Effective Elastic Properties of Additively Manufactured Metallic Lattice Structures: Unit-cell Modeling

O. Fashanu, D. Murphy, M. Spratt, J. Newkirk and K. Chandrashekhara
Missouri University of Science and Technology, Rolla, MO 65409

B. Brown and J. Porter
Department of Energy's Kansas City National Security Campus, Kansas City, MO 64147

Abstract

Lattice structures are lightweight materials, which exhibit a unique combination of properties such as air and water permeability, energy and acoustic absorption, low thermal conductivity, and electrical insulation. In this work, unit-cell homogenization was used to predict the effective elastic moduli of octet-truss (OT) lattice structures manufactured using selective laser melting (SLM). OT structures were manufactured using a Renishaw AM 250 SLM machine with various relative densities. Compression test was carried out at strain rate 5×10^{-3} m^{-1} using an MTS frame. Finite element analysis was used in the determination of the OT's effective elastic properties. Results from the finite element analysis were validated using experiments. It was observed that the finite element predictions were in good agreement with the experimental results. This work was funded by the Department of Energy's Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing & Technologies, LLC under contract number DE-NA0002839.

1. Introduction

The development and continuous improvement of additive manufacturing methods have dramatically changed the way designers and engineers pursue design and manufacturing [1]. Additive manufacturing, widely known as 3D-printing, is a method that forms parts from powder, wire, or sheets in a process that proceeds layer-by-layer [2]. This process has been used in many fields for concept modeling; for example, to manufacture customized and lightweight cellular structures.

Cellular structures, which include honeycombs, lattice structures, and foams, are lightweight structures that exhibit excellent mechanical, thermal, and acoustic properties. These structures are excellent candidates for applications, which require a high strength to weight ratio as used in the aerospace industry [3-4]. The properties of cellular structures are dependent on three factors: the topology of the cellular structure, the properties of the parent material, and the relative density ($\bar{\rho}$) of the lattice structure. The mechanical performance of cellular structures are usually estimated by the effective properties. Considering the same material and relative density, the topology controls the deformation mode (bending or stretching) of the structure. According to Gibson and Ashby [5], the strength of bending dominated structures for all loading conditions scales with $\bar{\rho}^{1.5}$, while the strength of stretching dominated structures scale with $\bar{\rho}$. For example, for a relative density of 0.2, a stretching dominated structure is expected to be about two times as strong as a bending dominated structure. The topology space (i.e. different types of topologies) has not been fully investigated due to the cost of trial and error experimentations. Numerical homogenization, a less expensive alternative is proposed in this study as a possible way of investigating different topologies.

In this study, a unit-cell homogenization model was developed to predict the effective elastic properties of an octet-truss structure. The unit-cell homogenization predictions were compared against experimental results to review the accuracy of the homogenization method.

2. Theory

Numerical homogenization has been used to predict the mechanical properties of composites [6-7]. It involves the transformation of a heterogeneous solid into a homogenous solid. The effective elastic properties of the homogenous body is determined by the relationship between the average stress and average strain in a unit-cell or representative volume element (Eq. 1). Equations 2 and 3 show the estimate of the average stresses and strains.

$$\{\bar{\sigma}_{ij}\} = [C_{ijkl}]\{\bar{\varepsilon}_{ij}\} \tag{1}$$

$$\bar{\sigma}_{ij} = \frac{1}{V}\int_V \sigma_{ij}\, dV \tag{2}$$

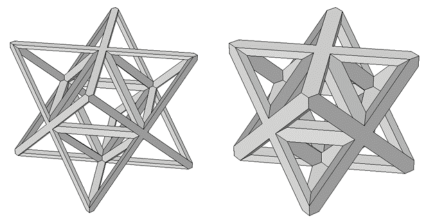
$$\bar{\varepsilon}_{ij} = \frac{1}{V}\int_V \varepsilon_{ij}\, dV \tag{3}$$

In this study, the numerical unit-cell homogenization approach was used to evaluate the effective elastic properties of two different OT structures.

3. Methodology

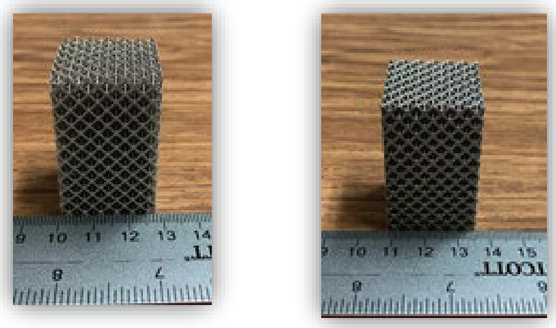
3.1. Manufacturing of test specimens

A Renishaw AM250 SLM machine was used to manufacture two different octet-truss (OT) structures. OT-A was designed with a relative density ($\bar{\rho}$) of 0.05 (Fig. 1a) and cell size of 4.56 mm, while OT-B was designed with $\bar{\rho}$ of 0.2 (Fig. 1b) and cell size 4.56 mm. Both OT structures had a configuration of 6 × 6 × 10 unit cells (Fig. 2).



