Digital Investigation of Trabecular Bone to Mimic and Manipulate Building Structures

Prof. Mohammad Taha
Assistant Professor, dept. of Architecture,
MIT College,
Aurangabad, India

Abstract **— the Aim of this research is to Study and analyse the microstructure of bone i.e., trabecular bone and translating it into compressive member of a building Biomimicry is the study of natural forms, systems, and processes in nature to find more effective and sustainable ways to design and engineer products, buildings, service, and systems.**

Biomimicry is not a style of building, nor is it an identifiable design product. It is, rather, a design process, a way of seeking solutions. Biomimetics has given rise to new technologies inspired by biological solutions at macro and nanoscales. Humans have looked at nature for answers to problems throughout our existence.

One such inspiration can be taken from the bone of a human body. There are different types of bones found in human body which are of different shapes and sizes. But structurally, Bones are of two types: (1) The cortical bone or compact bone and (2) Spongy bone or Trabecular bone.

Trabecular bone or spongy bone can be one such inspiration for the development of compressive members of a building. The research presents the study and analysis of generation and development of a trabecular bone and mimicking the microstructure using a genetic algorithm. The algorithm begins by translating a trabecular genome into Computer aided software to develop structure. Then simulation is done on structures by using computer aided software to see the response under an applied load. The selected genome is then replicated, mutated, and manipulated. Simulations of microstructure evolution consist of iterating through this process across multiple generations. A series of simulations was conducted demonstrating the ability of the algorithm to improve trabecular inspired architecture.

Keywords— Biomimicry, Human bone, Trabecular, Structure.

INTRODUCTION

Architecture has long drawn from nature as a source of inspiration. Biomimetic architecture is a contemporary philosophy of architecture that seeks solutions for sustainability in nature, but by understanding the rules and parameters governing those forms and not by simply creating a replication of the natural forms. It is part of a larger movement known asbiomimicry.

One such inspiration was taken from the trabecular bone of human body for the development of structural members of a building. This work presents a model for trabecular microstructure evolution using a genetic algorithm, the same mechanism through which that ability evolved. The algorithm begins by translating a trabecular genome into a developed structure.

This research attempts to investigate new strategies for design of a column, which are derived from the evolutionary development of a bone, from their material properties and from their adaptive response to changes in them by the change of an organism and the environment around. This is achieved through an attempt to link the two emerging sciences: biomimicry and computational design, exploring their potential in developing more lightweight structures.

I. CORRELATING BIOMIMICRY WITH ARCHITECTURE AND PROCESS DESIGN

The concept of Biomimicry can be summarized as the inspiration from nature's processes & ecosystems, which would provide useful parameters to design societies and complexes. Biomimicry offers an innovative and nature friendly approach which can create more adaptive and flexible solutions. Theories in Biomimicry feature similarities between biological and social complex systems that can provide guidance in the management of several issues, the design process and collective intelligence.

Bottom-up approach theories in Biomimicry include, self-organization, optimize rather than maximize, use free energy, cross-pollinate, embrace diversity, adapt and evolve, use life-friendly materials and processes, engage in symbiotic relationships, and enhance the biosphere. The applications of these theories have been majorly done in industrial products till date. However, so far, its application in architecture and its allied design processes often shows its limited and unexplored use.

Application of Biomimicry

Approach to biomimicry as a design process can broadly be distinguished in two categories:

1. Defining design problem and then identifying & mimicking the ecosystem of other organisms to that design problem.

2. Looking to biological systems or processes and identifying a particular characteristic or behaviour or function in an organism or system and translating that to human designs.

Within these two approaches application of biomimicry to the architectural design can be categorized under three levels, viz, form, process & function. In analysing an organism or ecosystem, form and process are the key components that could be mimicked. These levels are termed as organism level, behaviour level and ecosystem level. The organism refers to a specific living thing like a plant or an animal and it may involve mimicking a part or the whole organism.

II. ARCHITECTURAL SYSTEMS

The architecture of space/form/enclosure is the product of organizational pattern, hierarchy and relationship with the surrounding. It also has a defined image, shape, scale and proportion, the quality of colour and texture. These defined parameters of architecture are experienced through movement in space and time. The 'Experience ' of approach, space, volume, light, colour, touch, etc. gives a clear image of the built environment. But to achieve this ' Experience ' of built environment, certain technology has to be adopted which benefits to create environmental protected, comfortable and durable structure.

