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Theoretical Analysis of the Mechanical Response of Lattice Structures Manufactured using Selective Laser Melting

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Abstract Metallic lattice structure manufactured by selective laser melting (SLM) is deemed a promising lightweight solution that can be widely used in the fields such as aerospace, automobile and bioscience. However, it is still difficult to design and optimize lattice structures made of a large number of complex units. In this paper, aiming to establish an effective mechanical method, typical cube-based lattice structures are studied using statically indeterminate equations joint with finite element modelling. For experimental study, sample structures were manufactured by SLM using Ti6Al4V powder. A series of uniaxial compressive tests of lattice structure were conducted to show the merits of the proposed mechanical method.
Key words: SLM technique, lattice structures, Mechanical analysis and tests, Finite Element Method.

1. Introduction

Lattice structure, because of its well-regulated topology, has been attracting more attention from researchers recently. With desirable properties of higher strength and lower weight, lattice structures are suitable for lightweight design which is environmentally friendly, especially in terms of energy-saving. However, due to the current limitations of SLM, metallic lattice structures are often made homogeneously and orderly at both macro and micro scale.

Due to the fast-growing demand for extremely light-weight designs in some field applications, two measures have been explored in the making of such structures. The first one is to use lighter parent materials such as titanium alloy with properties of higher strength and higher heat resistance. In this case, metallic lattice structures made of Ti alloy powder can meet the challenges in aerospace and aviation industry. Another effective means is to optimize the topology of a lattice structure, thus the shape and topology of any inner unit should match its unique stress condition. Hence, in application, lattice structures with superior mechanical properties are not homogenous at the macro scale. Their complicated geometrical features cause several really difficult problems in both theoretical analysis and numerical simulation. Therefore, as a consequence, it is pressing to find a suitable way to implement typological optimization on lattice structures.

In order to lower the difficulty during the typological optimization, it is wise to conduct a step-by-step optimizing method. At the preliminary stage, a typical homogenous lattice should be designed properly under certain load conditions. Then based on stress distribution in the structure and setting volume fraction as the optimal object, material in different zones is removed or added to form a new and better topology. In the next step, shape and sizes are optimized repeatedly in order to make maximum stress in the structure as low as possible. After all above steps, the optimum structure can be obtained. This step-by-step method is on the basis of the design of homogenous lattice structures. However, there are still obstacles in the process of designing even typical homogeneous lattice structures as a great number of tiny units in a normal lattice part, leading to inaccurate results of mechanical response of lattice structures.

Therefore, this paper aims at investigating geometrical factors which effect mechanical response of typical cube-based homogeneous lattice structures. And it is structured as follows: section 2 provides relevant literature review, and in section 3 mechanical equations and numerical simulation method are established to estimate mechanical properties of cube-based structures. Sample experiments and resulting discussion were conducted to verify and evaluate the correction and practicably of this theoretical method. Several conclusions are drawn in section 5 in which plans of further studies are also introduced.

2. Literature Review

Selective laser melting, which is an additive manufacturing process, can manufacture metal parts directly from metallic powder [1]. A great many of achievements have been made for recent years, nevertheless, there are still several obstacles to eliminate in the process of designing metallic lattice structures.

In the process of SLM, as temperature gradient exists between melting metal and powder, long cantilever beams in a lattice structure are difficult to build because designing support structures for each unit is impractical. Therefore, at present, the minimum angle limit exists between a strut and the horizontal plane [2]. Some researchers studied BCC-type and FCC-type lattice structures and discussed optimization methods about those structures, such as G. N. Labeas et al. [3] and

Olaf Rehme et al [4]. Chunze Yan et al. put forward a gyroid type lattice structure having the characteristic of self-supporting and edge length in a unit reached up to 8mm [5]. O. Cansizoglu et al. studied the design of non-stochastic Ti–6Al–4V alloy structures and discussed the optimization method in the view of build orientation and angle [6].

