IOP Conf. Series: Materials Science and Engineering **207** (2017) 012035 doi:10.1088/1757-899X/207/1/012035

# Lightweight design for servo frame based on lattice material

**Xin Jin[1, *], Guoxi Li[1], Encai Liu[1] and Jingzhong Gong[2]**

[1]College of Mechatronics Engineering and Automation, National University of Defense Technology, Changsha 410073, China
[2]School of Mechanical Engineering, Hunan International Economics University, Changsha 410205, China

[*]Corresponding author e-mail: anmajin@163.com

**Abstract.** Lattice material infilling is an important way to achieve lightweight. Focusing on the problems of non-uniform arrangement and the finite element analysis (FEA) of lattice material in the parts, a lightweight design method based on lattice material is proposed with the spacecraft servo frame as the design object. Modal analysis and topology optimization are carried out according to the boundary conditions. The optimized density results are used to guide the design of lattice material parameters and arrangement. The equivalent mechanical properties of lattice material are obtained through the standard specimens experiments. The equivalent material FEA model of the lightweight servo frame is established, and the performance of the lightweight structure is tested by FEA simulation and experiment. The results show that under the impact condition, the lightweight servo frame meets the performance requirements and the simulation method through the equivalent material model is validated.

## 1. Introduction

In the spacecraft structure, the quality proportion of servo frame is large. Under the premise of high rigidity and impact resistance, lightweight design of servo frame can not only reduce energy consumption in the production and operation, but also bring higher maneuverability and better dynamic and static performance, which are key indicators related to the product competitiveness.

In recent years, with the rapid development of material preparation and forming technology, lattice material emerges as a kind of novel multifunctional lightweight material [1]. It exhibits properties of high strength and rigidity except for weight reduction, realizes the shock resistance [2], heat transfer and insulation [3], sound absorption [4], and meets the requirements of multifunction [5]. Currently, when lattice material is used in the lightweight design of parts, mostly one kind of lattice material is chosen based on the designer’s experience [6]. The uniform distribution of material doesn't consider the load condition and the lightweight efficiency is not sufficient.

Topology optimization is an important way to achieve lightweight when satisfying performance. The essence of this method is to seek the structural layout with the optimal load transfer path under the action of external force and constraint [7]. Topology optimization plays a significant role in the structural design of automobile, aerospace, industrial equipment and other fields [8]. At present, the most mature commercial application is solid isotropic material penalty model (SIMP) proposed by Rozvany [9]. The density of each element in the design space is used as the design variable and the optimal design result is the density distribution between 1 and 0. We can get the distribution law of lattice material by referring to the density results of topology optimization, and fill different positions with different lattice material parameters, so as to improve the efficiency of lightweight.

FEA simulation is an effective method to analyze the mechanical properties of the lightweight designed structure. However, the finite element mesh and analysis of the lattice material require more elements than the solid material, and the calculation cost is relatively larger. The equivalent continuous material model can be used in FEA instead of lattice material, to accelerate the verification of the design, effectively shorten the design cycle and reduce cost.

In this paper, based on the topology optimization results, the lightweight model of the spacecraft servo frame is designed with lattice materials. The equivalent mechanical properties of lattice materials in different positions are obtained by compression test. Based on these parameters, the equivalent material FEA model of the lightweight structure is established. Finally, performance of the lightweight structure is verified by FEA and experiment.

## 2. Overall design scheme

Taking the spacecraft servo frame as the background, the overall design scheme is proposed to guide the lightweight design of parts based on lattice materials. The details are shown in Fig. 1.

