Research Article

Optimal Design of Honeycomb Beams with Unit Cell Structure Based on Multiobjective Optimization Algorithm

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In order to promote the development of honeycomb composite reinforcements, the mechanical properties and optimization methods of honeycomb beams are studied. A structural optimization design method is proposed based on natural frequency and stiffness and the lightest weight. According to the vibration frequencies and mechanical analysis, the equivalent density and equivalent stiffness of the section in the unit length are deduced, which is considered a typical example. The geometric parameters of the structure system are trained by multiobjective optimization minimax algorithm (MOMA), and the Pareto optimal solution of variable combination is obtained. The results show that optimized objects are significantly better than that previously. Therefore, the optimized scheduling algorithm has some reference value and prospects for practical application.

1. Introduction

A honeycomb beam is an I-shaped beam with holes in the web. The holes on the web can have different shapes, such as polygon, long hole, or circle, and most of them are regular hexagonal holes. Compared with the original H-shaped solid web beam, the honeycomb beam can save material, reduce weight, and increase bearing capacity and stiffness. In the structure, it can allow the flexible installation of other components passing through. Its structure has good economic benefits and has promotion and application value in engineering practice of aerospace, construction bridge, ship crane, and other industries [1–3]. In recent years, the main research contents of honeycomb beams include bending analysis, shear analysis, and stability analysis [4, 5].

For the first aspect of the structural property, the multiscale and multiobjective optimization design method was applied in the design of functional material honeycomb structures. Starting from the geometry of the truncated section of the honeycomb beam, the coordination relationship between the stiffness, strength, and relative density of the honeycomb beam was analyzed from the macroscopic characterization of size parameters and the micromechanical principle [6]. The anisotropic characteristics of the porous material were analyzed. The honeycomb structure with circular pores and the honeycomb structure with hexagonal pores were compared, and the elastic modulus of the porous material was analyzed. Under the action of external load, the bending deformation and stress of the honeycomb material were designed, and geometric parameters such as pore shape, pore spacing, and pore horizontal and vertical ratio were designed [7]. The impact failure of aluminum honeycomb-filled beams was analyzed by a combination of simulation and test methods. The mechanism of the influence of the layup angle of the interlayer on the internal change process of the material was explored from the perspective of damage energy absorption and dilution in different directions. The change process from microlocal to macrodamage was obtained [8]. The vibration characteristics of honeycomb composites were analyzed using the finite element method. On this basis, the optimization algorithm of the finite difference method and quadratic linear programming was used to design the geometric structure of honeycomb composites. After the comparison of the Nomex structure, initial honeycomb aluminum plate, and optimized honeycomb aluminum plate, the dynamic modal
performance of the optimized structure was obviously improved [9]. For the other aspect of optimized design, the triangular honeycomb beam was topology optimized. In order to reduce the weight, the optimization design was carried out from the perspective of studying the equivalent density. The research solved the problem of modeling and design of triangular honeycomb variable-density structure; moreover, it upgraded and improved the constant shape honeycomb structure [10]. The impact mechanics of two different sizes of aluminum honeycomb Sandwich structures were compared. The collapse model was established and verified by experiment. Thus, the influence of the dimensions of the internal details of the honeycomb structure unit on the bending limit and the fracture mechanism was described [11]. The researchers used the beam as a continuum to study the cross-section of the beam, the impact and failure mechanism of the aluminum honeycomb beam, the elastic behavior of bending and shear deformation, and so on. Analytical numerical methods and experimental research methods were mostly used. For the optimal design of beam structures, quadratic linear programming was used for global function optimization and also for topology optimization of variable-density triangular honeycomb structures. However, considering the multifield coupling characteristics of the total structural system, the honeycomb beam designed according to this optimization result will show higher comprehensive performance.

The holds on the webs of the honeycomb beams effectively reduce the weight, resulting in transverse and longitudinal discontinuity and uneven stress-strain of the webs. Aiming at the mechanical properties and lightweight of honeycomb beams, this paper applies an advanced optimization algorithm to match weight and reliability reasonably according to the theory of structural dynamics and structural optimization. Finally, obtain the best configuration, size, and layout plan and ensure stable characteristics.