When shape, sizes and topology of a lattice structure are chosen, researching about its mechanical properties is the next significant step. Comprehensive analysis method including mechanics theory analysis, numerical simulation and prototype testing is therefore introduced. Deshpande et al. designed a stretching-dominated octet-truss-type lattice structure, and studied its effective elastic modulus and yield criterion [7]. S.Mckown et al. analysed stress-strain relationship and failure mechanism of two BCC structures under quasi-static and blast loading [8]. K Ushijima et al. established force balance equations and concluded theoretical methods about initial stiffness and plastic yield condition of BCC lattice structures based on beam theory and plastic hinge generation conditions [9]. Jens Bauer et al. utilized size effects in microstructures to obtain high-strength cellular structures with compressive strengths up to 280Mpa while relative densities are under 1000kg/m3 [10]. Jianfeng Su et al. studied fracture loads of Ti6Al4V lattice structures manufactured by SLM using experimental and theoretical method, and found an exponential relationship between the fracture load and the porosity of lattice structures [11].

Numerical simulation is an effective method when studying the mechanical properties of lattice structures. G.N.Labeas et al. pointed out that when analyzing mechanical properties of BCC-type or FCC-type lattice structures, beam elements method is an effective and lower-hardware-requiring finite element method (FEM) [3]. Luxner MH et al. used an increased stiffness in the vicinity of the nodes to explain the material concentration [12]. M.Smith et al. established finite element models of lattice structures under compressive loading and pointed out that beam elements models are suitable to structures with large number of units while more mechanical properties are obtained using 3D brick element models [13]. K.Ushijima et al. compared analytical solutions by using beam elements and 3D solid elements and found that FEM predictions using the 3D solid elements agree well with the experimental data for a wide range of strut aspect ratio [9]. Fuhong Dai et al. proposed a numerical method to study the behaviours of contact and constrain in a multi-multi-stable lattice structure consisting of tri-stable lattice unit [14]. Unfortunately numerical simulation of a lattice structure is still difficult and time-consuming, as large number of units exist, it is necessary to establish an effective and accurate simulating method [15].

In this paper, aiming to typical homogenous lattice structures, elastic response of BCC and FCC lattice structures are studied. Using mechanical theory elastic modules are calculated and comparatively analysed with results of uniaxial compressive testing on samples made in Ti6Al4V powder. 3D continuum element models of those lattices are also established in order to evaluate preliminarily the deformation and failure mechanism.

3. Methods

Body-centred cubic (BCC) and Face-centred cubic (FCC) lattice are typical and common cube-based topologies which are suitable for manufacturing using SLM. Lattice structures can be obtained by repeat BCC or FCC unit in certain order, as Fig 1 shows. In this section, an equation which illustrates the relationship between elastic response of a structure and its geometrical features was established by solving a series of theoretical equations on a featured unit under uniaxial compressive load first. The response of a whole structure can be estimated by the equation obtained in the end of this section. Although elastic modulus of a unit obtained in this section is definitely different from that of whole structure, however, if geometrical complexity of general lattice structure was taken into account, it would be a valid method to evaluate elastic response of whole lattice structure [13].

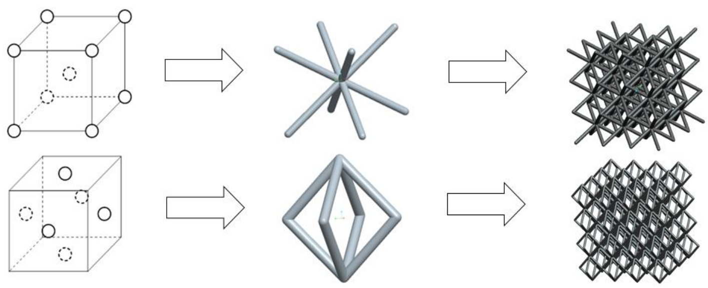

Figure 1. Cube, lattice unit and structure

3.1. Theoretical Method

According to unit-load method, the displacement of the structure bearing certain loads can be calculated by Mohr integration, and only the effect of bending moment is taken into account for a structure made of slender struts.

First, because FCC lattice is typologically similar to BCC lattice, mechanical properties of BCC lattice structure was studied. There are several assumptions in section 3 : 1, material in the structure is continuum and uniform; 2, deformation in the struts is quite small; 3, number of units is unlimited; 4, torsion is ignored in the analysis; 5, aspect ratio of a strut is small enough (it is usually smaller than 0.1). Moreover, the unit used in mechanical analysis is called enclosed unit, as BCC unit obtained from above method is opened unit, the below unit was used according to the assumption 2. And both lattice structures adopted in this paper are isotropic, a uniaxial compressive load was apply along Z-axial first.

