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Finite Element Analysis of Different Architectures for Bone Scaffold

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***Abstract*—**Bone Scaffolds are fundamental architecture or a support structure that allows the regeneration of lost or damaged tissues and they are developed as a crucial tool in biomedical engineering. The structure of bone scaffolds plays an important role in treating bone defects. The shape of the bone scaffold performs a vital role, specifically pore size and shape, which help understand the behavior and strength of the scaffold. In this article, first, fundamental aspects of bone scaffold design are established. Second, the behavior of each architecture of the bone scaffold with biomaterials is discussed. Finally, for each structure, the stress analysis was carried out. This study aimed to design a porous and mechanically strong bone regeneration scaffold that can be successfully manufactured. Four porous architectures of the bone scaffold were designed using Rhinoceros solid modelling software. The structure model consisted of repeatable unit cells arranged in layers to fill the chosen scaffold volume. The mechanical behavior of used biocompatible material is studied with the help of ANSYS 19.2 software. It is also playing significant role to predict the strength of defined structures or 3 dimensional models.

***Keywords*—**Bone scaffold, stress analysis, porous structure, static loading.

I. INTRODUCTION

BONES are solid organs of a combination of osseous tissue, bone marrow, endosteum, periosteum, cartilage, nerves, and vascular channels. The use of bone grafts is the common treatment to treat different fractures, or to replace and regenerate the lost bone. It is determined by the numbers of bone graft method function worldwide. The most frequent of these is the autograft (transplanting a patient's own tissue), however, its use can result into complications or limitations such as pain, infection, scarring, blood loss, and donor-site morbidity. The next alternate is allografts (transplanting tissues from donor to patient) [1], but harvesting enough number of tissues is also a difficult task of autografts and there is always a risk of carrying infectious agents or rejection by immune system. An ideal bone graft or scaffold should be made of bio compatible or biodegradable materials that act as the support structure and properties of natural bone. Bones have mechanical, synthetic, and metabolic functions. The mechanical functions of bone are to protect internal organs, to provide body support, and to interact with muscles and tendons to generate body movement. The anatomy and functionality of human body is very important. In bio-mechanism of human body, bones play very crucial role. Bones are the elements in human body which supports the load and help human being to carry various activity like walking, running, holding loads. All these activities lead to introduce different stresses, these stresses can be tensile, compressive, share in nature. Scaffold stiffness, mechanical resistance, and permeability are important properties to study [2]. For the bone scaffold fabrication, important factors like size, porosity of the structure and for material its biocompatibility, biomaterial must be considered. The design, stress analysis and performance of lattice structures in analysis software were studied in this paper.

II. SCAFFOLD DESIGN

A. Geometry

Scaffolds for biomedical engineering bone and cartilage provide better solutions that improve healing and minimize the need for complicated surgical treatments. Porous scaffolds have appeared as an attractive alternative solution over bone grafting. However, the success of advanced materials, use of biological factors, and manufacturing techniques can vary depending on the use case. This research provides perspective on porous scaffolds, different structures and materials, and the static loading condition [3].

The design of 3D bone scaffolds for biomedical application should, if possible, bio mimic. This is particularly true for the design of bone tissue replacement with mechanical properties to the replaced bone. [4] In the field of bone scaffold particularly in its geometry Gibson defines the scaffold as cellular materials as consisting of "an interconnected network of struts or plates" [5].

B. Architecture 1

Fig. 1 shows the architecture of bone scaffold in which the single cell is of 3X3X3 mm and by combining these cells the scaffold is made of 12X12X12 mm, in which the inclined rods are used in order to make the structure more complicated. The designed bone scaffold internally made by keeping orientation diagonally started from each of the corner of cube towards center of cube. All faces of the cube are kept as square hole.

C. Architecture 2

The architecture 2 is also of the same dimensions and porosity as of architecture 1. Fig. 2 shows the shell architecture. It can be seen that the outer faces are kept as two triangular holes while internal structure is made with circular rods kept diagonal which intersects at center.