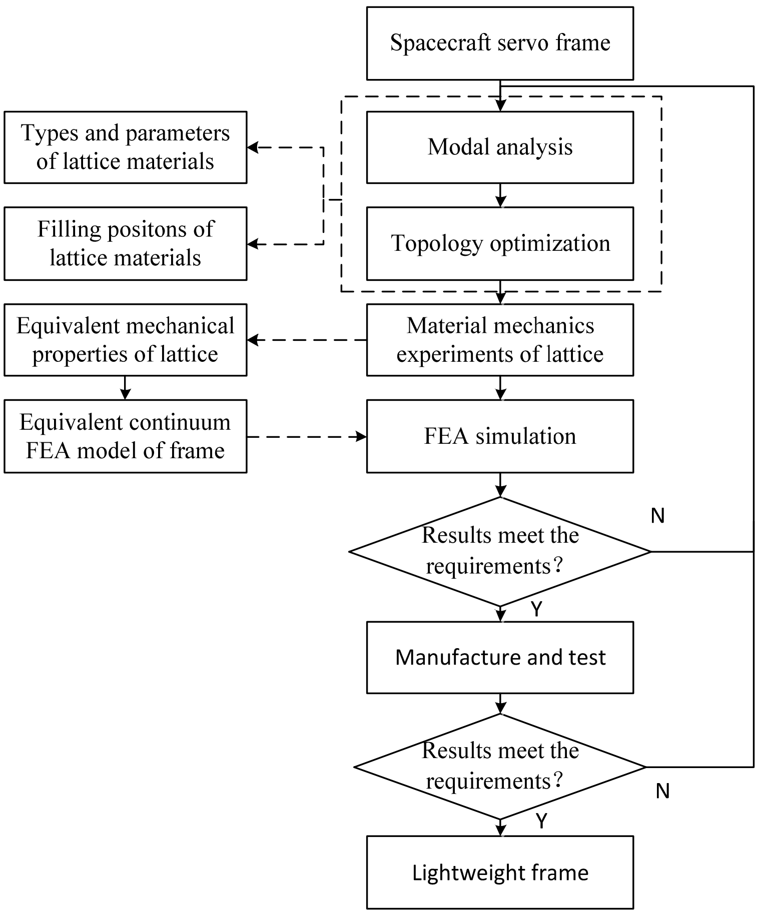



**Figure 1.** Overall design scheme.

(1) Modal analysis of servo frame is carried out to obtain the natural frequency and the form of vibration, where the weak position and direction of the structure are distinguished. Loads are applied in the position and direction to topology optimize the structure.

IOP Conf. Series: Materials Science and Engineering **207** (2017) 012035 doi:10.1088/1757-899X/207/1/012035

(2) According to the topology optimization results, the filling position and relative density of lattice materials are determined. Types and parameters of lattice materials are selected in consideration of manufacturing and arrangement.

(3) The selected lattice materials are fabricated into standard specimens, and the material mechanics experiments are carried out. The equivalent mechanical properties of the lattice materials can be obtained from the experimental results.

(4) The equivalent continuum FEA model of the lightweight frame is constructed by replacing the lattice materials with the equivalent solid materials. The simulation results are analyzed to judge whether the design results meet the requirements.

(5) Finally, lightweight frame can be manufactured by selective laser sintering (SLS). The structure is tested to determine whether it meets the performance requirements and whether the simulation results are correct.

## 3. Modal analysis and topology optimization

The simplified servo structure is shown in Fig. 2, including the frame and the internal structure. The impact load on the structure is much greater than the static load. The servo frame is subjected to a sinusoidal impact with amplitude of $10g$ acceleration and duration of $10ms$. In this paper, the servo frame is fabricated by Nylon with the density of $950kg/m^3$, the Young's modulus of $1.646Gpa$ and the Poisson ratio of 0.394. The mass of internal structure is also calculated as Nylon, and the value is $0.1kg$. The maximum impact force from the internal structure to the frame is about $10N$, and the direction is uncertain. The weak direction and position of the structure for the impact force must be determined by modal analysis to obtain the natural mode before topology optimization.