(a) (b)

Figure 1. OT unit-cell (a) relative density 0.05, (b) relative density 0.20



(a) (b)

Figure 2. Manufactured OT structures (a) relative density 0.05, (b) relative density 0.20

3.2. Mechanical testing

Mechanical compression testing of the manufactured OT structures was performed using an MTS 380 frame. The crosshead speed was set at 0.228 mm/min, resulting in a nominal strain rate of 5 × $10^{-3}min^{-1}$. Three specimens were tested for each OT structure type. After the compression testing, the effective elastic moduli were estimated from the resulting true stress-strain curves.

4. Results and Discussion

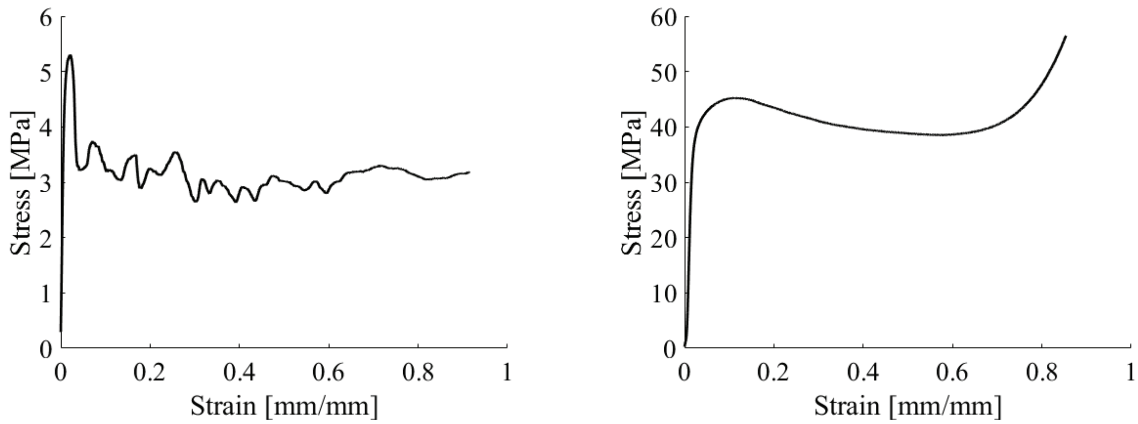
4.1. Experimental results

At the completion of each compression test, the true stress-strain curves were obtained by dividing the force by the actual cross-sectional area. The actual cross-sectional area of the OT structure was assumed to increase in the same manner as a solid under compression. Fig. 3 shows the true stress-strain curves of OT-A ($\bar{\rho}$ = 0.05) and OT-B ($\bar{\rho}$ = 0.20). It can be observed that the stress-strain curve of OT-A is different in terms of behavior from OT-B. The difference in behavior can be attributed to the difference in strut thicknesses. The thin struts of OT-A allow it to deform differently when compared to OT-B which had thicker struts. Fig. 3 also shows that the strength and effective modulus increases as the strut thickness increases. The mechanical properties of the two different OT structures are presented in Table 1.

Table 1. Mechanical properties of SLM 304L stainless steel OT structures

	OT-A	**OT-B**

Relative density ($\overline{\rho}$)	0.05	0.20
Effective strength (MPa)	4.28 ± 0.1	34.28 ± 0.2
Effective modulus (GPa)	0.61 ± 0.03	2.77 ± 0.01

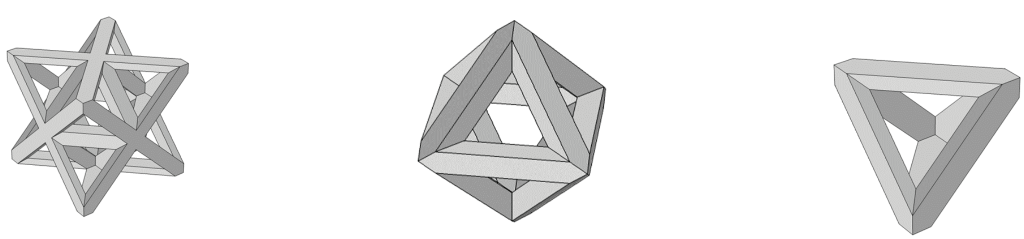


(a) (b)

Figure 3. True stress-strain curve (a) OT-A, (b) OT-B

4.2. Numerical homogenization

In this study, the unit-cell homogenization method was used to predict the effective elastic properties of the OT structure (Fig. 1). The unit-cell was selected because of the low computational cost associated with it. The OT structure consists of an octahedral cell as well as eight tetrahedral cells (Fig. 4). The heterogeneous body was assumed to consist of the combination of the octahedral cell and air. The octahedral cell alone was considered for this analysis because this cell absorbs all the loads within the OT structure [8-9].