III. OBJECT DESIGN, REALIZATION DESIGN, AND PROCESS DESIGN.

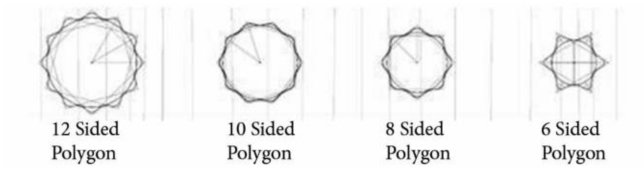
In any design, it is necessary to plan design processes. However, in most of the cases, one tends to use conventional approaches to process design. But for better and professional approach to create object design and realization design, it is necessary to design "the design process".

IV. BIOINSPIRED BUILDING EXAMPLE.

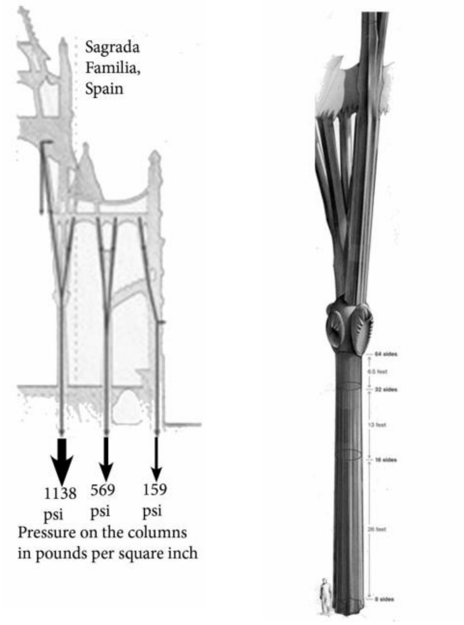
Sagrada Familia: Gaudi took his inspiration from the observation of the natural world, providing him with a conceptual and methodological framework. Gaudi did not copy nature but analysed the function of its elements to formulate structural and formal designs which he then applied to architecture.

Antoni Gaudi used twisted surface and curved planes as the organic bases of his building after observing there functional perfection in nature. His columns, arches and stairways all stem from this notion of natural design.

Gaudi Studied the helicoid growth of many plants-patterns that let leaves receive sunlight and lend structural strength. Column in Sagrada Familia follows the natural weight distribution pattern of trees. Beginning with an eight-sided polygon and following the logic of a double-twisting helicoid, columns gain sides and strength with height.



Columns comes in four sizes and shapes, all are finished in circle. The diameter and numbers of sides depend on the load the column needs to bear.



V. TYPES OF BONE ON THE BASIS OF STRUCTURE::

all bones are composed of same material. The difference only is in the pattern of arrangement. This classification is based on the same thing that is pattern of arrangement of bony tissue. The structural classification has two approaches that are macroscopic approach and microscopic approach.

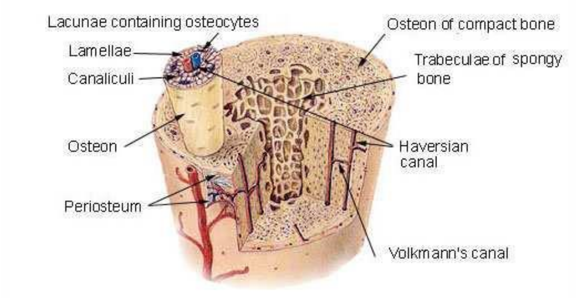
Compact bone:

The part of a bone where bone substance to bone space ration is a bigger quantity is called compact bone. This means that there is more bone tissue and less empty space.

Spongy bone:

The part of a bone where bone substance to bone space ratio is a smaller quantity. This means that there is more empty space and less bone tissue.

Compact Bone & Spongy (Cancellous Bone)



All bones have an exterior layer called cortex that is smooth, compact, continuous, and of varying thickness. In its interior, bony tissue is arranged in a network of intersecting plates and spicules called trabeculae, which vary in amount in different bones and enclose spaces filled with blood vessels and marrow. This honeycombed bone is termed cancellous or trabecular. In mature bone, trabeculae are arranged in an orderly pattern that provides continuous units of bony tissue aligned parallel with the lines of major compressive or tensile force. Trabeculae thus provide a complex series of crossbraced interior struts arranged to provide maximal rigidity with minimal material.

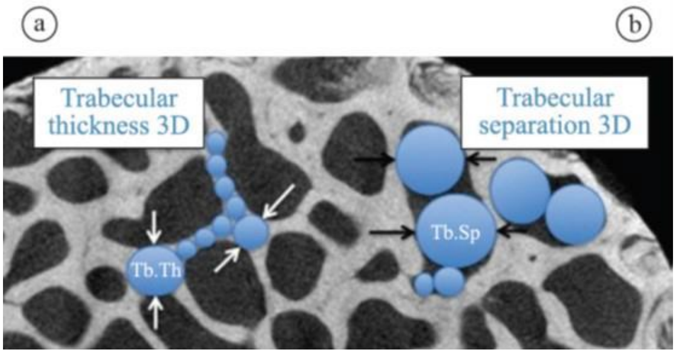
VI. Spongy Bone or Trabecular bone: Spongy Bone or Trabecular bone:

Trabecular or spongy bone is a highly porous, lamellar bone that is composed of interconnected platelets and rods and has a density of ~0.4 g/cm3. This bone is surrounded by higher density compact bone (~2 g/cm3), which is characterized by microstructural features called osteons. Osteons have concentric lamellae surrounding a main channel (blood vessel) that have alternating oriented collagen fibrils in the lamellae. The collagen fibrils are composed of tropocollagen molecules, which are a triple helix of the collagen molecule. These fibrils are held together by other proteins and have the mineral phase dispersed between and around them.

The bone density of cancellous bone was related to strength and was observed a strong positive correlation between the density and the maximum breakdown stress and between density and stiffness (Carter and Hayes, 1977; Ciarelli et al., 1991; Currey, 1969; Rice et al., 1988). Despite the density represents an important component of mechanical strength, it is not influenced by the microstructure of trabecular bone and does not explain certain variations observed in this resistance, thus representing a partial measure of this resistance characterization.

The 3D Morphometric Analysis is not based on a structural model of plates or rods and all the measurements of parameters, including the primaries (bone surface (BS); bone volume (BV); tissue volume (TV)) are performed directly from the volume of bone reconstructed of sample. The (BS) measurement is calculated using the method of "Marching Cubes" which is performed by placing triangles to the bone surface sample (Lorensen and Cline, 1987; Muller et al., 1994). The (BV) measurement is calculated using tetrahedrons built in triangle's surface (Guilak, 1994). And TV is determined by a count of voxels. To compare samples with different sizes are used standardized indexes (BV/TV), (BS/TV) and (BS/BV). The parameter (Tb.Th) is calculated using spheres in which the diameter must satisfy the structure of the trabeculae (Hildebrand et al. 1999). In the calculating of parameter (Tb.Sp) is used the same principle of determining (Tb.Th) in the voxels that contains the bone marrow.

Figure shows schematic drawing of the principle of determination (Tb.Th) in A, and (Tb.Sp) in B, by 3D analysis.



VII. Femur Bone:

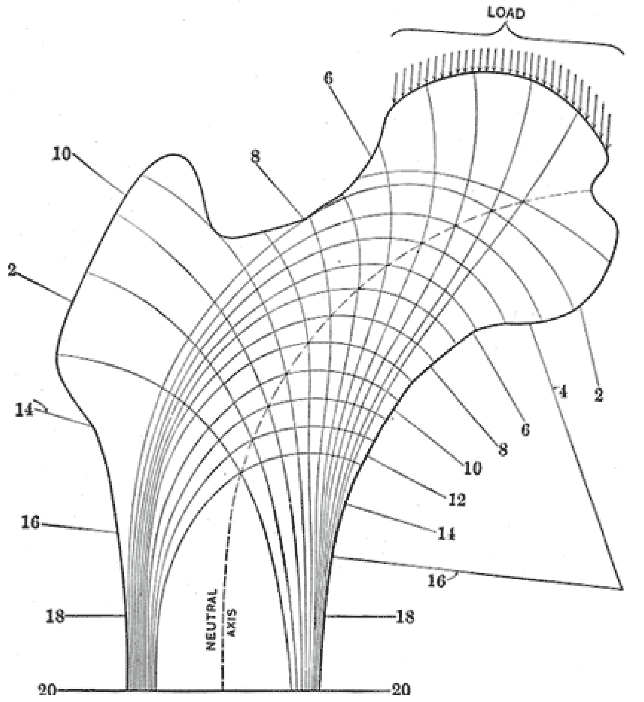
The femur is the longest and, by most measures, the strongest bone in the human body. Its length on average is 26.74% of a person's height. The femur or thigh bone is the most proximal (closest to the hip joint) bone of the leg in tetrapod vertebrates capable of walking or jumping, such as most land mammals, birds, many reptiles such as lizards, and amphibians such as frogs. In vertebrates with four legs such as dogs and horses, the femur is found only in the hindlimbs. The head of the femur articulates with the acetabulum in the pelvic bone forming the hip joint, while the distal part of the femur articulates with the tibia and kneecap forming the knee joint. By most measures the femur is the strongest bone in the body. The femur is also the longest bone in the body.

VIII. Inner Architecture of the Upper Femur:

"The spongy bone of the upper femur (to the lower limit of the lesser trochanter) is composed of two distinct systems of trabeculæ arranged in curved paths: one, which has its origin in the medial (inner) side of the shaft and curving upward in a fan-like radiation to the opposite side of the bone; the other, having origin in the lateral (outer) portion of the shaft and arching upward and medially to end in the upper surface of the greater trochanter, neck and head. These two systems intersect each other at right angles.