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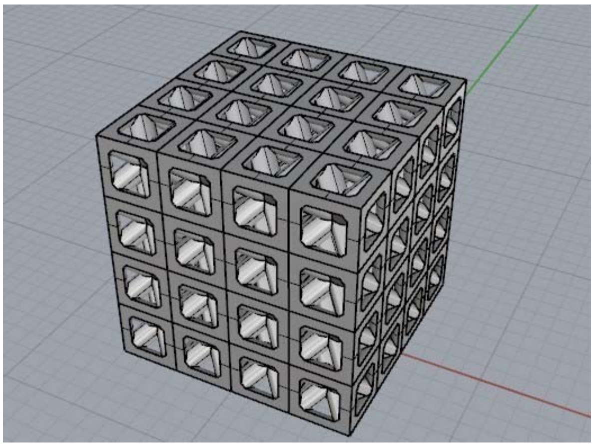

Fig. 1 Shell architecture 1

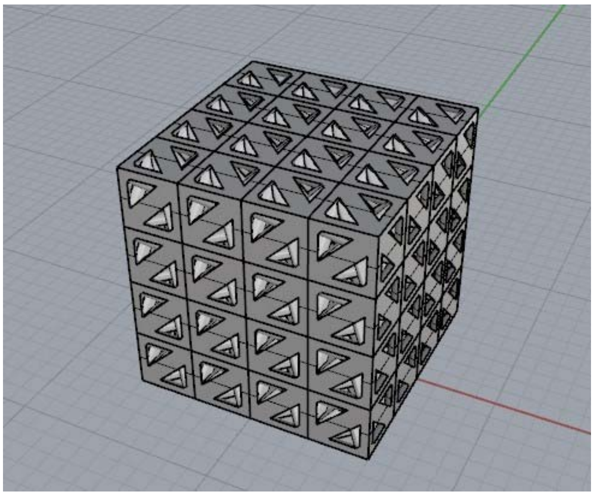

Fig. 2 Shell architecture 2

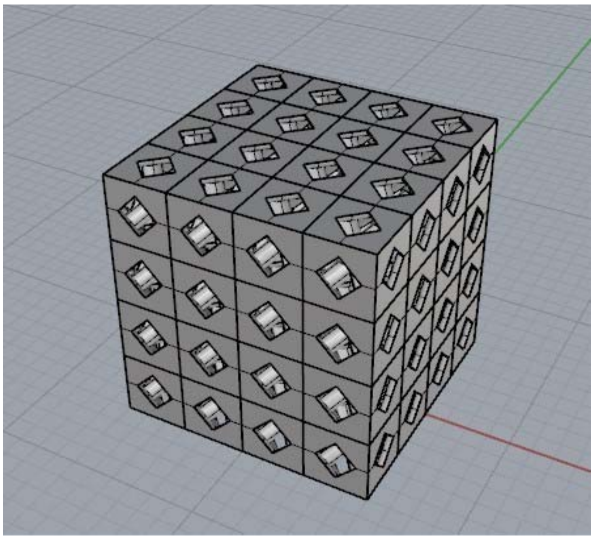

Fig. 3 Shell architecture 3

D. Architecture 3

Fig. 3 shows another architecture with same dimensions and porosity. Here in architecture 3, the outer surface of the cube has a hole in diamond shape. The inner side is designed with circular diagonal rods which intersect at center of cube.

E. Architecture 4

Fig. 4 shows the lactic structure made for bone scaffold with same design in which the square holes penetrated through.

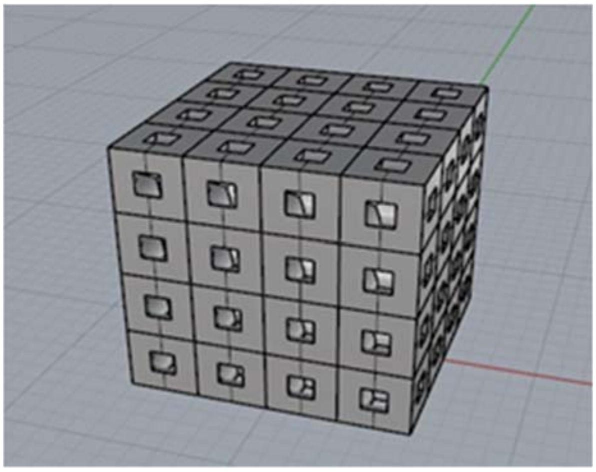

Fig. 4 Shell architecture 4

Fig. 5 shows the different orientation of architectures of bone scaffold and it also shows different lattice structure designed for bone scaffold. The main intention of designing different architecture is for checking the load barring capacity for same biocompatible material and same static load. CAD software Rhino is used to design these different architectures.

