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RESEARCH ARTICLE

Design and analysis of strut-based lattice structure cranial implant

M.Z. Khan*, J. Bhaskar, A. Kumar

Department of Mechanical Engineering, Harcourt Butler Technical University, East Campus, Nawabganj, Kanpur 208002, Uttar Pradesh, India

ABSTRACT - A specialized medical cranioplasty procedure entails the use of implants of various materials, forms, and sizes. Computational technologies such as modelling and simulation, have refined the technique for creating these implants catering to patient specific needs. Superior qualities of lattice structures have considerable usage in implants. This study mainly focuses on three distinct types of strut-based lattice structures, Octet, Diamond, and Kelvin, for constructing cranial implant models using CAD tools like Solidworks and nTopology. Titanium alloy (Ti6Al4V) is used to test the behaviour of the designed implants in two cases: impact of external force and increase in intracranial pressure. Level of porosity is compared to determine extent of porosity of these implants, as porosity is significant in osseointegration. According to the study, these lattice structures give satisfactory results and can be utilized to make the implant more porous while satisfying the load bearing capacity

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1.0 INTRODUCTION

Cranioplasty is used to repair the damaged skull. It may be caused by birth anomalies, congenital deformities, tumours, or trauma. One of the most intricate organs the brain is shielded by the cranium, a group of total eight skull bones hold together by sutures [1, 2]. Meninges, three very thin membrane layers provide cover to it. For cushioning, it is suspended in cerebral spinal fluid which is produced by ventricles [3]. For performing cranioplasty surgeons require cranial implant. There are many different types of cranial implants available. Autologous bone grafts, use the patient's bone from a different region to construct the implant. Conventional synthetic implants are made of metal, ceramic, or polymer materials using traditional manufacturing methods like casting, forging, machining, etc [4].

Studies conducted on different types of implants have shown that implants which are porous in nature provides better osseointegration and result in better interfacial adhesion to the bone, as the initial cell seeding depends on the surface area and permeability of the implant because it will enable nutrients to pass through it for cell and bone growth [5]. For improved osseointegration, titanium implants with porosity closer to 50% are recommended as desirable [6, 7]. It is calculated by using formula [8],

$$\frac{Vs}{Vd} \times 10 \tag{1}$$

where, *"V_s"* is volume of solid sample and *"V_d"* is the volume of designed sample. Similarly, the requirements in cranial implant are shown in Figure 1.

In the research study to develop a Voronoi based lattice structure cranial prosthesis, as the redesigning of implants based on natural similarities is making the implants more compatible with the human body, they designed and manufactured a light weight, biomimetic cranial implant using the Selective Laser Melting technology [9]. In the study done for manufacturing the shoulder implant using Laser Additive Manufacturing technology, the use of titanium alloy lattice structure-based implants has shown promising results. This leads to improvement in the implant, reducing the need for revision surgery due to implant loosening [10]. Lattice structures have shown better results when used in medical implants due to their suitable properties, such as high specific strength and stiffness, higher surface area, lightweight, porous and ability to absorb external forces [11, 12]. These structures are versatile, enabling us to optimise their properties by taking into consideration some variables such as their beam length, beam thickness, or by restricting the volume of unit cell in which they will be arranged stochastically [13, 14]. These structures can be classified in a variety of ways. They are divided into two categories based on their topologies: stochastic (unsystematic distribution) and periodic (systematic distribution) [15]. They can also be divided into groups based on the structures that are dominated by stretching and bending. They can also be categorised into three accordingly to their architectures i.e., Strut-based, Skeletal-Triply Periodical Minimal Surface (TPMS) and Sheet-TPMS [16]. Compared to normal or solid structures, these structures have higher elastic and stiffness, and deformation is eversible. In these structures, porosity and relative density are inversely correlated, and stiffness has a direct relationship with both. Lattice structures have superior mechanical properties than honeycomb and foam type of structures [15, 17].