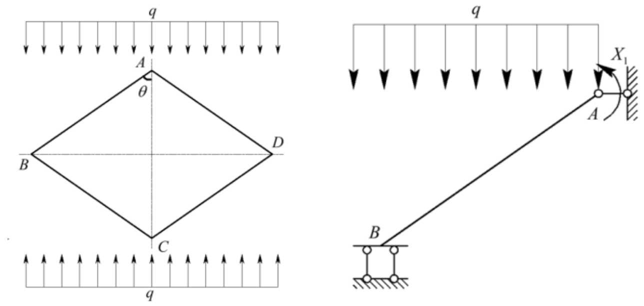

Figure 2. Force diagram of BCC unit under uniaxial compression

The uniaxial force diagram in Fig 2 illustrates that mechanical analysis of a BCC unit is a statically indeterminate problem. Utilizing symmetry of BCC unit, a strut can be analysed first. In the latter equations, l and d represent length and diameter of the strut respectively.

According to the force method equation,

$$\delta_{ji} X_i + \Delta_{jP} = 0 \tag{1}$$

In this case, δ_{ji} and Δ_{jP} can be calculated using Mohr's integrals. Therefore, the additional force X_i can be calculated using the above equation. Then equation of bending moment of a strut can be obtained as:

$$M(x) = \frac{1}{6} q \sin^2\theta \left(6lx - 3x^2 - 2l^2\right), \ 0 \le x \le l \tag{2}$$

Applying a unit-load on point A in Fig 2, therefore, the corresponding bending moment equation of strut AB is gotten as:

$$\overline{M}(x) = \frac{1}{2} \sin\theta (2x - l), \ 0 \le x \le l \tag{3}$$

Then using Mohr integration, the change of the unit height (ΔH) under uniaxial press equals twice of ΔA. Moreover, E_s represents the elastic modulus of parent material.

$$\Delta H = 2\Delta A = 2\int_0^l \frac{M(x)\overline{M}(x)}{EI}dx = \frac{ql^4 \sin^3\theta}{12E_s I} \tag{4}$$

While force q has a relationship with stress σ_z , that is:

$$ql\sin\theta = \frac{1}{4}H^2\sigma_Z \tag{5}$$

For a unit, when stress applied in vertical direction,

$$H = 2l\cos\theta \tag{6}$$

Then in the vertical direction, the nominate strain and elastic modulus of the unit are:

$$\varepsilon_z = \frac{\Delta H}{H} = \frac{\sigma_z l^4 \sin^2\theta\cos\theta}{24E_s I} \tag{7}$$

$$E_z = \frac{\sigma_z}{\varepsilon_z} = \frac{24E_s I}{l^4\sin^2\theta\cos\theta} \tag{8}$$

Therefore, the equation of elastic modulus and respect ratio of strut can be obtained:

$$E_z = \frac{\sigma_z}{\varepsilon_z} = \frac{3\pi}{8\sin^2\theta\cos\theta}\left(\frac{d}{l}\right)^4 E_s \tag{9}$$

The above equation was rewritten in the below form:

$$E_Z = E_s f(\theta)\left(\frac{d}{l}\right)^4 \tag{10}$$

3.2. Finite Element Simulation

In this paper, in order to verify the above analysis in mechanical method, one unit from a lattice structure is simulated using 3D continuum element method.

An enclosed unit is selected from whole lattice structure to be the simulating model using Abaqus Standard. As shown in Fig 3. An analytical rigid face was built to represent the compressive head. Two analysis step was created, in the first step, the head moved downwards to create contact condition between the head and the unit. In the second step, the head pressed the unit for 1 mm. Material is set to Ti6Al4V, which was also used in the compressive tests, whose elastic modulus is 110 GPa and compressive yield strength is 1110 Mpa [16]. Moreover, boundary conditions were set as Fig 3. As geometry of BCC or FCC unit is complicated and contact analysis is needed, C3D10M was selected from the element library of abaqus to mesh the part for the purpose of accuracy.

