Lattice-skin Structures Design with Orientation Optimization

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Abstract

Parts with complex geometry can be produced by an additive manufacturing process without a significant increase of fabrication time and cost. One application of AM technologies is to fabricate customized lattice structures to enhance products' performance with less material and less weight. Thus, design methods of customized lattice structures have recently attracted great research interests. Most existing design methods only consider the distribution of lattice struts' thickness as a primary design variable for customized lattice structures. Few of them notice the importance of lattice orientation with regard to its structural performance. In this paper, a design method for customized lattice-skin structures is proposed to optimize the distribution of lattice orientations inside the design domain. In this design method, an initial Functional Volume (FV) is divided into several sub-FVs and connected with additional Functional Surfaces (FSs). The orientation of uniform lattice in each sub-FV is regarded as the design variable. To optimize the design variables, an equivalent analysis model based on the effective orthotropic properties of lattice structures is built. On the basis of this model, genetic algorithm is applied to obtain the optimized distribution of lattice orientations. Two case studies are provided at the end of this paper to validate the proposed design method.

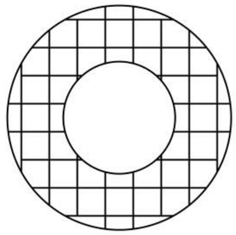
1 Introduction

Lattice structures are a unique classification of cellular structures. This type of structure can be regarded as a space truss structure composed of struts, nodes with certain repeated arrangement in three-dimensional space. Among different cellular structures, lattice structures are the most attractive type for their inherent advantages. Firstly, compared to those disordered cellular foam, only a small portion of a lattice structure is needed to determine its properties for the high degree of order. Thus, this type of structure enables designers much more freedom to realize their design goals. Besides that, lattice structures can also be designed to be a stretching dominated structure for load bearing with high stiffness as well as a bending dominated structure for compliant mechanism with a large deformation. Due to the aforementioned reasons, lattice structures have high potential in a wide range of applications, such as automobile, aerospace and medical devices and bio-implants.

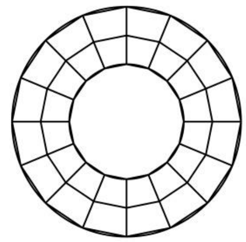
However, the high manufacturing complexity is always the biggest barrier for the wide application of lattice structures. Traditionally, lattice structures are usually fabricated by conventional manufacturing techniques such as sheet-metal forming, investment casting and metal wire bonding. These fabrication processes are both time and cost consuming. Moreover, because of manufacturing limitation, only the lattice structures with simple external geometry and some specific topologies can be fabricated, which severely restricts the design freedom to achieve advanced functionalities. Recently, this situation has been changed by the rapid development of Additive Manufacturing (AM) technologies. AM enables the fabrication of lattice structures without additional cost and time. Moreover, it also provides more design freedom to further optimize the lattice structures for the improvement of functional performance. To take full advantage of those design freedom provided by AM for the fabrication of a wide variety of lattice structures, some research has been done on the optimization of lattice structures for a better functional performance. Most of them focus on redistribution of material inside lattice structures. To achieve this purpose, there are two ways. The first way is to optimize the distribution of lattice strut's thickness. For example, an optimization method of lattice strut's thickness is proposed by Rosen [1]. In this design method, the thickness of lattice strut is regarded as design variables. To reduce the number of design variables, lattice struts are divided into ten groups and the thickness of struts in each group are supposed to be equal. Besides directly taking lattice strut's thickness as a design variable, different topology optimization methods [2, 3] have also been used to optimize the distribution of lattice strut's thickness. In these design methods, the thickness of each lattice strut has been decided by the optimal relative density distribution which can be obtained from the topology optimization methods. To further reduce the number of design variables, a heuristic optimization method of lattice structure is recently developed by Nguyen et al.[4]. In this optimization method, there are only two design variables which are the largest and smallest strut's diameter. The diameter of each strut can be interpolated between these two design variables based on local stress value.

The second way to achieve the optimal distribution of material is to change the lattice frame. Originally, a lattice structure consists of several lattice unit cells which are periodically distributed inside 3D space. To achieve the optimal distribution of material, some techniques have been used to reshape the lattice unit cells. Thus, the frame of a lattice structure has been changed. For example, based on a space warping technique, a lattice frame design method has been proposed by Chen [5] to redistribute material according to the stress distribution of a designed structure. Brackeet et al. [6] recently proposed another similar design method for a lattice frame. Instead of using space warping technique in Chen's method, a dithering method is used to represent a gray scale stress fringe with variably spaced black dots. These spaced black dots can be also used as the lattice cell's vertices. Like Chen's approach, this design method also enables the variation of lattice size and shape according to stress distribution inside the design space.

Besides those design methods which aim to redistribute material inside a design domain for a better performance, a few design methods are proposed to adapt lattice unit cell's shape and orientation according to given design conditions. Design methods of a conformal lattice structure are firstly proposed by Wang and Rosen [7-9]. Differences between a conformal lattice structure and an ordinary periodic lattice structure are shown in Figure 1. It is clear that both shape and orientation of lattice unit cells are changed to adapt to macro shape of the design domain. A case study has been provided by Wang to compare the performance between a conformal lattice and an ordinary periodic lattice. The result shows that a conformal lattice may have a better strength than periodic lattice since the lattice unit cells are reoriented according to the external loads. Instead of conforming to the macro shape of the design domain, a design method of load adaptive lattice is proposed by Teufelhart and Reignhart [10-12]. In this design method, lattice frame is built based on the force flux inside the design domain, which can align the orientation of each lattice unit cell along the principal stress direction. Thus, the structural performance of the designed structure can be improved by this design method.



