A FINITE ELEMENT ANALYSIS OF A BOA CONSTRICTOR SKULL

AND

THE DESIGN OF A JAW BONE TRANSDUCER

by

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A THESIS

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ABSTRACT

The purpose of this research is to analyze the finite element model of a Boa constrictor skull and design a transducer at the jaw bone to measure the forces applied during feeding. The concepts in mechanics are applied to simulate and study the behavior of jaws while feeding.. In this study, the images of the skull of a boa constrictor were scanned to obtain the precise size and shape of each of the bones inside. The specimen was scanned using the X-ray micro tomography procedure. This process left several regions in the finite element model unconnected. These regions are corrected using the software HYPERMESH. The loading and boundary conditions along with the various properties like the Elastic modulus, Poisson's ratio are given to the FE model in ABAQUS before analyzing it. Electrical resistance strain gauges are simulated to have attached to the jawbone at two different points. The strain measured is then used to find out the forces that caused it, by using the various concepts and principles in solid and continuum mechanics. Electrical resistance strain gauges, numerical methods, moments of inertia are some of the commonly used terms in this analysis.

DEDICATION

To my dear parents,

Shri. GangiReddy Tadi and Smt. SaradaReddy Tadi.

LIST OF ABBREVIATIONS AND SYMBOLS

FEA	Finite element analysis
GF	Gauge Factor
in.	Inch
mm.	Millimeter
cm.	Centimeter
g	gram
3D	Three dimensional
CT	Computed tomography
*.INP	Input file
Gpa	Giga Pascal
C	Centigrade
F	Force
A	Cross sectional Area
σ	Stress
ε	Strain
ε_1	Longitudinal Strain
ε_2	Transverse Strain
$\mu\epsilon$	Microstrain
L	Total Length
ΔL	Change in length

E	Elastic Modulus
ϑ	Poisson's ratio
R	Resistance
ΔR	Change in resistance
V_{EX}	Excitation Voltage
V_0	Output voltage
V_r	Voltage Ratio
R_1	Resistance in arm 1
R_2	Resistance in arm 2
R_3	Resistance in arm 3
R_4	Resistance in arm 4
R_G	Nominal resistance value of the strain gauge
R_L	Lead resistance
P	Force applied at the end
Z	Section modulus of the material.
I	Moment of inertia

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I wish to thank my parents, Shri. GangiReddy Tadi and Smt. SaradaReddy Tadi, who have always been a source of moral support, inspiration and encouragement. Finally, I wish to thank all my friends for being there and making my stay in Tuscaloosa a very memorable one.

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CHAPTER 1

INTRODUCTION

In the field of engineering analysis, Finite Element Analysis (FEA) has been a useful analysis tool in many industries since the late 1970's because of the phenomenal increase in computing power and the rapid decline in the cost of computers. FEA has been developed to an incredible precision and present day supercomputers are now able to produce accurate results for all kinds of parameters[1]. FEA as an engineering analysis tool has undergone development over the last half century. Modern FEA programs simulate static, dynamic, linear, nonlinear, thermal, modal, and random vibrations[2]. FEA provides solutions to the tasks of failure and fatigue prediction due to known or unknown stresses by finding the areas in a structure and allowing designers to see all of the theoretical stresses within the structure. This method of product design and testing is superior to the manufacturing costs which would accrue if each sample was actually built and tested.[3]

Dr. Scott Boback had the idea of making the mechanical models of live snakes. In this research, a boa constrictor skull is modeled and analyzed using FEA with the purpose to design a jaw bone transducer. By using FEA, the transducer can be designed before making a prototype. The primary interest in this research is the Boa constrictor skull.

The Boa constrictor skull is a highly evolved complex structure. It is characterized by mobility, flexibility, and a greatly reduced number of bones, with numerous joints to allow the snake to swallow prey far larger than its head[4]. The bones within the snake skull are not fused, but loosely attached by ligaments. This allows the expansion and flexion of the skull itself necessary to engulf prey. The two bottom jaws are not fused together as in mammals [4].

The jaws were given the material properties of Titanium. Titanium is a low density, strong, corrosion resistant material and easily fabricated. The two most useful properties of the metal form are corrosion resistance and the highest strength-to-weight ratio of any metal. It is often used for surgical implants. A variety of implants of many designs are made from this metal in its pure form or the alloy form. Strength and long lasting properties of a material are the most desired properties of any material to be used in bone implants.

This research mainly revolves around the forces acting on the jaw and their measurement using a transducer.

Thesis organization :

The current study is conducted in two phases.

Phase 1:

1. Analyzing the meshed model of the Boa constrictor skull to check for irregularities and accuracy of the meshing and other aspects.
2. Analyzing each and every component in the skull for its compatibility with the other components surrounding it in the skull.
3. Building necessary connectors in between the components.
4. Applying proper boundary conditions and loads to check the flow of stresses from one end to the other end of the skull.

Phase 2:

1. Simulating strain gauges on the jawbone to record the strain in the jaw bone when forces are applied.
2. Design a transducer in such a way that it uses the strain recorded to find out the forces applied automatically.

In phase 1, the software packages ABAQUS and HYPERMESH are extensively used for all the main steps like meshing, applying loads and boundary conditions, analyzing the stress flow, to build the connectors. Thus the objective of the research is to save a lot of manufacturing costs of the specimen by running a simulation and analyzing it in FEA.

This thesis starts with an introductory chapter (Chapter 1). A brief background on FEA, The objectives and phases of this research are stated.

Chapter 2 reviews the related literature.

Chapter 3 presents the details of the specimen, meshing techniques, modeling procedures, steps of analysis. This chapter is the core of the thesis as the validity of the model is determined in this chapter.

Chapter 4 describes the construction of a transducer, working of a strain gauge and its application to measure stresses.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the general aspects of Finite Element analysis, Structural analysis, Strain gauges and the biological aspects of Boa constrictors are reviewed.

2.1. FINITE ELEMENT ANALYSIS

Finite Element analysis is less expensive than physical experiments but still requires substantial preparation and execution time. There has been a considerable interest in developing and applying design of experiments methods.[5] Improvements in the experiments require better modeling and simulation. Theoretical and experimental investigations of metals and metal models have been extensively carried out using various techniques.[6] On the other hand, complicated mechanisms usually in metal assemblies and machinery has been a great interest to researchers. Many researchers have been focusing on computer modeling and simulation of the models. Research methodologies have been formulated to solve many complicated problems arising in the modeling and simulation.

The process in which the system is subdivided into their individual components or elements whose behavior is readily understood and then rebuilding the original system from such components to study its behavior is a natural way in which an engineer carries out his experiments or studies.[7]

The existence of a unified treatment of standard discrete problems leads us to the first definition of the finite element analysis as a method of approximation to continuum problems such that,[7]

a. The continuum is divided into a finite number of parts or elements, the behavior of which is specified by a finite number of parameters and

b. The solution of the complete system as an assembly of its elements follows precisely the same rules as those applicable to standard discrete problems.

2.2. STRUCTURAL ANALYSIS

Structural analysis is the prediction of the performance of a given structure under prescribed loads and other external effects. The analysis of a structure usually involves determination of stresses, moments, deflections and support reactions[8].

Many structures are arranged in symmetric forms. A symmetric structure is linearly elastic. The response of the entire structure under any general loading can be obtained from the response of one of its portions separated by the axes of symmetry. It is sufficient to analyze a portion of the symmetric structure. This reduces the computational effort required in the analysis of symmetric structures.

Structures can either have a single axis of symmetry or multiple axes of symmetry.

2.3 STRAIN GAUGE

The strain gauge was invented by Edward E. Simmons and Arthur C. Ruge in 1938. A strain gauge typically consists of an insulating flexible backing which supports a metallic foil pattern. The gauge is attached to the object by a suitable adhesive. As the specimen deforms, the foil deforms, causing its electrical resistance to change. This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the GF, *gauge factor*. There are a number of different applications for strain gages.[9]

- Experimental stress analysis. Diagnosis on machines and failure analysis.
- multi axial stress fatigue testing, proof testing

- residual stress
- vibration measurement
- torque measurement
- bending and deflection measurement
- compression and tension measurement
- strain measurement

The deformation of an object can be measured by mechanical, optical, acoustical, pneumatic, and electrical means. The earliest strain gages were mechanical devices that measured strain by measuring the change in length and comparing it to the original length of the object.[10]

The most widely used characteristic that varies in proportion to strain is electrical resistance. The capacitance and inductance-based strain gages are also constructed, but these devices' sensitivity to vibration and their mounting requirements, and circuit complexity have limited their application[10].

The metallic foil-type strain gage consists of a grid of wire filament (a resistor) of approximately 0.001 in. (0.025 mm) thickness, bonded directly to the strained surface by a thin layer of epoxy resin[11].

When a load is applied to the surface, the resulting change in surface length is communicated to the resistor and the corresponding strain is measured in terms of the electrical resistance of the foil wire, which varies linearly with strain[10]. The foil diaphragm and the adhesive bonding agent must work together in transmitting the strain, while the adhesive must also serve as an electrical insulator between the foil grid and the surface. When choosing a strain gage, one must consider the strain characteristics of the sensor, and its stability and temperature sensitivity[10]. The most desirable strain gage materials are also sensitive to temperature variations and tend to change resistance as they age. For tests of short duration, this may not be a serious concern, but for continuous industrial measurement, one must include temperature and drift compensation.[12]

Each strain gage wire material has its characteristic gage factor, resistance, temperature coefficient of gage factor, thermal coefficient of resistivity, and stability. Typical materials include Constantan (copper-nickel alloy), Nichrome V (nickel-chrome alloy), platinum alloys, or semiconductor materials. The most popular alloys used for strain gages are copper-nickel alloys and nickel-chromium alloys.[13]

The piezoresistive characteristics of germanium and silicon exhibit substantial nonlinearity and temperature sensitivity, and also have gage factors more than fifty times, and sensitivity more than a 100 times, that of metallic wire or foil strain gages[13].

The first semiconductor (silicon) strain gages were developed for the automotive industry. As opposed to other types of strain gages, semiconductor strain gages depend on the piezoresistive effects of silicon or germanium and measure the change in resistance with stress as opposed to strain. [14]

In summary, the ideal strain gage is small size and mass, low cost, easily mounted and attached, and highly sensitive to strain but insensitive to ambient or process temperature variations.

2.4 BOA CONSTRICTORS:

A Boa Constrictor skeleton consists primarily of the skull, vertebrae, and ribs. The primary interest in this research is the skull. The skull is a highly evolved complex structure which is characterized by mobility, flexibility, and a greatly reduced number of bones, with numerous joints to allow swallowing prey far larger than its head. There are also several hinge joints located at various points that allow the movement and slight rotation of certain segments. Most of the bones within the skull are not fused, but rather loosely attached by ligaments. This allows the expansion and flexion of the skull to engulf prey. The two bottom jaws are not fused together as in mammals. Instead, the dental bones are connected via a ligament

This research mainly revolves around the forces acting on the jaw and their measurement using a transducer.

CHAPTER 3

MESHING AND MODELLING PROCEDURES

3.1. SPECIMEN

A Boa constrictor specimen was collected in Panama by H. C. Clark. It was made available to The University of Texas High-Resolution X-ray CT Facility for scanning by Dr. Jessie Maisano of The University of Texas at Austin and Mr. Alan Resetar of the Field Museum. The specimen was scanned by the X ray microtomography procedure by Matthew Colbert on 27 April 2004 along the coronal axis for a total of 555 slices. The basic 3D model of the specimen is obtained from the process MicroTomography.

3.2. Microtomography:

Microtomography uses x-rays to create cross-sections of a 3D-objects that later can be used to recreate a virtual model without destroying the original model[15]. Tomography is a technique for digitally cutting a specimen open using X-rays to reveal its interior details. A CT image is typically called a slice[16]. A typical digital image is composed of pixels (picture elements), a CT slice image is composed of voxels (volume elements). The term micro is used to indicate that the pixel sizes of the cross-sections are in the micrometer range.[17]

By directing the X-rays through the slice plane from multiple orientations and measuring their resultant decrease in intensity, a CT image can be produced. A specialized algorithm is then used to reconstruct the distribution of X-ray attenuation in the slice plane[18]. By acquiring a stacked, contiguous series of CT images, data describing an entire volume can be obtained. The software allows reconstruction of objects from the stack of 2D sections, after interactive thresholding[19]. Using a specialized surface rendering algorithm, these 3D models were reconstructed.