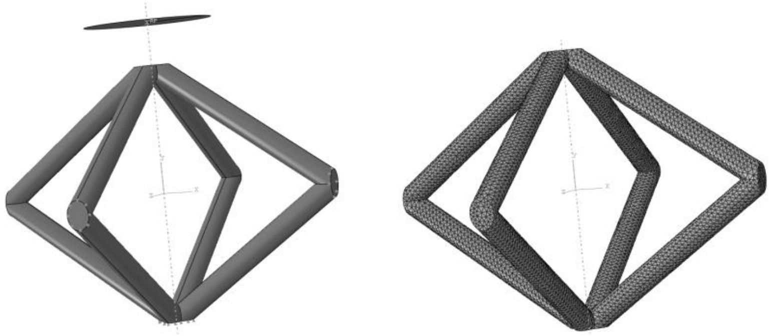

Figure 3. Boundary Conditions and Mesh

4. Experimental Studying, Results and Discussion

Equation (10) illustrates that factors effecting elastic response of BCC or FCC type lattice include aspect ratio of a strut (d/l), elastic modulus of parent material E_s, and a function of θ. Therefore, if topologies of BCC or FCC units were determined based on same cube, stiffness of FCC lattice would be greater than that of BCC lattice. Moreover, as $f(\theta)$ is varied to different aspect ratio of a unit while $(d/l)^4$ is quite smaller than $f(\theta)$, aspect ratio of a strut has a conspicuous impact on the elastic response of such lattice structures. Bending moment of a unit can be calculated using equation (2), which is able to estimate deformation of a strut and show the possible failure position.

To verify rationality of above theoretical equations, a series of sample tests were conducted. The edge length of each unit in these samples length is 6mm and every sample contain 64 units in total and 4 units at each edge. Diameter of each strut is 0.52mm. Samples were manufactured by EOS M280 which is one of the most advanced SLM machine in the world. During manufacturing process, build orientation were keeping consistent with direction-Z in section 3. Then samples were put in a material testing machine in order to get elastic modulus as well as yield strength. Strain rate during press tests is 0.005 per minutes (ASTM standards). All samples didn't suffer any heat treatment and were tested in two directions: vertical direction and lateral direction, in which vertical direction represents the direction of material accumulation in SLM.

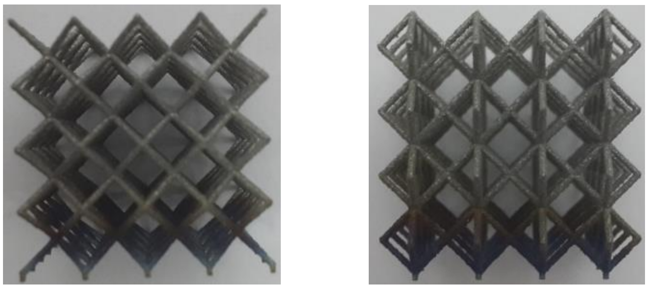

Figure 4. BCC lattice sample FCC lattice sample

4.1. Theoretical and Experimental Results

Fig 5 and Table 1 show elastic response of lattices in vertical and lateral direction. Comparing with experimental results, elastic modules obtained using theoretical method exists a certain degree of deviation.

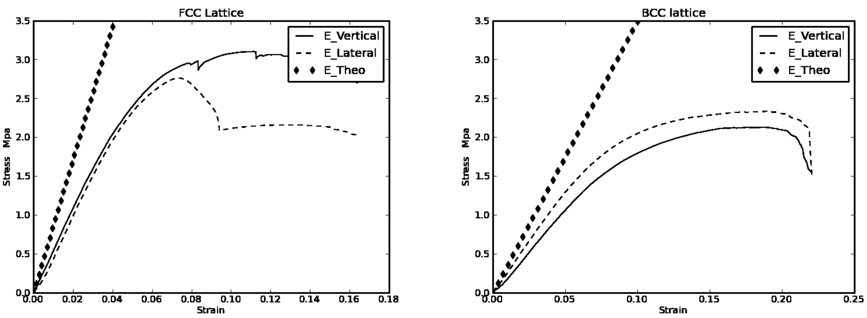

Figure 5. Stress-strain diagrams

Table 1.