(a) (b) (c)

Figure 4. (a) Octet-truss structure, (b) octahedral cell, (c) tetrahedral cell

Numerical homogenization of the OT unit-cell was carried out using ABAQUS commercial software. The used input parameters are shown in Table 2. The mesh used consisted of approximately 94948 tetrahedron solid elements with an average global size of 0.2, as shown in Fig. 5.

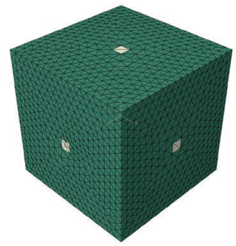


Figure 5. Meshed heterogeneous unit-cell

Table 2. Finite element input parameters

Property	Air [assumed]	Stainless steel
Elastic modulus (Pa)	50E3	165E9 **[3]**
Density (kg/m^3)	1.225	7904 **[10]**
Poisson's ratio	0.3	0.30 [assumed]

In a bid to obtain the constants of the stiffness matrix, three independent loads (Case 1: ε_x=1, ε_y = ε_z= 0, Case 2: ε_y=1, ε_x = ε_z= 0, Case 3: ε_z =1, ε_x= ε_y= 0) were applied to the OT structure using a uniform displacement boundary condition. The effective elastic modulus for the two different OT structures were evaluated using the relationship between the stiffness matrix, compliance matrix, and elastic constants. Fig. 6 and Table 3 show the comparison between the predicted unit-cell homogenization results and the experimental results.

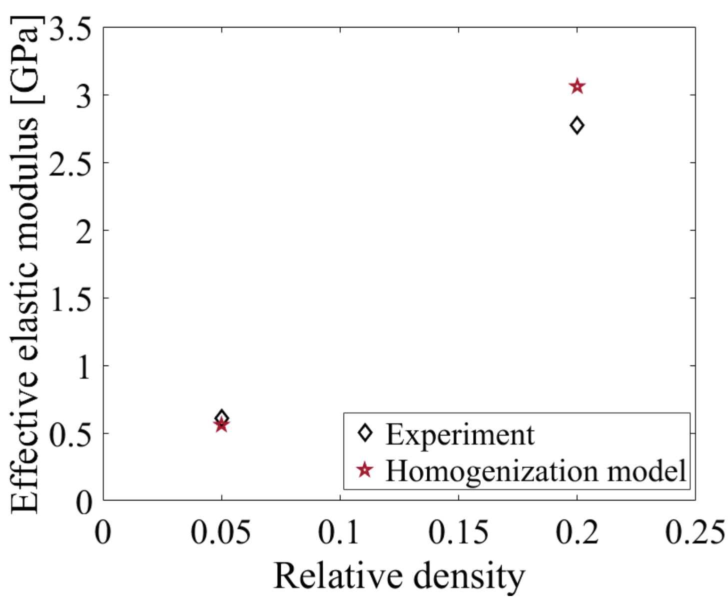


Figure 6. Comparison between the numerical model and experiment

From the figure, it can be observed in both cases (numerical model and experiment) that an increase in relative density led to an increase in stiffness. This increase in stiffness can be attributed to the increase in strut thickness. Increasing the relative density led to an increase in strut thickness, and, a larger strut is expected to have a higher stiffness. From Table 3, it can also be observed that the elastic moduli predicted by the unit-cell homogenization model was within 10% of the experimental results. Therefore, it can be concluded the unit-cell homogenization model can be used to predict the effective elastic properties of cellular structures.

Table 3. Comparison between numerical model and experiment

Property	**Homogenization model**		**Experiment**	
Relative density	0.05	0.20	0.05	0.20
E^*_{11} (GPa)	0.56	3.06	0.61	2.77

5. Conclusion

In order to numerically predict the effective elastic properties of lattice structures manufactured using SLM, a unit-cell homogenization approach was investigated. Two octet-truss structures with different relative densities (0.05 and 0.20) were manufactured and tested. The unit-cell homogenization model was used to predict the effective stiffness of these two structures. From the results, it was observed that the numerical unit-cell predictions were within 10% of the experimental results. As such, it can be concluded that the unit-cell homogenization approach can be used to effectively predict the effective stiffness of lattice structures.

6. Acknowledgments

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