

Study and Analysis of Tissue Engineering Scaffold for Human Mandibular Bone Using Finite Element Method



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Abstract:

In this study, focused on to understand the fundamental concepts of biomechanics (deformations, stresses, and strains occurring in the mandible during biting and chewing) of mandibular bone is studied. Finite element models of intact and birth defect mandibles are modeled in order to understand the bio-mechanical motion of mandibular bone. The intact CAD model of mandibular bone is modeled from the non-invasive images of cranio-maxillary bone and then NURBS model is generated using commercial software packages.

The NURBS CAD model is meshed with Hypermesh. The finite element analysis was carried out under the physiological conditions of biting and chewing. The displacement under chewing and biting conditions are 0.0012mm and 0.38mm respectively. The von misses stress under chewing and biting conditions are 7.3N/mm² and 1.345 N/mm² respectively.

Similarly, the patient specific birth defect mandibular bone was modeled from CT images and stress distributions was observed and compared with intact model. Theoretical stress value is calculated by which bone is considered as a curved beam. The successfulness of regenerative medicine approach is mainly depends on the scaffold. The scaffold should satisfy the biological, mechanical and anatomy requirements.

The mechanical requirements of tissue scaffold parameters like porosity, pore shape, pore size and surface area to volume ratio. The structural integrity of scaffold mainly depends on the porosity. The tissue scaffold is modeled for a segment of premolar region of birth defect mandibular bone using unit cell design approach. Finite element analysis was carried out in order to predict the stress distribution in the tissue scaffold.

INTRODUCTION

1.1.BIO-MECHANICS

The study of biomechanics ranges from the inner workings of a cell to the movement and development of limbs, to the mechanical properties of soft tissue, and bones. As develop a greater understanding of the physiological behavior of living tissues, researchers are able to advance the field of tissue engineering, as well as develop improved treatments for a wide array of pathologies. Biomechanics is also applied to studying human musculoskeletal systems.

Such research utilizes force platforms to study human ground reaction forces and infrared videography to capture the trajectories of markers attached to the human body to study human 3D motion. Research also applies electromyography (EMG) system to study the muscle activation. By this, it is feasible to investigate the muscle responses to the external forces as well as perturbations.

1.2.REGENERATIVE MEDICINE APPROACH:

Regenerative medicine approach is the “process of replacing or regenerating human cells, tissues or organs to restore normal function” This field holds the promise of regenerating damaged tissues and organs in the body by replacing damaged tissue and/or by stimulating the body’s own repair mechanisms to heal previously irreparable tissues or organs.

Regeneration can be affected by external conditions, such as temperature, Pressure, food, light, gravity, or chemical change, or by internal factors including polarity, orientation, or the material constitution and structure.

1.3 BONE GRAFTING:

Bone grafting is a surgical procedure that replaces missing bone in order to repair bone fractures that are extremely complex, pose a significant health risk to the patient, or fail to heal properly. Bone generally has the ability to regenerate completely but requires a very small fracture space or some sort of scaffold to do so. Bone grafts may be autologous (bone harvested from the patient's own body, often from the iliac crest), allograft (cadaveric bone usually obtained from a bone bank), or synthetic (often made of hydroxyapatite or other naturally occurring and biocompatible substances) with similar mechanical properties to bone. Most bone grafts are expected to be reabsorbed and replaced as the natural bone heals over a few months' time.