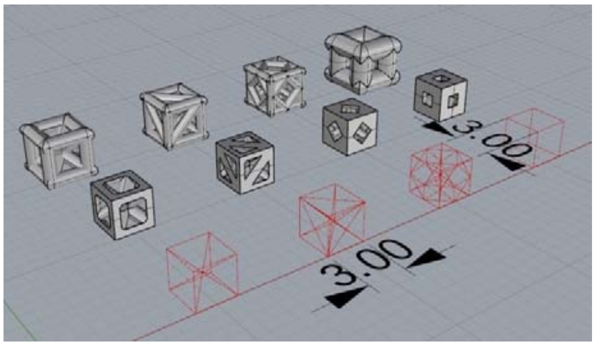

Fig. 5 Representative unit block structures

III. Biocompatible Materials

Ti-6Al-4V

In this stress analysis the biocompatible material used is Ti-6Al-4V. Titanium and titanium alloys exhibit a high specific strength [6], which makes titanium an excellent choice for biomedical applications [6], [7]. Biocompatible material Titanium and its alloys are prominently used in biomedical application for making implants and the devices, and these implants are used to replace the damaged section. In biomedical field the application of titanium is broad. Examples of uses of Ti in biomedical applications are orthopedic, density, organ implants, artificial bone, joints and many more [8]. Pure

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Titanium and its different alloys with many biocompatible materials are extensively used in the field of biomedical for the implants, tools etc. Especially in dental stream, titanium is a very useful biomaterial because of its extremely good mechanical properties and biological advantages. After the addition of direct laser metal sintering (DLMS) 3D printing technology Titanium has enlarged its boundaries.

Ti-6Al-4V is of (alpha + beta) type of titanium alloy. It has been widely used in aerospace, petrochemical, biomedical and other fields because of its low density, high specific strength, excellent corrosion resistance and good welding performance, and its usage has reached over 50% of titanium consumption in the world [9].

Polylactic Acid

Polylactic Acid, most commonly known as PLA, is a polymer made from renewable resources. Contrary to other thermoplastics which are petroleum-based, some of the raw materials used for PLA production include corn starch, tapioca roots, or sugarcane. Its properties, however, are comparable to other plastics in the industry

PLA is widely used in the medical field in temporary implants because it is highly biocompatible with the human body and is also biodegradable and bio absorbable, as is desirable for these kinds of biomaterials [10]

IV. Stress Analysis

In this study, the effective elastic moduli of porous structure were studied using finite element analysis. In this analysis two different biocompatible materials were used. First is Ti-6Al-4V and second is PLA. The material properties are assigned as linear isotropic of elastic moduli (E) for Ti-6Al-4V (E =104 GPa) and Poisson's ratio is 0.31. For PLA (E = 3.986 GPa and Poisson's ratio is 0.33 used.

Two different materials and loading conditions used in this analysis for evaluating the strength of different structure are shown in Fig. 5.

The boundary conditions used are:

1. The compressive load applied.
2. The bottom face of the bone scaffold kept fixed
3. And also, the gravity considered

With these constraints the finite element analysis is carried out for all four architectures. Table I shows the result.

TABLE I
Result For Ti-6Al-4V And 10 N Load

Architecture	Material	Lo ad (N)	Principal Stress (Mpa)	Total Deformation (mm)
Architecture 1	Ti-6Al-4V	10	0.365	2.8e-5
Architecture 2	Ti-6Al-4V	10	0.748	4.09e-5
Architecture3	Ti-6Al-4V	10	0.473	2.82e-5
Architecture 4	Ti-6Al-4V	10	0.146	2.21e-5

Next analysis is for the same architectures 1 to 4 to study the effect of another combination of material and load (PLA, 20 N load). Results found for maximum principal stress and the total deformation were summarized in Table II.

V. Graphical Representation

Graphical illustration includes the use of bar chart for visual display. Graphs represent the information or it can be interpretation of data. These data are used to conclude the result, analysis of result from the given numerical data. Figs. 6 and 7 show the maximum principal stress and the total deformation respectively for the material Ti-6Al-4V.

Fig. 6 shows maximum principal stress induced in different architectures. It can be seen that the magnitude of maximum stress induces is minimum in the architecture 4. Similarly, for Fig. 7 it drowns for total deformation in mm after the loading of 10N. In this figure it can be seen that, architecture 4 shows the minimum value for total deformation.