The CT scans were converted into an .inp file (INPUT FILE) for ABAQUS by Dr. Mohammed Akhter at Creighton University in Lincoln, Nebraska. However, this process is imperfect and several regions in the finite element model were unconnected and the model was not scaled properly. The scaling of the model was done by Dr. Mark Barkey in HYPERMESH and ABAQUS.

3.3. FEA MODELING

The FEA modeling consisted of four steps:

- Importing the model.
- Examining the mesh for defects and correcting them.
- Specification of the material property.
- Specification of boundary and loading conditions.

3.4. COMPONENTS

The final model consists of nine components assembled into a single model. The 9 components are

1. Central
2. Jaw upper
3. Mandible
4. Maxilla
5. Pterygoid
6. Quadrate
7. Spine
8. Supratemporal
9. Vomer

The picture below shows all the 9 components of the boa skull assembled into one single component.

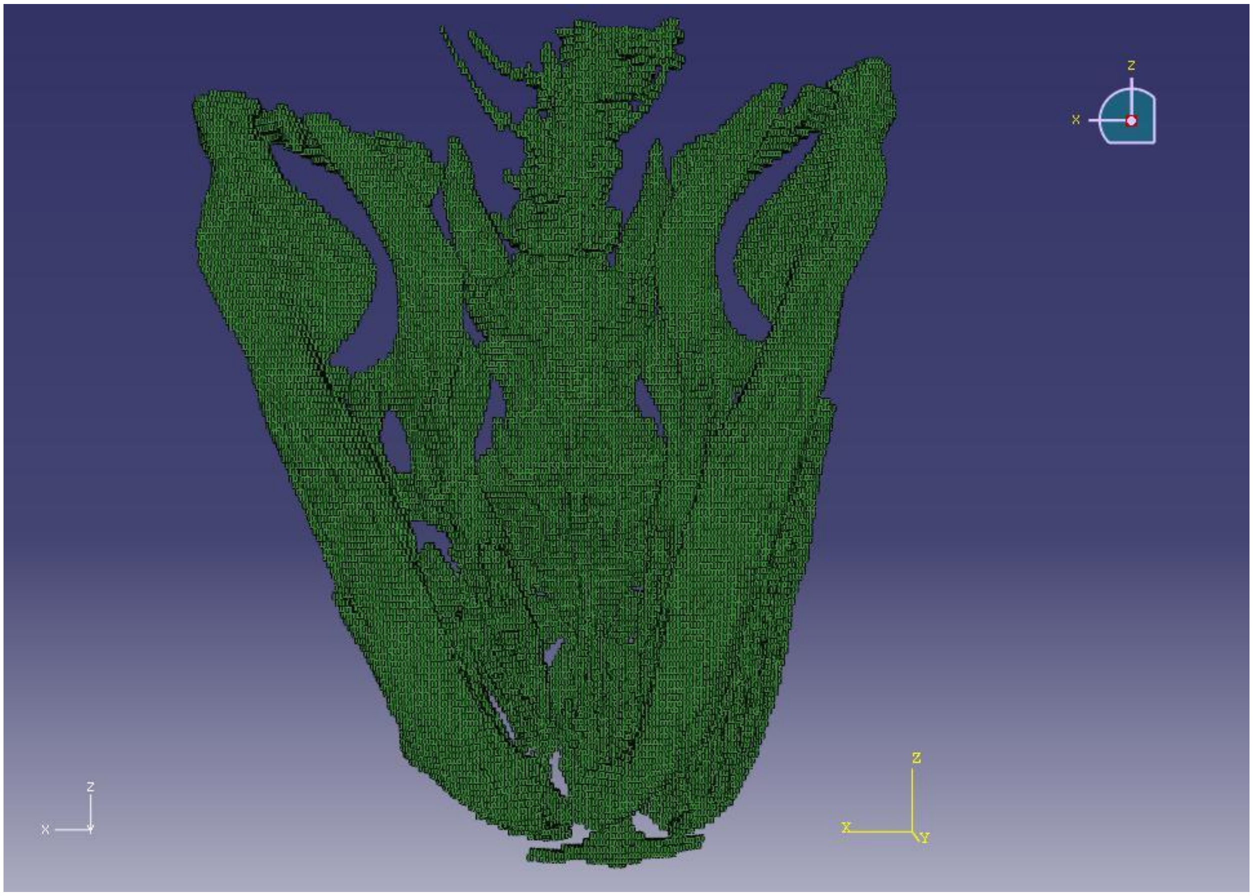

Figure 3.1: Full Model of the Boa skull in ABAQUS

Central:

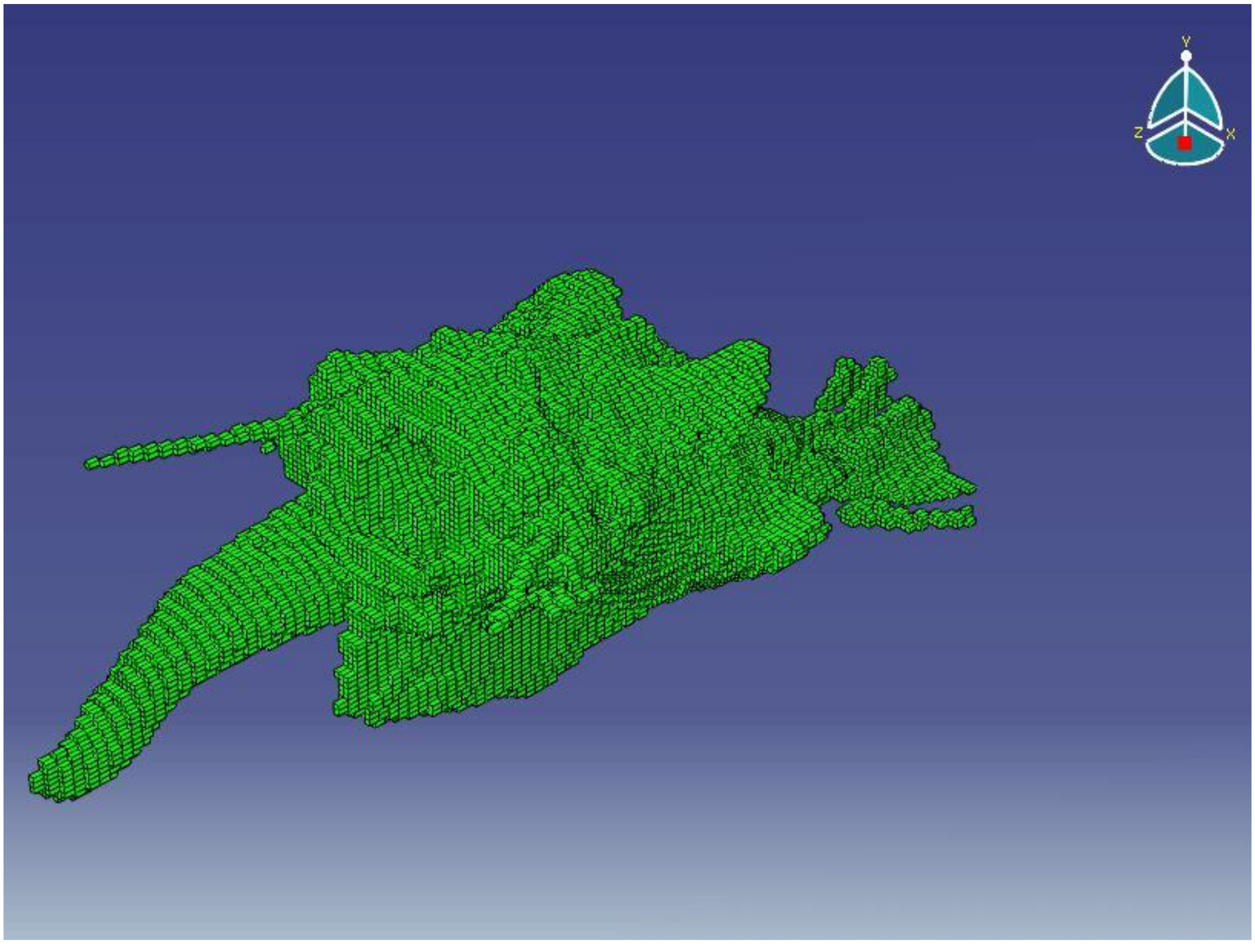

Figure 3.2: Central part of the Boa skull in ABAQUS

Jaw upper:

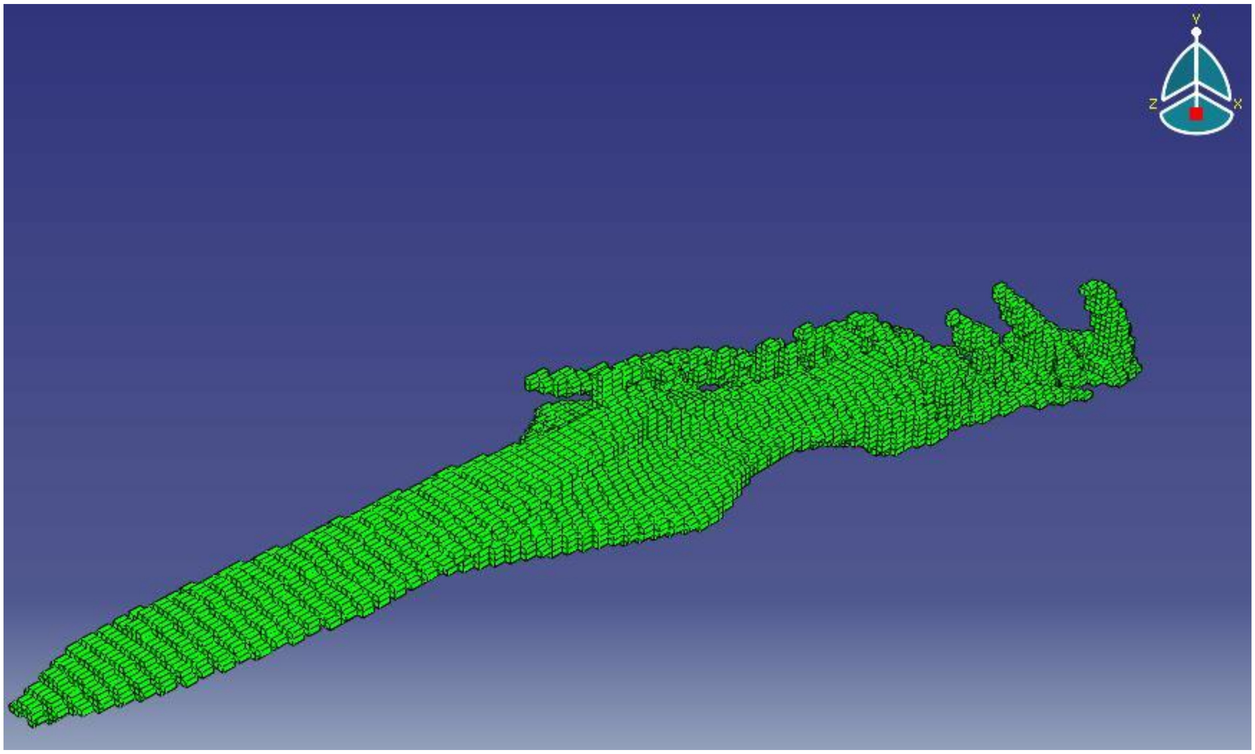

Figure 3.3: Jaw upper part of the Boa skull in ABAQUS

Mandible:

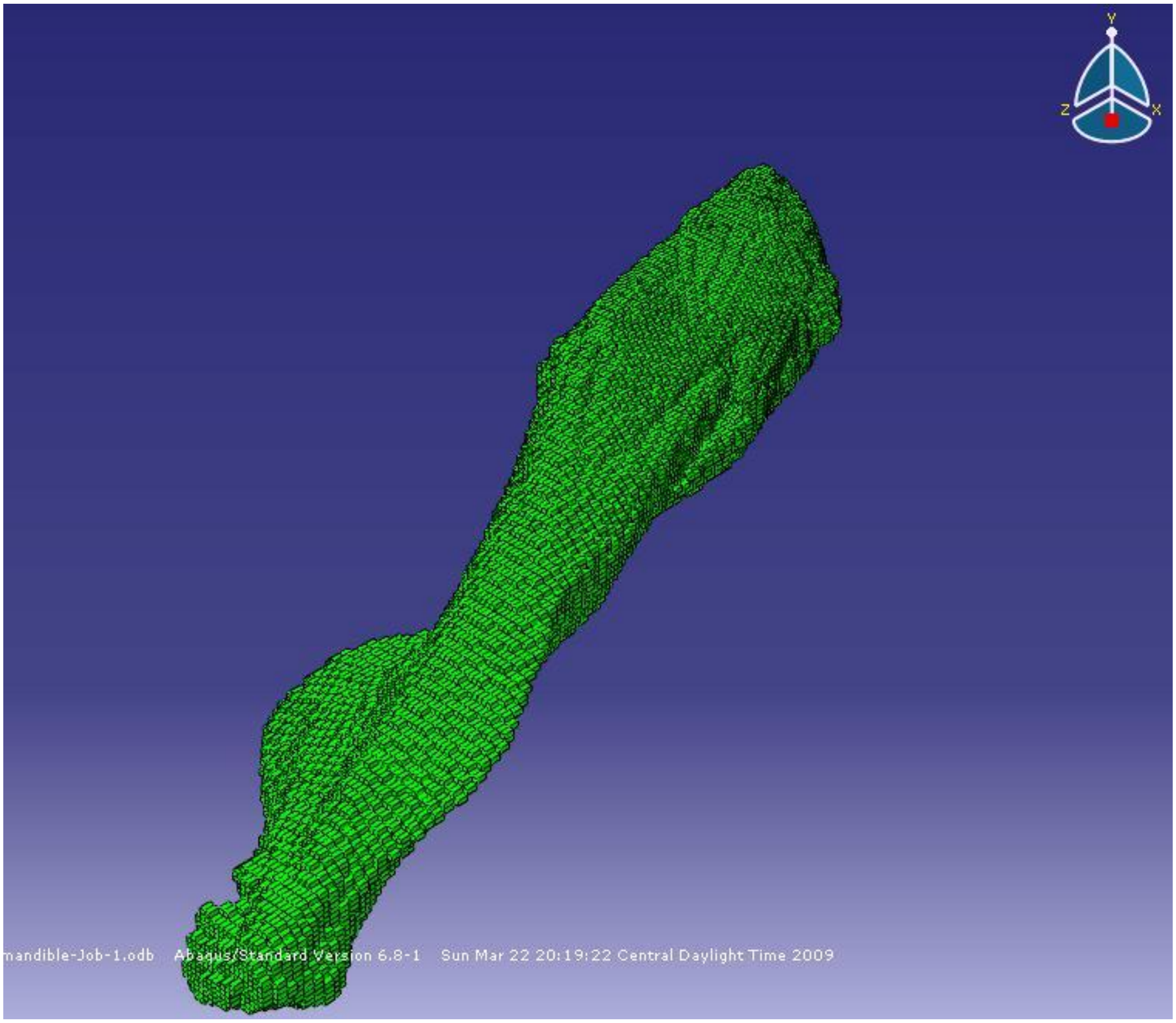

Figure 3.4: Mandible part of the Boa skull in ABAQUS

Maxilla :

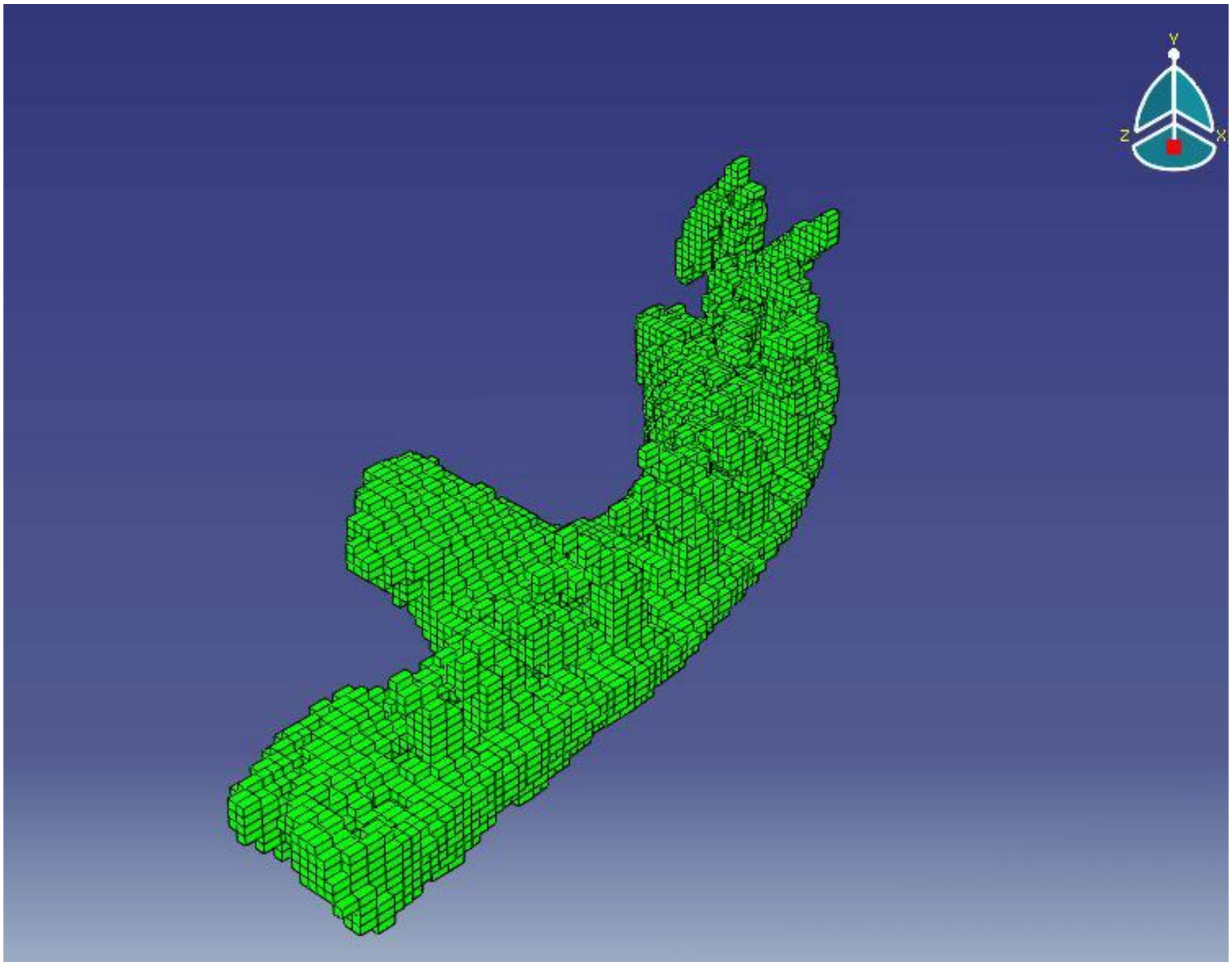

Figure 3.5: Maxilla part of the Boa skull in ABAQUS

Pterygoid:

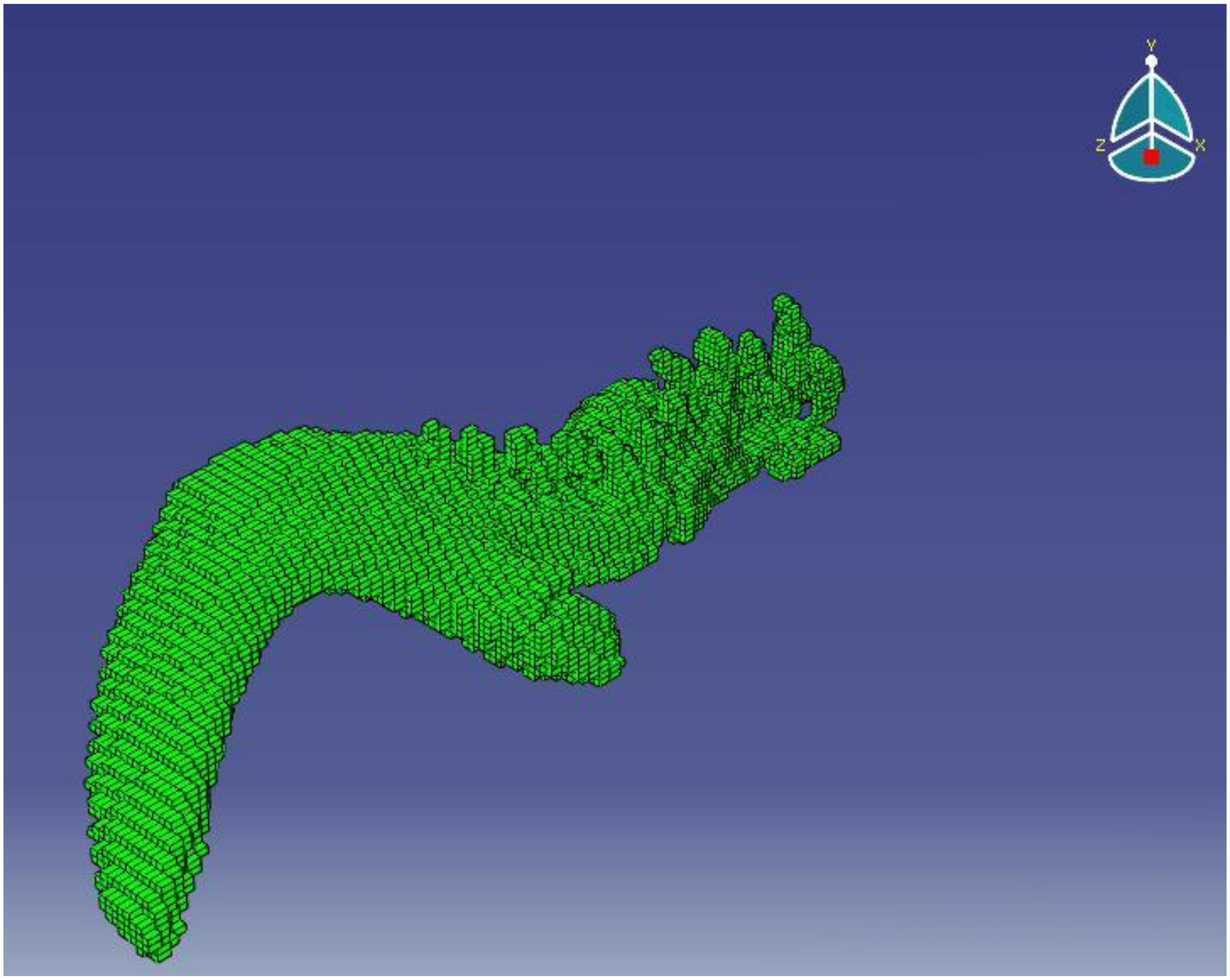

Figure 3.6: Pterygoid part of the Boa skull in ABAQUS

Quadrate :

