Title:
Optimum Design for Additive Manufacturing of Heterogenous Lattice Structure with Orthotropic Material Model

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Introduction:
Recently, there has been a huge advancement in the field of additive manufacturing [2], bringing both challenges and opportunities to the product design process. Unlike with conventional subtractive manufacturing process, additive manufacturing fabricates parts by the layer-by-layer build strategy. This characteristic of additive manufacturing process enables the ability of complex geometry fabrication which could not be done with conventional manufacturing process. Thus, the design process also needs to change to cope with this essence of additive manufacturing.

Lattice structure (or cellular structure) is well-known as a solution for high performance over weight ratio and multi-functionality structures. With the development of additive manufacturing, the design of lattice structure is far more flexible in comparison with the past, leading to the massive development in this area. This issue permits the development of a field of research so-called design for additive manufacturing (DfAM) with lattice structure. There are several classifications of lattice structures, leading to the existence of many kinds of lattice structure with regard to scale and shapes. In this work, the mesoscale three-dimensional (3D) non-stochastic lattice structure [6] is considered. Also, the heterogenous lattice structure, in which the material distribution is optimally determined by varying the relative density of lattice unit-cells, is specially considered due to its dominant performance over homogenous ones. Fig. 1. Illustrates both homogenous and heterogenous mesoscale non-stochastic lattice structures.

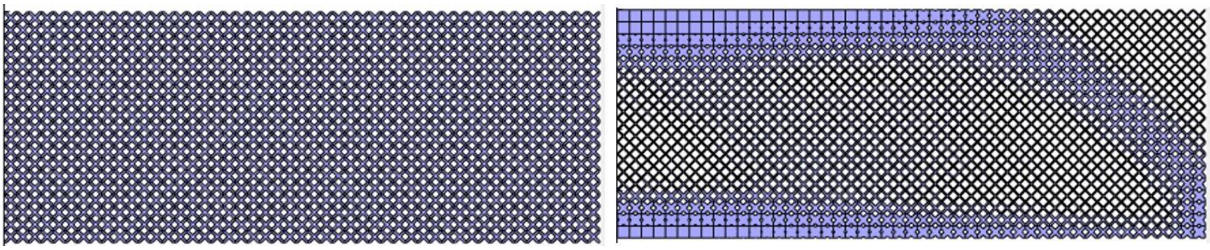

Fig. 1: Non-stochastic lattice structure: (a) Homogenous structure, (b) Heterogenous structure.

Although some of the additive manufacturing constraints have been considered in the design of lattice structure, they are limited in the geometric aspect (such as allowed featured size, self-support constraint and so on). In this work, an optimum design method for additive manufacturing of heterogenous lattice structure with the consideration of not only geometric constraints but also additively manufactured parts' mechanical properties will be proposed. The proposed optimum design method utilized the density-based topology optimization approach with a customized additively manufactured lattice (AM-Lattice) material model to optimally determine the material distribution of heterogenous lattice structure. By doing so, the mechanical behavior of as-built lattice structure will be considered along with sizing constraints.

The contribution of the proposed method in comparison with other methods are: (1) the utilization of a customized AM-Lattice material model, enabling the ability for AM constraints consideration in term of mechanical properties of as-built part and (2) the volumetric approach, enabling the ability of multifunctional structure design.

Main Idea:

There are three main steps in the proposed optimum design method for mesoscale lattice structure which are: (1) derivation of the AM-Lattice material model, (2) optimal distribution of the material by using topology optimization, and (3) 3D reconstruction of lattice structure from the optimization result (Fig. 2.). In this research, to reduce the size and complexity of the design problem, the additive manufacturing term is limited within the fused deposit modeling (FDM) process