1.3.1 Types of Bone Grafting :

1. Auto graft is a tissue graft transferred from one part of the patient's body to another part
2. Allograft is a tissue graft from a donor of the same species as the recipient but not genetically identical
3. Xenograft is a Tissue or organs from an individual of one species transplanted into or grafted onto an organism of another species, genus, or family

1.4. TISSUE ENGINEERING :

Tissue engineering, the science and engineering of creating functional tissues and organs for transplantation, integrates a variety of scientific and engineering disciplines to produce physiologic 'replacement parts' for the development of viable substitutes which restore, maintain or improve the function of human tissues. In the success of tissue engineering, three-dimensional (3D) scaffolds play important roles as extra-cellular matrices onto which cells can attach, grow, and form new tissues. Modeling, design and fabrication of tissue scaffolds to meet multiple biological and biophysical requirements is always a challenge in regenerative tissue engineering. Basic principle of Tissue engineering is illustrated in the following Figure 1.1 The Computer Aided Tissue Engineering based design approach begins with the acquisition of non-invasive images and image processing of appropriate tissue region of interest. This is followed by a three-dimensional reconstruction of anatomical structure using commercially available medical reconstructive and reverse engineering software [3].

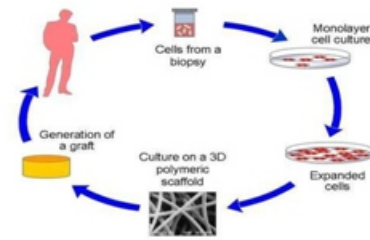


Figure 1.1: Principles of Tissue engineering (Courtesy: textile.iitd.ac.in)

1.4.1 Tissue Engineering Scaffold :

Cells are often implanted or 'seeded' into an artificial structure capable of supporting three-dimensional tissue formation. These structures typically called scaffolds, are often critical, both ex vivo as well as in vivo, to recapitulating in vivo and allowing cells to influence their own microenvironments.

IMAGE BASED BIO-CAD MODELING OF MANDIBULAR BONE

3.1 MODELING OF MANDIBULAR BONE

The Computer Aided Design (CAD) tool is normally used to engineering design, modeling and analysis. Due to technological advancement the CAD tools are implemented in biological applications to develop bio-mimetic modeling and analysis. The Image-based CAD design approach begins with the acquisition of non-invasive images and its subsequent processing of appropriate region of interest. In this work consider a subject specific edentulated human mandible CT images consisting of 225 slices are consider to develop 3-D model of anatomical structure using commercially available medical reconstructive software (MIMICS) with the following steps . Step 1: Image Acquisition, Processing and 3-D reconstruction Our region of study involved from the CT images of a cranio-maxillary bone (source: SRM Hospital) consists of 225 slice with 1mm slice thickness. The image segmentation process [1] was carried out and the region of interest was identified and a 3D voxel model of the bone is developed As a first step, an appropriate threshold range was found that could best capture the relevant information contained in the cranio-maxillary bone. Using this threshold value, all pixels within this range were grown to a color mask and hence the segmentation process achieved by making use of region growing techniques available in the software. This color mask acts as the input to the 3-D reconstruction process. The process is depicted in Figure 3.1, 3.2 & 3.3.

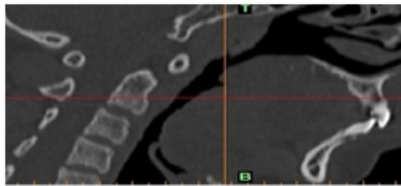


Figure 3.1: CT images of cranio- maxillary bone – Sagittal view

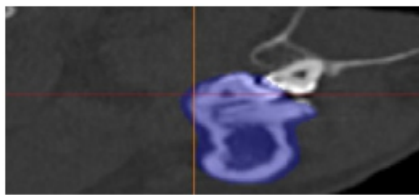


Figure 3.2: Region of Interest

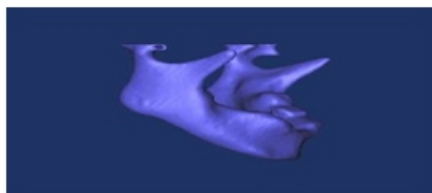


Figure 3.3: 3D Voxel reconstruction of segmented images

Step 2: CAD model generations using reverse engineering approach

The Reverse engineering approach is used to convert 3D voxel data to a NURBS-based CAD model. The process path as followed shown in Figure 3.2 below for generating a CAD model from data.

