ANALYSIS OF FRACTURE CHARACTERISTICS OF CRANIAL BONE FOR FE MODELLING

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ABSTRACT

At K.U.Leuven, experimental skull fracture analysis is performed in the framework of bicycle helmet research. This particular work describes the testing of 191 cranial bone specimens to generate data for use in finite element modelling of the head. Specimens are taken from the parietal area of the head and are beam-shaped (approximately 1cm width, 5cm length). Specimen age ranges from early post mortem (fresh) to 20-30 years post mortem (embalmed). Results show Young's moduli ranging from 1.6 to 2.5 GPa for embalmed and from 2.3 to 5.4 GPa for fresh specimens. Fresh sample tests clearly showed a viscoelastic behaviour, which is not be observed in the embalmed specimen tests.

Keywords: CRANIAL BONE, CADAVERS, VISCOELASTICTY, MATERIAL PROPERTIES

EXPERIMENTAL SKULL FRACTURE ANAYSIS has been performed at K.U.Leuven since several years in the framework of bicycle helmet research. The goal of this particular work is to establish mechanical properties for cranial bone and to investigate in particular the viscoelastic behaviour of bone specimens. This data will be incorporated in a finite element model of the human head.

Mechanical testing on human cranial bone has already been performed since the 1940's by Gurdjian (1949). Since the 1950's several researchers have performed material properties assessment tests on cranial bone. Table 1 presents a brief overview of some historically important tests and results. A distinction is made between tests on pure trabecular bone, pure cortical bone and the true biological sandwich material with a layer of trabecular bone surrounded by two layers of cortical cranial bone.

Table 1. Overview of cranial bone material properties

Author	Mechanical loading	Specimen shape	Bone specifications	E (GPa)	σ_{max} or σ_{frac} (MPa)
Melvin (1969)	Compression	-	Trabecular	1,03	$\sigma_{frac} = 32,4$
McElhaney (1970)	Compression	Beam (5,1x6,4mm)	Complete	5.6	$\sigma_{max} = 96.5$
	Tension	Halter (12,7x 3mm)	Complete	5.4	$\sigma_{max} = 43.4$
			Cortical	12.3	$\sigma_{max} = 79.3$
Wood (1971)	Tension	Halter (2,5x1,1mm)	Cortical	10.3-22.06	$\sigma_{frac} =$ 48.3-127.6
Hubbard (1971)	3 Point-bending	Beam (10x32mm)	Complete	9.5	-

From further comparison of the different loading types in literature, it can be observed that bone reacts both stiffer and stronger when loaded in bending and compression as compared to tension. For compression versus tension this was already seen in the data from McElhaney. For bending versus tension, Sedlin and Hirsch (1966) found that the average calculated tensile strength from maximal loading in bending is 2.1 times larger than the value in an axial tensile test.

Bone material properties are influenced by several factors. Firstly, there is the method of preservation and hydration. The preferred conservation method was found to be storage at temperatures around -20°C (Sedlin, 1965). Sedlin did not find significant differences in mechanical properties between specimens tested 3 hours after prelevation and specimens that were frozen at -20°C for a period of three to four weeks. Specimens were wrapped in a piece of cloth that is drenched in physiological water. This prevents the effects of dry frosting. The specimens were then stored in an air sealed package to avoid initial vaporization. A second factor determining material properties is the bone structure. Different bone locations on the cranium show a very different bone layer thickness and therefore different mechanical properties. All specimens in this study originate from the parietal area of the skull as specimen geometry is the most uniform in this region.

Furthermore, cranial bone is an anisotropic, viscoelastic and porous structure, which indicates that a very strict testing and analysis protocol is needed in order to achieve a good estimation of the material properties for this type of human bone.

MATERIALS AND METHODS

TESTING PROTOCOL: From the anatomy department of the K.U.Leuven, 113 dry skulls were obtained. They originate from embalmed human cadavers, 20-30 years post mortem, from which soft tissues were removed by immersing them in water of 80°C for 24 hours. 14 skulls were selected for mechanical testing and specimens originating from these skulls will further be called the embalmed specimens. Also from the anatomy department, 5 recent skulls (< 5 days post mortem) were obtained. Specimens that originate from these skulls will further be called the fresh specimens. The recent skulls are stored at a temperature of -40°C in a cloth which is drenched in physiological water as described by Sedlin (1995). After excision, specimens are filed, weighed and support structures are added to avoid tilting during the test. Figure 1 (left) shows the rest of the testing protocol and figure 1 (right) shows the test set-up.