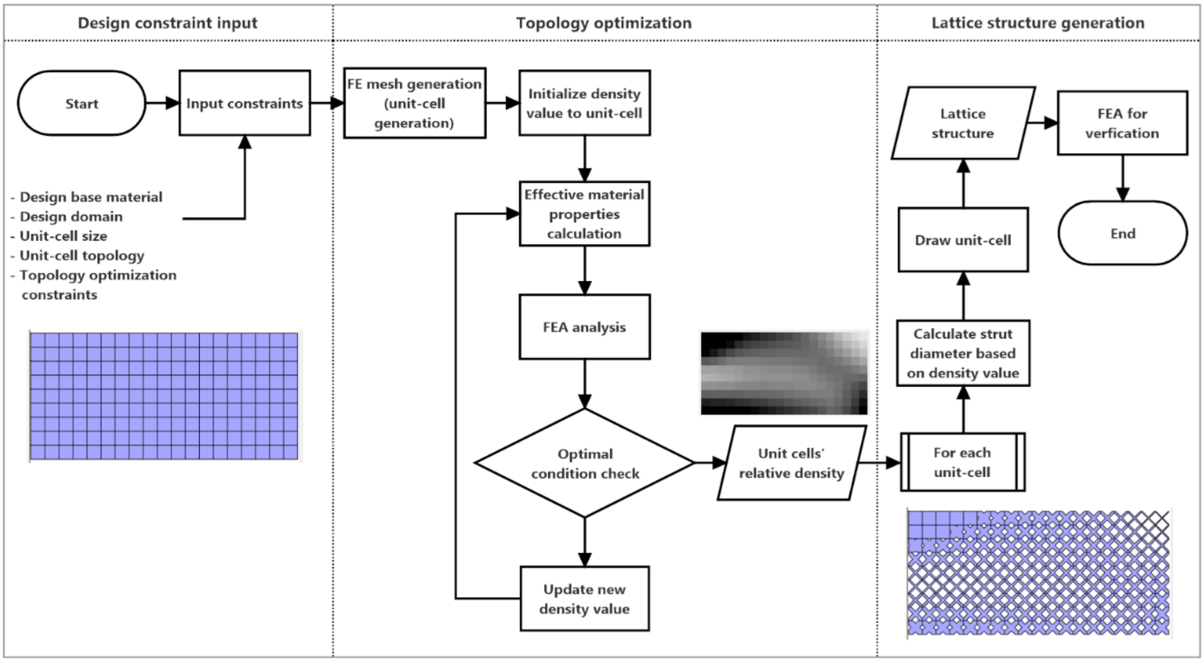

Fig. 2: Overall design workflow.

As illustrated in Fig.2., along with the given design domain, the input design constraints include given base material, unit-cell size and topology type, and additional topology optimization constraints (such as minimum stress allowed and so on). Consequently, a topology optimization process utilizing the FDM-Lattice material model will be performed to optimally distribute the density of the lattice unit-cell. Other AM geometric constraints such as smallest feature size and self-support constraints are also reflected into the topology optimization by limiting the smallest allow relative density of the lattice unit cell. The topology optimization result providing optimal value of unit-cell relative densities will be used as input for the lattice 3D model generation process.

AM-Lattice material model derivation

As being mentioned above, the key issue of this work is the utilization of FDM-Lattice material model in the optimum design. As in [1], one of the most crucial properties of lattice structures is their density-properties relationship which is so-called the 'scaling law'. Several scaling laws have been developed for lattice structures [1, 3, 7]. However, none of the proposed scaling law are successful in replicating the behavior of additively manufactured structures.

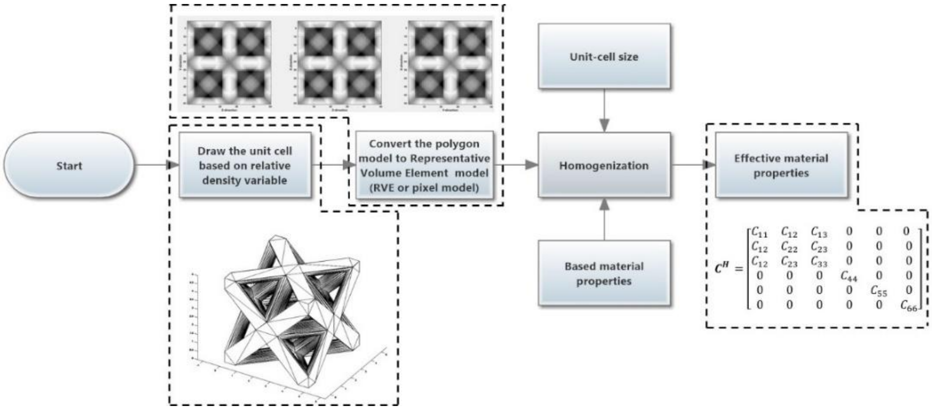

Fig. 3: Homogenization method for lattice effective material properties derivation.

From the literatures, FDM parts and additively manufactured parts in general have anisotropic mechanical properties due to their nature of layer-by-layer fabrication; as a result, the fabricated FDM lattice structure is not an exception. Among many material models have been proposed to model the constitutive law of as fabricated FDM structures, the orthotropic material model is the most acceptable [4]. In this work, the orthotropic material model is used to model the fabricated FDM-Lattice constitutive law. The target of the FDM-Lattice material model establishment process is to derive an effective stiffness matrix as a function of unit-cell relative density. Fig. 3. And Fig. 4. depicts the FDM-Lattice material model of the octet lattice unit-cell by using homogenization and power function regression methods.