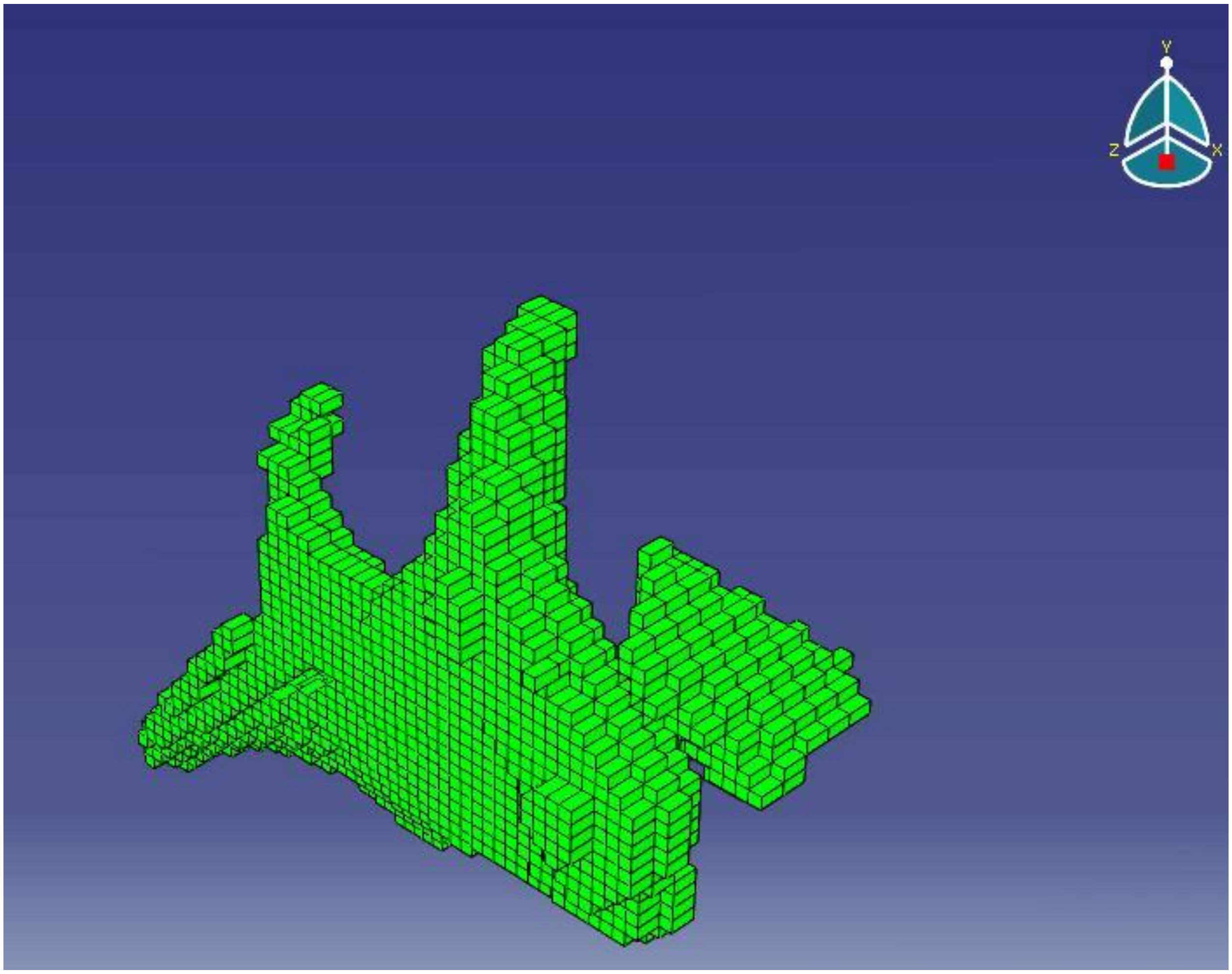

Figure 3.7: Quadrate part of the Boa skull in ABAQUS

Spine:

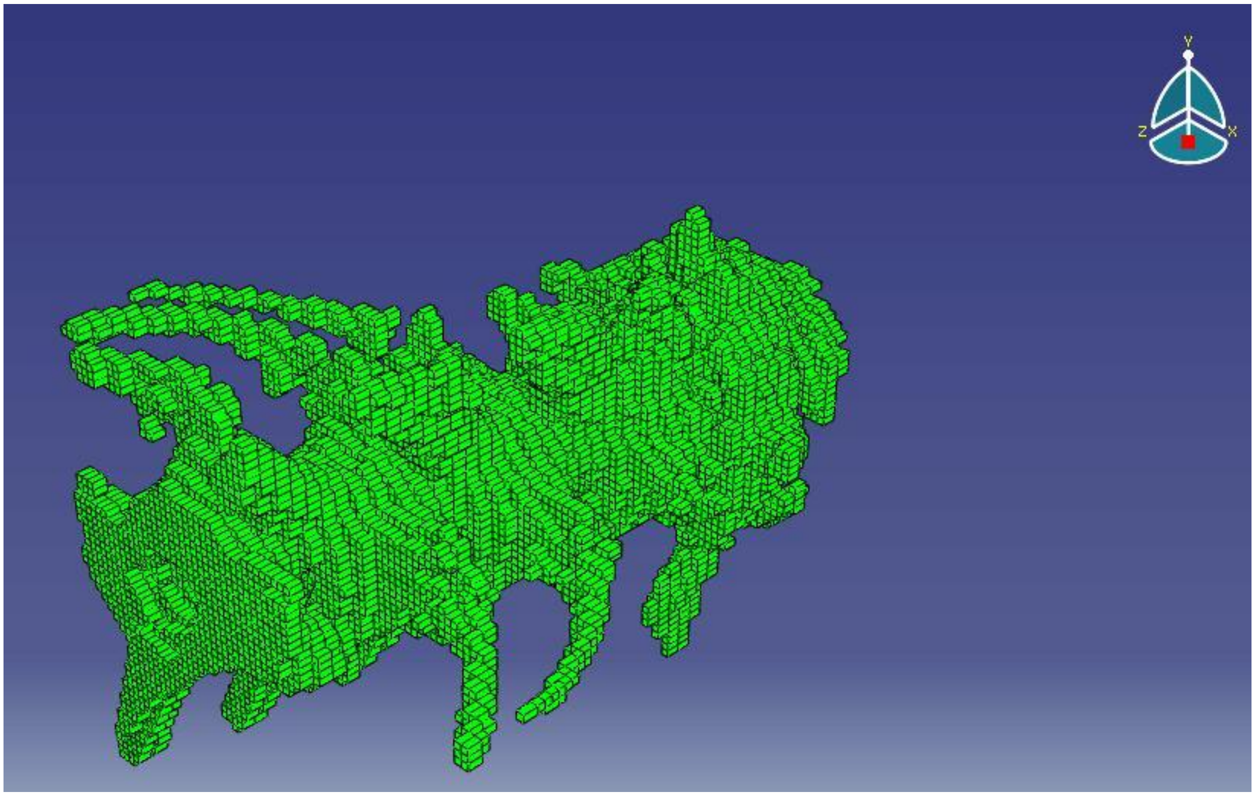

Figure 3.8: Spine part of the Boa skull in ABAQUS

Supratemporal:

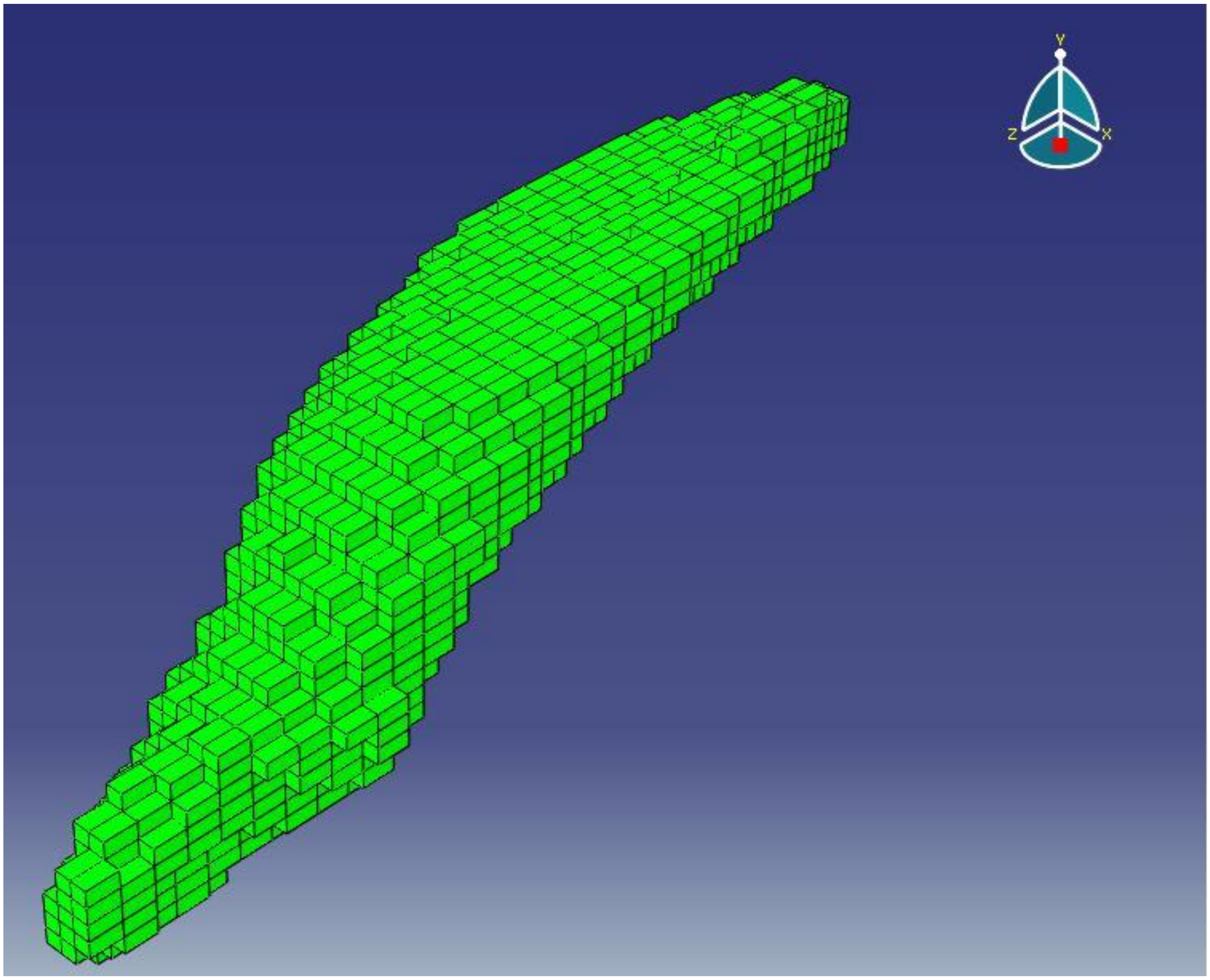

Figure 3.9: Supratemporal part of the Boa skull in ABAQUS

Vomer:

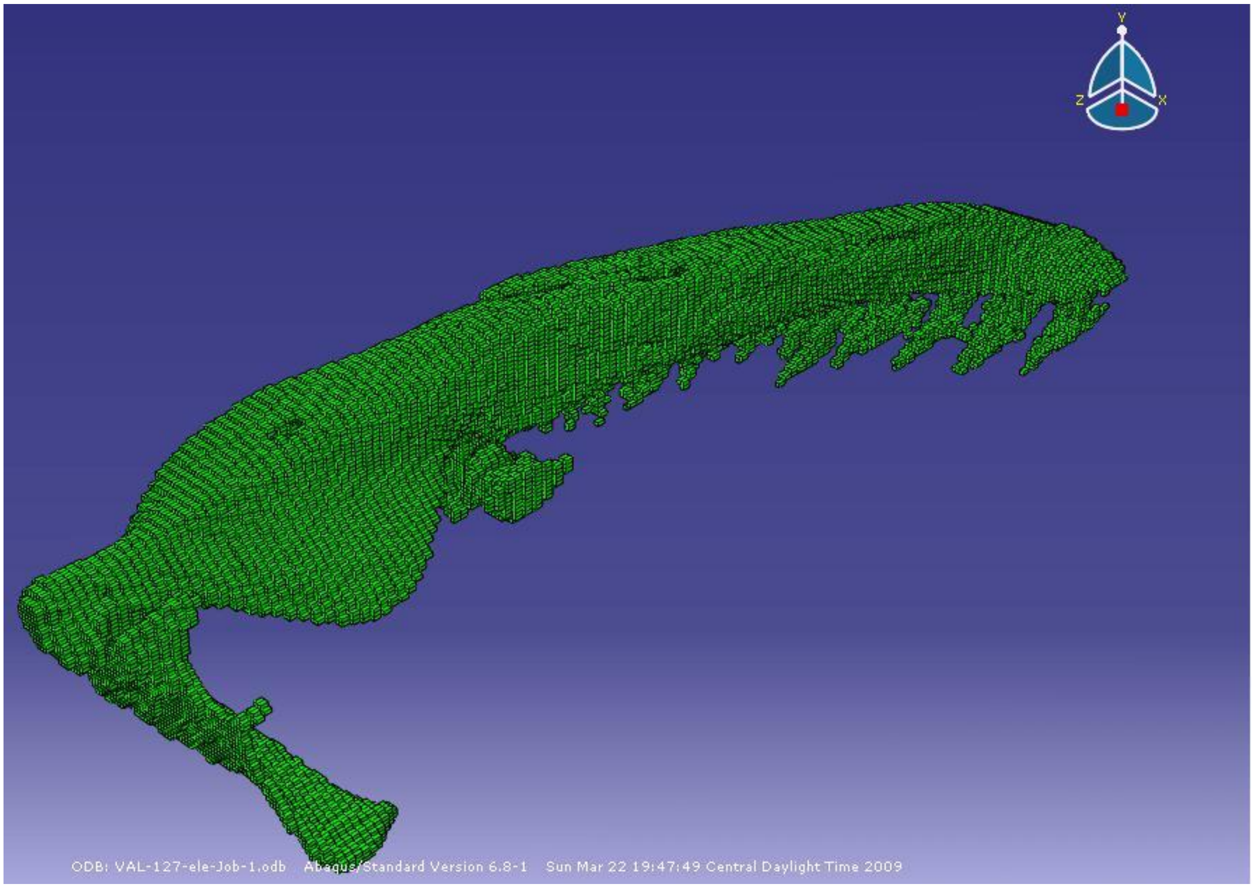

Figure 3.10: Vomer part of the Boa skull in ABAQUS

Though there are 9 different parts in the boa skull the stress flows through only a few parts, when there is a bite. From the full assembly, it can be seen that the model has symmetry along the Z-axis. This enables us to use the principles of symmetric geometry structural analysis.

3.5. ANALYSIS OF THE MODEL

The total analysis of the model has been performed in several steps as described below.

3.5.1. MESHING IN HYPERMESH

The model is meshed in HYPERMESH. The entire model is an assembly of 9 components which can be viewed and worked on separately in HYPERMESH. Each and every part has a connection to one or more parts in the model. Since the model is obtained through the process of Micro tomography, and not modeled specifically in HYPERMESH, but from the 3-D model of the snake, there is a possibility of having unconnected regions in the model. These unconnected regions are basically loose chunks of flesh in the real model. These can be found attached to the bones or in the space between the arrangements of the bones. The meshing software assumes these loose chunks of flesh also to be a part of the model and does the meshing. Therefore, the model in HYPERMESH had many unconnected regions which had to be corrected in the final model.

3.5.2. CORRECTING THE MODEL

The meshed model is corrected in HYPERMESH. Separately, each of the 9 components is thoroughly examined for any unconnected regions. The unconnected regions, or the free elements, are then deleted from the component. This is to make the component free of any unconnected regions and thus making it compatible for the continuous stress flow without any breaks when the forces are applied. HYPERMESH has the option to delete the elements after they are meshed. All the brick elements are checked for their connectivity with the adjacent brick elements. All the nodes and elements are checked for their degrees of freedom, connectivity and other aspects.

3.5.3 EXPORTING THE MODEL FROM HYPERMESH

After the components are corrected, all the components are individually exported from HYPERMESH to be used in ABAQUS. This is to check the proper stress flow in the components and their compatibility to be used in the complete model. In HYPERMESH, the ABAQUS module is used in the preferences to export the components. The components are exported as *.INP files which can be used to work in ABAQUS. While exporting the model, the nodes and elements are of the primary interest. This *.INP file consists of the nodes and elements of a corrected model. Other than the nodes and elements no other properties of the components are exported.

3.5.4. IMPORTING THE MODEL INTO ABAQUS:

The *.INP file generated from HYPERMESH is used in ABAQUS to check the consistency of the component. This file consists of the elements and nodes of the meshed component. After the *.INP file is opened in ABAQUS, it is given the material properties, loads and boundary conditions and is submitted for analysis. The analysis is monitored to check for any unconnected regions in the component. After the analysis is complete, the component is checked for the stresses at different points on the component to check for the stress flow.

3.5.5. PREPARING THE ABAQUS MODEL

The component is given the material properties, loads and boundary conditions. The component is encastered at one end and forces are applied at the other end. This makes the model a typical cantilever which is completely fixed at one end and forces applied at other end. The forces used are either a concentrated or a pressure force.

3.5.6. EXAMINING THE ABAQUS MODEL

After completing the analysis in ABAQUS, the following steps are performed to check the consistency of the component.

1. Stresses at different points on the surfaces: With the help of the ABAQUS/CAE interface, the stress at different points is examined.
2. Stress flow inside the component by cutting the component at various sections.
3. Monitoring the deformation of the model.
4. Monitoring the analysis for any unconnected regions or elements.

3.6. JAW ANALYSIS

The main interest in this research is to analyze the jawbone. The lower jaw bone of the boa called the Mandible and the upper jaw bone Maxilla are analyzed in this research. When a boa catches its prey in its mouth, these are the two main bones inside its mouth that hold a firm grip on the prey. In order to have a firm grip, the boa uses a certain amount of force to catch the pray. This results in a non-uniformly distributed pressure force on the upper and the lower jaw. As a result stresses are formed in the jaws of the boa.

The figure below shows the model of the jaw bone before the analysis.

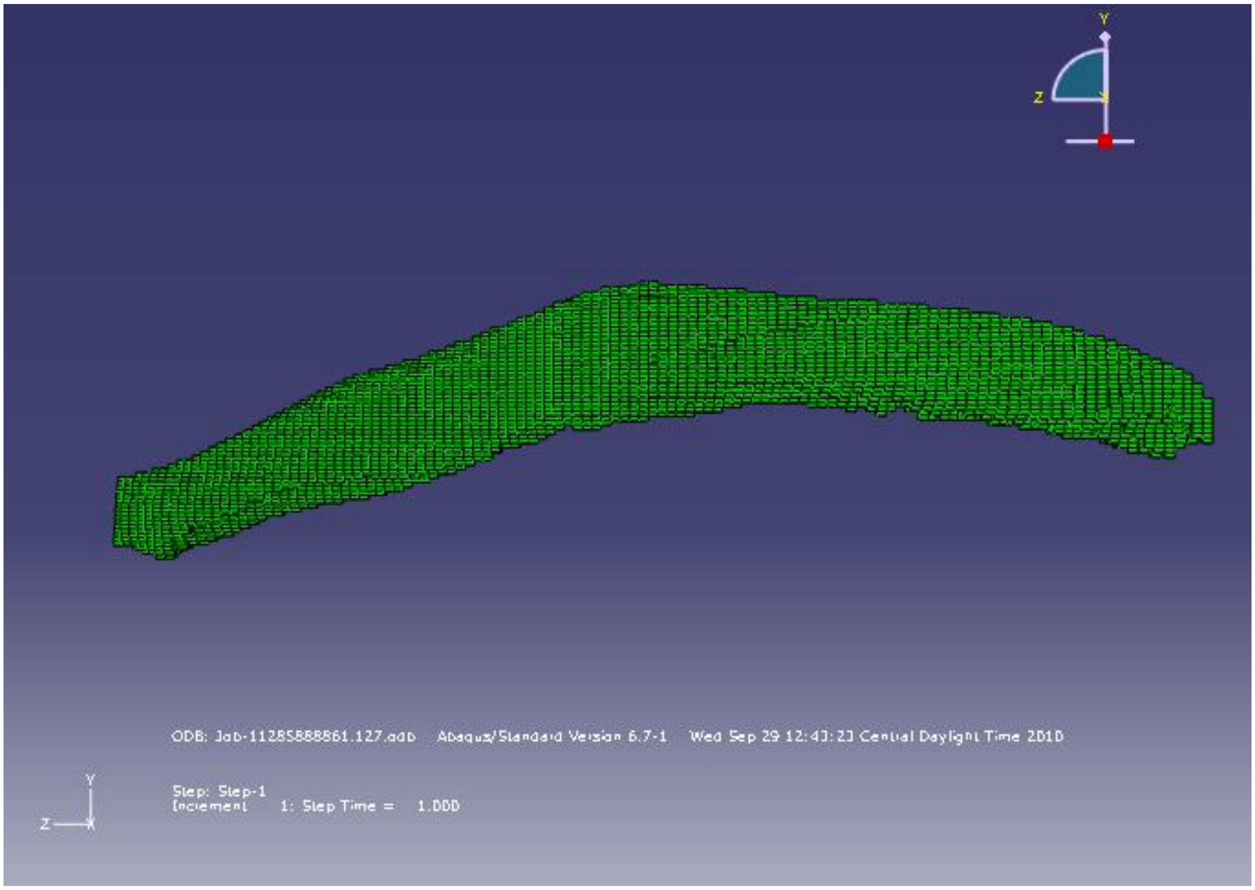

Figure 3.11 Jaw bone before the analysis in ABAQUS

The figure below shows the model of the jaw bone after the analysis.

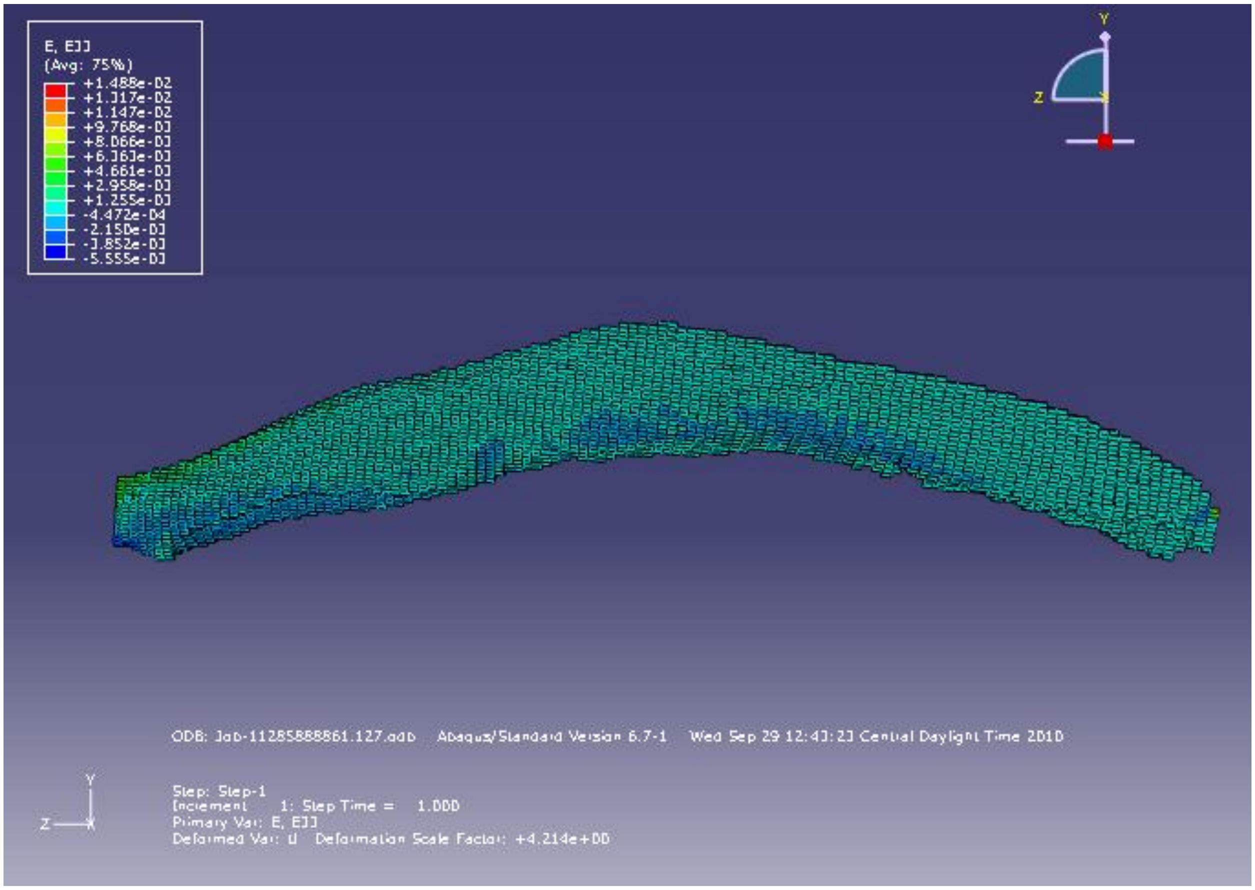

Figure 3.12 Jaw bone after the analysis in ABAQUS

3.7 MATERIAL PROPERTIES

The jaws were given the material properties of Titanium. Titanium is a low density, strong, corrosion resistant material and easily fabricated [20]. The two most useful properties of the metal form are corrosion resistance and the highest strength-to-weight ratio of any metal[21]. It is often used for surgical implants. Titanium is important as an alloying agent with aluminum and other metals [22].