The Principal Compressive Group. — This group of trabecula springs from the medial portion of the shaft just above the group above-described, and spreads upward and in slightly radial smooth curved lines to reach the upper portion of the articular surface of the head of the femur. These trabeculae are placed very closely together and are the thickest ones seen in the upper femur. They are a prolongation of the shaft from which they spring in straight lines which gradually curve to meet at right-angles the articular surface. There is no change as they cross the epiphyseal line. They also intersect at right-angles the system of lines which rise from the lateral side of the femur.

The Secondary Compressive Group. — This group of trabecula leaves the inner border of the shaft beginning at about the level of the lesser trochanter, and for almost 2 inches along the curving shaft, with which the separate trabecula makes an angle of about 45 degrees. They curve outwardly and upwardly to cross in radiating smooth curves to the opposite side. The lower filaments end in the region of the greater trochanter: the adjacent filaments above these pursue a more nearly vertical course and end in the upper portion of the neck of the femur. The trabecula of this group is thin and with wide spaces between them. As they traverse the space between the medial and lateral surfaces of the bone, they cross at right angles the system of curved trabecula which arise from the lateral (outer) portion of the shaft.

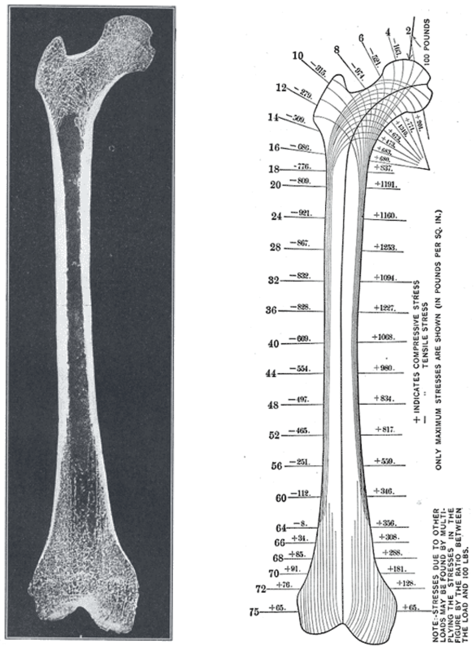


This system of principal and secondary compressive trabeculae corresponds in position and in curvature with the lines of maximum compressive stress, which were traced out in the mathematical analysis of this portion of the femur.

Lateral (Tensile) System of Trabeculae. — As the compact bone of the outer portion of the shaft approaches the greater trochanter it gradually decreases in thickness. Beginning at a point about 1 inch below the level of the lower border of the greater trochanter, numerous thin trabeculae are given off from the outer portion of the shaft.

The Greater Trochanter Group. — These trabeculae rise from the outer part of the shaft just below the greater trochanter and rise in thin, curving lines to cross the region of the greater trochanter and end in its upper surface. Some of these filaments are poorly defined.

The trabeculae of the tensile system are lighter in structure than those of the compressive system in corresponding positions. The significance of the difference in thickness of these two systems is that the thickness of the trabeculae varies with the intensity of the stresses at any given point. Comparison figures will show that the trabeculae of the compressive system carry heavier stresses than those of the tensile system in corresponding positions.



1) The trabeculae of the upper femur, as shown in frontal sections, are arranged in two general systems, compressive and tensile, which correspond in position with the lines of maximum and minimum stresses in the femur determined by the mathematical analysis of the femur as a mechanical structure.

2) The thickness and spacing of the trabeculae vary with the intensity of the maximum stresses at various points in the upper femur, being thickest and most closely spaced in the regions where the greatest stresses occur.

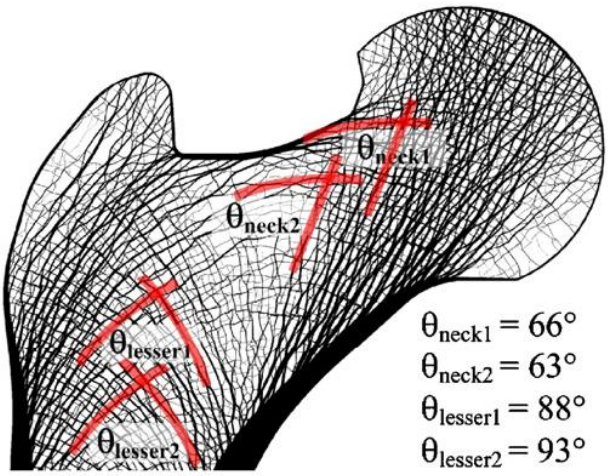
3) The amount of bony material in the spongy bone of the upper femur varies in proportion to the intensity of the shearing force at the various sections.

