41 ±387.45	1221.13 ±524.75
Energy Absorbed to failure (kN.m/m^3)	123.15 ±56.77	115.87 ±72.97	167.82 ±104.19
Average Strain Rate (%)	21.16 ±6.79	28.25 ±7.82	107.20 ±26.07
Max Bending Stress (MPa)	85.11 ±23.55	86.44 ±27.08	127.84 ±46.88

Table 2. Results Summary (Average ± Standard Deviation)

The average percent porosity was 10.24±3.72% (frontal) and 13.94±4.02% (parietal) and the average percent bone volume was 74.94±7.17% (frontal) and 69.59±10.62% (parietal).

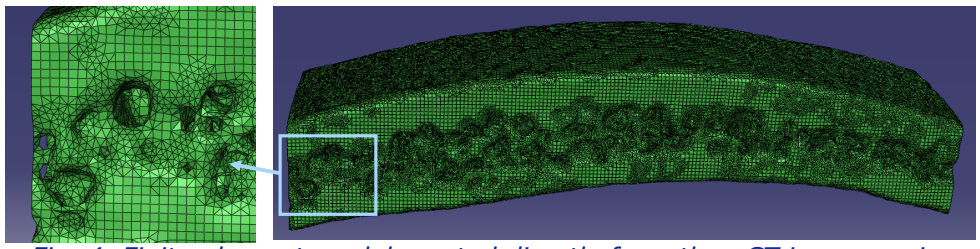

Fig. 4. Finite element model created directly from the µCT images using Simpleware software.

Structurally detailed 3D FE models were developed from the µCT scan sets. These models are currently being validated against the experimental results and the high speed videos (~20,000 fps) taken of the testing of each specimen.

Discussion

The viscoelastic properties of cranial bone were evident from the results. The cranial bone was significantly stiffer at the higher strain rates. The mechanical properties were consistent with those previously reported in the literature (Hubbard, 1971; Delille et al., 2007). The cranial sampling site was also a factor in the resulting mechanical properties. The frontal bone tends to be thicker, less porous and have a higher % bone volume than the parietal bones.

The results from this work can used to improve the skull material definitions and failure definitions in the UCD 3DFE model of the skull-brain complex which is currently used to aid helmet design.

✧Motherway, J.A. et al., J. Biomech. Vol 42, pp 2129-2135 (2009).
✧Delille, R. et al., Int. J. Crashworthiness, Vol. 12(2) pp 101-108 (2007).
✧Hubbard, R.P., J. Biomech, Vol. 4, pp 251-263 (1971).

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