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Review

Characterization and micromechanical modeling of the human cranial bone elastic properties

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ABSTRACT

This paper is devoted to the experimental characterization and micromechanical modeling of the elastic behavior of the human cranial bone. Three points bending tests on the frontal, parietal and temporal bone specimens have been performed to determine their mechanical characteristics under quasi-static loading. It is shown that Young's modulus and the bending stiffness are significantly influenced by the bone morphology and orientation. The anisotropic bone elastic properties have been then estimated by means of the Mori–Tanaka homogenization scheme coupled to experimental measurements of structural anisotropy by microtomography techniques. The obtained micromechanical model has been implemented as an UMAT routine within the explicit dynamics code LS-DYNA© and applied successfully for the estimation of the mechanical properties of the human cranial frontal bone. The obtained numerical results show an overall good agreement when compared to the experimental data.

Contents

1. Introduction

The cranial bone and brain tissue are the important parts of the human head. Housing the brain, the cranial bone protects the soft tissue from deformations secondary to external forces. Mechanically induced trauma, particularly impact forces, are routinely delivered to the complex anatomy of the cranium in different ways. A significant majority of studies determining human tolerance to impact have focused on the frontal bone because frontal impacts are the mostly causes of head injury in motor vehicle crashes and pedestrian accidents (McElhaney et al., 1976). A better understanding of the head injury mechanisms requires adequate relevant experimental data of the cranial bone material properties and an appropriate multiscale model which is capable of predicting accurate skull fracture at different impact loading conditions.

The human adult cranial bone, analogous to engineering sandwich structures, is composed of a stiff outer cortical strata and

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an inner energy absorbing porous lightweight core, the diploë. Structurally, the diploë is soft, with material properties similar to the cancellous bone and acts to increase its thickness thereby increasing its bending strength (Agur and Lee, 1991). The mechanical properties of human cranial bones have been experimentally investigated by means of a several methods, such as compression, tension, and bending tests (Coats and Margulies, 2006; Motherway et al., 2009). Wood (1971) performed a study of the tensile properties of small specimens extracted from the cortical bone of the outer layer while Roberts and Melvin (1968) have presented an estimation of the mechanical behavior of the diploë layer in compression. Dempster (1967) studied the relative importance of the influence of structural anisotropy and material anisotropy on mechanical response. McElhaney et al. (1970) tested 237 through the diploë under quasi-static compression and estimated the elastic modulus to be 2.4 ± 1.5 GPa and failure stress of 73.8 ± 35.2 MPa. These specimens were obtained from both fresh donors and embalmed cadavers. McElhaney et al. (1970) attributed the high values of standard deviations to naturally occurring variations in the diploë and then developed linear and power law models to correlate density to material properties.

Alternatively, computational Finite Element (FE) models are considered as an efficient tool to describe the complex geometry of cranial bone in detail and provide valuable information for prediction of head injuries (Raul et al., 2008; Coats and Margulies, 2006). FE technique is able to simulate the load response realistically (Raul et al., 2008) by computing critical bone material properties such as elastic modulus and ultimate stress and strain at different locations in order to establish a robust injury tolerance limit (Guan et al., 2011). Furthermore, computed tomography based FE analysis, which incorporates information on microscopic architecture, have shown to achieve precise assessment of the cranial bone strength with reasonable accuracy for given boundary conditions (Koivumäki et al., 2012). Unfortunately, the resulting FE analyses usually require high volumes of data which makes them useless in the practice.

Due to the multiscale nature of the skull bone, there have been several theoretical developments to obtain reasonable estimates of the micro and macroscopic bone mechanical behavior within the context of homogenization scheme (Aoubiza et al., 1996; Hellmich et al., 2004). Furthermore, micromechanical approaches coupled with CT-based FE models were revealed to be more appropriate when the robustness of computation and accuracy of results are of interest. The predictive potential of the so-called micromechanical formulations has been established using physically and statistically independent sets of experiments.