3.8 TITANIUM AS AN IMPLANT MATERIAL

Titanium, because of its unique properties, is the material of choice for bone implants. Since the late forties, titanium has been used as a material used in the implants and it is until recently that much research and attention is conducted on improving the properties of this biomaterial [23]. Strength and long lasting properties of a material are the most desired properties of any material to be used in bone implants. Several methods may be employed to modify the surface structure of titanium implants, which all may lead to altered chemical and mechanical properties of the metal surface [24]. A variety of implants of many designs are made from this metal in its pure form or the alloy form [25].

Basic properties of Titanium:
Elastic Modulus : 116 GPa
Poisson's ratio : 0.32
Density : 4.506 g $/cm^3$
Melting Point: 1668 C
Boiling Point: 3287 C

CHAPTER 4

DESIGN OF THE TRANSDUCER

4.1. FORCE TRANSDUCERS

There are many types of force sensors or load cells to measure force. Force transducers are devices used to directly measuring forces within a mechanical system.

4.1.1. CONCEPT OF MEASURING FORCES

There are many reasons why there is a need to directly measure forces. Each system needs a correct amount of force to be applied on it. Overweight or underweight below a specified level would probably destroy the system or sometimes give inaccurate results because of the underweight. To overcome these situations it is very important to know the forces acting on the system. The basic limitation of all measurement sciences is that all measurements are relative. Therefore, all sensors contain a reference point against which the quantity to be measured must be compared. A force transducer is a device that converts the force applied into a measurable electrical signal. The force transducer works on the principle of a Piezoresistive effect.

4.1.2. ELECTRICAL RESISTANCE STRAIN GAUGE MEASUREMENTS

It describes the changing electrical resistance of a material due to applied mechanical stress. It has been known that metal films, semi conductors and film resistors are characterized by a resistance variation when mechanical stress is applied. The deformation sensitivity of a resistor can be described with the gauge factor that is defined as the ratio of fractional change in resistance to the fractional change in geometrical sizes. The gauge factor is separate for both currents that are parallel and perpendicular to the direction of the strain. The gauge factor is independent of the properties of the resistor material. The piezoresistive effect is the basis of operation in the majority of mechanical sensor types, including pressure and acceleration sensors. The great advantage of piezoresistive effect is that static pressure and force measurement can be accurately measured and there is no interference of any other effects. The only concerns are the temperature dependence and long term stability when designing piezoresistive mechanical sensors. [26]

4.2. STRAIN GAUGE

An ideal strain gage changes resistance due to the deformations of the surface to which it is attached. In real time applications, temperature, material properties, the adhesive that bonds the gage to the surface, and the stability of the metal all affect the detected resistance. When selecting a strain gage, the strain characteristics of the sensor, its stability and temperature sensitivity are to be considered. The most used strain gage materials are also sensitive to temperature variations and tend to change resistance as they age. For tests and experiments that run for long periods of time, these factors must be compensated. Each strain gage wire material has its characteristic gage factor, resistance, temperature coefficient of gage factor, thermal coefficient of resistivity, and stability.

Typical materials include Constantan (copper-nickel alloy), Nichrome V (nickel-chrome alloy), platinum alloys (usually tungsten), Isoelastic (nickel-iron alloy), or Karma-type alloy wires (nickel-chrome alloy), foils, or semiconductor materials. The most popular alloys used for strain gages are copper-nickel alloys and nickel-chromium alloys. [27]

After the characteristics of germanium and silicon were discovered, these materials exhibited substantial nonlinearity and temperature sensitivity and they also had gage factors more than fifty times, and sensitivity more than a 100 times, that of metallic wire or foil strain gages. Silicon wafers are more elastic than metallic ones. An ideal strain gage must return readily to its original shapes.

An ideal strain gage is small in size and mass, low in cost, easily attached, and highly sensitive to strain but insensitive to ambient or process temperature variations.

4.3. STRAIN MEASUREMENT

4.3.1. STRESS AND STRAIN

External forces when applied to an object which is stationary, the results are stress and strain. Stress is defined as the object's internal resisting forces. Stress can be calculated by dividing the force (F) applied by the unit area (A):

$$Stress = \frac{Force}{Area}$$

$$\sigma = F/A$$

Strain is defined as the amount of deformation per unit length of an object when a load is applied. Strain is calculated by dividing the total deformation of the original length by the original length (L).

$$\varepsilon = \frac{\Delta L}{L}$$

The values for strain are less than 0.005 inch/inch and are often expressed in micro-strain units denoted by $\mu\epsilon$.

It was discovered that metallic conductors subjected to mechanical strain exhibit a change in their electrical resistance [28]. All strain gages convert mechanical motion into an electronic signal and a change in capacitance, inductance, or resistance is proportional to the strain experienced by the sensor. If a wire is held under tension, it gets slightly longer and its cross-sectional area is reduced. The change in resistance is proportion to the strain sensitivity of the resistance of the wire.

Using the Hooke's law, the relation between the stress and strain can be formulated with the Elastic modulus of the material. Stress is thus obtained by multiplying strain by the elastic Modulus.

$$E = \frac{\sigma}{\varepsilon}$$

$\sigma = stress$

$\varepsilon = strain$

$E = Elastic\ modulus.$

When a material is stretched in one direction, it contracts in the other direction perpendicular to the direction of stretch. Conversely, when a sample of material is compressed in one direction, it tends to expand in the other direction. This phenomenon is called the Poisson effect.

$$\vartheta = \varepsilon_2/\varepsilon_1$$

$\varepsilon_1 = Longitudinal\ strain$

$\varepsilon_2 = Transverse\ strain$

Poisson's ratio differs depending on the material.

4.3.2. STRAIN GAUGE MEASUREMENT

An external tensile force increases the resistance and external compressive force decreases the resistance by contracting it. The strain gauge should be properly mounted onto the test specimen so that the strain is accurately transferred from the test specimen.

A strain gauge's sensitivity to strain is expressed as the gauge factor (GF). Gauge factor is defined as the ratio of fractional change in electrical resistance to the fractional change in length (strain)

$$GF = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}}$$

$$GF = \frac{\frac{\Delta R}{R}}{strain}$$

$$GF = gauge\,factor$$

It is the coefficient expressing strain gage sensitivity. General-purpose strain gages use copper nickel or nickel-chrome alloy for the resistive element, and the gage factor is approximately 2.

Strain-initiated resistance change is extremely small. The strain measurements rarely involve quantities larger than a few mill strain. Therefore, measuring strain requires accurate measurement of very small changes in resistance. Thus, for strain measurement a Wheatstone bridge is formed to convert the resistance change to a voltage change.

A Wheatstone bridge measures the unknown electrical resistance by balancing two arms of a bridge circuit, one arm of which includes the unknown component.

The general Wheatstone bridge shown below, consists of four resistive arms with an excitation voltage, V_{EX}, that is applied across the bridge.

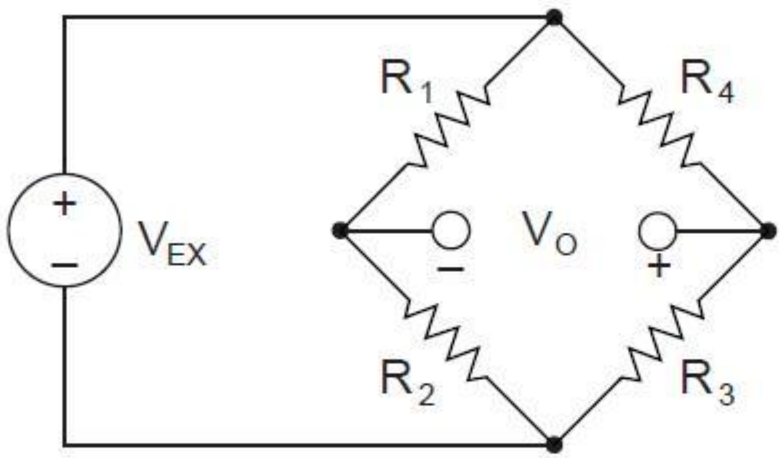

Figure 4.1 Wheatstone bridge

The output voltage,[32]

$$V_0 = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2}\right] * V_{ex}$$

From this equation, it is apparent that when the voltage output V_0 will be zero. Under these conditions, the bridge is said to be balanced. Any change in resistance in any arm of the bridge will result in a nonzero output voltage.

If R_4 is replaced in the above figure with an active strain gauge, any changes in the strain gauge resistance will unbalance the bridge and produce a nonzero output voltage. If the nominal resistance of the strain gauge is designated as R_G, then the strain-induced change in resistance, ΔR.[32]

$$\Delta R = R_G * GF * \varepsilon$$

Assuming $R_1 = R_2$ and $R_3 = R_G$, the above equation can be written as[32]

$$\frac{V_0}{V_{EX}} = -(GF * \varepsilon * 0.25)*[\frac{1}{1+GF*^{\varepsilon}/_2}]$$

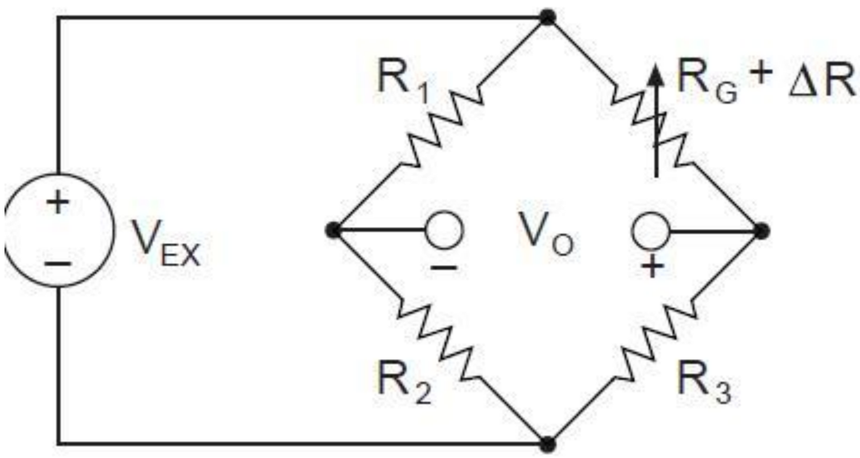

Figure 4.2 Quarter Bridge

By using two strain gauges in the bridge, the effect of temperature can be avoided. The sensitivity of the bridge can be doubled by making both gauges active, although in different directions.

The figure below shows a bending beam application with one bridge mounted in tension ($R_G + R$) and the other mounted in compression ($R_G - R$).