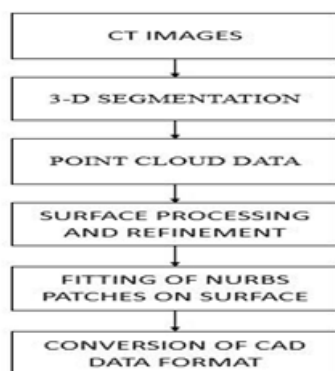


Figure.3.4: Work Flow and its process

The 3D voxel model created after segmentation is used as the starting point for this method. The 3D voxel dataset of the bone structure is converted to point data form and then these points are loaded into any reverse engineering software.

To generate out the CAD model, it is necessary to model the bone using freeform surfaces. Figure 3.5, 3.6 & 3.7 shows NURBS patches used to fit across the outer shape of the model.

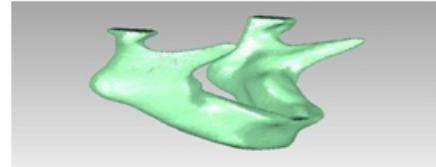


Figure 3.5: Triangulation Model

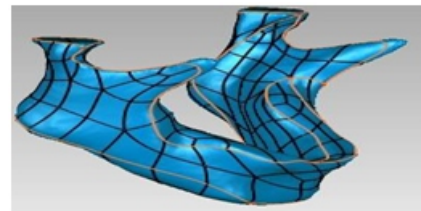


Figure 3.6: Grid Generation Model

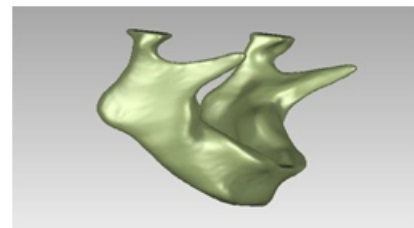


Figure 3.7: NURBS Model

3.2 THRESHOLD VALUES BY USING PROFILE LINE :

With Mimics, you can perform point-to-point measurements on both the 2D slices and the 3D reconstruction. By using the tools in mimics we can measure the length and divide the length according to total length. Calculated the threshold value by using the profile line as explained in below.



Figure 3.8: Threshold value by using profile line

3.4 3D CONGENITAL MODEL:

3.4.1 Segmentation of the Congenital Mandibular Bone from CT Images

The Segmentation is the process where the region of interest part will be isolated from the rest body part. As shown in Figure 3.9.



Figure 3.9: Segmented model from the CT data

3.4.2 Conversion into Nurbs Surface Model:

1. Point cloud data of the mandibular bone model is extracted from MIMICS and it has been imported in Geomagic for surface generation.
2. Point cloud data of models are imported in Geomagic Studio as .IGES file format from MIMICS software. Figure 3.10 shows the point clouds of mandibular bone boundaries .

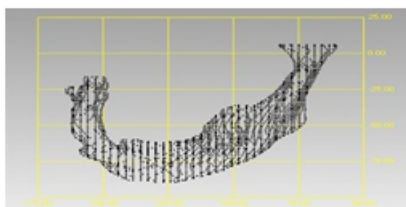


Figure 3.10: Point clouds of the congenital mandibular bone

3. Then point clouds are converted into polygons using 'wrap' option in Geomagic Studio.
4. Model error can be rectified using 'Mesh Doctor'.
5. Mesh Doctor automatically detect and corrects errors in the polygon mesh.
6. Polygons are then converted into surface model using exact surface option.
7. Surface model of congenital mandibular bone are shown in Figure 3.11 .