***CORRESPONDING AUTHOR | M.Z. Khan** | ✉ 200204006@hbtu.ac.in

Because of their intricate geometry, lattice structures cannot be produced using traditional CAD and production techniques. The use of these structures in various fields, including aerospace structures, biomedical implants, robotic systems, heat exchangers, actuators, vibration absorbers or dampers [17] has resulted from the introduction of additive manufacturing technology, which can produce these complex structures with various types of materials, including polymer, metal powder, and photopolymer resin, with various types of additive manufacturing techniques [18, 19]. In addition to additive methods, CAD programmes like Autodesk Within, Mimics Innovation suite, nTopology are readily accessible in the market to produce lattice structures. These CAD programmes are effective in designing these complicated structures, but they each have significant drawbacks, such as a lack of structure libraries, a lack of design variables for variation, and the need for high processing power.

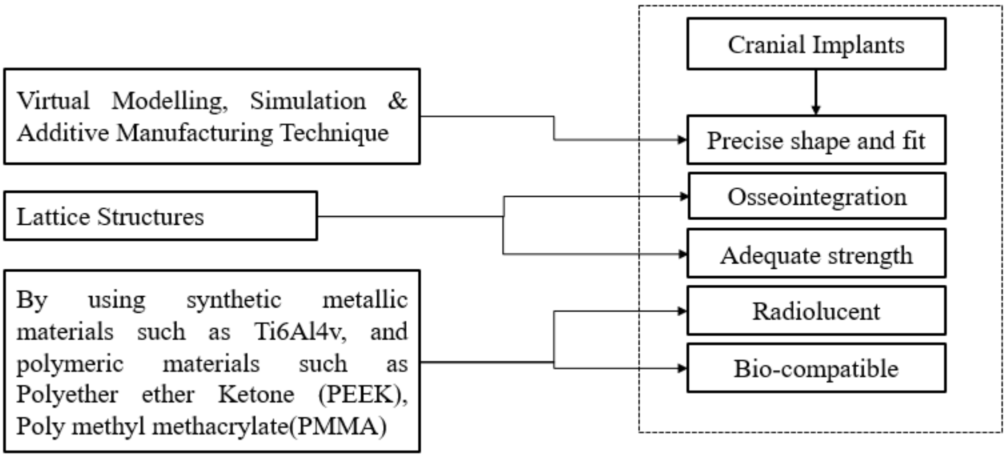

Figure 1. Cranial implant requirements

Titanium alloy (Ti6Al4V) is one of the favourite biomaterials for many types of implants. It is suited for the application due to its high strength to weight ratio, biocompatibility, resistance to corrosion, high stiffness, non-magnetic nature, and chemical stability [20]. Due to its greater elastic modulus than bone, the titanium implant's major concern is the stress shielding effect, which causes failure or bone loss. Study conducted by Thywill Cephas Dzogbewu in 2020, basic strut-based structures with rhombic and diagonal lattice structures were produced using the additive manufacturing technique known as laser powder bed fusion. Mechanical and microstructural analysis were carried out, and it was discovered that these structures were capable of lowering elastic moduli, which may be useful in significantly reducing the stress shielding effect [21].

Aim of this research work is to examine how a medium-sized cranial implant incorporates a strut-based lattice structure (25 to 200 cm^2) [22]. Three types of unit cell structures shown in Figure 2, Octet, Diamond, and Kelvin are used. Their porosity level, von-Mises stress and displacement produced in the implant with Ti6Al4v material properties under load of 400N which is comparable to an adult man striking [23] and the effect of intracranial pressure, which ranges from 7-15mm of Hg (2667Pa to 5333Pa) for an adult [24] are determined using finite element analysis of the three structures. This study helped in determining the feasibility of lattice structures for brain protection.

Figure 2. (a) Octet, (b) Diamond and (c) Kelvin

2.0 METHODOLOGY

2.1 Modelling

Using SOLIDWORKS, a solid CAD sample is created for this investigation in the shape of an elliptical dome to mimic the curvature of the cranial bones. Figure 3 displays the sample along with its dimensions. The surface area is determined to be 148.97 cm^2. 1.5 mm implant thickness is taken into consideration [20].

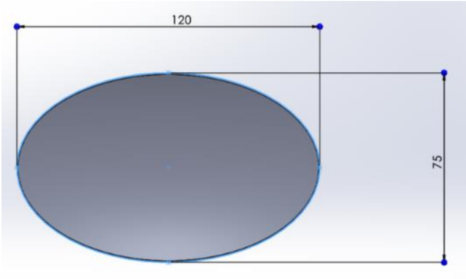

Figure 3. Elliptical sample for cranial implant

The CAD part is developed and imported into the nTopology application. Using it the selected lattice structures of beam thickness 0.5 mm as shown in Figure 4 are created.

