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CRANIAL DEFORMATION APPLYING FINITE ELEMENT ANALYSIS (FEA)

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Abstract. Intracranial pressure is a complex variable that involves intracranial elements such as the cerebral parenchyma, cerebrospinal fluid (CSF) and circulating blood. The pressure value remains constant due to regulatory mechanisms that promote compensatory displacement of blood and CSF. When damage to these mechanisms occurs, the value of the ICP can increase and, consequently, generate serious injuries. The effect of the increase of the ICP in the cranial deformation rates is the objective of this work. The present work presents analyzes for the determination of cranial deformation levels through numerical simulation by finite elements in a skull model. The cranial structure will be manufactured in 3D printer for future experimental analysis.

Keywords: Intracranial pressure, cranial deformation, strain rates, additive manufacture.

1. INTRODUCTION

Intracranial pressure is defined as the pressure that the cranium exerts on three components that fill the cranial cavity: brain tissue, cerebrospinal fluid, and circulating blood in the brain (Carvalho *et al*., 2008). In healthy individuals, the amount of these components remain relatively constant. Therefore, they do not increase or decrease maintaining the ICP in normal values. This balance of the volume of intracranial structures is known as the Monro-Kellie Doctrine (Cangussu, 2006). In any situation that there is an increase of volume of some intracranial component it is necessary the decrease of another to maintain the constant ICP (Giugno *et al*., 2003). However, when these compensation mechanisms are exhausted, an exponential increase of ICP occurs (CANGUSSU, 2006).

The physiological values of ICP in humans range from 3 to 15 mmHg (Marmarou; Beaumont, 2004) leading to intracranial hypertension and consequent neurological sequel in the event of changes in these values (Marmarou, Tabaddor, 1993). Moderately elevated values are between 20 and 40 mmHg and above that are severely elevated (Carlotti JR., 1998).

This increase in the value of ICP can cause deformation in the cranium and, therefore, the present work proposes an analysis of the rates of cranial deformations originating from the variation of the intracranial pressure.

The evaluation of these levels of deformation is important for the estimation of methods of non-invasive analysis. Initially, the modeling is done numerically using finite element technique considering the skull made of plastic material (PLA) normally used in additive manufacture. The deformation levels obtained by numerical simulation will be validated through an experimental analysis that is under development.

2. METHODOLOGY

2.1 Determination of the PLA Young's modulus

In the numerical simulation using finite element technique will be considered plastic (PLA) as the material of the cranium in order to obtain the validation of the results experimentally in a 3D skull printed in PLA using additive manufacture type FDM, Fig. 1.

Figure 1. Printed cranium on PLA using additive manufacture

For the numerical analysis, the mechanical properties of the material (PLA) are necessary. Since this material has different properties from that of a bone, these were obtained in a tensile test.

For the tensile test, five specimens were printed with the geometry defined by the standard for tensile tests on plastics ASTM D638 (Fig. 2) (Standard, 2010).
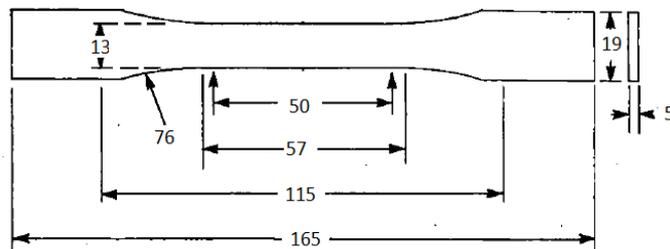

Figure 2. Specimen geometry (mm)

Using the tensile testing machine, the applied loads were determined and the consequent displacement using a strain gauge, Fig. 3. With this data, it is possible to determine the modulus of elasticity of the material.
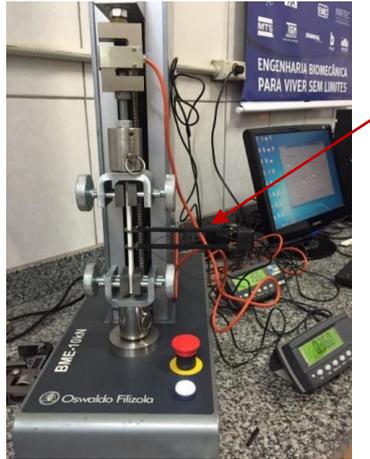
Figure 3. Tensile testing machine and strain gauge used

2.2 Numerical Simulation

With the modulus of elasticity of the PLA determined by the tensile test, a finite element numerical simulation was performed using the Abaqus® software. The purpose of this simulation is to evaluate the rates of deformation in the cranium caused by the variation of ICP. The region of analysis was the calvaria, which is the superior region of the cranium, more specifically in the parietal region.