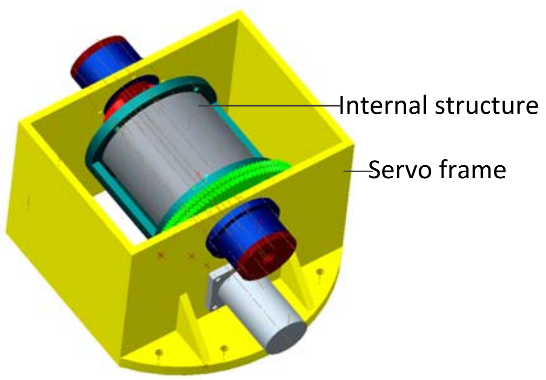


**Figure 2.** Simplified servo structure.

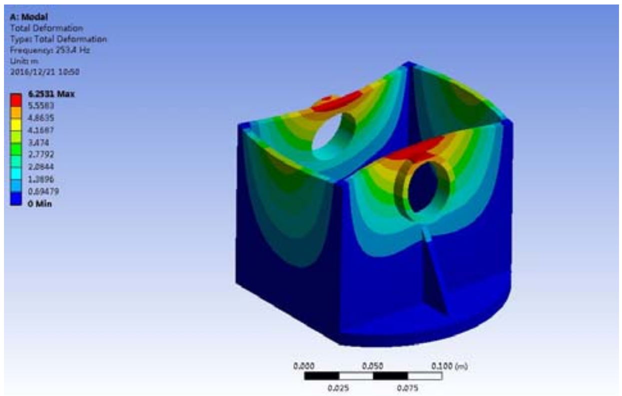


**Figure 3.** The first-order modal shape of frame.

The first-order modal shape is shown in Fig. 3. The natural frequency is $253.4Hz$. The main deformation is in the axial direction near the hole. So the weak position is the axial hole and the weak direction is the axial direction.

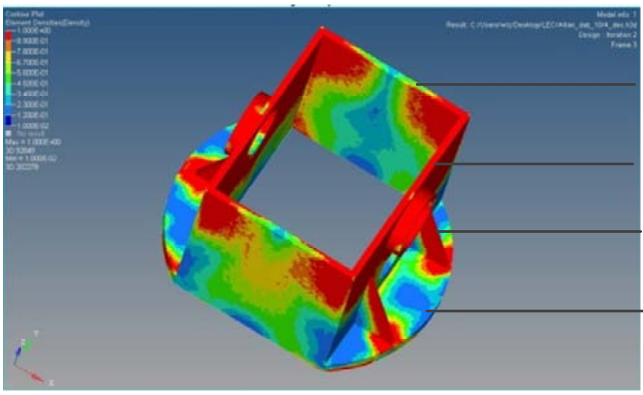



**Figure 4.** Topology optimization result of frame.

The Optistruct solver of Hyperworks software is choose to solve the topology optimization of the servo frame model. The material property is set to Nylon. According to the modal analysis results, the load is applied in the weak position and direction. The objective function is the maximum stiffness of the structure, and the constraint is that volume fraction of the lightweight structure must be less than 70%. The relative density distribution result is shown in Fig. 4.

Refer to the optimization result, the bottom can be filled with lattice material of relative density between 25% and 35%, the ribs can be filled with lattice material of relative density between 30% and 40%, the two sides without holes can be filled with 35% to 45% relative density lattice, and the two sides with holes is still solid material.

## 4. Determination of the lattice types and parameters

### *4.1. Lattice types selection*
On the impact condition in the weak direction, deformation on the frame sides is bending-dominated, and deformation on the frame bottom is compressing-dominated. Therefore, lattice material in the sides should have good bending capacity, and lattice material in the bottom should have good compressive capacity.


**Figure 5.** Three types of lattice materials.

Face center lattice, tetrahedral lattice and cross face center lattice are shown in Fig. 5. The three lattices possess excellent mechanical properties in tension/compression and bending [10]. In consideration of arrangement, the section of tetrahedral lattice is triangle, which is difficult to fill in the structure. In consideration of manufacturability, the interspace size of cross face center lattice is very small, which can lead to defects and affect the quality of manufacturing in SLS. So face center lattice is selected to design the frame.

*4.2. Lattice parameters determination*
In the lattice cell, strut's length is $l$, strut's diameter is $d$, and the angle between strut and the middle plane is $\theta$. The relative density $\bar{\rho}$ can be calculated as the ratio of solid volume to cell volume:

$$\bar{\rho} = \frac{\rho}{\rho_s} = \frac{V_{solid}}{V_{cell}} = \frac{\left(2+\sqrt{2}\cos\theta\right)\pi d^2}{8l^2\cos^2\theta\sin\theta} \tag{1}$$

In the frame, thickness of bottom, ribs and sides is 10mm, 5mm and 5mm respectively. Cell size of lattice material can be 2.5mm or 5mm to full fill the frame. At last cell size is set to 5mm, strut's angle is $45^\circ$, and strut's length is calculated as 3.5mm to satisfy the manufacturing constraints in SLS including strut's diameter $d \geq 1mm$ and angle $\theta \geq 45^\circ$.

Combined with topology optimization results, it can be calculated in formula (1) that $d = 1.3mm$ in the bottom, $d = 1.4mm$ in the ribs, $d = 1.5mm$ in the two sides without holes, and the two sides with holes is still solid material. In practical measurement, the relative density of face center lattice materials in bottom, ribs and sides are 30.8%、34.7%、38.4% respectively.