2. Model of Honeycomb Beam with Hexagonal Holds on the Web

Based on Kirchhoff’s thin plate theory and Vlasov’s rigid periphery hypothesis, the energy variational model and differential equation model of the torsion and flexural-torsional buckling theory of long and narrow rectangular thin plates are established by using the classic thin plate theory. According to the theory, thin-walled components such as I-shaped, T-shaped, and box-shaped commonly used in engineering can be regarded as a combination of flat plates (Figure 1). The torsion and flexural buckling of flat plates are the basic problems in the theoretical analysis of thin-walled components. This theory can solve a series of more complicated open and closed thin-walled members’ elastic torsion and elastic bending-torsional buckling problems, which provides a theoretical basis for the study of torsion and the overall stability of honeycomb beams. In this paper, a typical regular hexagonal honeycomb beam is selected as the typical research object.

According to this method, the deflection is composed of the bending deflection, the shear deflection, and the shear secondary bending moment. The bending deflection of the honeycomb beam is obtained by multiplying the bending deflection of the corresponding solid web beam by the expansion coefficient, which is similar to the shear deflection algorithm [12]. The open-web truss comparison method does not clearly propose the concept of equivalent bending stiffness or shear stiffness, and whether the expansion coefficient is appropriate must be judged based on the grasp of the equivalent stiffness. The equivalent stiffness means that a solid web beam with the same load, constraint, and length is used instead of a honeycomb beam with a regular change in section, and the macroscopic deformation of the solid web beam is the same as that of the honeycomb beam, under the condition of linear distribution of the average strain on the length of a member. The bending stiffness of the I-beam can be expressed as the sum of the flange bending stiffness and the web bending stiffness, so the equivalent bending stiffness can be expressed as the sum of the flange bending stiffness and the weakened web bending stiffness. The reduction factor $i$ of web bending stiffness is introduced to reflect the reduction of web bending stiffness. Through the equivalent stiffness, the corresponding deformation of the honeycomb beam can be calculated directly by the material mechanics formulas [13, 14].

The bending stiffness of the honeycomb beam as shown in Figure 2 is

$$EI = EI_w + EI_f = E \left( \frac{(H - h)w^3}{12} + E \cdot i \cdot \frac{hw^3}{12} \right)$$  \hspace{1cm} (1)

where $EI$ is the bending stiffness of the honeycomb beam flange, $EI_w$ is the bending stiffness of the web, $EI_f$ is the bending stiffness of the flange, $H$ is the height of the honeycomb beam, $h$ is the height of the web, $w$ is the width of the honeycomb beam, $w$ is the width of the web, and $i$ is the bending stiffness reduction coefficient of the web, which is equal to the ratio of the equivalent bending stiffness $EI_w$ of the honeycomb beam web to the bending stiffness $EI_w$ of the corresponding solid web of equal height.

The honeycomb beam is an I-shaped steel beam with holes in the web, and its equivalent bending stiffness $K$ is lower than the bending stiffness $K_w$ of the corresponding solid web beam. As shown in Figure 2, the bending stiffness of the section in the length range of $2a + b$ is considered as a typical example [9, 15]; according to classical material mechanics, the moment of inertia of the section is

$$I_{we} = \frac{(a + b)h^3}{12}$$  \hspace{1cm} (2)
The inertia moment of the honeycomb beam in this range is

\[ I_w = \frac{(2a + b)h^3}{12} - \frac{5 \sqrt{3} a^4}{16}. \]  

(3)

The reduction coefficient of bending stiffness is

\[ i = \frac{I_w}{I_{we}} = 1 - \frac{15 \sqrt{3} a^4}{4(2a + b)h^2} = 1 - \frac{6.5}{(2 + b/a)(h/a)^3}. \]  

(4)

When the hole size is small and the spacing is large, the bending stiffness reduction coefficient \( i \) is close to 1, that is, the bending stiffness of the honeycomb beam is close to the section stiffness of the solid web beam. With the expansion and densification of the holes, the stiffness reduction becomes more obvious. The size of the hole has a greater influence on the stiffness, and the stiffness decreases with the expansion of the hole. The net distance between adjacent holes has a relatively small effect on the stiffness, and the stiffness gradually decreases with the proximity of adjacent holes.