First, the cranium was fixed in all the movements of rotations and translations, in all axes, in the inferior and posterior regions to simulate a locking of the head in an actual measurement of the intracranial pressure, Fig. 4.
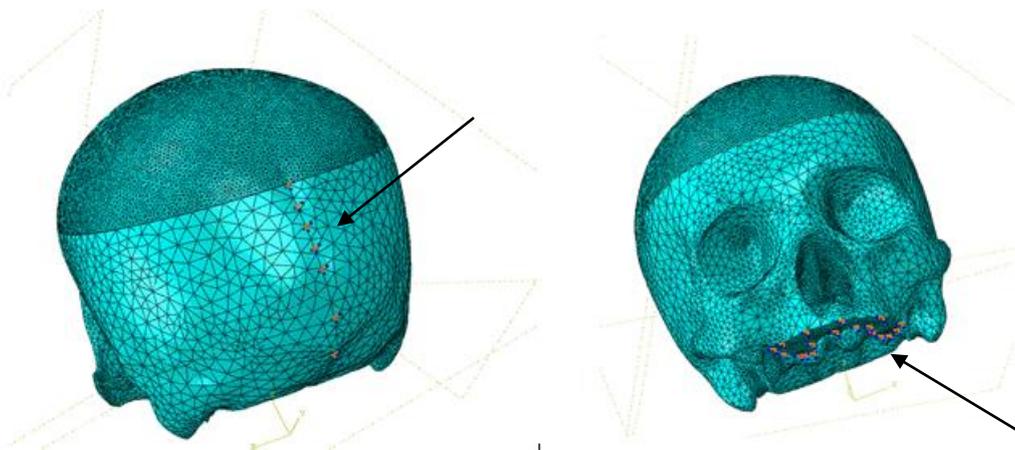

Figure 4. Fixation regions

The arrows in Fig. 4 indicate the posterior and lower regions of fixation of the skull.

For the analysis of the deformations, a mesh study was performed with the purpose of improving the accuracy and reducing numerical errors taking into consideration the processing time. The refinement was conduced in the calvaria region because this is the main region of interest for the deformation rate analysis. For this study, the load application region was submitted to different mesh configurations in the same loading and contour conditions already described previously. Within this region, the points on the same predetermined line were analyzed. Thus, it was chosen, as the most appropriate mesh, the one that presents convergence and had the lowest computational cost due to processing time. The characteristics of the defined mesh are presented in Tab. 1.

Table 1. Characteristics of the mesh for the sensitivity analysis.

Elements	Nodes	Processing time (seconds)
250357	380393	716,7

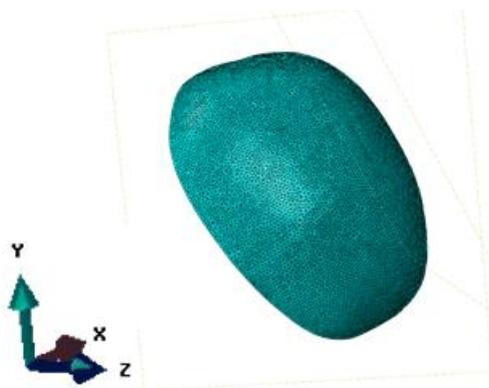The calvaria model with the mesh refinement can be seen in Fig. 5.

Figure 5. Mesh refinement of the calvaria region

For the deformation analysis, different pressure values were applied to the skullcap that simulated the variation of the ICP ranging from normal values to severely elevated cases (5 mmHg to 35 mmHg). For each applied pressure value, three values of principal deformations were obtained in the x, y and z axes. The directions of these axes are represented in Fig 5.

In the simulation, in addition to the modulus of elasticity of PLA, the Poisson ratio (ν) equals to 0,36 obtained from the literature was used (Torres *et al*., 2015).

3. RESULTS AND DISCUSSION

The values of the loads applied and the displacement measured by the strain gauge during the tensile test were used to determine the stress and strain of the specimen in order to determine the modulus of elasticity.

Five curves of σ x ε (stress x strain) were obtained, one for each specimen. The relationship between stress and strain was calculated using linear regression and, in consequence, the modulus of elasticity was obtained through the linear portion of the elastic phase. Five values were calculated according to the Tab. 2.