After types and parameters for the lattice materials are determined, the lightweight frame CAD model is shown in Fig. 6.

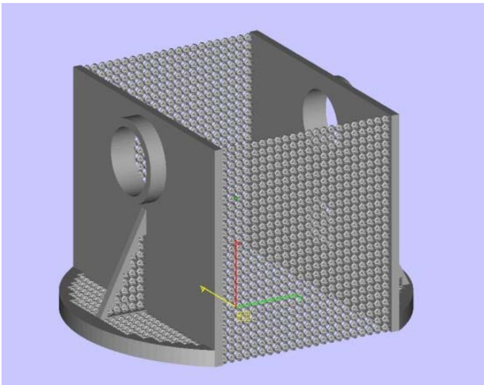


**Figure 6.** Lightweight frame CAD model.

## 5. Construction of equivalent continuum FEA model
The three kinds of face center lattice with different relative densities are fabricated into $15 \times 15 \times 50mm$ rectangular specimens by SLS with Nylon material. Equivalent mechanical properties of lattice materials are obtained through compression experiment. The load-displacement curves obtained by the test are shown in Fig. 7. The stress values can be simply obtained by dividing the force by the area of the cross section. The strain is calculated by dividing the displacement by the length of the specimen. The Young’s modulus is calculated by the linear portion of the stress-strain curve while the compression strength can be obtained with the non-linear portion of the curve. Poisson’s ratio is obtained by dividing transverse strain by longitudinal strain.

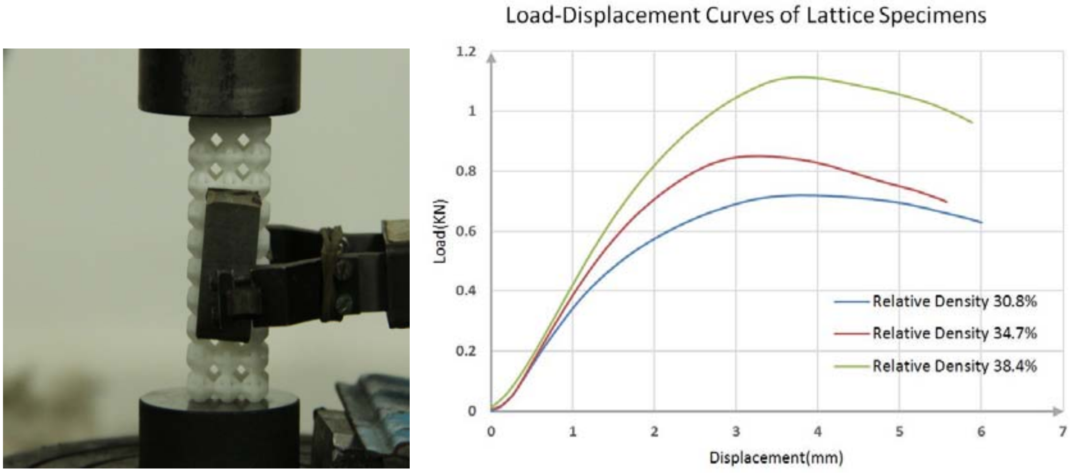



**Figure 7.** Compression experiment and results of lattice materials.

The mechanical properties of solid Nylon and three lattice materials are shown in Table 1.

**Table 1.** Mechanical properties of solid Nylon and three lattice materials.

| Materials | Relative density | Density ( $g / mm^3$ ) | Young's modulus( $Gpa$ ) | Poisson's ratio | compression strength( $Mpa$ ) |
|---|---|---|---|---|---|
| Equivalent material 1 | 30.8% | $0.278\times10^{-3}$ | 0.095 | 0.130 | 3.11 |
| Equivalent material 2 | 34.7% | $0.315\times10^{-3}$ | 0.105 | 0.140 | 3.78 |
| Equivalent material 3 | 38.4% | $0.354\times10^{-3}$ | 0.107 | 0.183 | 4.44 |
| Nylon | 100% | $0.950\times10^{-3}$ | 1.646 | 0.394 | 48.1 |