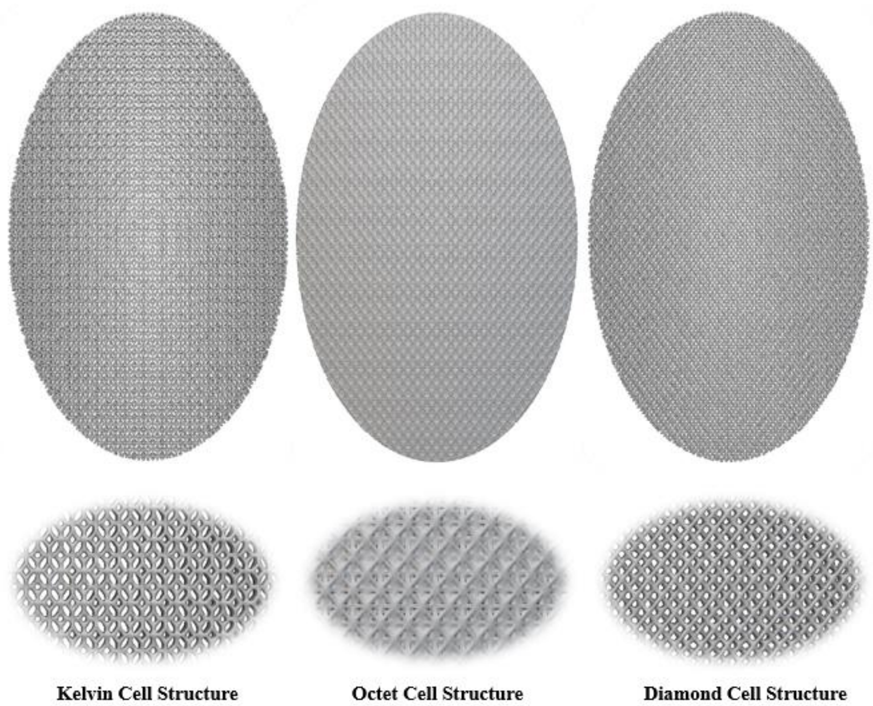

Figure 4. Lattice structure developed using nTopology software

2.2 Analysis

Two investigations are done on the intended implant, taking into account the effects of external load and intracranial pressure, respectively. Different boundary conditions are taken into consideration for both cases as shown in Figure. 5. Material properties considered for Ti6Al4V [20] is presented in Table 1.

Table 1. Material properties

Properties	TiAl64V
Youngs Modulus (MPa)	110000
Poisson's ratio	0.3
Density (kg/mm^3)	4430 X 10^{-9}
Yield Strength (MPa)	880

Due of their incredibly sharp and detailed features, the CAD files containing lattice structures are exceptionally difficult to mesh, necessitating significant computing needs. The "FE LATTICE MESH" block in the nTopology application is specifically designed for meshing files with lattice structures. It takes into account the number of beams in the lattice structure and converts them into nodes and elements. However, in order to ensure error-free results, a convergence study is carried out by varying the variable "SUBDIVISION." For instance, if the subdivision value is "1," just one beam element is considered, but when the value changes, it is taken into account as the number of elements.

After modifying this variable, it has been determined that the value of 16 is satisfactory for continuing on because the variation in the outcomes is quite minor. With the help of it the results for the first case are obtained.

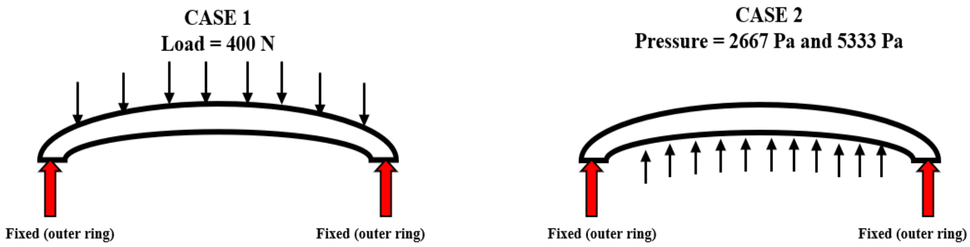

Figure 5. Boundary conditions for Case 1 and 2

For second case, the meshed model of all three designs with the boundary conditions is exported. Robust Tetrahedral Mesh is considered before exporting the model to Ansys 2020 R1. Number of elements and nodes generated for both cases are mentioned in Table 2.