\[ S = EI = E \frac{(H - h)W^3}{12} + E \left( 1 - \frac{6.5}{(2 + b/a)(h/a)^3} \right) \cdot \frac{hw^3}{12}. \]  

(5)

The warping stiffness of a solid web beam is proportional to the lateral bending stiffness. According to the contribution of the flange and the web, the warping stiffness of the honeycomb beam can be expressed as follows:

\[ S_q = EI_q = \frac{1}{4} EIh^2 = E \frac{(H - h)W^3h^2}{48} + E \cdot \left( 1 - \frac{6.5}{(2 + b/a)(h/a)^3} \right) \cdot \frac{hw^3}{48}. \]  

(6)

For the torsional stiffness of the honeycomb beam, the flange size of the honeycomb beam and the equivalent solid web beam are the same. The torsional stiffness of the honeycomb beam flange is almost unchanged. Considering the weakening effect of the holes on honeycomb beam web stiffness, the torsional stiffness of the honeycomb beam is

\[ S_t = EI_t = E \frac{(H - h)W^3}{3H} + E \cdot \left( 1 - \frac{6.5}{(2 + b/a)(h/a)^3} \right) \cdot \frac{w^3}{3}. \]  

(7)

2.1. Equivalent Density. Take a hole period of the web as an example to calculate the density reduction in a two-dimensional space. The density reduction coefficient is equal to the ratio of the equivalent density \( \rho_w \) of the honeycomb beam web part to the density \( \rho_{we} \) of the corresponding solid web with equal height. When the matrix material is evenly distributed, the density reduction coefficient can be obtained by the ratio of the volume of nonporous part of the web, which is the volume difference of solid web and the regular hexagonal prism hole, to the volume of the solid web, so

\[ \rho_w = \left( 1 - \frac{18 \sqrt{3} a^2}{(2a + b)h} \right) \rho_{we}, \]  

where \( \rho_w \) is the equivalent density of the web part, and \( \rho_{we} \) is the density of the solid web.

\[ m = m_w + m_f = \rho_w V_w + \rho_f V_f = \left( 1 - \frac{18 \sqrt{3} a^2}{(2a + b)h} \right) \rho_{we} (2a + b)hw + \rho_{we} (2a + b)(H - h)W. \]  

(9)
3. Dynamic Model of Honeycomb Beam Structure

The natural frequency parameters of the honeycomb beam can be determined through modal analysis. Modal analysis [16] refers to an analysis method based on vibration theory to obtain modal parameters. It is the basis of dynamic analysis and can determine the natural frequencies and main modes of vibration characteristics. In modal analysis, the effect of external load is generally not considered. Therefore, the matrices $M$, $K$, and $\phi$ are only related to the geometric properties of the honeycomb beam, and $\omega$ is only related to the coefficients $D$, $\rho$, and $h$ of the matrix.

\[
[M][\ddot{x}(t)] + [K][x(t)] = \{0\}, \tag{10}
\]

where $[M]$ is the overall mass matrix, $[K]$ is the overall stiffness matrix, and $x(t)$ is the movement parameters of each.

Solve the characteristic equation as follows:

\[
[K] - \eta_j^2[M][\phi]_j = 0, j = 1, 2, \ldots, n, \tag{11}
\]

where $n$ is the structure degrees of freedom, $\eta_j$ is the $j$-th natural frequency, and $[\phi]_j$ is the natural mode shape of the $j$-th natural frequency.

Eigenvalue $\lambda = \eta_j^2$ can be calculated by Rayleigh quotient.

Based on the vibration theory of the two-dimensional model of the honeycomb beam, the equation of the system frequency and the structure parameters of the honeycomb beam is established according to the relationship between the equivalent bending stiffness and equivalent density of the honeycomb beam as follows:

\[
[K - Mf^2] = 0, \tag{12}
\]

where $f$ is the system angular frequency, $K = D[k_{ij}]$, and $M = \rho h [m_{ij}]$; $D$ and $\rho$ are separately equivalent bending stiffness and equivalent density, respectively.