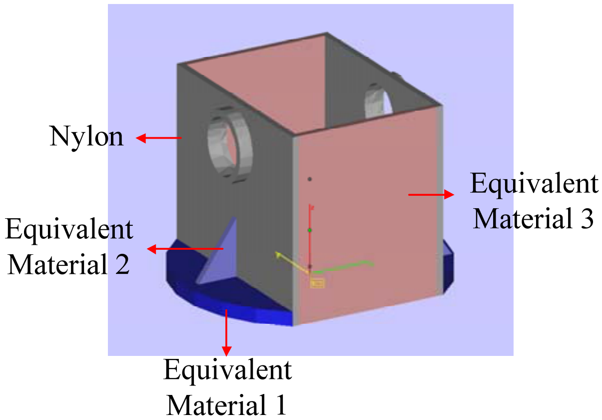
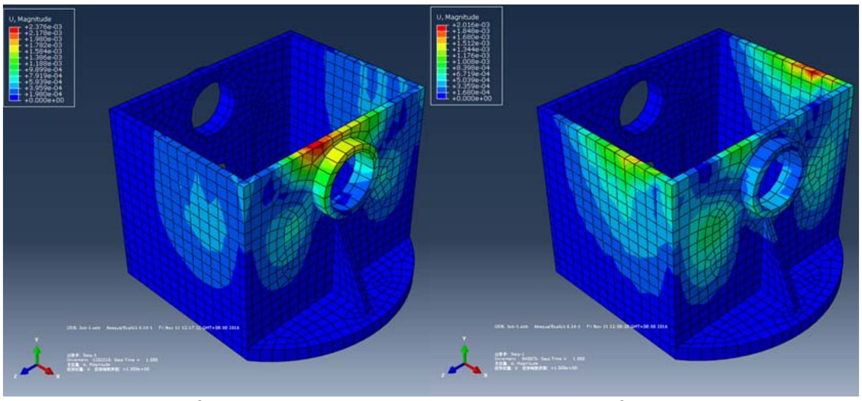



**Figure 8.** Equivalent continuum FEA model of the lightweight frame.

The equivalent continuum FEA model of the lightweight frame is constructed in Fig. 8 by replacing the lattice materials with the equivalent materials, where different colors mean materials with different properties. Then the difficulty and cost of mesh and analysis can be reduced.

## 6. Impact simulation and experiment for the lightweight frame

With ABAQUS as the simulation tools, compare of impact stiffness of original and lightweight structures is carried out by applying material properties shown in Table 1 and Fig. 8. A sinusoidal impact with maximum impact force of 10N and duration of 10ms is applied in the axial hole in axial direction. The impact displacement in Fig. 9 shows that the maximum displacement of original structure is near the hole and the value is $2.376\times10^{-3}mm$, while the maximum displacement of lightweight structure is on the sides without hole and the value is $2.016\times10^{-3}mm$. Impact stiffness can be improved by lightweight design and the extent is about 15%.



Displacement of original structure Displacement of lightweight structure

**Figure 9.** Impact simulation of servo frame.

Simulation results show that the lightweight design method proposed in this paper can improve the impact stiffness while achieve the weight reduction. Under the impact condition, failure is not found in the lightweight servo frame and the performance requirements are meet.

The lightweight frame can be fabricated with Nylon via SLS. In practical measurement, the weight reduction ratio is 30%. Impact experiment for the structure is shown in Fig. 10. The experiment device is DC-3200-36 electromagnetic vibration test platform. The frame bottom is fixed on the platform and two sensors are attached near the holes to measure the response to impact. A sinusoidal acceleration impact with amplitude of 10g and duration of 10ms is applied on the structure in the axial direction of holes.

**Figure 10.** Impact experiment for the lightweight frame.

Input and output curves are shown in Fig.11 Curve 1 is the input signal; curve 2 and curve 3 are output signals. It is clear that when subjected to 10g acceleration impact, the lightweight frame does not amplify the input signal, which means that the there is no failure in the structure on the impact condition.

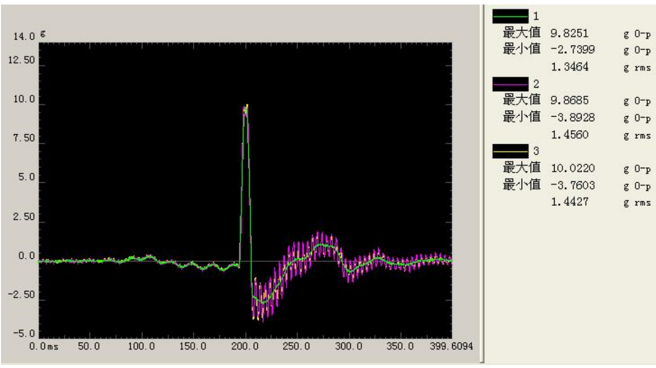



**Figure 11.** Impact response of the lightweight frame.

At the same time, for the servo frame, the natural frequency should keep away from the one of shell and control system in spacecraft, which are about 15Hz and 150Hz respectively. So the sweep frequency experiment is carried out on the platform and the result is shown in Fig. 12.