Table 2. Mesh details

Unit cell	Case-1		Case-2	
	Elements	Nodes	Elements	Nodes
Diamond	418080	826884	448104	894473
Kelvin	624576	1233476	399062	806103
Octet	633536	1242238	840581	1471548

3.0 RESULTS AND DISCUSSION

The influence of external force on the implant is investigated in the first case by providing a load of 400N, which is equivalent to the force that an adult man would strike with. The findings indicate that the stresses range from 37.124 MPa to 88.825 MPa and the displacement values range from 0.012 mm to 0.03 mm. In second case, minimum and maximum intracranial pressure of 2667 Pa and 5333 Pa, respectively are taken into consideration while examining the impact of intracranial pressure on implant. Deformation measurements vary from 0.026 mm to 0.076 mm and stress values from 0.092 MPa to 0.448 MPa at the lowest pressure. The deformation ranges from 0.052 mm to 0.152 mm and the stress ranges from 0.184 MPa to 0.897 MPa at maximum pressure. Figure 6,7 and Table 3 shows the results obtained in both cases for the selected lattice structures.

Table 4 shows the porosity level of each designed implant with different lattice structures with considered beam thickness of 0.5 mm. Calculated values show that diamond and kelvin attained porosity level of 57.82 % and 52.02 % which is considered favourable. The results of the investigation of various samples with lattice structures have revealed minimal deformation values (Figure 8) under various loading circumstances, values that are so small as to essentially not impact the brain in any manner. The von-Mises stress values are similarly low, below the yield strength of Ti6Al4V as shown in Figure 9 and 10.

Table 3. Analysis results for both cases

Unit Cell	Case -1		Case-2			
	Load applied-400N		Pressure applied-2667 Pa		Pressure applied-5333 Pa	
	Deformation (mm)	Stress (MPa)	Deformation (mm)	Stress (MPa)	Deformation (mm)	Stress (MPa)
Diamond	0.0303	88.825	0.076	0.448	0.152	0.897
Kelvin	0.0267	62.635	0.075	0.334	0.151	0.668
Octet	0.0120	37.105	0.026	0.092	0.052	0.184

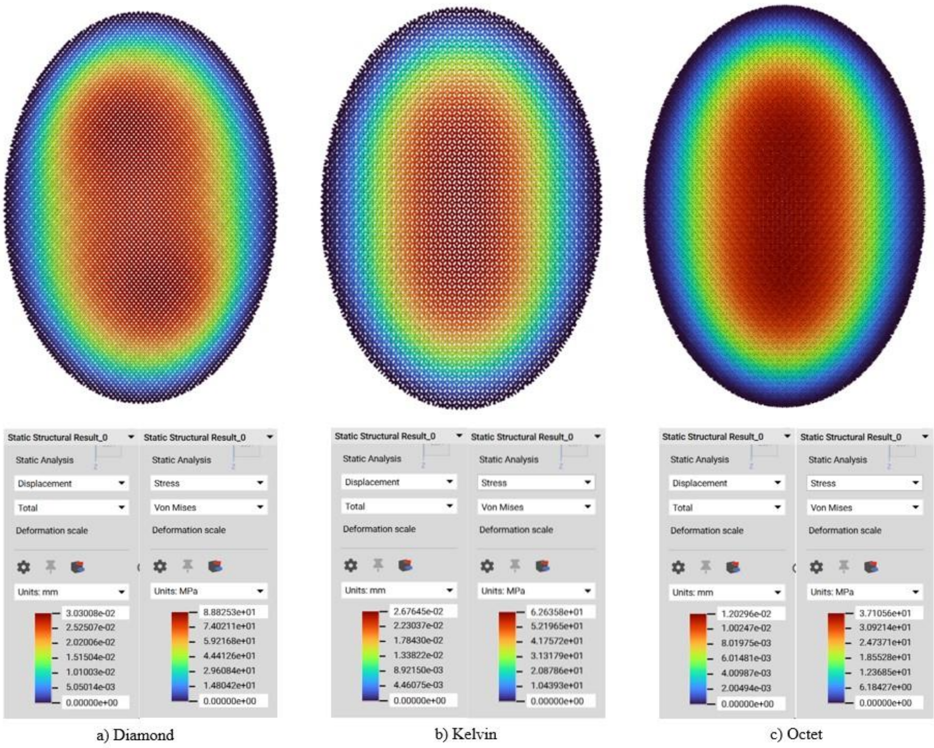

Figure 6. Analysis results of Case-1 (nTopology)

