Bending Strength of 3D-Printed Zirconia Ceramic Cellular Structures

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Abstract: Cellular structure has been applied in lightweight engineering application because of its high specific strength, high modulus and low relative density. Here we used 3Y-TZP ceramic to realize two typical cellular structures, Kelvin and Octet-truss, through a novel digital light processing (DLP) 3D printing method. The strut size was changed systematically to generate structures with porosities in the range of 10% ~ 80% and the bending strength of these structures were investigated and analyzed by three-point bending test.

1. Introduction
The cellular structures are abundant in nature, such as in tree trunks and bones [1]. Cellular structures also has been widely used in lightweight engineering because of high specific strength, high modulus and low relative density[2,3]. Many studies[3,4] have shown that cellular structures can be deformed by bending or stretching when they were subjected to external forces. The bending-dominated structure will undergoing bending of itself struts while the stretching-dominated structure deforms mainly stretched or compressed by the individual struts under loading. Kelvin structure and octet truss structure are common cellular structures. Kelvin is a bending-dominated structure, while octet truss is a structure dominated by stretching [5-9].

Leonid Kucherov and Michael Ryvkin studied the fracture toughness of open cell Kelvin foam structure under uniaxial tensile load, and further discussed the relationship between fracture toughness and relative density[10,11]. The Kelvin cell structure is used to simulate the foam structure in Zhang et al. study, and explored the influence of relative density and geometric properties on the foam failure behavior, and proved that the failure limit surface of Kelvin foam is anisotropic[12]. The mechanical properties of the octet truss structure were studied by Ashby et al. from both theoretically and experimentally. The elastic buckling and plastic yielding of the octet truss structure are analyzed. The results show that the stiffness and strength of the truss structure are mainly stretch-dominated [5]. Kaur et al. investigated the deformation of octet truss and octahedral structure fabricated by fused deposition modeling (FDM) made of different polymer materials using compression testing and finite element
analysis (FEA) simulation methods, and showed that octet structure greater stretching dominance than octahedral structure[13]. Köhnen et al. established a cubic lattice cell structure and a hollow spherical structure by powder bed fusion selective laser melting (SLM) technology, and studied the plastic deformation behavior under tension, compression and cyclic tests. The result revealed that the lattice cell structure is mainly stretching-dominated, and the hollow sphere structure is mainly bending-dominated. The lattice cell sample also has considerable energy absorption capacity compared to the bulk reference sample[14]. Chen investigated the mechanical behavior of truss structures made of two different resins under quasi-static and dynamic loads, which fabricated by stereolithography (SLA) additive manufacturing, and explore the relationship between relative density and yield stress[15].

Ceramic materials are inorganic non-metallic materials with excellent properties, such as acid resistance, alkali resistance, corrosion resistance, high temperature resistance, and the ability to withstand high compressive strength, so widely used in lightweight manufacturing [16]. However, the manufacturing process becomes difficult due to the hardness and brittleness of the ceramic material. With the development of additive manufacturing technology, it is faster and more convenient to make lightweight ceramic materials[17].

The purpose of this experiment is to studied the mechanical behavior of the Kelvin structure and the octet truss structure during the bending test, the influence of relative density on the mechanical behavior of the structure through mechanical test data was analyzed, the scanning electron microscope (SEM) to fracture the surface of the sample was used to analyze[18,19].3D printing technology can made complex structures easily, so the Kelvin structure and the octet truss structure fabricated by digital light processing (DLP) additive manufacturing made of by zirconia ceramic.

![Figure 1. Different 3D structures were designed by CAD software. (a) Octet-truss structure, (b) Kelvin structure](image)

| Structures | Strut size(mm) |
|------------|----------------|
| Octet truss | 0.2 0.25 0.3 0.35 0.4 0.5 0.55 0.6 |
| Kelvin     | 0.35 0.4 0.45 0.5 0.55 0.6 |

2. Experimental

2.1. Model fabrication

A computer aided design drawing software was used to generate the octet-truss and Kelvin basic unit cell models, the basic cell structure was repeated in order to generate the required test model, as shown in Figure 1(a) and (b). The strut size was changed systematically to obtain structures of different relative densities, the unit cell strut size of the octet truss and Kelvin structures were shown in Table 1. A sheet with a length and width value equal to the test model and a thickness of 0.2 mm was added to the bottom of the Kelvin structure to ensure uniform force during the bending test of the Kelvin structure. The model files were exported in STL format and then transferred to the 3D printer for printing. The 3D truss structures were printed using a top-down printer based on Digital Light
Processing (DLP) method (CeramPlus DLP-50, Jiaxing CeramPlus Co., Ltd. (China)). The TZP ceramic printing material[20,21] was also provided by the company.

During 3D printing, selected areas of the surface of the photosensitive liquid are exposed to specific wavelengths of light. As a result, the monomers in the irradiated area coalesced into a specified depth and adhered to the supporting platform. Once assembled, the first layer moves down to the height of the first layer, which has a movable table on which the supporting platform is fixed. The first layer is then dipped into the unsolidified liquid. After immersion, the unsolidified liquid covers the polymerization surface to provide a new liquid surface. The second layer is then aggregated by exposing the parts. Steps are repeated until the fabrication of the entire part is done. 3D printing can create complex structures quickly and easily. Therefore, the octet truss and Kelvin green bodies can be quickly fabricated, the green bodies were cleaned and then sintered, the specimens as shown in Figure 2 were obtained.