Table 2 – Modulus of Elasticity for specimens tested

Specimen	Modulus of Elasticity (MPa)
1	3295,0
2	3034,8
3	3007,0
4	3187,8
5	3172,0
Average	3139,3

Thus, the modulus of elasticity used in the numerical simulation was the average obtained with the tests or E = 3139,3 MPa.

It was also possible to determine the rupture limit of the material, σ_{rup} = 42,7 MPa. Figure 6 shows the ruptured specimen.

Figure 6. Specimen disruption in tensile test

After the determination of the modulus of elasticity of the PLA, it was applied in the numerical simulation to get the strain rates. Pressure values of 5, 7, 10, 12, 15, 20, 25, 30 and 35 mmHg were applied and the principal deformations in the x, y and z directions were calculated. Figure 7 shows the deformed region in the y-direction when the highest pressure value was applied.
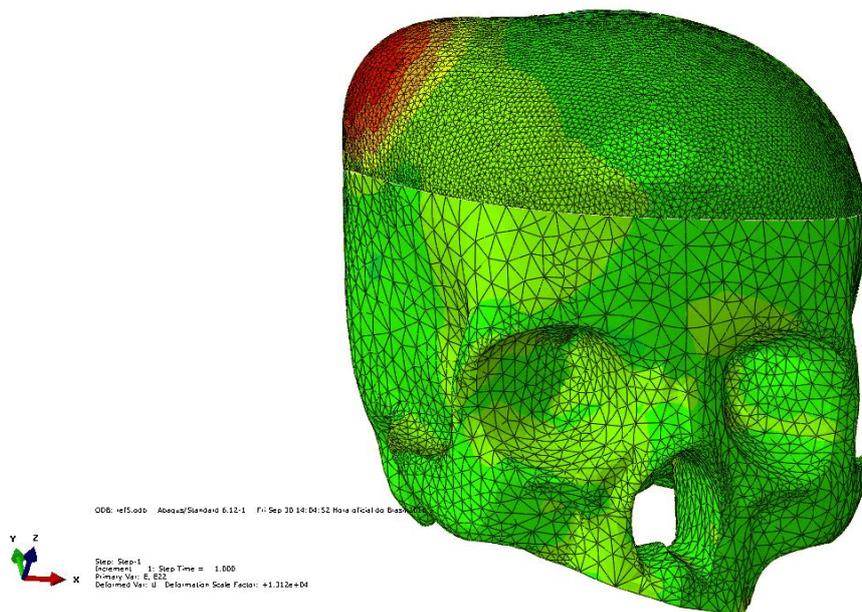

Figure 7. Deformation of the cranial bone in the y direction

For each pressure value the respective principal deformations in the directions x, y and z are shown in Figs. 8, 9 and 10 respectively.
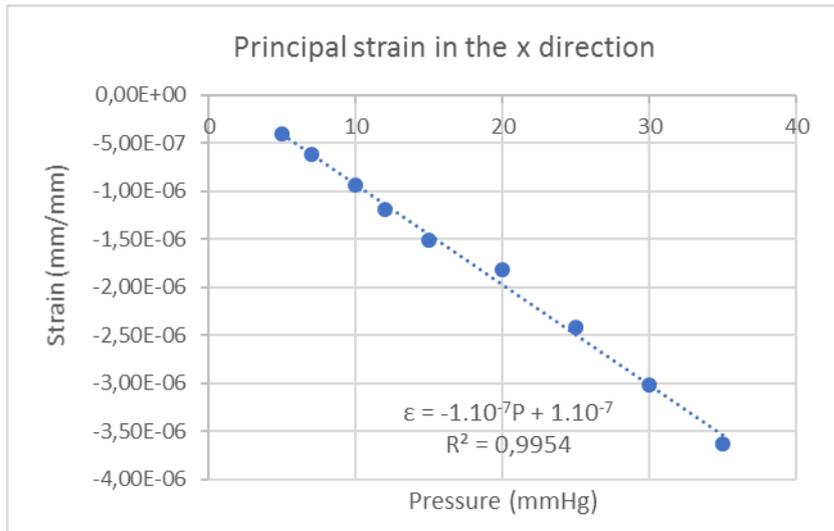
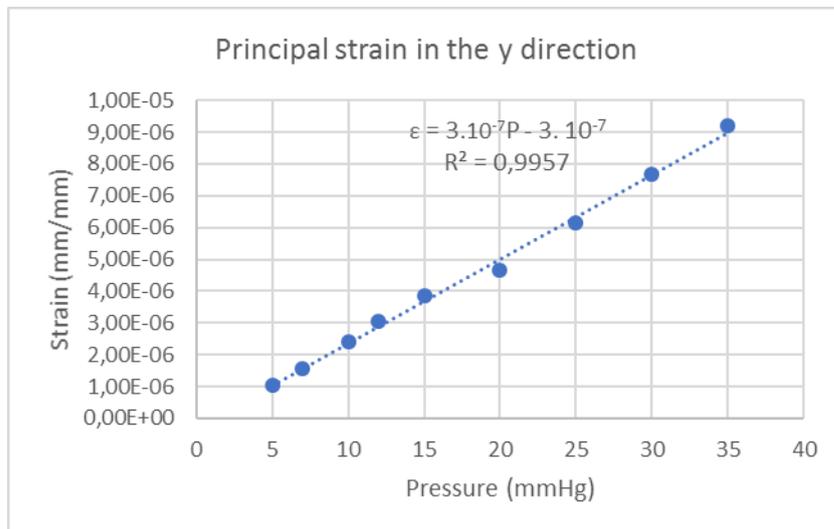Figure 8 – Principal deformation in "x" axis as a pressure function