The matrices $[k_{ij}]$ and $[m_{ij}]$ are only related to the in-plane dimension parameters (the length and width of the rectangular honeycomb beam) and Poisson's ratio, instead of the design variables in the honeycomb sandwich structure. Therefore, $[k_{ij}]$ and $[m_{ij}]$ can be regarded as constants. According to the matrix operation theory, natural frequency $\omega$ is only related to the coefficients $D$, $\rho$, and $h$ of the matrix. Therefore,

\[
\omega = \frac{f}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{D}{m}}. \tag{13}
\]

4. Optimization Design Algorithm of Honeycomb Beam

4.1. Optimization Algorithm. A single period of honeycomb beam, that is, the sum of a unit regular hexagonal cavity length and an interval length, is the representative of the whole beam to be optimized. The overall performance is reproducible and superpositional [17].

The optimization problem can be described by the following mathematical model:

\[
\begin{align*}
\min \ f(x) &= [f1(x), f2(x), \ldots, fn(x)]^T, \\
\text{Find: } X &= (x_i, i = 1, 2, \ldots, m, \\
\text{s.t. } g_j(x) &\leq 0, j = 1, 2, \ldots, n, \\
&\ x \in X, \\
&\ X \in \mathbb{R}^n, 
\end{align*}
\]

where $f(x)$ is the objective function, $g_j(x)$ is the constraint function, $x$ is the design variable, $n$ is the number of design variables, $m$ is the number of constraint conditions, and $\mathbb{R}^n$ is the value range of the design variable during the lower limit and upper limit.

In order to obtain multiple high-quality properties of the honeycomb beam through the adjustment of the structural size. According to this condition, there are multiple objectives. The solution of a multiobjective optimization problem is usually a set of equilibrium solutions [18–20], that is, there is no optimal solution for a multi-objective optimization problem, and all possible solutions are called noninferior solutions, also called Pareto solutions.

The minimax strategy, also called the minimum chance loss decision method, judges the pros and cons of the plan based on the chance loss of each plan. When making decisions, it is safe to adopt a conservative strategy, that is, to seek the best results in the worst case. An evaluation function with weight factors is constructed, which could plan multiple objectives at the same time. Thus, a comprehensive optimal solution for each objective could be obtained. The multi-objective optimization minimax algorithm (MOMA) procedure is shown in Figure 3.

4.2. Optimization Model. Establish an optimization model of the honeycomb beam as follows:

(1) The design variables are the dimension parameters [21, 22] of the beam unit, including the height $H$ of the honeycomb beam, the height $h$ of the web, the width of the honeycomb beam $w$, the width of the web $w$, the side length $a$ of the regular hexagon of the honeycomb hole, and the distance $b$ between two adjacent honeycomb holes. The upper and lower limits of the parameters are 0.01 m and 0.5 m, respectively.

(2) The design constraints should meet the displacement and stress constraints under the transverse and longitudinal overload conditions. Due to the process requirements, the wall thickness of the I-beam section is required to be no less than 0.01 m, and in the honeycomb regular hexagon structure, there are constraints for the side length and web height.

(3) The objective functions are: the total mass $m$ of the structure is the lightest, the warping stiffness $S_q$ is the highest, the torsional stiffness $S_t$ is the highest, and the natural frequency $\omega$ is the highest.
The mathematical model of the above optimization model can be expressed as follows:

\[
\min f(x) = [m, -S_q, -S_t, -\omega]^T,
\]

Find: \( X = (H, h, a, b) \),

s.t.: \( 0.01 < h < H < 0.5 \),

\( 0.01 < a < 0.5 \),

\( 0.01 < b < 0.5 \),

\( \sqrt{5}a < h \). \hfill (15)

4.3. Parameter Optimization Results. After the multi-objective optimization minimax algorithm (MOMA) takes effect, the variables and objective functions continue to modify the parameters iteration speed and parameters optimization process, shown as in Figures 4 and 5. According to multiobjective optimization minimax algorithm (MOMA), the optimized result of honeycomb beams is obtained. Structural parameters are optimized and the results are shown in Tables 1 and 2.