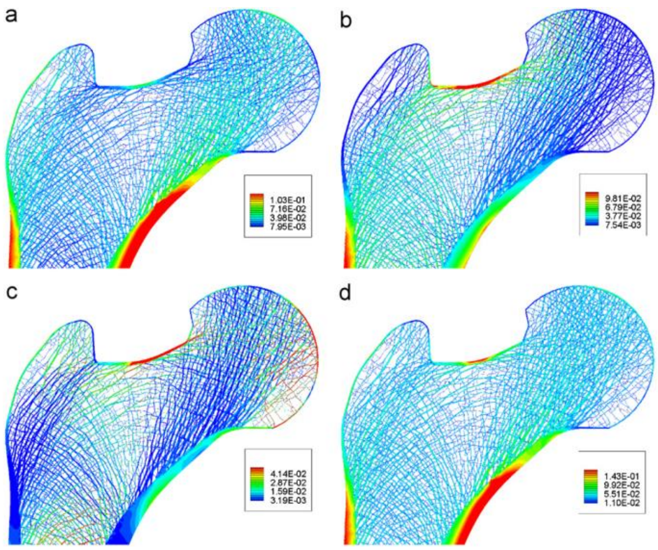
4) The arrangement of the trabeculae in the positions of maximum stresses is such that the greatest strength is secured with a minimum of material.

IX. LOAD SIMULATIONS ON FEMUR BONE TO STUDY TRABECULAR BONE:

Research done by Ken-ichi Tsubota (Chiba University) and Taiji Adachi (Kyoto University) studying how remodelling of trabecular bone takes places according to the loads acting on a femur bone. The purpose of this study is to investigate a characteristic of the uniform stress hypothesis under a heterogeneously distributed mechanical environment through two-dimensional simulation of trabecular surface remodeling for a human proximal femur. To evaluate the mechanical environment at the trabecular level over the entire bone, the architecture of each trabecula is directly modelled using a large number of pixel-based finite elements in the remodeling simulation. Trabecular structural changes due to surface remodeling are simulated under both single and multiple external loading conditions to clarify the relationships between the local regulation process at the trabecular level and functional adaptation phenomenon at the apparent tissue level.

Remodelling simulations were conducted under both single- and multiple-loading conditions.





It was found that the external-loading condition affected the stress distribution of each trabecula, as shown in Fig. These figures illustrate the ability of a large-scale pixel-based finite element model to predict the micro–macro relationships in the cancellous bone that has a hierarchical structure. Exploring the mechanical stimulus at the cellular level might be possible by considering the internal structure of each trabecula. Therefore, it should be noted that the large-scale computational simulation of bone remodeling would be an effective tool not only for clarifying the relationships between the functional adaptation at the apparent tissue level and the local regulation process at the trabecular level, but also for providing insight into cellular response to the mechanical stimuli in vivo. local regulation process at the trabecular level, but also for providing insight into cellular response to the mechanical stimuli in vivo.

X. DESIGN PROPOSAL:

The column was designed so that the loads of a building acting on it can be a factor for modelling it. The interconnecting nodes can be achieved according to the loads acting on a column.

The grasshopper script was created so that a column of a particular defined size as an input. Then input geometry is broken down into nodes and lines such that we can get polyhedral which can mimic the rod and plate structure in a trabecular bone. Further the nodes and line we provided with a thickness so that it can mimic the structure of trabecular bone.

The design which is achieved is further tested so that the loads which are acting on it is properly distributed and transferred to the footing. For testing Karamba (grasshopper plugin) is used so that we can get amount out displacement happening after applying loads.

The column is further optimised by using genome solver i.e. Galapagos so that it can give the optimised nodes and negligible displacement to achieve a well-designed, optimised, lightweight structural element.

OPTION- 1

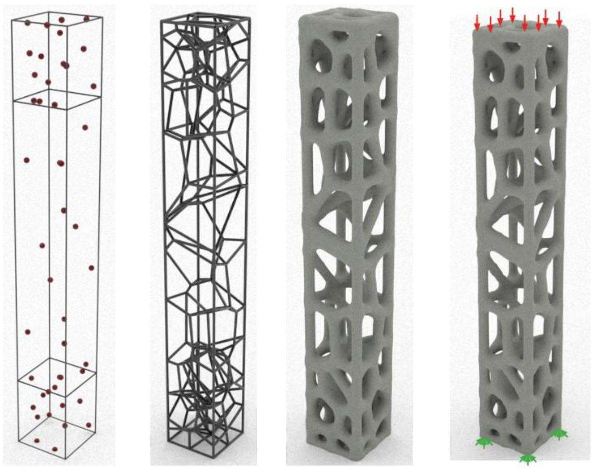
The first option is designed by keeping by interconnecting the nodes and then evaluating them by genetic algorithm. The design is further evaluated my using loading simulation to verify that there should be minimum displacement. The nodes created are random so that maximum iterations can be achieved. The network formed is then converted into mesh. Further the supports and loads are applied for the evaluation of a mesh by using genetic algorithm. Further it will be analysed for its structural stability by doing stable static structural analysis.