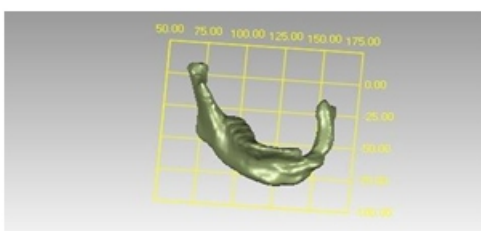


Figure 3.11: Surface model of the birth defect mandibular bone

FINITE ELEMENT ANALYSIS

4.1 FEA MODEL OF MANDIBLES

The FEM models is generated from the NURBS model using hyper mesh software. The mesh was generated with fine density of 154922 nodes and 138222 elements were created in the edentulated human mandible and fine density of 1116 nodes and 5488 elements were created in the congenital bone. The element type of solid 72 (3-D 4 Node Tetrahedral Structural solid) volume element were used to mesh these models as shown in Figure 4.1 and 4.2. The material properties was give as young's modulus of cortical region and poison's ratio [Nagasao et.al, 2002] of 15,000 MPa and 0.3 respectively .

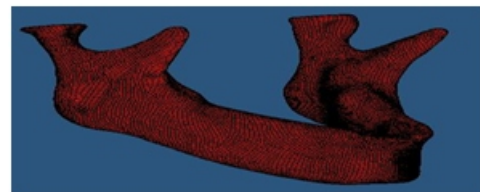


Figure 4.1: 3D FEA model of EdentulatedMandible

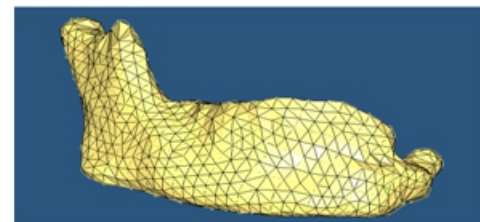


Figure 4.2: 3D FEA model of congenitalMandible.

4.2 SOLID 45 ELEMENT:

SOLID 45 is used for the 3-D modeling of solid structures in ANSYS. The geometry of SOLID 45 element is shown in Figure 4.3. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. A reduced integration option with hourglass control is available.

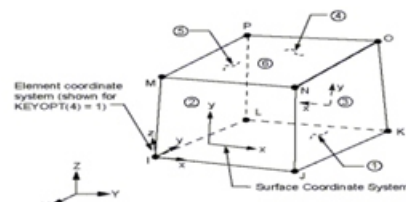


Figure 4.3: SOLID 45 Geometry (Ansys Help document)

4.3 SOLID 72 ELEMENT:

The element is defined by four nodes having six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z directions.

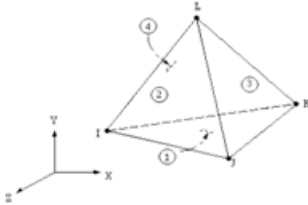


Figure 4.4: SOLID 72 Geometry (Ansys Help document)

COMPUTER AIDED TISSUE ENGINEERING SCAFFOLD

5.1 TISSUE ENGINEERING SCAFFOLD

Cells are often implanted or 'seeded' into an artificial structure capable of supporting three-dimensional tissue formation, called scaffolds, are often critical, both ex vivo as well as in vivo, to recapitulating the in vivo and allowing cells to influence their own microenvironments. Scaffolds usually serve at least one of the following purposes:

1. Allow cell attachment and migration
2. Deliver and retain cells and biochemical factors
3. Enable diffusion of vital cell nutrients and expressed products
4. Exert certain mechanical and biological influences to modify the behavior of the cell phase

5.1.1 REQUIREMENTS OF TISSUE SCAFFOLD

1. Mechanical
2. Scaffold structural integrity
3. Internal architecture stability
4. Scaffold strength and stiffness
5. A scaffold requires more flexibility or rigidity depending on the application in e.g. cardiovascular versus bone prostheses.
6. Biological
7. Cell loading, distribution and nutrition
8. Cell attachment and growth
9. Cell-tissue aggregation and formation
10. Geometric
11. Anatomical fitting

5.2 UNIT CELL :

- Unit cell is define a set of parameters relevant for the geometrical, structural, mechanical and biological properties in tissue engineering scaffold
- Mainly these are the properties have to be satisfied
- Connectivity
- Porosity
- Structural integrity
- Appropriate unit cells would be then integrated with the shape of the bone to form