TABLE II
Result PLA and 20 N Load

Architecture	Material	Load (N)	Principal Stress (Mpa)	Total Deformation (mm)
Architecture 1	PLA	20	0.774	0.0014
Architecture 2	PLA	20	1.449	0.0024
Architecture3	PLA	20	0.600	0.0015
Architecture 4	PLA	20	0.276	0.0013

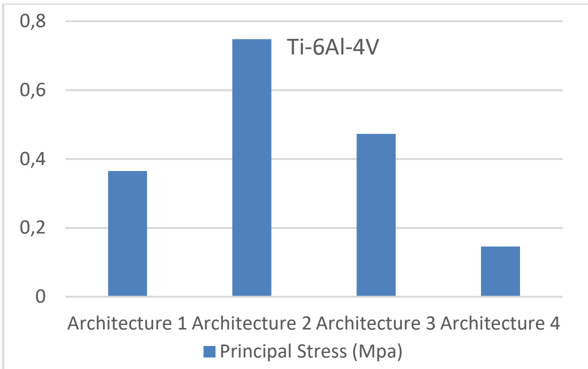

Fig. 6 Principal Maximum stress for Ti-6Al-4V

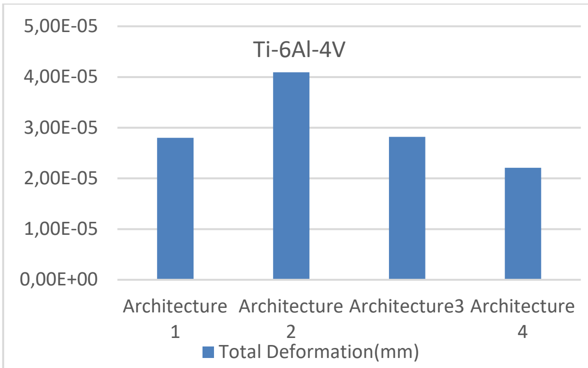

Fig. 7 Total deformation stress for Ti-6Al-4V

Figs. 8 and 9 show the maximum principal stress and the total deformation after application of 20 N load. And in both of the figures, it can be seen that the stress value induces and the total deformation value are minimum in architecture 4.

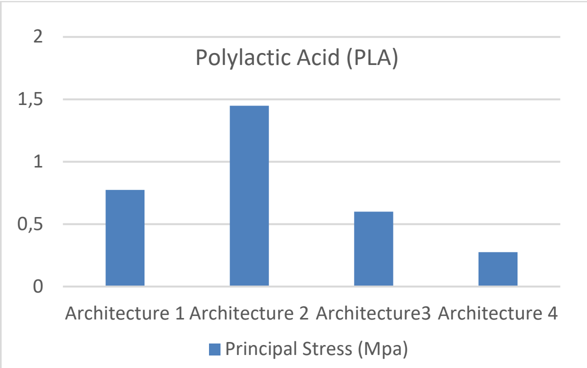

Fig. 8 Principal Maximum stress for PLA

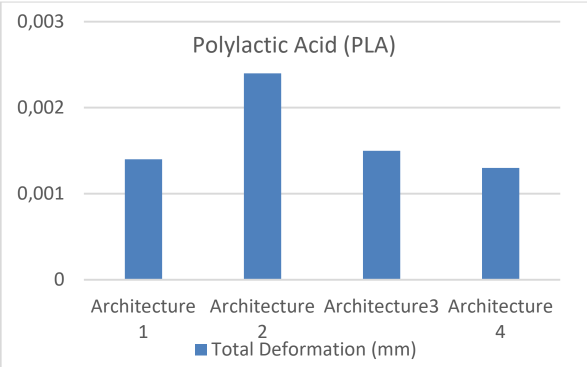

Fig. 9 Total deformation stress for PLA

VI. Conclusion

Bone scaffolds are porous structure made up of biocompatible material. The use of bone scaffold is a promising future treatment. The bone scaffold can be used in human body. It helps initiating natural cell growth in the damaged section of the bone. Considering the implantation of bone scaffold in lower part of the body below knee, the boundary conditions are chosen. The bone scaffold is intentionally made porous through, in order to initiate natural cell growth. All architectures are designed for same porosity. Four different architectures, two biocompatible materials, two loading conditions are used in two sets and analysis is carried out in ANSYS 19.2. After comparison, it can be seen that architecture 4 shows minimum value for Maximum Principal Stress and the total deformation value in both the sets. So, we can conclude that, architecture 4 is suitable architecture among all architectures used for analysis of different complex architecture of bone scaffold.

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