OPTION- 2

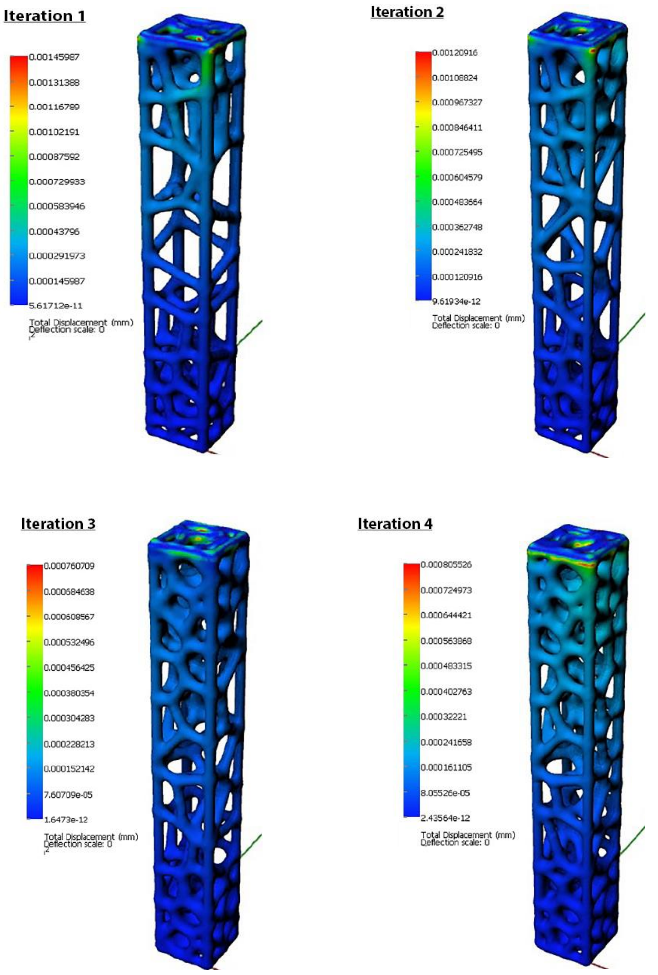
In option 2 the design is further altered so that the design should be alike to the structure of a trabecular bones. As we know the trabecular structure is comprised of voids and spacing between them. Therefore option 2 is designed to decrease and optimize the volume of the structure. The points created for the creation of a system are random, the constructed points will represent the voids or spacing between them and the network between them will be the members. Further the network is converted into a mesh then further it will be applied with supports and loads on it. Finally, it is evaluated by genetic algorithm for the minimum displacement and volume. Further it will be analysed for its structural stability by doing stable static structural analysis.

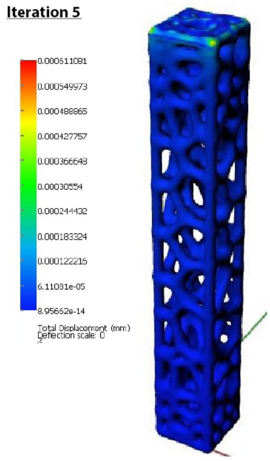
OPTION- 3

In option 3 the design is further altered so that the design should be stable by making minimum displacement and to look alike to the structure of a trabecular bones. Therefore option 3 is designed by studying how a concrete column takes loads, by studying we can say that the loads coming on a column are large on the supporting ends. We can say that the ends should be much stronger infect they should be much dense near supports. The points created should be much dense near supports or towards ends. By using those points the network is created in which it will be dense towards ends. Then the network is converted into a mesh then further it will be applied with supports and loads on it. Finally, it is evaluated by genetic algorithm for the minimum displacement and volume. Further it will be analysed for its structural stability by doing stable static structural analysis.



The design is iterated by changing the number of nodes and network so that the displacement should be minimized within the column.





XI. FABRICATION:

Fabrication is a process that joins design with production using 3D modelling software or computer-aided design (CAD) and additive manufacturing process and subtractive manufacturing processes. Digital fabrication is a way of making that uses digital data to control a fabrication process. It relies on computer-driven machine tools to build, transform, or cut materials. Digital fabrication is currently mostly used to create prototypes during the design process, called Rapid Prototyping (RP). Rapid Manufacturing (RM) is an extension of rapid prototyping in which the digitally fabricated can be directly used as fully functional end products.