![Figure 2. 3D printed structures. (a) Octet-truss structure, (b) Kelvin structure.](image)

### 2.2. Mechanical testing

In order to characterize the bending resistance of the specimen, a standard three-point bending test was utilized, the universal testing machine was used for this experiment. Due to the different cell structure, two different standards were used in octet truss and Kelvin structures, respectively. Octet truss specimens were made into the dimensions of 35mm × 4mm × 3mm, while the Kelvin specimens were made into the dimensions of 70mm × 10mm × 2.5mm. The displacement of the loading noses was controlled at the rate of 0.5mm/min throughout the test. The force-displacement data are used to obtain the stress-strain curve, which is used to reflect the sample's response to external forces. The Archimedes drainage method was used to obtain...
the volume of the sample. The resulting data was divided by the volume of the solid sample of the same size, and the relative density was further obtained. The fracture surfaces and surface morphologies of the sintered samples were investigated by a desktop Scanning Electronic Microscope (SEM, Phenom Pro, Phenom World, Netherlands).

Figure 3. Stress-strain curve obtained from the three point bending test. (a) Octet truss structures, (b) Kelvin structures

3. Result and Discussion
In order to study the mechanical properties of the octet truss structures and the Kelvin structures, three-point bending test were carried out on the specimens. five specimens were carried out for each structural design. The stress data of specimens can be obtained by equation (1). The data was summarized into Figure 3. Figure 3 was showed that the stress-strain behavior changed with the strut size. The octet truss structures and Kelvin structures initially exhibited elastic deformation, where the stress increased linearly up to the yield point. In general, the fracture stress and flexural modulus increase with the strut size while maximum strain remains much less changed when strut size change. This indicate that the structure itself decide the deformation capability while the strut size/relative density of the cellular structure was determinative for the fracture stress. Meanwhile, the stress drops rapidly after reaching the maximum value, which may be caused by the brittleness of zirconia ceramics.

$$\sigma_f = \frac{3FL}{2bd^2}$$  \hspace{1cm} (1)

Where $\sigma_f$ is the flexural strength that specimen can withstand, $F$ is the break force, $L$ is the outer (support) span, $b$ is specimen width and $d$ is specimen thickness[22].

$$\frac{\sigma_{pl, latt}}{\sigma_{y, sol}} = C_5 \left( \frac{\rho_{latt}}{\rho_{sol}} \right)^m$$  \hspace{1cm} (2)

Figure 4 showed the bending strength against relative density for octet truss and Kelvin structures with different strut size. The stress that the specimens can withstand increases as the relative density increases illustrated in Figure 4. The slope obtained by fitting the points in Figure 4 (a) with equation (2) is 1.837, and in Figure 4 (b) is 1.878. The value of $m$ can be used to justify if the structure is bending- or stretching-dominated. If $m \leq 1$, the structure is always characterized by stretching-dominated when the force applied, the stretching-dominated structure deforms mainly stretched or compressed by the individual struts under loading. When $m \geq 1$, the structure is characterized by bending-dominated when the force
applied, the bending-dominated structure will undergoing bending of itself struts. In this study, \( m \) was determined to be 1.84 and 1.88 for octet-truss and Kelvin structure respectively. Both structures made by 3Y-TZP ceramic presented bending-dominated characteristic. To be noticed that octet-truss had been always approved to be stretching-dominated in classical metal cellular structures. However, further careful investigation is still necessary to elucidate the final conclusion on this structure-linked mechanical behavior. The possible minor structural defects are still not possible to be excluded from the DLP 3D printing.

Figure 4. Stress against relative density with different strut size. (a) octet truss structures, (b) Kelvin structures.

Figure 5. SEM images of the fracture surface of specimen.

Anyway, the SEM image shown in Figure 5 demonstrate that little pores in the fracture surface with a dense and uniform microstructure from SEM photograph. Archimedes principle was also employed to measure the density of the sintered specimen to illustrate the phenomenon, and a good sintered density could be achieved, which can reach 6.01 ± 0.02 g/cm³, with compactness of 99%. Figure 6 further presented the difference in the bending strength of Octet-truss and Kelvin cellular structures, Kelvin structure showed advantage of reaching higher fracture strength and also maximum strain at least in the density range of <40%.
4. Conclusions
The bending strength and flexural modulus of the stretching-dominated octet truss structure and bending-dominated Kelvin structure generally increase with the increase of strut size, while the maximum strain remains relatively constant and thus indicate that the deformation capability is kind of structure-linked property for ceramic cellular structures. At a rather high porosity level of ~50%, both cellular ceramic structures processed a high bending strength of ~50MPa while Kelvin structure can provide a strain of >6% without failure. With the help of the development of ceramic 3D printing, the further exploration of interesting cellular structures/mechanical metamaterials will be very promising for the future biomedical and engineering applications.

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