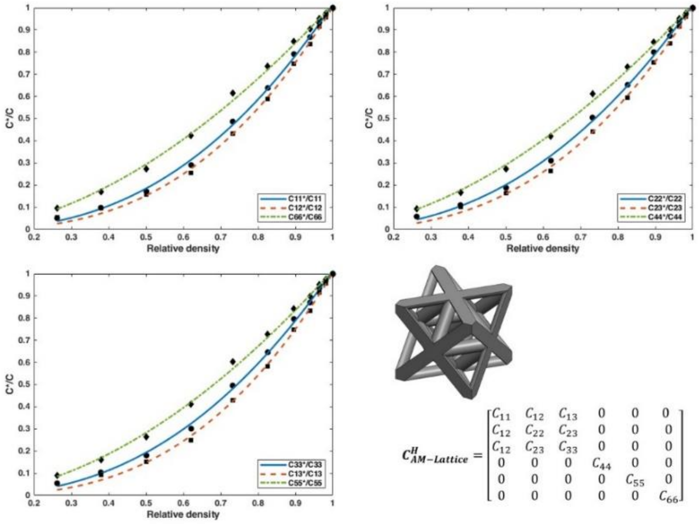

Fig. 4: Scaling law of octet unit cell.

Topology optimization with AM-Lattice material model

The optimization of the compliance minimization problem could be formulated as follow

$$\min c(\boldsymbol{x}) = \boldsymbol{u(x)}^{T} \boldsymbol{K(x)u(x)} \tag{1}$$

s.t

$$\boldsymbol{K(x)u} = \boldsymbol{f}; \tag{2}$$

$$\boldsymbol{C} = \boldsymbol{C(x)}; \tag{3}$$

$$\sum_{e=1}^{N} x_e v_e = V; \tag{4}$$

$$0 \le x_{\min} < x < x_{\max} \le 1; \tag{5}$$

Where $\boldsymbol{x}$ is the relative density of the lattice unit cell, $\boldsymbol{u(x)}$ is the displacement field, $\boldsymbol{K(x)}$ is the stiffness matrix and $c(\boldsymbol{x})$ is the total compliance of the structure. The relative density value $\boldsymbol{x}$ varies within the bound $[x_{\min}, x_{\max}]$ which will be determined by the manufacturing constraints. The FDM-Lattice material model is used as constraints of the optimization process. A volume fraction constraint will be also predetermined. Unlike the conventional density-based topology optimization which utilizes the Solid Isotropic Material with Penalization (SIMP) material model, the proposed method takes into account a customized FDM-Lattice material model which could provide a better scaling law of lattice structure, leading to a better optimum design. The optimization problem could be solved by several methods. In this work, the Optimal Criteria method was used [5]. Fig. 5(b). is the topology optimization result of the cantilever beam design problem illustrated in Fig. 5(a).

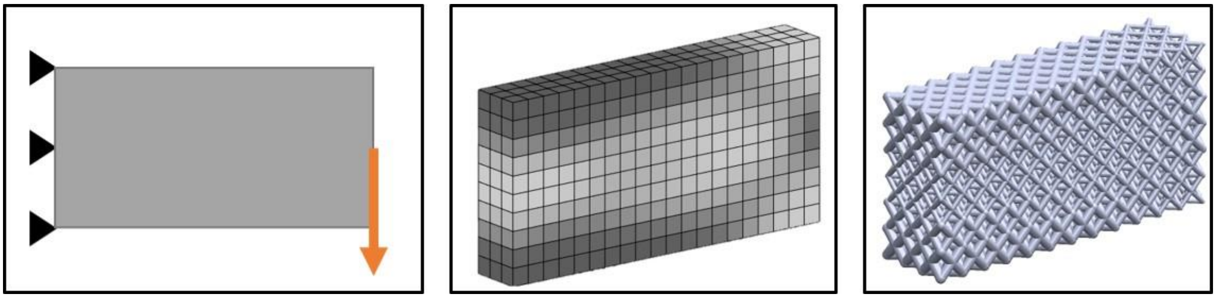

Fig. 5: The cantilever beam design problem: (a) Design problem, (b) Topology optimization result, (c) Lattice structure generation.

Reconstruction for optimal lattice 3D model generation

After the topology optimization process is finished, a 3D reconstruction process will be needed for the generation of optimally designed lattice structure 3D model which could be used either for fabrication or for downstream application. As illustrated in Fig. 2., the determination of unit cell geometric parameters is the most crucial. In the case of truss-based lattice unit cell, a regression method as proposed in [1] could be utilized. In this model, the ratio of strut diameter over unit cell size could be formulated as a function of unit cell relative density. Thus:

$$D / l = f(x) \tag{6}$$

Where l is the unit cell size, D is the strut diameter, and *x* is the unit cell relative density. Fig. 5(c). is the 3D model of the optimum design result of the cantilever beam problem.

Conclusion:

In this paper, a method for optimum design of lattice structure with customized FDM-Lattice material model has been proposed. The proposed design method has been successfully reflected the mechanical properties of additively manufactured parts into the optimum design by using the orthotropic material model. In the future, the design process for conformal lattice structure as well as build orientation optimization for minimizing the anisotropic effect of additive manufacturing on structure performance will be considered.

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