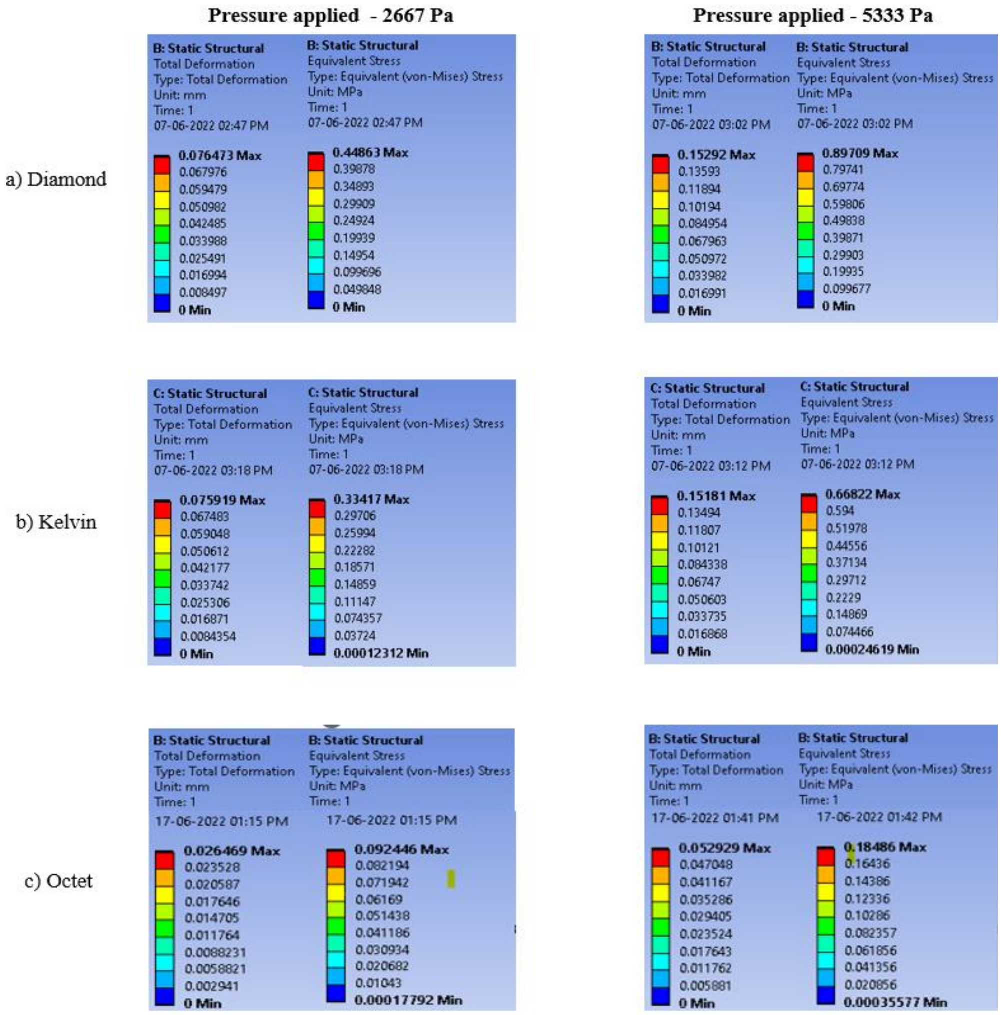

Figure 7. Analysis results of Case-2 (Ansys 2020 R1)

Table 4. Porosity values

Unit Cell	Solid Volume (mm3)	Lattice Volume (mm3)	Porosity %
Diamond	10812.42	4560.5980	57.82
Kelvin	10812.42	5187.5981	52.02
Octet	10812.42	9027.9633	16.50