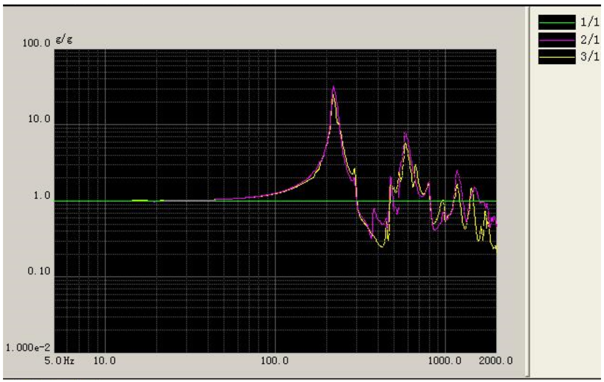



**Figure 12.** Sweep frequency result of the lightweight frame.

The three peaks in the curve represent that the first to three order natural frequency of lightweight frame is 310Hz, 580Hz and 1170Hz respectively, which is higher than the one of shell and control system in spacecraft. It means that the lightweight frame can meet the frequency requirement. The first order natural frequency of lightweight frame is higher than original structure, whose frequency is 253.4Hz in Fig. 3, and the extent is about 20%. The improvement on natural frequency also means the stiffness per unit mass is increased after lightweight design.

Above all, experiment results are consistent with the impact simulation and the effectiveness of the proposed lightweight method is validated.

## 7. Conclusion

(1) In this paper, a lightweight design method based on lattice material is proposed with the spacecraft servo frame as the design object. Modal analysis and topology optimization are carried out for the frame to guide the design of lattice material parameters and arrangement. The equivalent mechanical properties of lattice material are obtained through the standard specimens experiments. The equivalent material FEA model of the lightweight servo frame is established, and the performance of the lightweight structure is tested by FEA simulation and experiment.

(2) Simulation results show that the lightweight design method proposed in this paper can improve the impact stiffness while achieve the weight reduction. Under the impact condition, failure is not found in the lightweight servo frame and the performance requirements are meet.

(3) Experiment results are consistent with the impact simulation and the effectiveness of the proposed lightweight method is validated.

## References

[1] Wadley H N G, Multifunctional periodic cellular metals, Phil Trans R Soc A. 364 (2006) 31-68.
[2] Elnasri I, Pattofatto S, et al, Shock enhancement of cellular structures under impact loading: Part I Experiments, J Mech Phys Solids. 55 (2007) 2652-2671.
[3] Tian J, Kim T, Lu T J, et al, The effects of topology upon fluid-flow and heat-transfer within cellular copper structures, Int J Heat Mass Transf. 47 (2004) 3171-3186.
[4] Wang J, Lu T J, Woodhouse J, et al, Sound transmission through lightweight double-leaf partitions: theoretical modeling, J Sound Vibr. 286 (2005) 817-847
[5] Fan H L, Jin F N, Fang D N, Mechanical properties of hierarchical cellular materials: Part I Analysis, Compos Sci Technol. 68 (2008) 3380-3387
[6] Recep M. Gorguluarslan, Umesh N. Gandhi, et al, Design and fabrication of periodic lattice-based cellular structures, Computer-aided Design & Applications. 13 (2016) 50-62.
[7] Yan J, Guo X, Cheng G, Multi-scale concurrent material and structural design under mechanical and thermal loads, Comput Mech. 57 (2016) 437-446.
[8] Gil Ho Yoon, Maximizing the fundamental eigenfrequency of geometrically nonlinear structures by topology optimization based on element connectivity parameterization, Computers and Structures. 88 (2010) 120-133.
[9] Rozvany GIN, Zhou M, Birker T, Generalized shape optimization without homogenization, Struct Optim. 4 (1992) 250-254.
[10] Liangwei Zhong and Xiaowei Li, Simulation analysis of lightweight cylindrical lattice materials with different unit cells, Journal of Coastal Research. 73 (2015) 155-159.