(a) Periodic lattice structure



(b) Pseudo-periodic lattice structure

Figure 1 Difference between periodic lattice and conformal lattice

To summarize the existing design methods of lattice structures, it is clear most of them focus on redistribution of material inside the design domain. Only a few of them consider the effect of lattice orientation on the structural performance. Moreover, there are also some limitations of those design methods for lattice orientation. For example, geometrical conformal lattice cannot guarantee a better functional performance than that of periodic lattice. Furthermore, to generate a conformal lattice structure for arbitrary design domain is still a difficult task. As to load adaptive lattice, the frame of this type of lattice structures is built based on the analysis of design domain filled with solid materials. However, when the solid material is replaced by lattice structures, both stress and strain fields may change. Thus, the orientation of a lattice unit cell is no longer accordant with local principle stress direction. To deal with these limitations of existing lattice design method, a design method of a lattice-skin structure is proposed in this paper to optimize the lattice orientation. Compared to existing design methods, the proposed design methods can deal with design domain that has arbitrary shape. Moreover, this design method is also easy to implement without a heavy computational burden.

In this paper, several basic concepts are first introduced in the Section 2. Based on these basic concepts, a detailed discussion on the proposed process is presented in Section 3. In Section 4, two cases studies are given to validate the efficiency of the proposed design method. At end, this paper is wrapped up with a short conclusion and some future research work.

2 Basic concepts

2.1 Functional Volumes and Functional Surfaces

In the proposed design method, Functional Volumes (FVs) and Functional Surfaces (FSs) are used to represent the design space which can satisfy given functional requirements. These two concepts have been defined in the previous research [13] where a FV is a geometrical volume designed for certain functional purposes, while a FS is a geometrical surface which can fulfill certain functional requirements. A typical example of FSs and FVs is shown in Figure 2. In this example, there are seven FSs which are in green color. These FSs generally play to three functions. Two FSs at the bottom of pedestal bearing mainly provided support for the designed part. Two cylindrical surfaces and their connected top surfaces are used for the assembly of connection bolts. The big cylindrical surface at the top of part is designed to provide support for the connected shaft. To connect these seven FSs, a FV is given, which is in grey color shown in Figure 2.

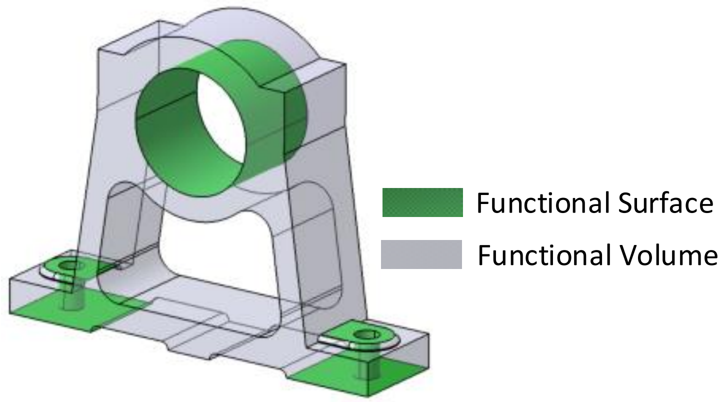


Figure 2 An example of functional surfaces and a functional volume

Both FSs and FVs can be obtained from the conceptual design stage. Thus, in this design method both FSs and FVs are assumed as inputs. During the design process, the input FVs can be filled with either solid material, lattice structure or a combination of them. In the proposed design method, the input FVs can be categorized into two groups according to their features on a mesoscale. They are FVs with lattice and FVs with solid material. As for those FVs filled with a combination of lattice and solid material, a further decomposition should be done to divide them into these two basic types FVs mentioned above. An example of FV decomposition is shown in Figure 3. In this example, the initial FV are divided into two FVs based on stress distribution calculated from the initial analysis. A solid material is used to fill FV1 which has a relatively high stress. As for FV2, due to the relatively low stress, the lattice structure is used. Moreover, to connect two new generated FVs, the additional FS is used which is also shown in Figure 3.