In the optimization, the minimax algorithm of multi-objective optimization problem is used to get the honeycomb beam structure. The optimal values found are all global optimal values within the range that satisfies the constraints, rather than local optimal values, and it also has a high search accuracy. Table 1 is the optimized design variables, and Table 2 is the iterative process of the objective function. The initial values of the objective functions are that the total mass
Figure 4: Variables iteration process: (a) iteration process of $H$, (b) iteration process of $h$, (c) iteration process of $w$, (d) iteration process of $w$, (e) iteration process of $a$, and (f) iteration process of $b$. 
Table 1: Optimization result.

|                          | Before optimization | After optimization |
|--------------------------|---------------------|--------------------|
| Total mass (kg)          | 2.9                 | 2.4                |
| Warping stiffness (N·m³) | $2.0 \times 10^2$   | $1.7 \times 10^3$  |
| Torsional stiffness (N·m) | $1.0 \times 10^9$   | $3.0 \times 10^9$  |
| Natural frequency (Hz)   | $8 \times 10^4$     | $5.2 \times 10^4$  |

Table 2: Parameters optimization results.

| Parameters                                         | Initial value (m) | Optimal results (m) |
|----------------------------------------------------|-------------------|---------------------|
| The height of the honeycomb beam, $H$              | 0.09              | 0.078               |
| The height of the web, $h$                         | 0.06              | 0.072               |
| The width of the honeycomb beam, $w$               | 0.07              | 0.073               |
| The width of the web, $w$                         | 0.098             | 0.048               |
| The side length of the regular hexagon of the honeycomb hole, $a$ | 0.1               | 0.062               |
| Distance between two adjacent honeycomb holes, $b$ | 0.023             | 0.06                |
is 2.9 kg, the warping stiffness is $2.0 \times 10^3 \, \text{N} \cdot \text{m}^4$, torsional stiffness is $1.0 \times 10^2 \, \text{N} \cdot \text{m}$, and natural frequency is $8 \times 10^3 \, \text{Hz}$. The optimization results show that when all the design constraints are satisfied, the total mass of the I-beam element structure is 2.4 kg, which is about 17.2% less than the original structure. The warping stiffness is $1.7 \times 10^2 \, \text{N} \cdot \text{m}^4$, which increases a lot. The torsional stiffness is $3.0 \times 10^3 \, \text{N} \cdot \text{m}$, which also increases a lot. The natural frequency is $5.2 \times 10^3 \, \text{Hz}$. It is about 35% lower than the original structure.

The results show that the mass of the optimized I-shaped honeycomb beam structure has been greatly reduced, and it is possible for the structural performance to improve. It shows that some structural components in the engineering have greater potential for weight reduction as well as improving mechanical performances, and it also shows that the optimization theory is an effective method in the design of an I-shaped honeycomb beam.

### 5. Conclusion

In this paper, the bending, warpage, and torsion of honeycomb beams are analyzed on the basis of reasonable assumptions, and the balance equations are established. The mechanical properties and vibration performances of the honeycomb beam are analyzed. The minimax strategy of multiobjective optimization is applied in honeycomb beam design. It provides a theoretical basis for the structural optimization design of the steel honeycomb beam. The optimized honeycomb beam has a better lightweight and mechanical properties than before.

The optimization results show that when all the design constraints are satisfied, the total mass decreases 17.2% and the warping stiffness and torsional stiffness increase a lot. The natural frequency is 35% lower than the original structure. Geometric variables are trained by a minimax algorithm and the Pareto solution (not the best, acceptable is not the worst) of optimal. Form for single-cell frame structure is obtained to achieve multiobjectives optimization.

The optimization design method provides an effective method for improving the system structure. The optimal configuration of structural properties is obtained by adjusting structural parameters, which provides guidance for the selection and design of material matrix in engineering.

### Data Availability

No data were used to support this study.

### Disclosure

The authors confirm that the content of the manuscript has not been published or submitted for publication elsewhere.

### Conflicts of Interest

There are no potential competing interests in our paper.

### Authors’ Contributions

All the authors have seen the manuscript and approved to submit it to the journal.

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