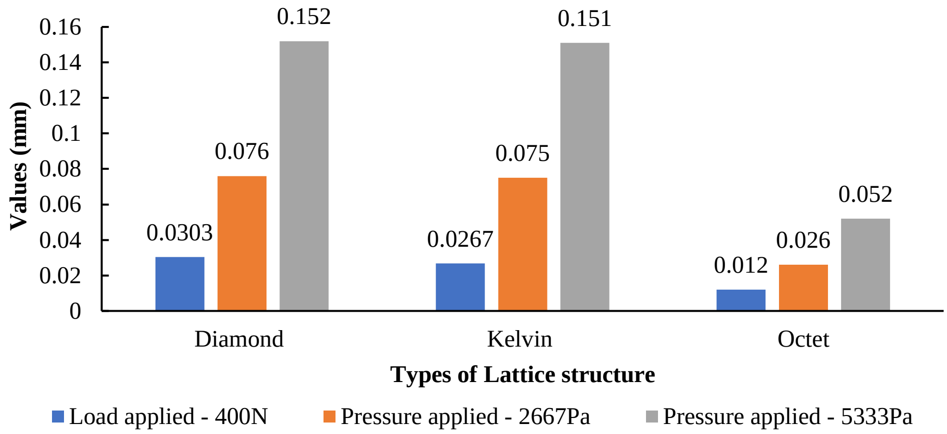

Figure 8. Deformation results for both cases at different load conditions

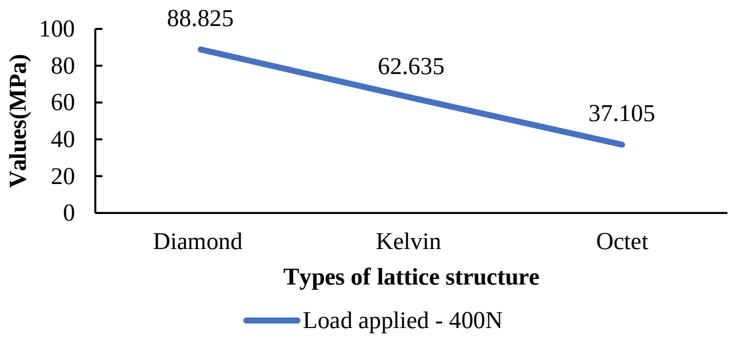

Figure 9. von-Mises stress values for Case-1

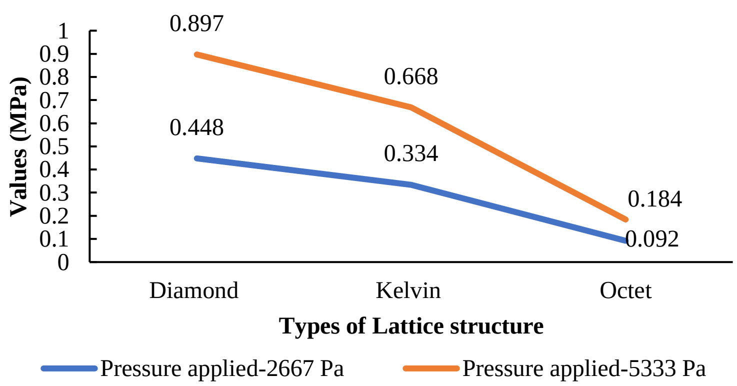

Figure 10. von-Mises stress values for Case-2

4.0 CONCLUSIONS

A cranial implant model is created employing several forms of strut-based lattice architectures that are inspired by our biosphere and have exceptional features.

1) Mechanical behavior of these implants is reported after study of these developed models under various loading circumstances. The progress of computational techniques has made the creation of these implants more rigorous and useful in completely analyzing every parameter.
2) The displacement and stress values obtained are very low and safe, implying that these structures can be used in the design of mesh-based cranial implants that are porous, lightweight and can be customized as needed.
3) For lattice constructions, many sorts of design factors may be considered to relatively raise and reduce the parameters as required, such as porosity, which can be increased and lowered by adjusting the unit cell volume or cell division.
4) These structures have the potential to play a critical role in giving an alternate method of developing implants and improving their qualities to make them more acceptable with the body.

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