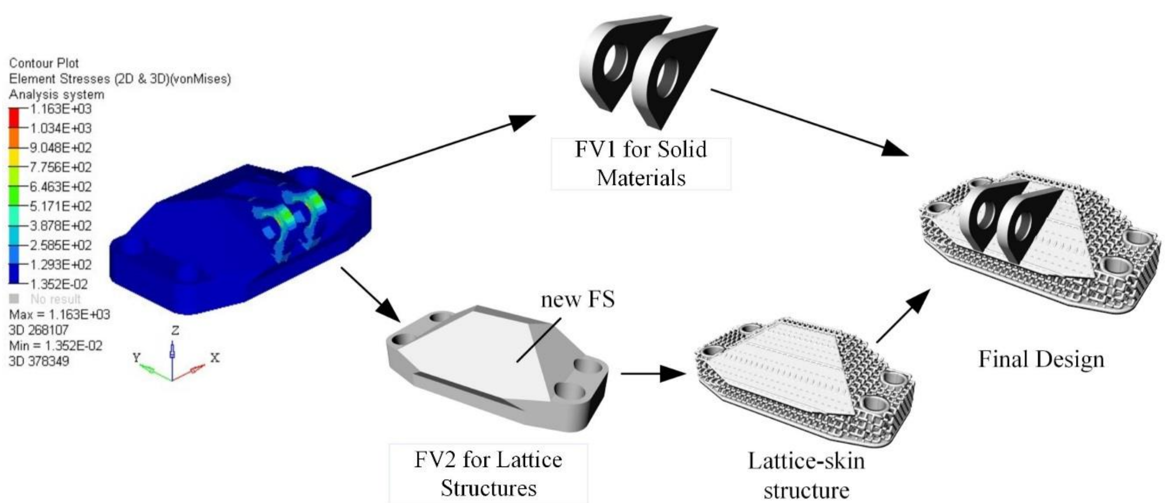


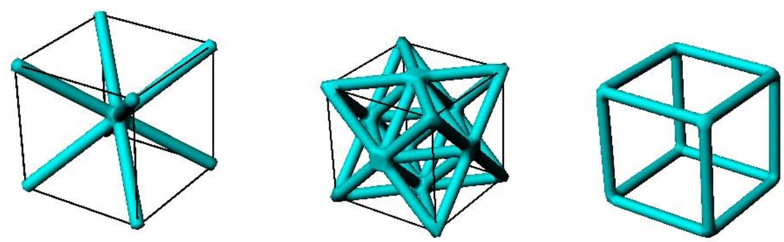
Figure 3 Decomposition of FV

Based on the given FSs and FVs, the design method described in this paper can be regarded as the process of seeking an optimized distribution of lattice orientation inside those

FVs filled with lattice structures. To realize this design purpose, the FVs with lattice structures are further divided into several sub-FVs which are connected by additional FSs. These sub-FVs will be filled with lattice structures in different orientations, which can further improve the functional performance of designed structures.

2.2 Effective material model for lattice structure

In this paper, we only consider linearly elastic design with orthotropic lattice structures. Some typical unit cells of orthotropic lattice structures are shown in Figure 4. It is clear that there are three mutually orthogonal symmetric planes for each unit cell. Thus, a Cartesian coordinate system can be built based on these three symmetric planes. This Cartesian coordinate system is called as lattice local coordinate system in this paper.



(a) "X" shape lattice **(b) Octet lattice** **(c) Square lattice**

Figure 4 typical orthotropic lattice topology

To reduce the computational load during the optimization process, the uniform lattice structures on a meso-scale are regarded as anisotropic homogenous materials on a macro-scale. The macro effective material properties in given FVs are characterized by the constitutive law shown below:

$$\sigma_{ij} = C_{ijkl}^{eff} \varepsilon_{kl} \tag{1}$$

Where C_{ijkl}^{eff} is the rotated effective stiffness tensor of lattice structure; σ_{ij} is the macro stress tensor and ε_{kl} is the macro strain tensor. In this paper, Voigt-Kelvin notation is used to describe the above tensors in a matrix form. To calculate the rotated effective stiffness tensor, the unrotated effective stiffness tensor $C_{0_{ijkl}}^{eff}$ must firstly be calculated. In this paper, an energy based homogenization method [14] is used to calculate the unrotated effective stiffness tensor in the lattice local coordinate system. Due to the symmetric properties, the unrotated stiffness tensor $C_{0_{ijkl}}^{eff}$ can be expressed in matrix notation as

$$\mathbf{C}_0^{eff} = \begin{bmatrix} c_{11}^0 & c_{12}^0 & c_{13}^0 & 0 & 0 & 0 \\ c_{21}^0 & c_{22}^0 & c_{23}^0 & 0 & 0 & 0 \\ c_{31}^0 & c_{32}^0 & c_{33}^0 & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44}^0 & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55}^0 & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66}^0 \end{bmatrix} \tag{2}$$

Where $\mathbf{C}_0^{eff}$ is the matrix form of tensor ${C_0}_{ijkl}^{eff}$. Based on the unrotated stiffness tensor, the following tensor transformation relationship can be used to calculate the rotated stiffness tensor:

$$C_{ijkl}^{eff} = \lambda_{im}\lambda_{in}\lambda_{ko}\lambda_{lp}{C_0}_{mnop}^{eff} \tag{3}$$

This relationship can also be expressed in the matrix form as:

$$\mathbf{C}^{eff} = \mathbf{Q}^{T} \cdot \mathbf{C}_0^{eff} \cdot \mathbf{Q} \tag{4}$$

Where $\mathbf{C}^{eff}$ is the matrix form of rotated stiffness tensor. $\mathbf{Q}$ is the rotational matrix which is defined as:

$$\mathbf{Q} = \begin{bmatrix} l_{11}^2 & l_{12}^2 & l_{13}^2 & l_{12}l_{13} & l_{11}l_{13} & l_{11}l_{12} \\ l_{21}^2 & l_{22}^2 & l_{23}^2 & l_{22}l_{23} & l_{21}l_{23} & l_{21}l_{22} \\ l_{31}^2 & l_{32}^2 & l_{33}^2 & l_{32}l_{33} & l_{31}l_{33} & l_{31}l_{32} \\ 2l_{21}l_{31} & 2l_{22}l_{32} & 2l_{23}l_{33} & l_{22}l_{33}+l_{23}l_{32} & l_{21}l_{33}+l_{23}l_{31} & l_{21}l_{32}+l_{22}l_{31} \\ 2l_{11}l_{31} & 2l_{12}l_{32} & 2l_{13}l_{33} & l_{12}l_{33}+l_{13}l_{32} & l_{11}l_{33}+l_{13}l_{31} & l_{11}l_{32}+l_{12}l_{31} \\ 2l_{11}l_{21} & 2l_{12}l_{22} & 2l_{13}l_{23} & l_{12}l_{23}+l_{13}l_{22} & l_{11}l_{23}+l_{13}l_{21} & l_{11}l_{22}+l_{12}l_{21} \end{bmatrix} \tag{5}$$

The component l_{ij} in the Eq.5 can be obtained from the transformation matrix between lattice local coordinate system and global coordinate system.