Elastic modules in theoretical analysis and tests

	E_{EXP} (Mpa)		E_{THEO} (Mpa)	
	Vertical	Lateral	Vertical	Lateral
FCC	50.66	48.40	82.71	82.71
BCC	20.90	25.02	33.76	33.76

From the Fig 5, for all above lattice structures, in the range of strain smaller than 0.02, analysis results using theoretical method are in good agreement with experiment results. Then obvious deviation occurs along with increase of strain. There are several factors which may cause deviation, apparently E_{THEO} is bigger that E_{EXP} for all above lattices. First, significant residual stress exists in sample parts due to the SLM process and sample parts may show different mechanical properties under certain load condition if different heat treatment methods are adopted. Therefore, E_s used in the period of theoretical analysis is not same as the real parent elastic modulus. Moreover, as a typical unit was chosen to estimate elastic response of whole sample, theoretical elastic modulus obtained using equation (10) is the elastic of a unit, while true elastic modulus of a sample would vary with the increasing of number of units because boundary conditions vary in the process. Since the unit-topology-based method proposed in this paper mainly to estimate mechanical response of complex lattice structures in the view of geometry and topology, equation (10) is reasonable and valid in some extent, which shows the correct variation trend among testing datum.

In further studies, consequently, three factors will be considered carefully in evaluating mechanical properties of lattice structures, i.e. E_s representing different heat treatment methods and material properties, $(d/l)^4$ representing different relative density and $f(\theta)$ caused by different topologies. Another factor which affects mechanical properties of lattice is anisotropy of material caused by layer-by-layer process form in SLM. In actual case, each layer in a structure is not perpendicular to a strut, resulting in anisotropic properties of BCC or FCC structure samples. Material anisotropy caused by the process of SLM will be studied and discussed in the follow-up research.

4.2. Numerical simulation result

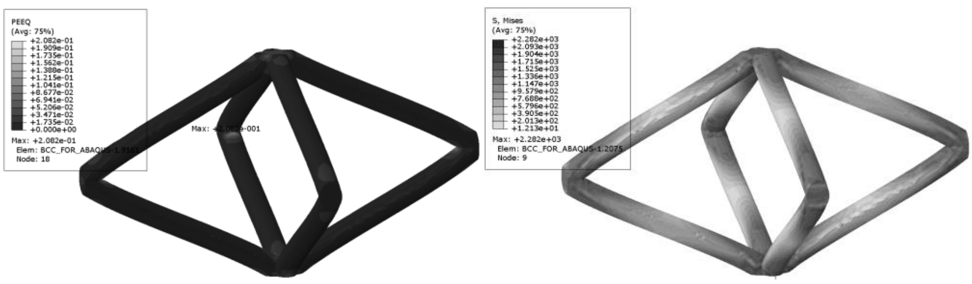

Figure 6. PEEQ and Mises stress of BCC unit

In the results of FE simulation, Mises stress and equivalent plastic strain (PEEQ) were considered to evaluate deformation forms and failure mechanism. For BCC unit (Fig 6), as predicted by bending moment equation (2), high stress zones appeared near nodes areas, in which Mises stress exceed 1110 Mpa, while stress in center areas of struts is below 200 Mpa. PEEQ in most areas in BCC unit is quite small, while it is above 0 in the junctions of struts, where plastic deformation occurs.

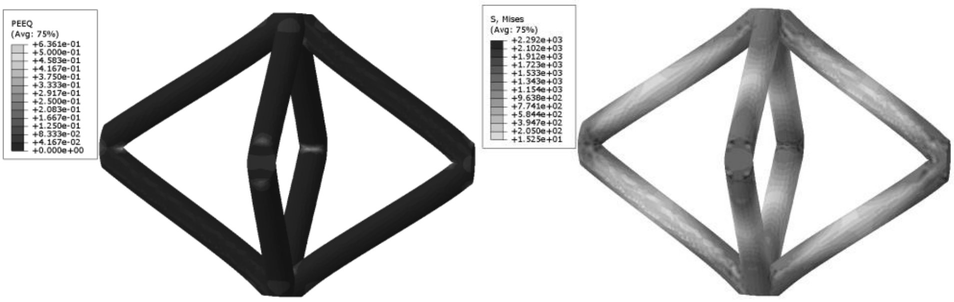

Figure 7. PEEQ and Mises stress of FCC unit

Similarly, in BCC unit (Fig 7), high stress zones exist near nodes areas and PEEQ in borders of struts is higher than 0. Therefore, when both BCC and FCC units are compressed, elastic deformation occurs mainly in units while a little of plastic deformation exist in junctions of struts in which material is stretched or squeezed severely. Furthermore, under the same deformation condition, FCC unit shows lower maximum Mises stress than BCC unit does, which means that FCC lattice has superior mechanical properties in that case. Similar phenomena appear both in theoretical results and experimental datum.