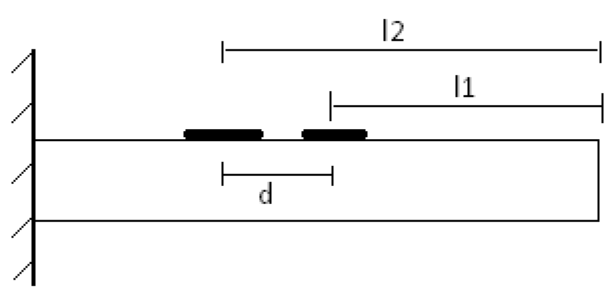

Figure 4.3 Cantilever with two strain gauges

The figure below shows the configuration of a Wheatstone half bridge yields an output voltage that is linear and approximately doubles the output of the quarter bridge circuit.[32]

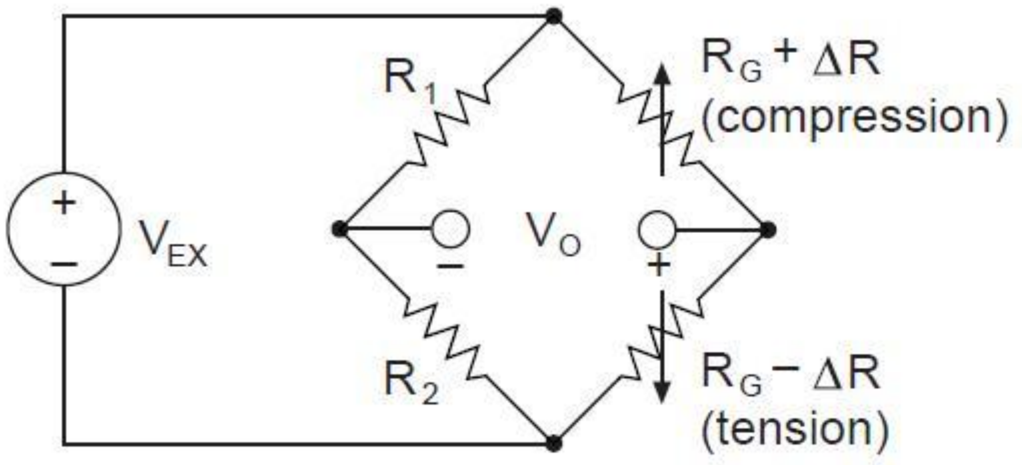

Figure 4.4 Wheatstone half bridge

$$\frac{V_0}{V_{EX}} = -(GF * \varepsilon * 0.5)$$

The sensitivity of the circuit can be further increased by making all four of the arms of the bridge active strain gauges, and mounting two gauges in tension and two gauges in compression.

The figure below shows the full bridge circuit.[32]

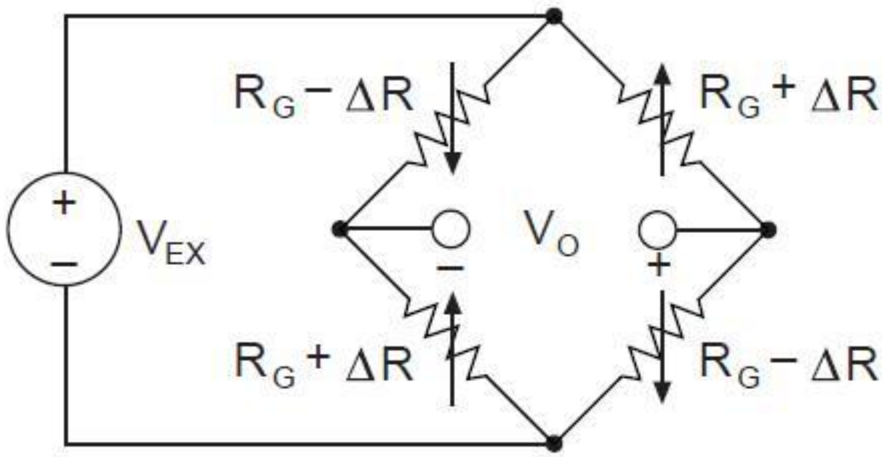

Figure 4.5 Wheatstone full bridge

$$\frac{V_0}{V_{EX}} = -(GF * \varepsilon)$$

The equations given here for the Wheatstone bridge circuits assume an initially balanced bridge that generates zero output when no strain is applied. In reality resistance tolerances and strain induced by gauge application will generate some initial offset voltage. This initial offset voltage is typically handled in two ways.

- A special offset-nulling, or balancing, circuit to adjust the resistance in the bridge to rebalance the bridge to zero output.
- By measuring the initial unstrained output of the circuit and compensate in software.

4.3.3 STRAIN GAUGE EQUATIONS

For the unbalanced equations and for simplicity of the equations, a ratio V_r[32]

$$V_r = \frac{V_0(strained) - V_0(unstrained)}{V_{Ex}}$$

For a quarter bridge,

$$Strain(\varepsilon) = \frac{-4V_r}{GF(1+2*V_r)} * \left(1 + \frac{R_L}{R_G}\right)$$

For a half bridge,

$$Strain(\varepsilon) = \frac{-2V_r}{GF} * \left(1 + \frac{R_L}{R_G}\right)$$

For a full bridge,

$$Strain(\varepsilon) = \frac{-V_r}{GF}.$$

$$R_G = nominal\ resistance\ value\ of\ the\ strain\ gauge$$
$$R_L = lead\ resistance$$
$$GF = gauge\ factor\ of\ strain\ gauge$$

4.4. DESIGN OF THE TRANSDUCER

In this study, the entire model of the jawbone, for which the analysis is done, is assumed to be a cantilever. A cantilever is a beam supported at only one end and load at the other end. Strain gauges are mounted on the cantilever to measure the strain in the cantilever when forces are applied.

Case 1:

A cantilever, as shown above, with a load P at the free end and a strain gauge at point a at a distance of L from the free end.

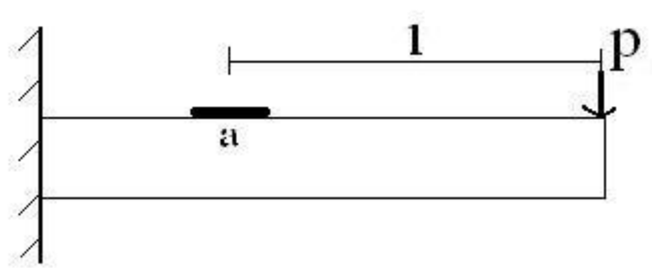

Figure 4.6: A Cantilever beam

For the cantilever, Moment M at point a is

$$M = P * L$$

$$P = force\ applied\ at\ the\ end$$

$$L = distance\ of\ the\ strain\ gauge\ from\ the\ free\ end\ of\ the\ cantilever.$$

Stress at point a is given by,

$$Stress, \sigma = \frac{M * y}{I}$$

$$Stress, \sigma = \frac{M}{I/y}$$

$$Section\ Modulus,\ {}^{I}/_{y} = Z,$$

$$Stress, \sigma = \frac{M}{Z}$$

where

$$Z = \ section\ modulus\ of\ the\ material.$$

$$I = \ moment\ of\ inertia$$

$$\sigma = stress\ at\ point\ a$$

From Hooke's law,

$$E = \frac{\sigma}{\varepsilon}$$

$$E = Elastic\ modulus$$

$$\sigma = stress\ at\ point\ a$$

$$\varepsilon = strain\ at\ point\ a$$

Therefore,

$$Strain(\varepsilon) = \frac{\sigma}{E}$$

$$Strain(\varepsilon) = {}^{(M/Z)}/_{E}$$

$$Strain(\varepsilon) = \frac{M}{ZE}$$

$$Strain(\varepsilon) = \frac{PL}{ZE}$$

This is the theoretical strain value for the applied load P at point a which is at a distance of L from the free end.

Case 2 :

In another case, where the distance from the free end is unknown, but only the distance between the two strain gauges is known.

In this study, strain gauges are fixed at two different points, L_1 and L_2 from the free end.

$$strain\ at\ a\ point\ distance\ L_1\ from\ the\ free\ end, \varepsilon_1 = \frac{PL_1}{ZE}$$

$$strain\ at\ a\ point\ distance\ L_2\ from\ the\ free\ end, \varepsilon_2 = \frac{PL_2}{ZE}$$

Let d be the distance between the two strain gauges.

And $L_2 - L_1 = d$

Now,

$$\varepsilon_2 - \varepsilon_1 = \frac{P}{ZE}\ (L_2 - L_1)$$

$$\varepsilon_2 - \varepsilon_1 = \frac{P}{ZE}\ (d)$$

$$P = (\varepsilon_2 - \varepsilon_1) * (\frac{ZE}{d})$$

From the equation derived above, Z, E, d are all constants, and $\varepsilon_2, \varepsilon_1$ can be found experimentally from the Wheatstone bridge.

The arrangement of the whole apparatus can be seen in the figure below.

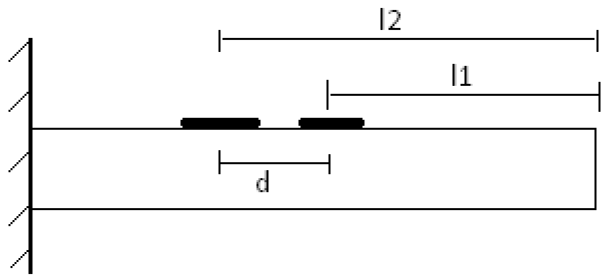

Figure 4.7 Cantilever beam with the two strain gauges.

This experimental strain value obtained from the strain gauge can be plugged into the theoretical strain equation derived above to determine the unknown force P.

$$Strain(\varepsilon) = \frac{PL}{ZE}$$

Therefore,

$$P = \frac{ZE\varepsilon}{L}$$

The equation above has Z, E which are known and constant values for a given specimen.

Therefore,

$$P \; \alpha \; \frac{\varepsilon}{L}$$

The value of P is directly proportional to the $strain(\varepsilon)$ and indirectly proportional to the distance from the free end of the cantilever(L).

For a Wheatstone full bridge, as shown below

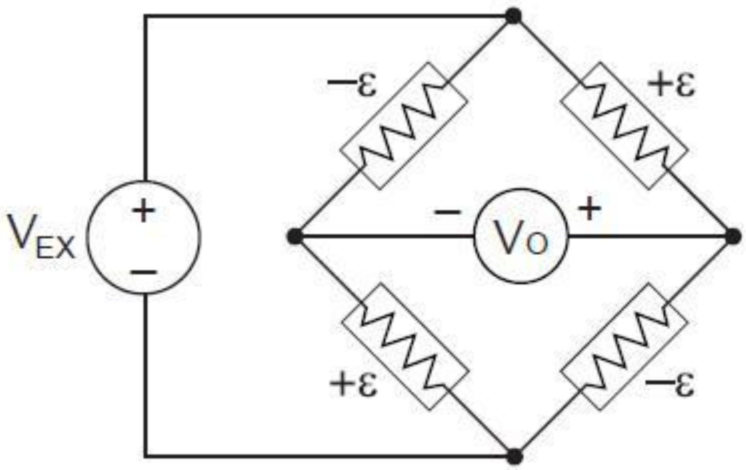

Figure 4.8 Wheatstone full bridge

$$Strain(\varepsilon) = \frac{-V_r}{GF}.$$

Using the same theory as above, it can be deduced that

$$P \; \alpha \; \varepsilon$$

Therefore,

$$P \; \alpha - V_r$$

CHAPTER 5

RESULTS AND CONCLUSIONS

The theory and mathematical procedure explained in the previous chapter is used to obtain the results.

COMPARISON OF THE THEORETICAL AND EXPERIMENTAL VALUES FOR THE CANTILEVER WITH A LOAD AT THE FREE END.

A Titanium cantilever beam with length 150mm, cross sectional dimensions 10mm*10mm. A concentrated load $500N$ acting downwards is applied at the free end.

A) A strain gauge is fixed at a point $100mm$ from the free end.

The material properties,

Elastic modulus, E = 116000 N/mm^2

Section modulus, $Z = \frac{bh^2}{6}$ =116.67 mm^3

Load at free end, $P = 500N$

Distance from the free end, $L = 100mm$

Strain at the point where the strain gauge is fixed,

$$\varepsilon = \frac{PL}{ZE}$$

$$\varepsilon = \frac{500 * 100}{166.67 * 116000}$$

$$\varepsilon = 0.00258\, mm/mm$$

Using the FEA software ABAQUS, this strain value ε for all the given dimensions and conditions is found out to be

$$\varepsilon = 0.00246298mm/mm$$

This gives a difference of 4.5 %. The error is mainly due to the quality of the mesh.

