The Fourteenth International Conference on
Computational Structures Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Fourteenth International Conference on
Computational Structures Technology
Edited by B.H.V. Topping and J. Kruis
Civil-Comp Conferences, Volume 3, Paper 5.1
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.3.5.1

A Novel Design Approach of Thin-Walled Structures with Lattices and Stiffeners based on Multi-Material Topology Optimization

Y. Li[1], T. Gao[1], Q.Y. Zhou[2], P. Chen[2], D.Z. Yin[3] and W.H. Zhang[1]

**[1] State IJR Center of Aerospace Design and Additive Manufacturing,
Northwestern Polytechnical University, Xi'an, China
[2] Beijing Aerospace Technology Institute, Beijing, China
[3] Beijing Institute of Long March Space Vehicle, Beijing, China**

Abstract

In this paper, a novel layout design approach of thin-walled structures with lattices and stiffeners based on the multi-materials topology optimization method is proposed. The main idea of this approach is as follows. The chosen lattice unit cells are equivalent to the virtual homogeneous materials, and then the optimal material layout of virtual homogeneous materials and solid material is found by employing the multi-material topology optimization method. This detailed design process is demonstrated as follows. First, depending on the design requirements, several typical lattice cells are selected. The energy-based homogenization method is employed to achieve the effective elastic matrix of the typical lattice unit cells. Second, the mathematical model of layout optimization of thin-walled structures with lattices and stiffeners under mass constraint is established, and the sensitivity analysis of the structural compliance is derived based on the adjoint method. The optimization model is solved by the optimization algorithm. This paper takes the panel structure of spacecraft as an example to demonstrate the specific process of design and analysis. In the example, three layouts, i.e. the stiffened panel structure, the lattice sandwich structure and the panel structure with lattices and stiffeners are obtained and compared. The simulation results from three different structures are quite encouraging since the panel structure with lattices and stiffeners obtained by the proposed method shows improved mechanical properties compared to other designs.

Keywords: layout design; thin-walled structures; topology optimization; lattice; stiffener; multi-material

1 Introduction

Demand is increasing for thin-walled structures with high mechanical performance and light-weight design in an array of engineering fields including aerospace, transportation, nuclear reactors, and civil engineering. Two representative thin-walled structures, stiffened thin-walled structures and sandwich structures are widely used in aerospace vehicles to meet the light-weight requirement. Here, the sandwich structures include several light-weight cores, such as the honeycombs, foams and lattices.

In contrast, the lattice structures and stiffened structures have their own advantages and disadvantages in mechanical performance and engineering application. Compared with the stiffened structures, the lattice structures have important advantages such as effective absorption of impact energy and greatly reduced vibration response while satisfying the load-bearing performance, and having better dynamic performance. However, the lattice structures also have their shortcomings. For example, compared with the stiffened structures, the lattice structures can’t provide sufficient structure stiffness at the specific location where has concentrated loads. In order to give full play to the advantages of the two structures, the structure with lattices and stiffeners can be employed. In the structure with lattices and stiffeners, the stiffened structures play the role of main support to ensure the overall stiffness of the structure; the lattice structures mainly assume the functions of buffering, energy absorption and shock absorption. Through the reasonable layout design of the two structures, it can achieve an overall structure with good static and dynamic properties.

The current research on the layout design method of structure with lattices and stiffeners mainly follows the steps that first perform a conventional topology optimization to achieve the layout result of the stiffened structures, then fill the void prat with lattice structures. This method only considers the influence of solid materials on the optimization result but does not consider the influence of the layout of different structures during the optimization process on the overall structural mechanical performance, thus, the optimization result achieved by this method is not necessarily the optimal structure optimization result. Inspired by the research on multi-materials and multi-types lattice layout optimization[1-5] based on multi-scale structure optimization in recent years, the layout design problem of structure with lattices and stiffeners could be transformed into a topology optimization problem with multi-materials.

This work tries to combine the stiffened structures with the lattice structures in the thin-walled structures, and focuses on the simultaneous layout optimization of the lattices and stiffeners in thin-walled structures.

2 Methods

The main thought of the design method can be summarized as follows: First, the representative lattice units of the selected lattices are equivalent to the virtual homogeneous materials whose effective elastic matrixes are achieved by the energy-based homogenization method. Meanwhile, the stiffeners are modelled using the solid material. Thus, the optimal layout of the lattices and stiffeners could be simultaneously attained by the multi-material topology optimization.