5.3 MESHING OF SELECTED UNIT CELL

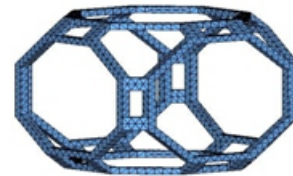


Figure 5.2: FEA model of rhombic truncated cuboctahedron

5.4 DESIGN OF SCAFFOLD

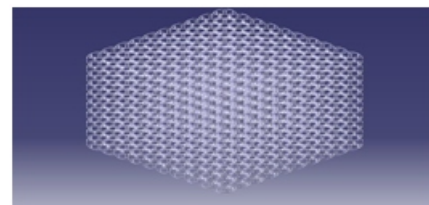


Figure 5.3: Tissue scaffold

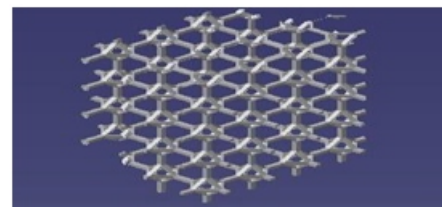


Figure 5.4: Tissue Scaffold for Mandibular Bone.

The geometry of the unit cell is mirrored manually to generate the CAD model of the scaffold assembly. The three-dimensional surface profile of the anatomical object is

5.5 POROSITY :

- The porosity is determined by the relationship between the volume of scaffold

- Length of hexahedron(L)=1mm
- Total Volume of hexahedron=L³
- Pore volume=0.784m³
- Solid volume=Total Volume-Pore volume
- Solid volume=0.216m³
- $\text{Porosity} = \frac{\text{void volume}}{\text{total volume}} = \frac{0.784}{1} = 78.04\%$

the bone tissue scaffold with specified internal architecture and structural properties to match that of the actual bone based on the characterization analysis. The desirable scaffold structure should have a porosity ranging from 55–70%. The unit cell having porosity 63% is taken into consideration for scaffold fabrication. it varies from region to region scaffold as per bone is shown in Figure 5.3. Appropriate unit cells would be then integrated with the shape of the bone to form the bone tissue scaffold with specified internal architecture and structural properties to match that of the actual bone based on the characterization analysis [1]. material and the apparent scaffold volume (bounding volume of scaffold).

- The porosity ranges from “0” to “1”. The nearly “0” value means the scaffold is dense (solid) whereas the nearly “1” value means the scaffold is more porous.

$$\text{Porosity} = \phi = \frac{V_p}{V_b} = \frac{V_b - V_m}{V_b}$$

Where, V_b= Bulk volume, V_m= Matrix volume, V_p=Pore volume

Table 5.1: Parameters of Unit Cell

S.NO	Unit cell	Length (mm)	Breadth (mm)	Thickness (mm)	Porosity (%)
1	Truncated hexahedron	1	1	0.05	67
2	Rhombitruncatedcuboctahedron	1	1	0.05	70
3	Rhombicuboctahedron	1	1	0.05	89.66
4	Hexahedron	1	1	0.05	78.4
5	Cub octahedron	1	1	0.05	72

5.5.1 Sample Calculation

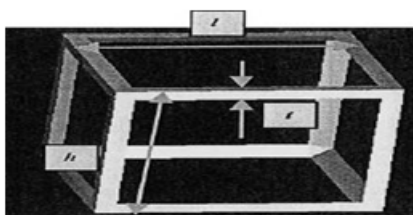


Figure 5.5: Hexahedron [10]

RESULTS AND DISCUSSIONS

6.1 THEORETICAL CALCULATION

The mechanics of curved beams can be applied, as illustrated by the analysis of (Hylander et.al) (1985). Consider a simplified curved beam with center of mass CM of a cross-section and center of curvature C. The bending stresses in a cross-section of a curved bone are non-linearly distributed. The difference in stress between outer and inner surfaces is inversely proportional to the radius of curvature (R). When a load is applied, the amount of bending stress along the inner (concave) and outer (convex) surfaces of the mandible differs [3].

$$R = \frac{a+c}{2}$$

A= Area of Cross Section

A_m = Mean area of cross section

a = Distance of inner fiber from Centre of curvature.

b = Distance of outer fiber from Centre of curvature.

c = Distance of centroidal axis from Centre of curvature.