B) A strain gauge is fixed at a point $75mm$ from the free end.

The material properties,

Elastic modulus, E = 116000 N/mm^2

Section modulus, $Z = \frac{bh^2}{6}$ =116.67 mm^3

Load at free end, $P = 500N$

Distance from the free end, $L = 100mm$

Strain at the point where the strain gauge is fixed,

$$\varepsilon = \frac{PL}{ZE}$$

$$\varepsilon = \frac{500 * 75}{166.67 * 116000}$$

$$\varepsilon = 0.0019396\ mm/mm$$

Using the FEA software ABAQUS, this strain value ε for all the given dimensions and conditions is found out to be

$$\varepsilon = 0.001851626\ mm/mm$$

This also gives a difference of 4.5 %. The error is due to the quality of the mesh.

The same theory can be applied to the jaw bone of the boa constrictor. In the analysis, the jawbone is treated as a cantilever. It is fixed at one end, and concentrated force acting downward is applied at the free end.

Applying the same theory that is explained in the previous section, the strain gauge is fixed at some point from the free end of the jaw. When an unknown force is applied at the free end, strain is produced at the point of interest. This strain is displayed by the strain gauge which in turn is used to calculate the amount of unknown force applied at the free end. The strain gauge can either be connected to a quarter, half or a full bridge according to the known parameters and required sensitivity.

The figure below shows the model of the jaw bone before the analysis.

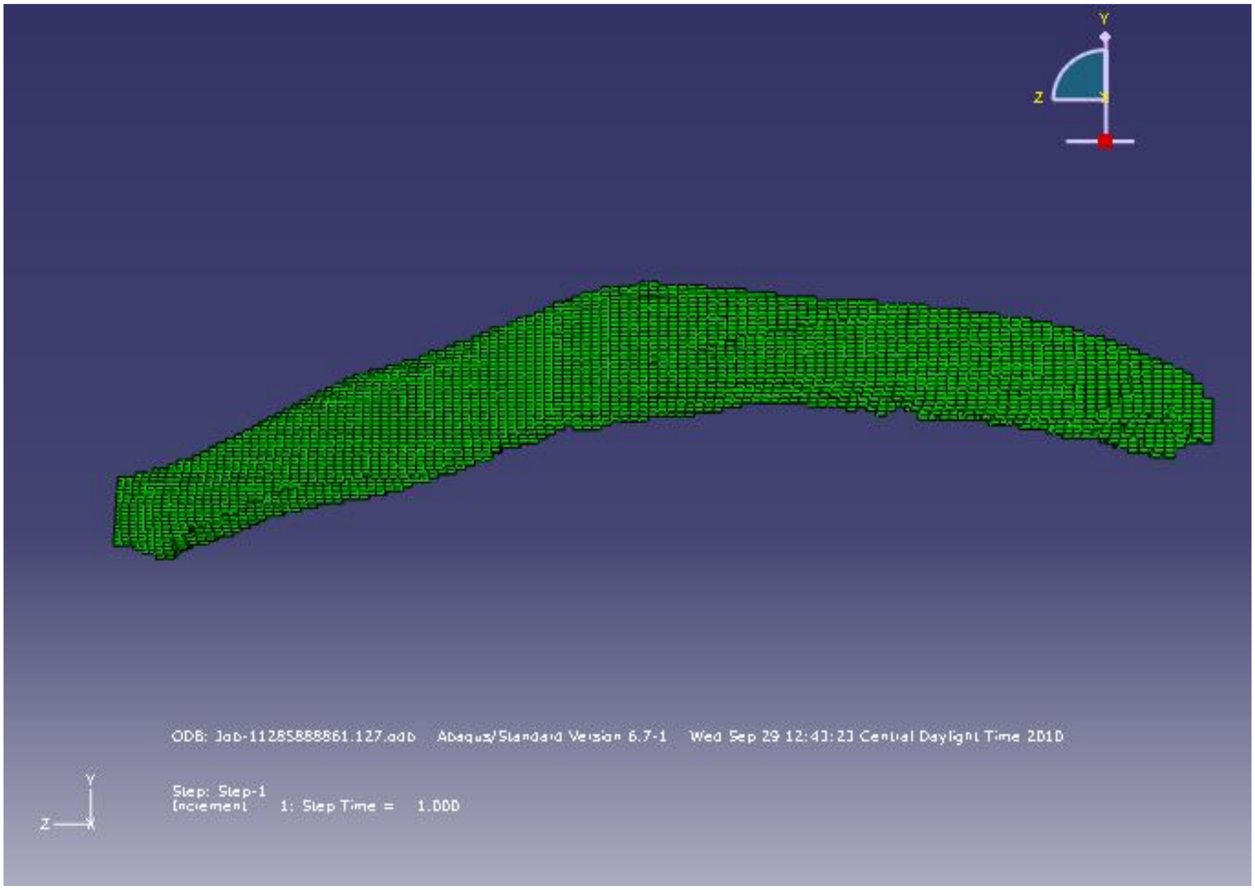

Figure 5.1 Jaw bone before the analysis in ABAQUS

The figure below shows the model of the jaw bone with the boundary conditions, location of the strain gauges and the applied loads.

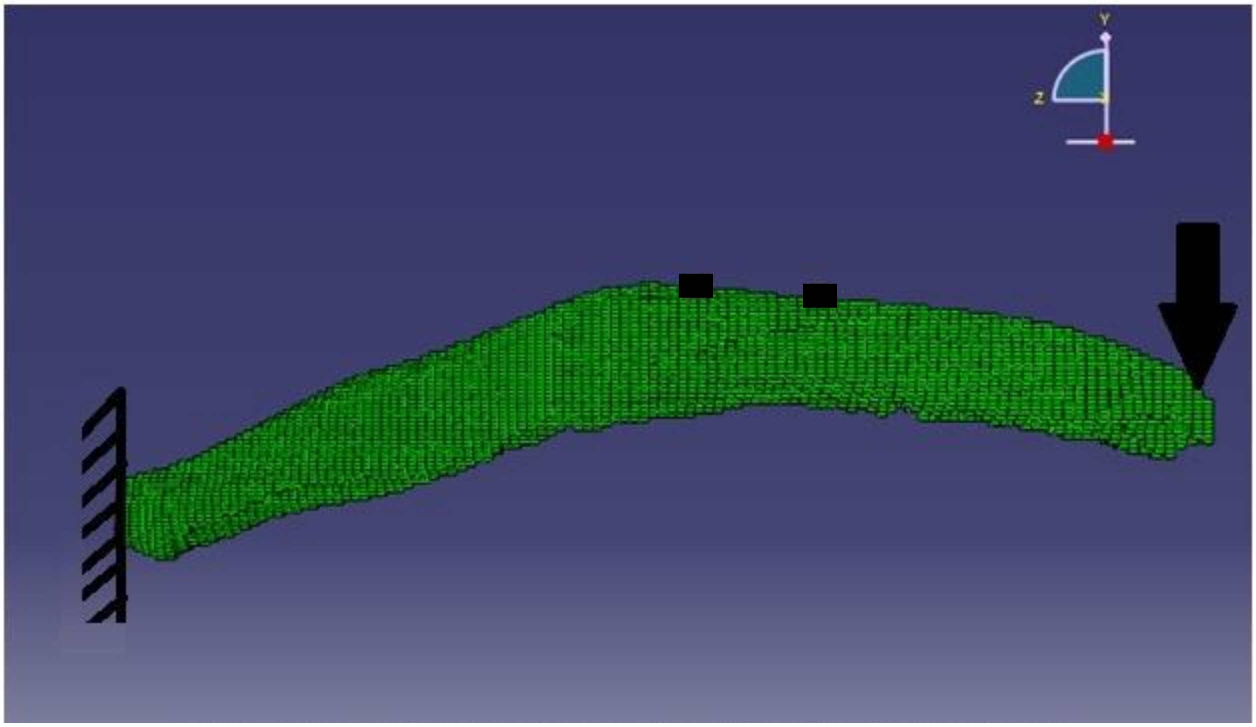

Figure 5.2 Jaw bone with the boundary conditions, location of strain gauges & the applied loads.

The figure below shows the model of the jaw bone after the analysis.

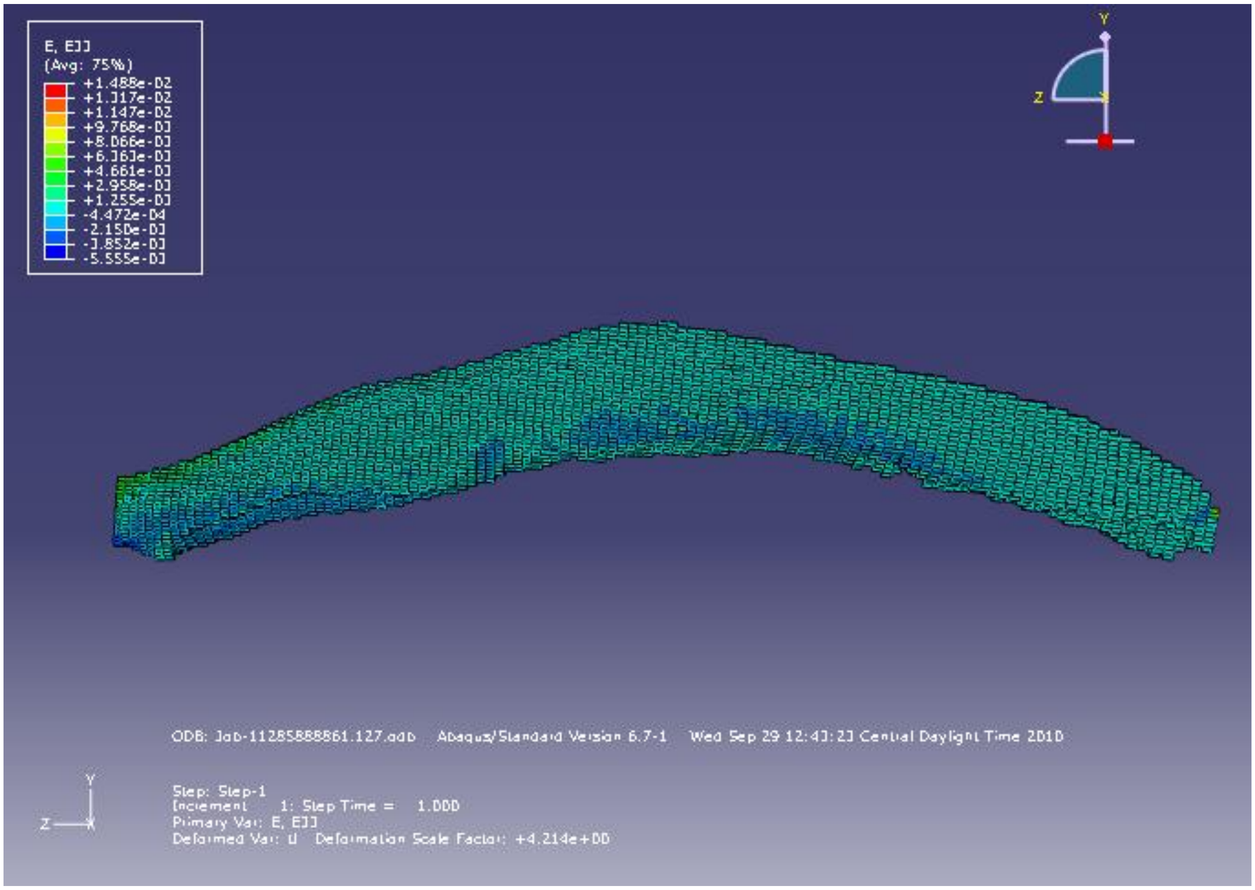

Figure 5.3 Jaw bone after the analysis in ABAQUS

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