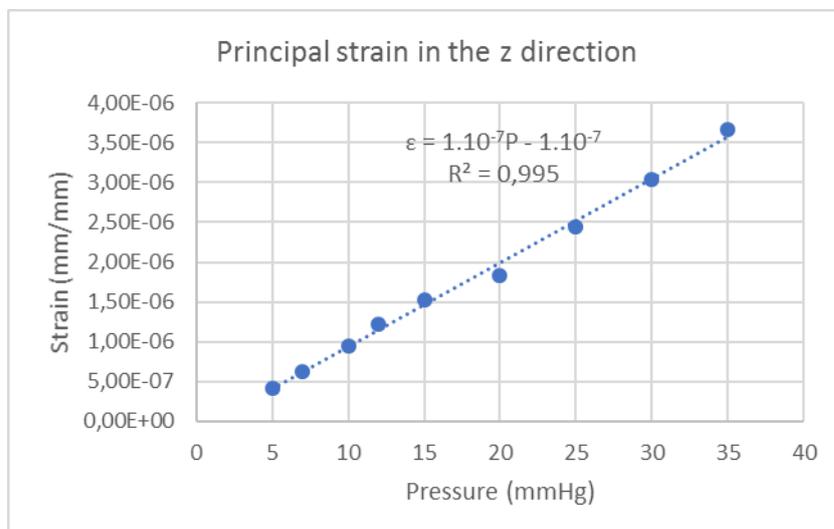Figure 9 – Principal deformation in "y" axis as a pressure function

Figure 10 – Principal deformation in "z" axis as a pressure function

According to Figs. 8, 9, 10 the obtained deformations present a very small order of magnitude in all directions analyzed, which requires for an experimental analysis the use of sensors capable of measuring such deformation.

Due to 3D geometry and the region where the pressure was applied, some regions of the cranium were subjected to traction and others to compression. This behavior is shown in Fig. 8 where the deformation values are negative indicating that the region in this direction is subjected to compression, while the regions of the cranium of the y and z directions are subjected to traction since the deformations obtained in these directions were positive.

The graphs present a linearity of the deformations obtained according to the increase of the values of the applied pressures, in all directions analyzed.

Taking into consideration the modulus, the largest deformation was found in the y direction ($\varepsilon_y = 9{,}22.10^{-6}$ (mm/mm)) with the application of the higher value of pressure (35 mmHg) as can be seen in Fig. 9. This can be explained by the direction of application of the load. When applying the lowest pressure value, 5 mmHg, the smallest deformation (in modulus) was in the x direction $\varepsilon_x = 4{,}06.10^{-7}$ (mm/mm).

With the data obtained in this simulation, the variation rate of the deformations in each direction were obtained. Thus, this fact allows choosing the suitable sensor to measure the strain in an experimental analysis. These data will be used, therefore, to evaluate the results that will be obtained experimentally by a sensor coupled to the printed cranium when subjected to a pressure variation that simulates the ICP.

4. CONCLUSION

The results obtained through numerical simulation are a basis for a later experimental analysis in which a strain gauge attached to the cranium will be used capable of measuring the induced deformation. These values will be compared to validate the experimental analysis.

Due to the linearity of the deformations obtained in the numerical simulation, this comparison of the results will be facilitated. On the other hand, the order of magnitude of these deformations is very small which requires the use of suitable sensors.

Subsequently the entire procedure (numerical and experimental analysis) will be repeated using a material with mechanical properties closer to the human bone to compare the obtained results.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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