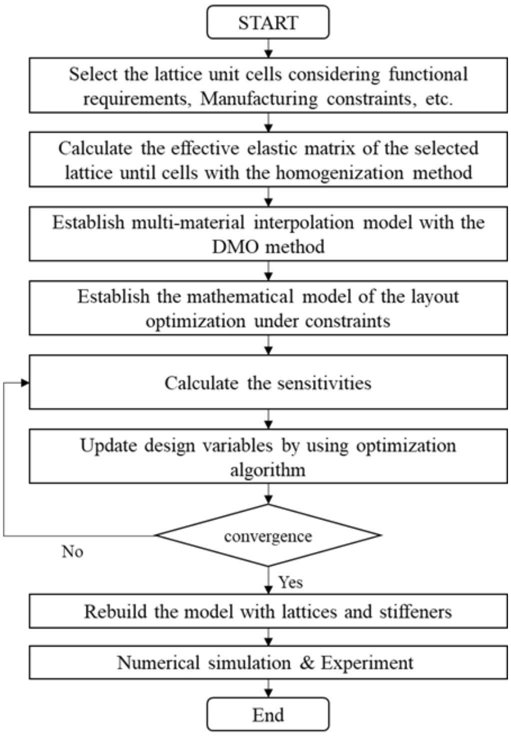


Figure. 1. Flowchart of the design process.

In this paper, the compliance of the whole structure Ω, hereinafter referred to as "overall compliance", is taken as the objective function and is computed by

$$C = \mathbf{u}^{\mathrm{T}}\mathbf{K}\mathbf{u} \tag{1}$$

The multi-material topology optimization formulation is established for the layout optimization of thin-walled structures with lattices and stiffeners to minimize the overall compliance of the structure under mass constraint

$$\begin{aligned} &\text{find:} \quad \mathbf{x}=\left\{x_{ij}\right\} \quad \left(i=1,\dots,n; \quad j=1,\dots,m\right) \\ &\text{minimize: } C \\ &\text{subject to: } \mathbf{Ku}=\mathbf{F}=\mathbf{F}^{\mathrm{a}}+\mathbf{F}^{\mathrm{d}}\left(\mathbf{x}\right) \\ &\qquad 0 < x_{\min} \le x_{ij} \le 1 \\ &\qquad M\left(\mathbf{x}\right) \le \overline{M} \end{aligned} \tag{2}$$

Herein, n and m are the number of designable elements and candidate materials, respectively, $\mathbf{x}$ denotes the set of design variables and x_{ij} represents the presence (1) or absence (0) of the jth candidate material in the ith finite element. In the static finite element analysis, **K**, **u** and **F** are the global stiffness matrix, nodal displacement vector and nodal force vector, respectively. The design-inependent applied force $\mathbf{F}^{\mathrm{a}}$ and the design-dependent force $\mathbf{F}^{\mathrm{d}}$ are both considered in this work.

In static finite element analysis, the element stiffness matrix could be calculated with

$$\mathbf{K}_i = \int_{V_i} \mathbf{B}_i^{\mathrm{T}}\mathbf{D}_i\mathbf{B}_i \, dV \tag{3}$$

where $\mathbf{B}_i$ is the strain–displacement matrix consisting of derivatives of element shape functions. Based on the DMO scheme[6], $\mathbf{D}_i$ can be expressed as the weighted summation of all of the candidate material phases

$$\mathbf{D}_i = \sum_{j=1}^{m} w_{ij}\mathbf{D}^{(j)} \tag{4}$$

where the subscripts i and j indicate the ith designable element and the jth candidate material, respectively. $\mathbf{D}^{(j)}$ is the elasticity matrix of the jth candidate material. Supposing p as the penalty factor in the SIMP scheme, the weighting functions in the above parameterization models then correspond to

$$w_{ij} = x_{ij}^{p}\prod_{\substack{\xi=1\\ \xi\neq j}}^{m}\left(1-x_{i\xi}^{p}\right) \tag{5}$$

Based on the Equation (1), the sensitivity of the structural overall compliance C then corresponds to

$$\frac{\partial C}{\partial x_{ij}} = \mathbf{u}^{\mathrm{T}}\frac{\partial \mathbf{K}}{\partial x_{ij}}\mathbf{u} + 2\mathbf{u}^{\mathrm{T}}\mathbf{K}\frac{\partial \mathbf{u}}{\partial x_{ij}} \tag{6}$$

According to the differentiation of the equilibrium equation, the partial derivative of the global nodal displacement vector can be written as

$$\frac{\partial \mathbf{u}}{\partial x_{ij}} = \mathbf{K}^{-1}\left(\frac{\partial \mathbf{F}}{\partial x_{ij}} - \frac{\partial \mathbf{K}}{\partial x_{ij}}\mathbf{u}\right) \tag{7}$$

Obviously, $\partial\mathbf{F}^{\mathrm{a}}/\partial x_{ij}=0$ for the design-independent applied force. Thus, the sensitivity of C is then expressed as

$$\frac{\partial C}{\partial x_{ij}} = 2\mathbf{u}_i^{\mathrm{T}}\frac{\partial \mathbf{F}^{\mathrm{d}}}{\partial x_{ij}} - \mathbf{u}_i^{\mathrm{T}}\frac{\partial \mathbf{K}_i}{\partial x_{ij}}\mathbf{u}_i \tag{8}$$