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \mathbf{L}\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} l_{11} & l_{12} & l_{13} \\ l_{21} & l_{22} & l_{23} \\ l_{31} & l_{32} & l_{33} \end{bmatrix}\begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{6}$$

Where l_{ij} is the component of transformation matrix $\mathbf{L}$; $(x, y, z)^T$ and $(x', y', z')^T$ are the representations of a vector $\mathbf{A}$ in lattice local and global coordinate system respectively. In this research, the relationship between lattice local system and global coordinate system is parameterized with triplet Euler angles (α, β, γ) in ZYZ order, which is demonstrated in Figure 5. In this parametrization scheme, the lattice local coordinate system is regarded as a reference coordinate system. Thus, the global coordinate system for structural analysis is the derived system from the reference coordinate system. The transformation matrix between a referenced coordinate system and a derived coordinate system can be obtained according to the definition of Euler angle, which can be expressed as:

$$\mathbf{L} = \begin{bmatrix} \cos\alpha\cos\beta\cos\gamma - \sin\alpha\sin\gamma & \sin\alpha\cos\beta\cos\gamma + \cos\alpha\sin\gamma & -\sin\beta\cos\gamma \\ -\cos\alpha\cos\beta\sin\gamma - \sin\alpha\cos\gamma & -\sin\alpha\cos\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\beta\sin\gamma \\ \cos\alpha\sin\beta & \sin\alpha\sin\beta & \cos\beta \end{bmatrix} \tag{7}$$

Based on Eq.4-7, the rotated effective stiffness tensor $\mathbf{C}^{eff}$ can be calculated from the unrotated stiffness tensor $\mathbf{C}_0^{eff}$. In the proposed design method, the rotated stiffness tensor is used in the optimization process to evaluate the performance of designed structures.

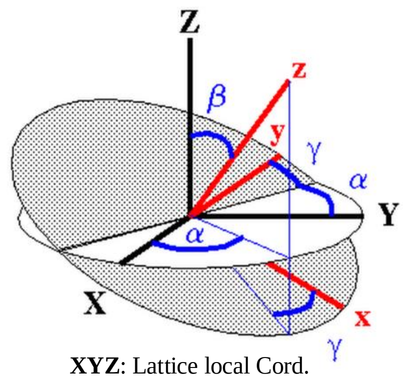


Figure 5 Relationship between lattice local coordinate and global coordinate

3 Proposed design method

The general design flow of the proposed design method is shown in Figure 6. It consists of six major design steps. These six design steps can be further divided into two categories. The first three design steps are used to prepare the equivalent analysis model. Based on this equivalent analysis model, the next three steps are applied to obtain the optimized distribution of lattice orientations and generate the optimized lattice-skin structure. In the next two sub-sections, the details about these major design steps will be discussed.

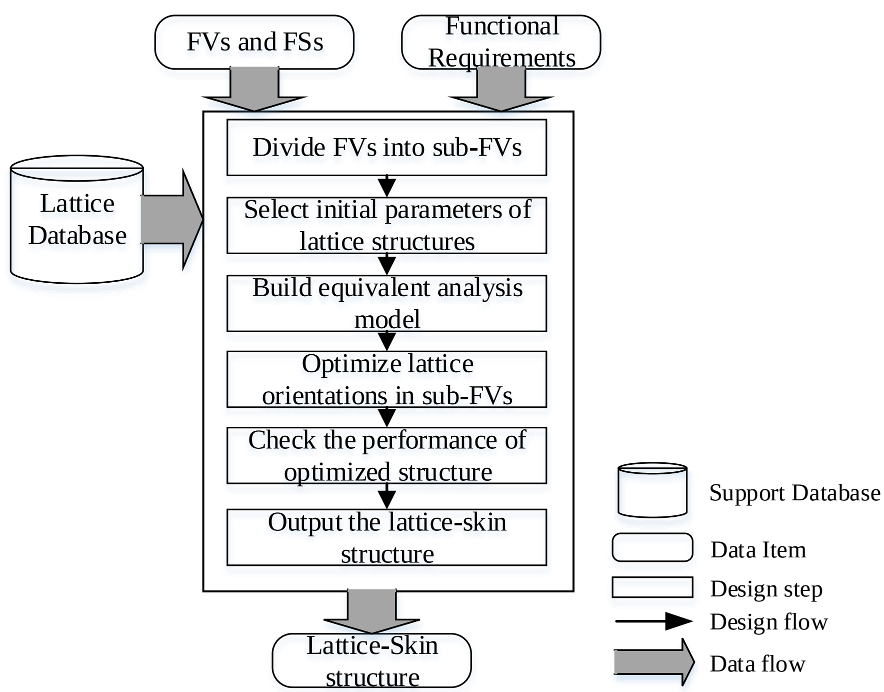


Figure 6 General design flow

3.1 Equivalent analysis model

The equivalent analysis model plays a pivotal role in the overall design process. The structural response calculated from this equivalent analysis model will be used in the following orientation optimization process. Thus, both accuracy and computational load should be considered in the equivalent analysis model. To achieve these purposes, a multi-material structural model is used as the equivalent analysis model in this paper. In this model, the effective orthotropic material properties of lattice structures in each sub-FV are firstly determined based on a homogenization method and its lattice orientation. Then, these properties are assigned to the elements for each sub-FVs respectively. For other elements which represent FSs and FVs filled with solid material, the solid isotropic material model is used to describe their material properties. The detailed steps of building this equivalent analysis model will be discussed in the following paragraphs.