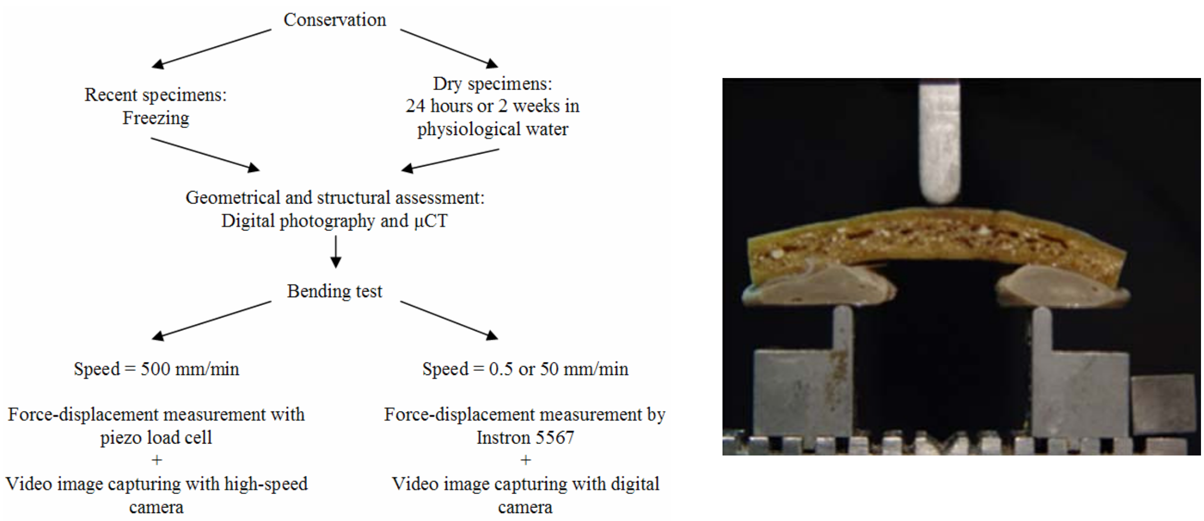

Fig. 1 – Testing protocol (left), test set-up (right)

All specimens are then divided into subcategories as shown in table 2, test group names are given between brackets.

Table 2. Test groups and number of successful tests in each group

Conservation (rehydration period)	$0.5\ \frac{mm}{\text{min}}$	$50\ \frac{mm}{\text{min}}$	$500\ \frac{mm}{\text{min}}$
Embalmed (24 hours)	19 (24h05)	21 (24h50)	21 (24h500)
Embalmed (2 weeks)	15 (2w05)	19 (2w50)	22 (2w500)
Fresh	22 (V05)	0	17 (V500)

A first subdivision is made by time after decease (embalmed vs. fresh) The embalmed skull specimens are rehydrated by immersing them in physiological water. The duration of this rehydration period is another subdivision category (24 hours vs. 2 weeks). A final distinction is made between the different loading rates (0.5, 50 and 500 mm/min).

ANALYSIS PROTOCOL: For all specimens the geometrical dimensions, density, curvature and layer thickness have been calculated from photographic images. Digital images are converted from colour to 256 grey values and inverted for better contrast. Images are then rotated and support structures are digitally removed from the specimen. After this a prefilter is applied: and further thresholding is performed using the grey value histogram. An upper - and lower limit are applied by the user in an iterative way to obtain the best monochrome image. Figure 2 shows an example (left).

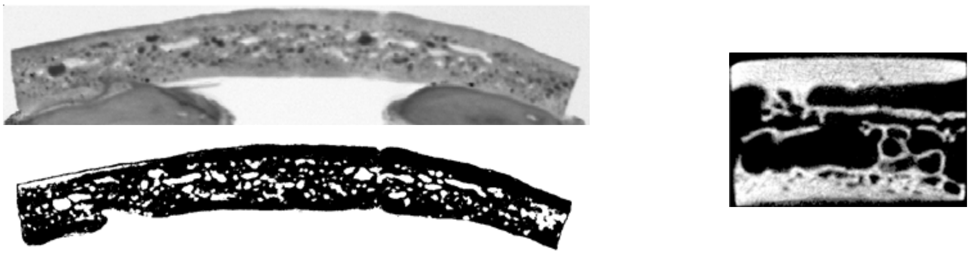

Fig. 2 – Photographic and processed image (left), μCT sectional image (right)

From these monochromized images, the sectional moment of inertia of each of the specimens is calculated from the central part of the frontal view (fig. 2, left) of the image and then scaled to the cross sectional width of the specimen. In this way porosity and internal structure are accounted for. Five of the total 191 specimens have been studied in a μCT scanner. An example is shown in figure 2 (right). These are used as a reference for the overall geometry as established from digital photographs and the sectional moment of inertia. For the latter, a linear relation between density and Young's modulus is assumed.