REFERENCES

[1] https://en.wikipedia.org/wiki/Biomimetics
[2] http://stanleybeamansears.com/biomimicry-looking-nature-architectural-innovation/
[3] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5097415/
[4] http://www.journal.bonfring.org/papers/iems/volume6/BIJ-10443.pdf
[5] http://scholarworks.umass.edu/cgi/viewcontent.cgi?article=1984&context=theses
[6] https://ac.els-cdn.com/S1877042812031928/1-s2.0-S1877042812031928-main.pdf?_tid=21fd60f0-c39c-11e7-9641-00000aacb362&acdnat=1510046281_7b42846c40d937a4fd0c24d4843c3aca
[7] https://www.terrapinbrightgreen.com/blog/2015/01/biomimicry-bioutilization-biomorphism/
[8] https://en.wikipedia.org/wiki/Antoni_Gaud%C3%AD
[9] https://www.biography.com/people/antoni-gaud%C3%AD-40695
[10] https://en.wikipedia.org/wiki/Sagrada_Fam%C3%ADlia

[11] http://www.sagradafamilia.org/en/
[12] http://www.sagradafamilia.org/en/structure-and-form/
[13] https://www.archdaily.com/519298/happy-birthday-antoni-gaudi
[14] https://www.google.co.in/search?q=sagrada+familia&rlz=1C1CHBF_enIN763IN763&source=lnms&tbm=isch&sa=X&ved=0ahUKEwiOt7TEkazXAhXDrI8KHSI9BbIQ_AUICigB&biw=1366&bih=637
[15] https://upload.wikimedia.org/wikipedia/commons/thumb/0/09/Sagrada_Familia_-_Juny_de_2016_-_03.jpg/220px-Sagrada_Familia_-_Juny_de_2016_-_03.jpg
[16] https://upload.wikimedia.org/wikipedia/commons/thumb/b/ba/Sagrada_Familia_nave_roof_detail.jpg/551px-Sagrada_Familia_nave_roof_detail.jpg
[17] https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcQCCnlhBSxCNxIOm0BmMxE7RtQ9bZdHRQtpKJNbHcEkEUSEjYctjA
[18] https://encryptedtbn0.gstatic.com/images?q=tbn:ANd9GcSEvXIp8zcURmuftQESUYi_QnjOwscBR7vTHd2Fpkgk7_nK33k7
[19] https://en.wikiarquitectura.com/building/tgv-station-lyon-saint-exupery/
[20] https://arcspace.com/feature/lyon-satolas-tgv-station/
[21] http://www.galinsky.com/buildings/lyonairport/
[22] http://architectuul.com/architecture/lyon-satolas-airport-railway-station
[23] http://www.understandconstruction.com/concrete-frame-structures.html
[24] https://www.scribd.com/document/306574837/1-Concrete-Frame-Structures
[25] https://en.wikipedia.org/wiki/Steel_frame
[26] http://article.sapub.org/10.5923.j.scit.20120201.02.html
[27] http://www.encyclopedia.com/medicine/news-wires-white-papers-and-books/skeletal-system
[28] https://www.google.co.in/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwi3k6r3lqzXAhVKpI8KHXiiDvQQFgglMAA&url=http%3A%2F%2Fwww.sapub.org%2Fglobal%2Fshowpaperpdf.aspx%3Fdoi%3D10.5923%2Fj.scit.20120201.02&usg=AOvVaw3A7gphJSvQBWTBdVI3L_ye
[29] http://www.teachpe.com/anatomy/skeleton_axial.php
[30] https://www.google.co.in/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=0ahUKEwjjtvDJl6zXAhXBrY8KHYIEAEgQjRwIBw&url=https%3A%2F%2Fsites.google.com%2Fa%2Fcoe.edu%2Fkelsey-jipp-practicum%2Flesson-2&psig=AOvVaw0JcQ8Ks1cYkce1HlL3D248&ust=1510134508119909
[31] http://study.com/academy/lesson/what-is-the-difference-between-the-axial-appendicular-skeleton.html
[32] https://www.visiblebody.com/learn/skeleton/appendicular-skeleton
[33] 33. https://www.google.co.in/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwia3YGYm6zXAhUBMo8KHbVXBRoQFgglMAA&url=http%3A%2F%2Fwww.jorislaarman.com%2Fwork%2Fbone-chair%2F&usg=AOvVaw2nhr5HNONifX0NLoDXWS6P
[34] http://www.jorislaarman.com/work/bone-chair/
[35] https://www.autodesk.com/customer-stories/airbus
[36] https://agmetalminer.com/2015/12/01/airbus-a320-3d-printed-partition-scalmalloy/