The first step of building the equivalent analysis model is to divide the initial FVs with lattice into several sub-FVs. As it mentioned in the Section 2.1, the lattice orientations in these sub-FVs will be regarded as the design variables during the optimization process. This paper offers two different ways to generate these sub-FVs. One of them is to direction divide the FVs according to its macro shape or load condition. The example of sub-FV generation for arch structures is shown in Figure 7. In this example, the initial FV are divided into 4 sub-FVS along the circumferential direction. This generation method of sub-FVs is suitable for those FVs with regular shapes. For those FVs with irregular shapes, solid meshing method is used to generate coarse volume elements for given FVs. These volume elements can be used to construct the sub-FVs. In this step, another factor which designers should consider is the number or the size of sub-FVs for each given FV. It is apparently a large number of sub-FVs or small size of sub-FVs will provide more design freedom to achieve the optimal orientation distribution. However, it should also be noted that the increasing of the number of sub-FVs will also lead to the increasing of design variables and computation load. Moreover, more additional FSs will be added to further increase the weight of a structure. Thus, an overall consideration is needed for designers to select an appropriate number of sub-FVs.

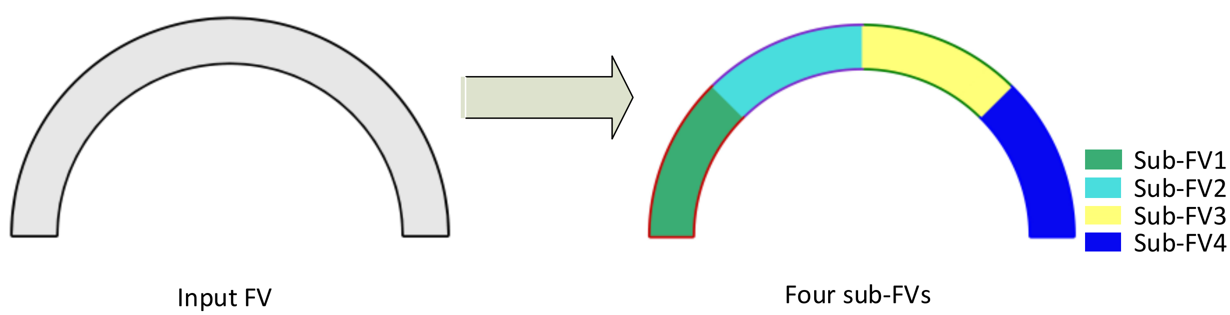


Figure 7 Generation of sub-FVs

Then, the initial parameters of lattice structures are selected based on the general functional requirements and initial structural analysis. These initial parameters include topology of the lattice unit cell, size of lattice unit cell and the relative density of lattice structures. To facilitate the selection process, a database which stores the properties of different types of lattice properties are needed. In this database, lattice structures on a meso scale are regarded as homogenous material on a macro scale. Effective properties are associated with lattice structures with different topology. The material selection method proposed by Ashby and Cebon [15] can be used to select appropriate lattice topologies for given design problems. It should be noted that the selection step of lattice topology may generate multiple results. Thus, further work is needed to compare the performance of these lattice structures with different topologies. Based on the selected lattice topology, the relationship between lattice relative density and lattice properties such as stiffness or thermal coefficient rate can be calculated. This relationship can help designers to determine the appropriate relative density of a lattice structure in each sub-FVs. As to lattice unit cell size, designers should consider both the characteristic dimension of a designed structure and the capability of selected manufacturing method. Generally, the unit cell size should be smaller than a tenth of the characteristic dimension of macro structure.

Based on the selected parameters of lattice structures, the unrotated effective properties of lattice structures can be calculated by homogenization method. In the following optimization process, the orientation of a uniform lattice structure in each sub-FV is given and regarded as a design variable. Based on lattice orientation and calculated effective properties, the rotated effective properties of the lattice structure in each sub-FV can be obtained. These rotated effective properties will be assigned to the elements in different sub-FVs respectively. At the end, the FEA method can be applied to solve this equivalent analysis model for its structural response under given boundary conditions. This structural response will be used to optimize the distribution of orientations inside FVs, which will be discussed in the next sub-section.

3.2 Orientation Optimization

Based on the equivalent analysis model discussed in the previous subsection, the optimization process can be applied to obtain the distribution of lattice orientation inside FVs. This paper mainly focuses on the design of structural stiffness. Thus, the strain energy of the designed structure under given boundary conditions is regarded as the optimization objective. To increase the stiffness of designed structure, the optimization problem of lattice orientation can be expressed as:

$$\begin{aligned} \text{min:} \quad & p(\boldsymbol{\theta}) = \frac{1}{2}\int \sigma_{ij}(\boldsymbol{\theta})\varepsilon_{ij}(\boldsymbol{\theta})\, dV \\ \text{S.T.:} \quad & \sigma_{ij} = C_{ijkl}^{eff}(\boldsymbol{\theta})\varepsilon_{kl} \end{aligned} \tag{8}$$

Where $\boldsymbol{\theta}$ is a vector of design variables. Its component θ_i is the Euler angle of lattice structures for the ith sub-FV. It should be noted from Eq.8 that both strain and stress fields are implicit functions of lattice orientation variables. They will change with the variations of orientation variables. Thus, it is difficult to analytically calculate the gradient of objective functions with respect to lattice orientations. Some relaxations have been made in existing optimization methods for orthotropic material. For example, in the strain based method [16], the strain field is assumed to be invariable with respect to the variation of orientation variables, while in the stress based method[17] , the stress field is assumed to be fixed. Besides these relaxations, finite difference method can also be used to calculate the gradient of objective function. However, the computational load of this method largely depends on the number of design variables. In view of these difficulties, a non-gradient based genetic optimization method is used in this paper. The flowchart of the genetic optimization algorithm used in this paper is described in Figure 8. It consists of six major steps. In the optimization process, the equivalent analysis model discussed in the previous sub-section will be used to calculate the value of objective function. This result will be considered as the fitness for each individual in every generation. Moreover, the maximum iteration number is defined as the stop criterion of the optimization algorithm used in this paper.