In this paper, we propose an experimental characterization using three points bending test and micromechanical modeling of the elastic behavior of the human cranial bone. The estimation of anisotropic elastic properties has been made by using the Mori–Tanaka scheme (Mori and Tanaka, 1973) coupled to experimental measurements of architectural anisotropy by X-ray microtomography techniques (Whitehouse, 1974; Harrigan and Mann, 1984). The obtained micromechanical behavior law is implemented in an user material routine UMAT within the explicit dynamics commercial code LS-DYNA© (LS-DYNA, 2007) for the prediction of the global response of the cranial bone behavior under quasi-static loading.

2. Experimental study of the human cranial bone mechanical behavior under quasi-static loading

The ethics committee of University Hospital of Marseille, and the anatomy laboratory of University Lyon I approved this research.

2.1. Specimen preparation

Human cranium were obtained from 11 male donors with an average age of 88 years. Each cranial bone has been submitted to a virological and serological analysis to ensure that they did not exhibit any bone disease on radiographic examination and scanned using a medical scanner to examine the absence of precracks due to pathological conditions. Then, 19 prismatic-shaped bone specimens (EP1–EP21) with an average size of 60 mm× 13 mm×7.5 mm are extracted from frontal (F), left parietal (LP) right parietal (RP), left temporal (LT), right temporal (RT) and coronal suture (CS) bones as shown in Fig. 1. The thickness and initial curvature of the specimens could not be controlled but care was taken to extract specimens with the least curvature. Furthermore, the orientation of specimens was kept as uniform as feasible to allow for realistic comparisons. Each specimen was introduced in sealed bottles filled with a saline solution to preserve its physiological hydration. This preservation technique has the ability to maintain the mechanical properties of fresh tissues, to simulate the response of living tissues, and to limit the transmittance of infectious diseases (see Crandall, 1994). All specimens were, then, conserved at 4 °C in a cold room for 1–12 months until the beginning of the experiments. Let us notice that bone tissue loses some of its freshness with time and storage conditions, despite precautions that can be taken according to Benalla et al. (2013). Keeping the bone specimens hydrated with physiological solution is critical for acquiring ex vivo measurements that are as close as possible to the in vivo condition.

By means of the X-ray micro tomography technique, scans of some specimens were performed using a SKYSCAN 1172 micro scanner with a resolution of 21 μm. In order to adapt the camera sensitivity for polychromatic X-ray radiation from the source, an aluminum filter is placed before the X-ray detector. The later allows to cut the low-energy X-ray radiation to reduce the nonlinear X-ray absorption in dense materials knows as beam hardening. For each sample, we obtain series of images in gray scale representing successive sagittal planes. Each slice is then threshold and transformed into binary images. A 2*D* analysis can be then performed on each slice in order to characterize the architectural anisotropy in the plane. This analysis can be extended to the 3*D* specimen architecture and a numerical 3*D* model can be reconstructed. The CT images for each sample have been analyzed with CT analyzed Software (SKYSCAN) and the mean intercept length based structural anisotropy measurements were calculated (see Whitehouse, 1974; Harrigan and Mann, 1984). These acquisitions are performed to extract the digital geometry data which have been saved using the STL standard format and sent to a CAD workstation.

2.2. Structural parameters measurements

In order to understand the contribution of the morphology to the mechanical behavior of the cranial bone specimens, structural parameters, namely the porosity f and the degree of anisotropy *DA*, associated with each specimen were calculated from the *CT* scans using CT Analyzer (SKYSCAN). The porosity f is the volume of micropores, within the volume of interest, divided by the volume of bone tissue, where a pore is defined as a connected assembly of space (white) voxels, i.e. fully surrounded on all sides in 3*D* by solid (black) pixels.

The degree of anisotropy *DA* was calculated according to the mean intercept length (MIL) (Whitehouse, 1974; Harrigan and Mann, 1984). It was calculated globally within each volume of interest and was used for quantifying if the pores were directionally dependent. MIL is found by sending, from the center of the volume, several vectors in all directions throughout the segmented volume. Each vector is divided by the number of times that it intercepted the