Evidently, $\frac{\partial \mathbf{K}_i}{\partial x_{ij}}$ can be easily derived as

$$\frac{\partial \mathbf{K}_i}{\partial x_{ij}} = \int_{V_i}\mathbf{B}_i^{\mathrm{T}}\frac{\partial \mathbf{D}_i}{\partial x_{ij}}\mathbf{B}_i\, dV \tag{9}$$

Based on the definition in Equation (4), the $\frac{\partial \mathbf{D}_i}{\partial x_{ij}}$ can be expressed as

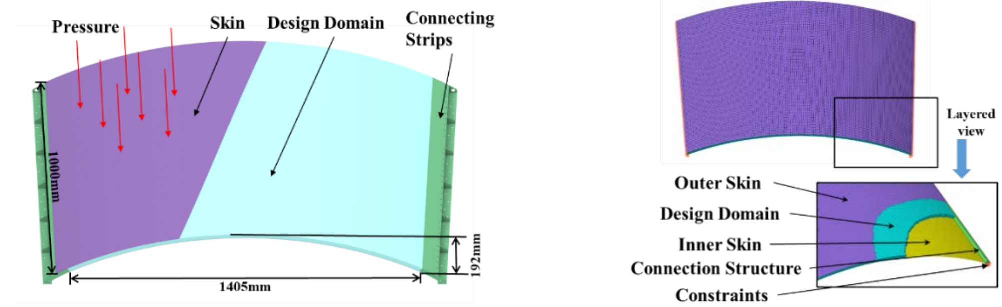
$$\frac{\partial \mathbf{D}_i}{\partial x_{ij}} = \sum_{\varsigma=1}^{m}\frac{\partial w_{i\varsigma}}{\partial x_{ij}}\mathbf{D}^{(\varsigma)} \tag{10}$$

To calculate the partial derivative of weight $w_{i\varsigma}$, the interpolation scheme given in Equation (5) is used to produce

$$\frac{\partial w_{i\varsigma}}{\partial x_{ij}} = \begin{cases} p x_{ij}^{p-1}\prod\limits_{\substack{\xi=1\\ \xi\neq j}}^{m}\left(1-x_{i\xi}^{p}\right) & j=\varsigma \\ -p x_{ij}^{p-1}x_{i\varsigma}^{p}\prod\limits_{\substack{\xi=1\\ \xi\neq j,\xi\neq\varsigma}}^{m}\left(1-x_{i\xi}^{p}\right) & j\neq\varsigma \end{cases} \tag{11}$$

3 Results

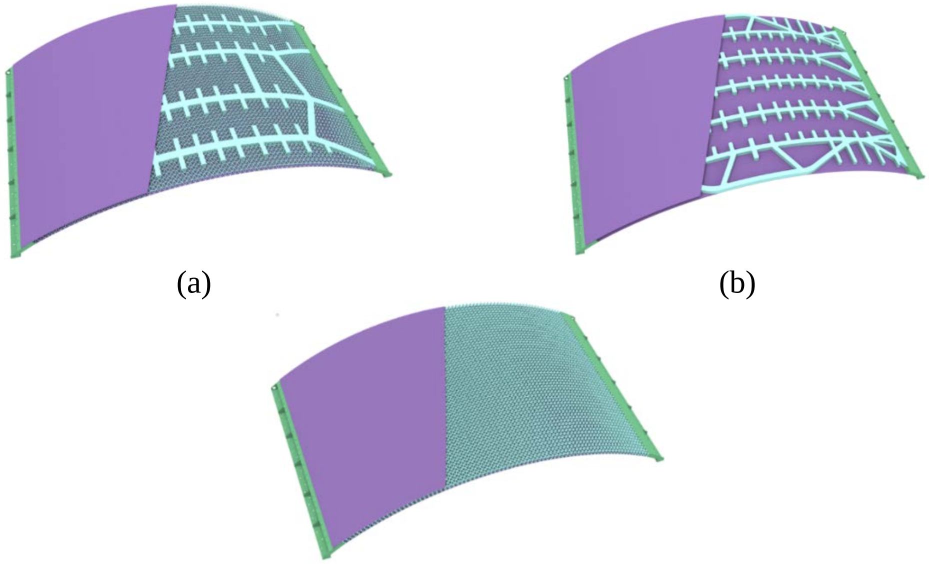
A typical aircraft panel structure is studied and the layout design of the lattices and stiffeners is achieved by the proposed optimization method. The geometric model and dimensions of the aircraft panel structure are illustrated in Figure 2. The panel structure is composed of the designable domain, upper skin, lower skin and connecting strips. The outer and inner skins are mainly used to keep the feature of the aircraft. Furthermore, the outer skin also plays the role of carrying the aerodynamic loads, and the inner skin is usually used to install some equipment. The thickness of both skins is 1 mm. The designable domain should be filled with stiffeners and lattices, and its thickness is 18 mm. The finite element model of the panel structure is established in which the skins are discretized into 47750 shell elements and the designable domain is discretized into 48000 hexahedron solid elements. A uniform aerodynamic pressure of 11.5 kPa is applied to the upper skin and fixed constraints are imposed on the connecting strips. According to the design requirements, the mass of the design domain must be less than 20kg.