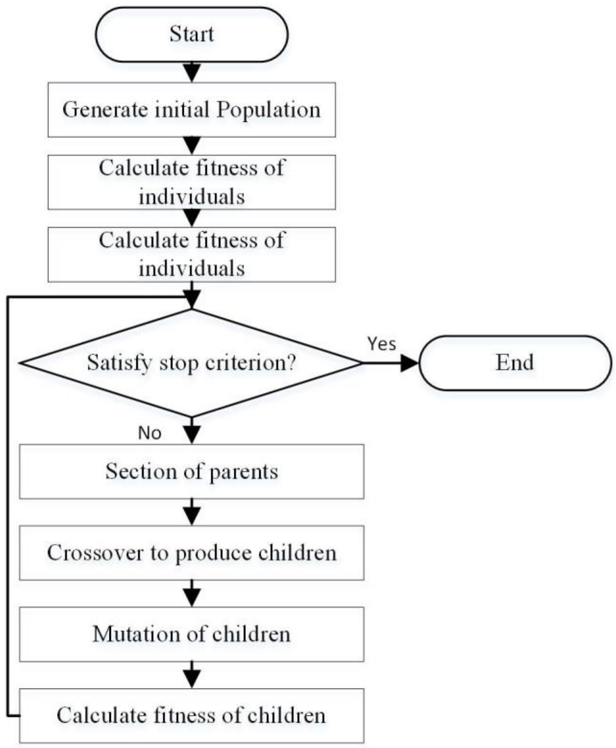


Figure 8 A general flow genetic algorithm

After the optimization process, the optimal distribution of lattice orientation in sub-FVs can be obtained. Based on the optimization result, the lattice-skin structure can be constructed for desired functional performance. To further verify the performance of designed lattice structures, another analysis model of generated lattice-skin structure is used after the orientation optimization. In this analysis model, a lattice-skin structure is considered as a truss structure with the combination of solid FVs and the skins generated based on FSs. In this structure, beam elements are used to represent the lattice struts, while tetrahedron elements are used to mesh solid FVs and skins. FEA is applied to solve this analysis model. Compared to the equivalent analysis model used in the optimization process, this verification model contains more detailed information on a meso-scale. Thus, it can provide a more accurate result. However, the computational load will also increase significantly compared to the equivalent analysis model used in the optimization process. Thus this model is only used at the end of a design process to check the functional performance of optimized structure. After verification process, the 3D model of optimized lattice-skin structure can be built by CAD software and fabricated by AM processes.

4 Case study

In this section, two different design cases are given to validate the proposed design method. The input FSs and FVs with given load and boundary conditions are shown in Figure 9 for these two design cases. In Figure 9, q represents a uniform pressure whose value equals to 1 MPa. To reduce the weight of designed structures, these two FVs will be filled with lattice structures in the following design processes.

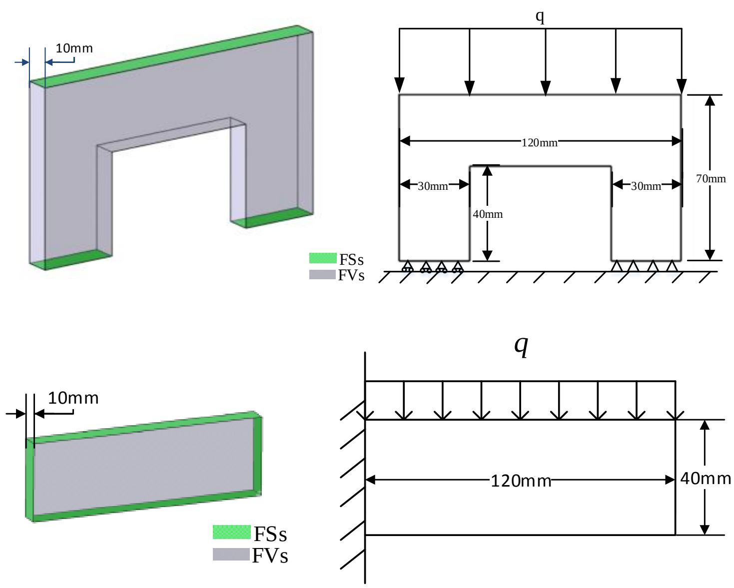


Figure 9 The input FSs and FVs of two design cases

This paper mainly focuses on the optimization of lattice orientation. Thus, for simplicity, lattice structures with the given initial parameters shown in Table 1 are supposed to fill those two input FVs. Moreover, Table 1 also provides the initial thickness of skins which is used to represent FSs in the design cases.

Table 1 Initial parameters of lattice-skin structure

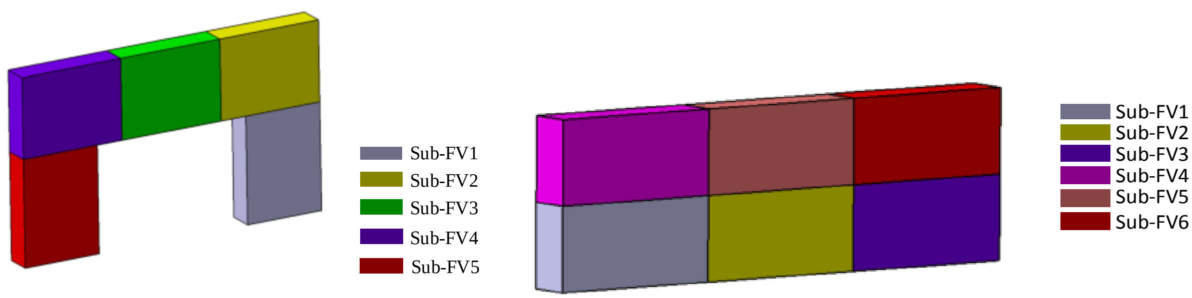
Lattice Topology	Lattice Size(mm)	Strut's thickness(mm)
Square lattice	$2 \times 2 \times 2$	0.3