5. Closing Remarks

In the current research stage, as described in this paper, several closing remarks can be drawn based on these research efforts.

A theoretical equation revealing influential factors on elastic modulus of cube-based lattice structures was established. From this equation, a direct-ratio relationship between elastic response and the fourth power of the aspect ratio of a strut was found. Plastic response and failure mechanism of lattices has not been completed and will be proposed and studied in further study.

Experimental results verified elastic properties calculated by theoretical equation. However, deviations between analytical and testing results indicated that mechanical properties of lattice samples are impacted by SLM process. A series of sample experiments focusing on selection of heat treatment procedures that carried out on lattice samples will be conducted in order to estimate the mechanical response of metallic lattice structures more accurately.

Elastic deformation occurred dominantly in units in the stage of small strain lower than 0.8 as predicted by bending moment equation of a unit, while a little of plastic deformation existed in junctions of struts in which material was stretched or squeezed severely. Thus optimization method of lattice topologies will be studied to improve the specific strength and stiffness of metallic lattices in the future.

Acknowledgements

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References

[1] Buchbinder.D et al. High Power Selective Laser Melting (HP SLM) of Aluminum Parts. Physics Procedia. 12, 271-278 (2011).
[2] Ahmed Hussein et al. Advanced lattice support structures for metal additive manufacturing. Journal of Material Processing Technology. 213, 1019-1026 (2013).
[3] G.N.Labeas et al. Investigation on the static response and failure process of metallic open lattice cellular structures. Strain. 46, 195-204 (2010).
[4] Olaf Rehme et al. Rapid manufacturing of lattice structures with selective laser melting. Proc. of SPIE, 6107, 1-12 (2006).
[5] Chunze Yan et al. Evaluation of cellular lattice structures manufactured using selective laser melting. International Journal of Machine Tools & Manufacture, 62, 32-38 (2012).
[6] O. Cansizoglu et al. Properties of Ti–6Al–4V non-stochastic lattice structures fabricated via electron beam melting. Materials Science and Engineering A, 492, 468-474 (2008).
[7] V.S. Deshpande et al. Effective properties of the octet-truss lattice material. Journal of the Mechanics and Physics of Solids. 49, 1747-1769 (2001).
[8] S. Mckown et al. The quasi-static and blast loading response of lattice structures [J]. International Journal of Impact Engineering. 35, 795-810 (2008).
[9] K Ushijima et al. An investigation into the compressive properties of stainless steel micro-lattice structures. Journal of Sandwich Structures and Materials, 13(3), 303-329 (2011).
[10] Jens Bauer et al. High-Strength cellular ceramic composites with 3D microarchitecture. PNAS Early Edition. 1-6 (2014).

[11] Jianfeng Sun et al. Mechanical properties of a Ti6Al4V porous structure produced by selective laser melting. Material and Design. 49, 545–552 (2013).
[12] Luxner MH et al. Finite element modeling concepts and linear analyses of 3D regular open cell structures. J Mater Sci. 40, 5859–66 (2005).
[13] M.Smith et al. Finite element modeling of the compressive response of lattice structures manufactured using the selective laser melting technique. International Journal of Mechanical Sciences. 67, 28-41 (2013).
[14] Fuhong Dai et al. A multi-stable lattice structure and its snap-through behavior among multiple states [J]. Composite Structures, 97, 56-63 (2013).
[15] Patrick S. Chang et al. The Size Matching and Scaling Method: A Synthesis Method for the Design of Mesoscale Cellular Structures. In: International Conference on Manufacturing Automation, 79-86 (2010).
[16] Bey Vrancken et al. Heat treatment of Ti6Al4V produced by Selective Laser Melting: Microstructure and Mechanical Properties. Journal of Alloys and Compounds, 541(0), 177-185 (2012).