The Instron 5567 and external data logger have a numerical force displacement output. From these force and displacement signals, stress-strain curves are calculated using a linear elastic model in pure bending. Using these curves, the cranial bone Young's modulus is calculated.

RESULTS

Means and standard deviations are shown in table 3. Mean Young's moduli range from 1.7 to 2.5 GPa for the embalmed specimens and from 2.3 to 5.5 GPa for the fresh specimens. First analysis of these values show a higher mean maximum stress σ_{max} and Young's modulus E for the fresh specimens in group V05 and V500 when compared to the embalmed specimens. Comparison of the fresh specimens shows a higher mean σ_{max} and E, but a smaller maximum strain ε_{max}.

Standard deviation within the groups is relatively high. Therefore, a multivariate ANOVA analysis is performed ($p < 0.05$) using the Statistica software package to quantify statistical significant differences for conservation and testing speed between the testing groups.

Firstly, the influence of **testing speed** on the mechanical behaviour of the cranial bone specimens is investigated. Comparison of groups 24h05, 24h50 and 24h500 shows no significant difference in any of the three mechanical parameters. The same is found for comparison between groups 2w05, 2w50 AND 2w500. Comparison of groups V05 and V500 shows a statistically strong influence of testing speed on all three mechanical parameters.

A second influencing parameter is **conservation**. Firstly, a comparison is made between groups 24h05, 2w05 and V05, all tested at 0.5 mm/min. Here, a significant difference is observed only for σ_{max}. This difference is observed between the embalmed testing sets on the one hand and the fresh set on the other hand. For groups 24h500, 2w500 and V500, all three parameters show to differ significantly between groups.

Table 3. Basic statistical analysis of cranial bone mechanical parameters

Test group	24h05		24h50		24h500		V05	
	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
σ_{max} (MPa)	29.1	27.1	39.7	18.9	32.7	13.5	48.4	18.3
ε_{max} (%)	2.6	1.5	2.6	1.0	2.3	1.0	3.4	2.1
E (GPa)	2.0	1.9	2.5	1.3	2.2	1.5	2.3	1.2
Test group	2w05		2w50		2w500		V500	
	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
σ_{max} (MPa)	25.3	11.5	30.7	14.1	34.8	17.0	68.0	23.2
ε_{max} (%)	3.4	2.2	2.7	1.1	2.2	0.8	1.6	0.4
E (GPa)	1.7	0.9	1.9	1.0	2.5	1.5	5.5	3.0

DISCUSSION

From the statistical analysis, it is found that testing speed has no significant influence on mechanical behaviour for the embalmed specimens whereas for the fresh specimens, mechanical loading rate is a major influencing parameter. No statistical mechanical difference is found between a rehydration period of 24 hours and 2 weeks. Rehydration is therefore proven inadequate to restore viscoelastic behaviour of cranial bone specimens. It can be concluded that viscoelasticity is lost for the embalmed specimens, while for the fresh specimens it is shown to result in a significantly stiffer and stronger behaviour at higher loading rates. When comparing mechanical properties against literature, it is observed that Young's modulus is relatively small. Notwithstanding the relatively large variation in Young's modulus E and the high sensitivity of the sectional moment of inertia I to thickness, results are considered a good estimation. In literature no attempts have been made to calculate I based on internal specimen structure. All literature models use a simplified homogeneous beam model. The values for the moments of inertia from photographic images are an overestimation but are still better approximations than in literature as information on internal structure is used.

There are several sources which induce some uncertainties and errors in the obtained results. Firstly, the specimen deformation is not measured using strain gauges. It is measured by the internal measurement circuit in the test bench. Use of miniaturized, humidity resistant strain gauges will result in more reliable results, but were not available for this first study. Secondly, specimen structure and geometry have an important influence on material properties. The specimen sectional moment of inertia I is calculated from a monochromized photographic image. This results in an overestimation of the true I, as is observed through the use of μCT scans to account for density and real internal structure. Although too time consuming for this study, acquisition of μCT images for all future specimens will be performed.

These results will be used in an FE model of the human head after mathematical modelling of the viscoelastic behaviour. For this purpose, more data is needed at higher testing speeds. New tests at speeds ranging up to 1 m/s have already been performed, using only fresh cranial bone specimens.

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