In these two design cases, all of external loads are in-plane loads and parallel to XY plane. Moreover, dimensions of given FVs on z direction are smaller than the dimensions on x or y direction. Thus, given FVs can be regarded as 2D plates and the structural analysis of these two design cases can be simplified as plane stress problems. Based on this simplification, the design variable of lattice orientation can also be simplified by assuming Euler angles β and γ as zero. This means lattice only rotated with respect to Z axis on XY plane. Moreover, due to the symmetrical properties of lattice topology, the Euler angle α only varies in the range of 0 to 90 degree.

To optimize the distribution of lattice orientation in given FVs. The given FVs for two design cases are divided into sub-FVs which are shown in Figure 10. Based on these sub-FVs, the equivalent analysis models of the two design cases are built respectively. In these equivalent analysis models, the effective material properties of lattice structures with given parameters are calculated by an energy based homogenization method. In the calculation process of lattice effective properties, the solid material is assumed to have normalized Young's modulus which equals to 2.1E5 MPa and Poisson Ratio which equals to 0.3. The calculation result of effective properties is shown in Eq.9.

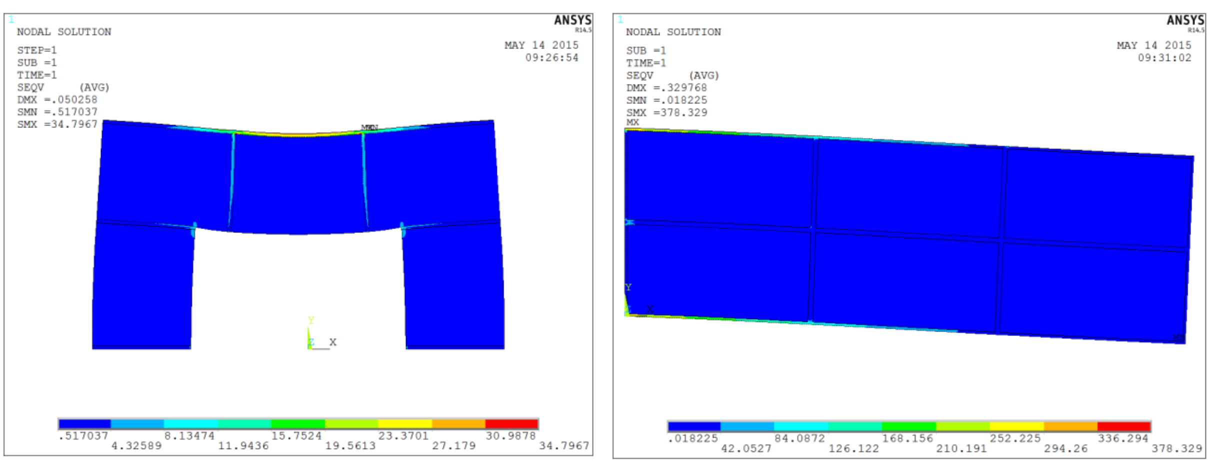
$$\mathbf{C}_0^{eff} = \begin{bmatrix} 6384 & 0.1378 & 0.1378 & 0 & 0 & 0 \\ 0.1378 & 6384 & 0.1378 & 0 & 0 & 0 \\ 0.1378 & 0.1378 & 6384 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1764 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1764 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1764 \end{bmatrix} \quad (9)$$

An initial analysis has been done for each design case by a commercial FEA software ANSYS. In the initial analysis, the orientation angle α for each sub-FVs is set as zero. The analysis result of these two design cases is shown in Figure 11. It is clear that stress in not continuous on the boundary between lattice structures and solid skins. This is due to their different material properties.



(a) sub-FVs for design case 1 **(b) sub-FVs for design case 2**

Figure 10 Sub-FVs of given two design cases



(a) Design case 1 **(b) Design case 2**

Figure 11 The stress distribution of initial analysis on the equivalent models

Based on these two equivalent analysis models, the optimization method described in Section3.2 is used to update the orientation angle α for each sub-FV. Table 2 is given to show the parameters used in the optimization process. The minimum strain energy and average strain energy of each generation are shown in Figure 12. The optimization results are shown in Table 3. To build a lattice-skin structure with optimized orientation angles, a parametric lattice-skin modeling tool called IntraLattice is developed based on Grasshopper a graphic algorithm editor for Rhino CAD software. Based on this lattice-skin modeling tool and optimal lattice orientation, 3D model of lattice-skin structure is built for each design case and shown in Figure 13.

Table 2 Parameters of GA algorithm

Population size	Generation gap	Chromosome length	Crossover rate	Mutation rate	Maximum Iteration
20	0.9	10	0.7	0.07	30

Table 3 The optimization result of orientation angle in each sub-FV

	Sub-FV1	Sub-FV2	Sub-FV3	Sub-FV4	Sub-FV5	Sub-FV6
Design Case 1	89.9120	12.1408	2.7354	77.0674	89.9120	-
Design Case 2	31.4078	35.1026	25.3372	60.8798	61.0557	84.7214