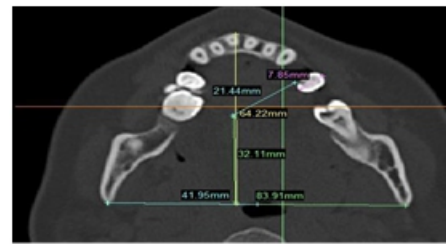
a = 21.4 mm

b = 25.365 mm

Geometrical Details of mandible from the mimics model as shown in Figure 6.3

Figure 6.3: Dimensions details from MIMICS for Curved beam

Table 6.1: Stresses obtained from the above equation (1)



Maximum tensile stress	Maximum compressive stress
0.180 Mpa	3.658 Mpa

6.2 FEM ANALYSIS :

Mandibular bone meshed properly in Hyper Mesh and they were imported in ANSYS to

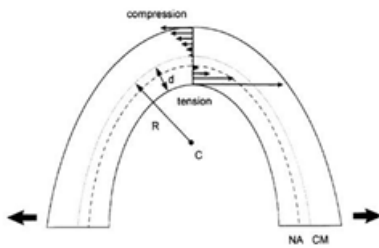


Figure 6.1: Stresses acted in the curved beam
The Hoop stress in the form

$$\sigma_{\theta\theta} = \frac{N}{A} + \frac{M(A - rA_m)}{Ar(RA_m - A)} \quad (1)$$

N, M = normal force and bending moment
computed from centroid
R = radius of curvature

c = 29.9 mm

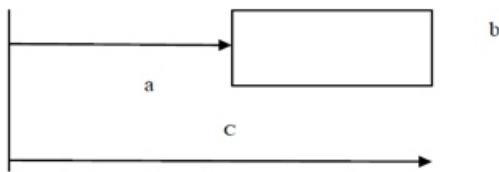


Figure 6.2: Radius of Curvatures of Curved beam

perform analysis. Finite element analysis is done using ANSYS 14.5 ANSYS is general purpose software with extensive capabilities to analyze. This software is equipped with an extremely efficient solver that can simulate and analyze all kinds of engineering models in shortest possible times. The element library provided within ANSYS database is also quiet extensive and user friendly. All tissues were defined as homogeneous, isotropic, and linearly elastic the mechanical properties of the bone structures were taken from the literature.