(a) (b)

Figure. 2. The panel structure with (a) Geometric model and dimensions; (b) Finite element model.

In order to verify the mechanical properties of the panel structure with lattices and stiffeners, the panel structure designed by the proposed method will be compared to the stiffened panel structure and the lattice sandwich panel structure. The three types of structures are designed and reconstructed under the same mass constraints. The reconstructed models of three structures are illustrated in Figure 3.



(a) (b)

(c)

Figure. 3. The reconstructed model of (a) panel structure with lattices and stiffeners; (b) stiffened panel structure; (c) lattice sandwich panel structure.

The three designs of the panel structure are analyzed under uniform aerodynamic pressure. Their global deformation, von-Mises stress distribution, the first three natural frequencies and buckling factor are illustrated in Table. 1. respectively.

	The panel structure with lattices and stiffeners	The stiffened panel structure	The lattice sandwich panel structure
Mass	18.594kg	19.045kg	18.812kg
Global deformation	Max: 0.195mm	Max: 0.322mm	Max: 0.294mm
Von-Mises stress	Max: 11.16MPa	Max: 26.30MPa	Max:12.93MPa
1st natural frequency	138.22Hz	135.25Hz	120.92Hz
Second natural frequency	238.66Hz	216.93Hz	203.88Hz
Third natural frequency	250.47Hz	228.98Hz	213.08Hz
Buckling factor	45.67	3.31	34.58

Table. 1. Numerical analysis results of the three designs of the panel structure.

4 Conclusions and Contributions

This paper proposes a new method for the layout design of thin-walled structures with lattices and stiffeners. By using the energy-based homogenization method, the lattice unit cell is equivalent to a virtual homogeneous material, and the layout design optimization problem of thin-walled structures with lattices and stiffeners is successfully transformed into a multi-material topology optimization problem. On this basis, this paper successfully establishes an efficient and reliable design process to obtain the desirable thin-walled structure with lattices and stiffeners. Moreover, a typical thin-walled structural component from engineering projects is employed as an example to demonstrate the practical validity and advantage of the proposed thin-walled structure design. The simulation results show that the thin-walled structure with lattices and stiffeners has better mechanical performance than the conventional stiffened structure and the lattice sandwich structure under the same mass constraint. The results not only verify the reliability and effectiveness of the design method proposed in this paper but also provide guidance and new ways for the design of thin-walled structures.

The rod diameter of the lattice unit cells employed in this work is constant. Based on recent achievements, a size optimization could achieve better non-uniform lattices and further improve the performance of the thin-walled structure. This is a valuable question worthy of further study and we will work on it in the near future.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (12172294, 51735005, 12032018).

References

[1] Y. Wang, Z. Kang, "Concurrent two-scale topological design of multiple unit cells and structure using combined velocity field level set and density model", Computer methods in applied mechanics and engineering, 347, 340-364, 2019. doi:10.1016/j.cma.2018.12.018

[2] Y. Chan, K. Shintani, W. Chen, "Robust topology optimization of multi-material lattice structures under material and load uncertainties", Frontiers of Mechanical Engineering, 14, 141-152, 2019. doi:10.1007/s11465-019-0531-4

[3] P. Liu, Z. Kang, Y. Luo, "Two-scale concurrent topology optimization of lattice structures with connectable microstructures", Additive Manufacturing, 36, 101427, 2020. doi:10.1016/j.addma.2020.101427

[4] J. Hu, Y. Luo, S. Liu, "Two-scale concurrent topology optimization method of hierarchical structures with self-connected multiple lattice-material domains", Composite Structures, 272, 114224, 2021. doi:10.1016/j.compstruct.2021.114224

[5] Y. Luo, J. Hu, S. Liu, "Self-connected multi-domain topology optimization of structures with multiple dissimilar microstructures", Structural and Multidisciplinary Optimization, 64, 125-140, 2021. doi: 10.1007/s00158-021-02865-8

[6] T. Gao, W. Zhang, "Topology optimization involving thermo-elastic stress loads", Structural and multidisciplinary optimization, 42, 725-738, 2010. doi: 10.1007/s00158-010-0527-5