[37] https://www.autodesk.com/redshift/bionic-design/
[38] http://www.contemporist.com/naturoscopie-shelf-by-noe-duchaufour-lawrance/
[39] https://www.google.co.in/search?q=naturoscopie+Shelf&rlz=1C1CHBF_enIN763IN763&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwjI7M3SnKzXAhUMKY8KHaOMBJwQsAQIOA&biw=1366&bih=588
[40] https://www.dezeen.com/2012/07/17/biomimicry-shoe-by-marieka-ratsma-and-kostika-spaho/
[41] https://trendland.com/marieka-ratsma-biomimicry-shoe/
[42] http://www.virtualshoemuseum.com/marieka-ratsma/biomimicry-shoe
[43] https://www.mananatomy.com/basic-anatomy/types-bone
[44] https://en.wikipedia.org/wiki/Bone_tissue
[45] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3279077/
[46] http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1517-31512014000200002
[47] https://en.wikipedia.org/wiki/Femur
[48] http://www.bartleby.com/107/59.html
[49] https://www.saylor.org/site/wp-content/uploads/2014/06/BIO302-Anatomy_of_the_Human_Body-Chapter-II-Bones-of-the-Lower-Extremity.pdf
[50] http://www.bartleby.com/107/pages/page252.html
[51] http://personal.strath.ac.uk/j.wood/Biomimetics/inspirtational%20designs/Eiffel%20Tower_files/Eiffel%20Tower.htm
[52] https://www.ncbi.nlm.nih.gov/pubmed/7929463
[53] https://en.wikipedia.org/wiki/Wolff%27s_law
[54] https://www.ncbi.nlm.nih.gov/pubmed/8060014
[55] https://www.britannica.com/science/Wolffs-law
[56] http://www.springer.com/cda/content/document/cda_downloaddocument/9783642180521-c2.pdf?SGWID=0-0-45-1346460-p174094761
[57] https://books.google.co.in/books?id=ym3jb6Vyq-kC&pg=PA34&lpg=PA34&dq=Trabecular+bone+is+found+at+the+end+of+the+medullary+cavities+of+hollow+long+bones+throughout+the+skeleton.+It+forms+a+trabecular+network,+of+interconnected+rod-like+and+plate-like+structures,+which+are+found+in+greater+or+lesser+proportion+depending+on+the+skeletal+site.&source=bl&ots=N1M7sel5ub&sig=x2gzE-1DHymS4cis9vAqFP_6wGA&hl=en&sa=X&ved=0ahUKEwjBz8ynpqzXAhVFK48KHYanBF4Q6AEIJTAA#v=onepage&q=Trabecular%20bone%20is%20found%20at%20the%20end%20of%20the%20medullary%20cavities%20of%20hollow%20long%20bones%20throughout%20the%20skeleton.%20It%20forms%20a%20trabecular%20network%2C%20of%20interconnected%20rod-like%20and%20plate-like%20structures%2C%20which%20are%20found%20in%20greater%20or%20lesser%20proportion%20depending%20on%20the%20skeletal%20site.&f=false
[58] https://www.researchgate.net/publication/11022731_Functional_adaptation_of_cancellous_bone_in_human_proximal_femur_predicted_by_trabecular_surface_remodeling_simulation_toward_uniform_stress_state?_iepl%5BviewId%5D=yfEers011bxBO5BZecVWZpoA0iUAZNpb1yo7&_iepl%5Bcontexts%5D%5B0%5D=prfhpi&_iepl%5Bdata%5D%5BstandardItemCount%5D=4&_iepl%5Bdata%5D%5BuserSelectedItemCount%5D=0&_iepl%5Bdata%5D%5BtopHighlightCount%5D=2&_iepl%5Bdata%5D%5BtopHighlightIndex%5D=2&_iepl%5Bdata%5D%5BfeaturedItem1of2%5D=1&_iepl%5BtargetEntityId%5D=PB%3A11022731&_iepl%5BinteractionType%5D=publicationTitle
[59] https://www.google.co.in/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjsie-Ap6zXAhVEO48KHdvzBjwQFgglMAA&url=https%3A%2F%2Fwww.witpress.com%2FSecure%2Felibrary%2Fpapers%2F9781853127496%2F9781853127496002FU1.pdf&usg=AOvVaw2P_e6OgMKEKOL9qi_cIo2R
[60] https://www.ncbi.nlm.nih.gov/pubmed/27554017
[61] https://www.ncbi.nlm.nih.gov/pubmed/25445457
[62] http://onlinelibrary.wiley.com/doi/10.1002/jmri.22158/pdf
[63] https://www.ncbi.nlm.nih.gov/pubmed/22225286
[64] http://www.weizmann.ac.il/Structural_Biology/Weiner/ita-app