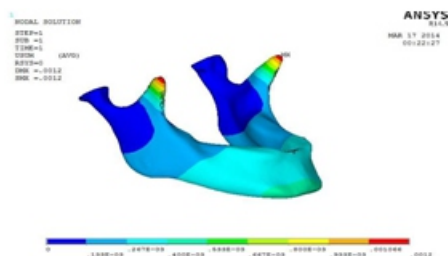


Figure 6.4: FEA Model – Displacement

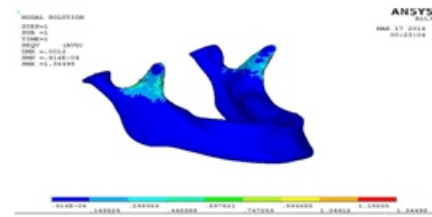


Figure 6.5: FEA Model – Stress distribution

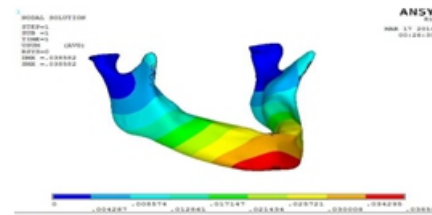


Figure 6.6: FEA Model – Displacement

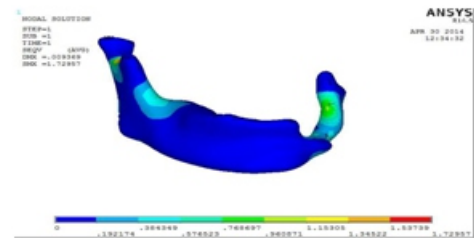


Figure 6.11: Von Mises Stress Distribution of CongenitalMandibular Bone

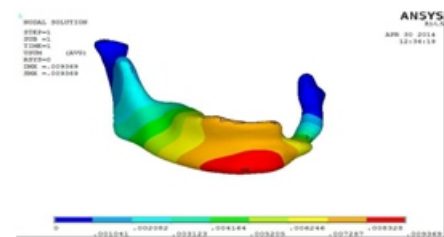


Figure 6.12: Displacement of Congenital Mandibular Bone

The results are reported at the level of analysis. In each analysis, it is tried to attain the convergence results by subjecting the developed models to the appropriate boundary and loading conditions.

6.4 LOADING OF MANDIBLE DURING A UNIMOLAR BITE

Loading of the mandible during a unilateral molar bite. Fb is the bite force, Fmb and Fmw and Fjb and Fjw are the muscle and joint forces at the balancing and working sides.

The distortion of the corpus can be described as a combination of sagittal bending, torsion, and lateral transverse bending [1].

- $F_m = F_{mw} = 125 \text{ N}$, $F_j = 90 \text{ N}$, $F_{jw} = 60 \text{ N}$.
- $F_b = 100 \text{ N}$

6.5 FEM ANALYSIS OF TISSUE SCAFFOLD :

The Appropriate unit cells would be then integrated with the segment of the bone to form the tissue scaffold. A solid 72 element type were used for analysis. In case of the analysis, Axial Force of 10 N (Newton) each was applied in the one side and constraint in opposite side. Stress was observed as shown in the Figure: 6.17.

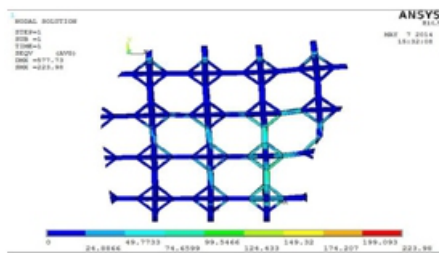


Figure 6.17 Stress distribution of tissue scaffold.

DISCUSSION :

The CT image based finite element modeling can provide a thorough understanding of the biomechanical influence on the mandibular bone and may offer reasonable explanations to biomechanically linked pathologies. It is useful in analyzing stress and strain distribution patterns of mandibular. The model is just one segment of the whole cranio-maxillary bone. The results may vary if done with the whole cranio-maxillary bone. There are lots of differences and uncertain factors induced by the individual working during modeling.

CONCLUSION:

In this work the 3D model of intact and birth defect mandibular bones was developed to observe the variation of displacement and stress distribution. Stress distribution of intact and birth defect mandibular bone was performed as high stress acted upon coronoid process region. The displacement values under biting condition is 0.38mm which is greater than chewing condition (0.0012mm) due to the movement of chin region in longitudinal and vertical directions.

The von misses stress under biting condition is 7.3N/mm² which is greater than chewing condition (1.345 N/mm²) due to reaction forces at the condyle. The tissue scaffold was modeled with unit cells by maintaining the porosity of 70 % for a portion of premolar region of birth defect mandible.

FUTURE SCOPE :

1. The models will include the cancellous and cortical regions which can improve the accuracy of results.
2. The algorithms can develop for reconstruction plates fixation and autogenous grafting.
3. The elastic and failure properties of the both mandibular bone and condyle depend on the loading direction can be done.
4. The forces during the function of the stomatognathic system act to the jaw bones in different directions depending on action of muscles.

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