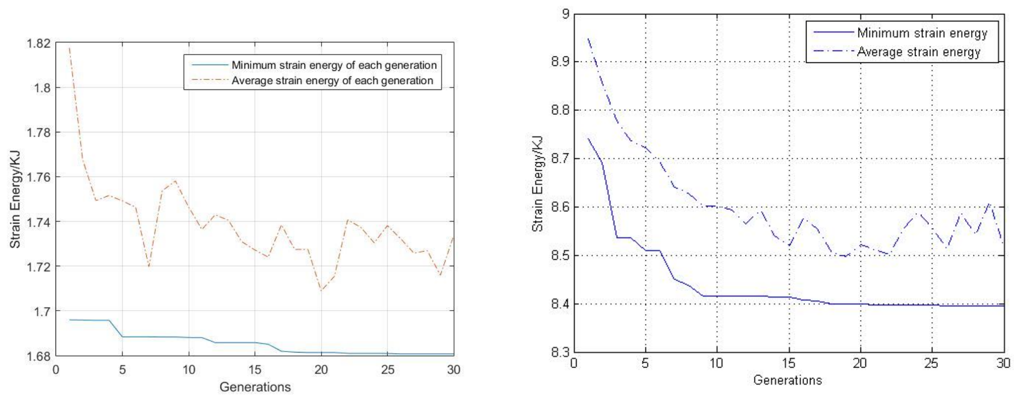
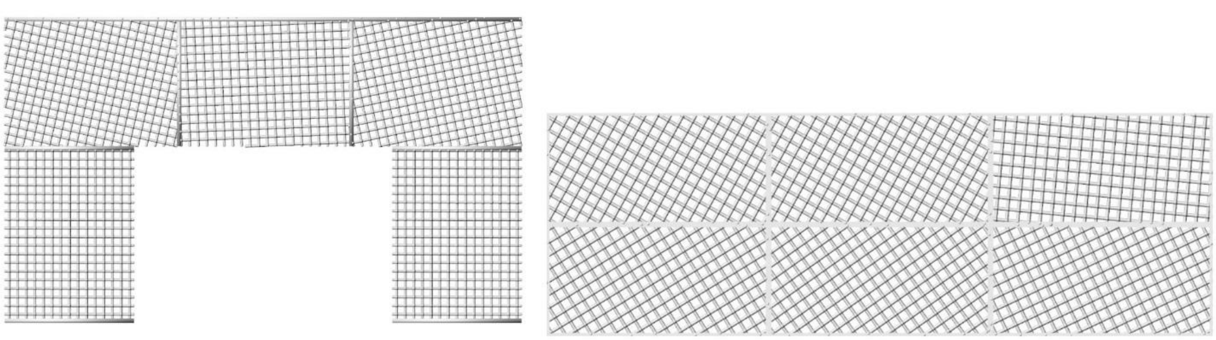


Figure 12 Optimization history of given design cases



(a) Design case 1 **(b) Design Case 2**

Figure 13 3D model of two design cases

To verify the design results of the proposed design method, verification models are built for both design cases based on Karamba a FEA analysis tool for Grasshopper. The strain energy of each optimal design is calculated based on these verification models. The results are shown in Table 4. Meanwhile, the uniform lattice with the same orientation angle in each sub-FVs is also considered for both two design cases. Based on the equivalent models, the maximum and minimum lattice orientation angles for each design case are firstly obtained. Then, verification models are used to calculate their strain energy respectively. The calculation results are shown in Table 5. This table clearly indicates that the orientation angle of lattice structures has a great effect on the overall structural performance. Moreover, compared to the results shown in Table 4 for optimal lattice orientation, it shows the proposed design methods can further improve the structural stiffness by reorienting the orientation angle in each sub-FV.

Table 4 Strain energy of optimal design

Design Configuration	Strain Energy/KJ	Volume/(mm^3)
Optimal orientation for design case 1	7.6	7088.68
Optimal orientation for design case 2	12.4	6110.37

Table 5 Strain energy of uniform lattice

Design Configuration	Strain Energy/KJ	Volume/(mm^3)	Orientation Angle
Design case 1 of minimal stiffness orientation	46.73	7088.68	45°
Design case 1 of maximal stiffness orientation	11.5	7088.60	0°
Design case 2 of minimal stiffness orientation	137.5	6100.63	5°
Design case 2 of maximal stiffness orientation	12.9	6118.37	50°

5 Conclusions and future research

In this paper, a design method of lattice-skin structure is proposed to determine the distribution of lattice orientation angles inside a design domain. This design method can be mainly divided into two stages. In the first stage, equivalent analysis model is established based on the effective material model of lattice structures on a macro scale. Then the genetic optimization algorithm is applied to find the optimal lattice orientation angle for each sub-FVs. Two design cases are given to validate the proposed design method. From their results, it is obvious that the orientation angle plays a significant role in the structural performance of designed parts. Moreover, the results also show that the optimal distribution of orientation angles can further improve the stiffness of designed parts without increasing their weight. Generally, the proposed design method in this paper provides a way to design and realize the non-uniform lattice orientation in a continuous design domain. This non-uniform lattice orientation has proved to be more stiffness efficient by two design cases. However, there are still some future research work needs to be done for this proposed method, which is listed below.

1 It is necessary to consider the distribution of relative density and lattice orientation simultaneously. The structural performance may be further improved by integrating those existing design methods of heterogeneous lattice into the proposed method in this paper.

2 The optimization method of skin thickness is needed to consider in the future research. It is clear that skins play an important role in the proposed design method. However, currently, the value of skin thickness is directly given by designers. Thus, to further improve the functional performance of designed parts, thickness of skin should be taken as another design variable in the future research.

3 A detailed guideline to build sub-FVs is needed. The proposed method in this paper only provides a general method to separate FV into sub-FVs. It should be noted that both the shape and size of sub-FVs may have the potential effect on the final performance of designed products. Thus, more research is needed to evaluate the quality of sub-FVs. Based on that, a detailed guideline can be generated.

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