GROUND-STRUCTURE-BASED TOPOLOGICAL OPTIMIZATION OF BIONIC SANDWICH STRUCTURES WITH HYBRID CORE AND CFRP FACE SHEETS

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ABSTRACT

As one kind of light-weight, high-mechanical-performance composite material, sandwich structure has built solid foundation on its practical application of engineering fields. However, traditional design methods and most relevant structural optimization methods always design sandwich structures considering single constraint, such as constraint of material volume or nodal displacement. Sandwich structures in modern engineering are in highly complex circumstances where strict mechanical, thermal, electromagnetic and functional requirements may be put forward. In this paper, a multi-constraint topology optimization method for sandwich structure with CFRP (Carbon Fibre Reinforced Polymer) face sheets is proposed. The metal core of sandwich structure is optimized based on a ground structure under structural stability constraint, adhesive-area constraint and embedding-volume constraint. In numerical examples, the single-constraint case and the multi-constraint case are both considered, and the results indicate that different conditions of constraints have remarkable influence on the topology of cores of sandwich structure. Sandwich structures with grid core and hybrid core (hybrid of grid core and honeycomb core) can be obtained through topology optimization in single-and multi-constraint cases, respectively.

1 INTRODUCTION

Sandwich structure has widespread application in fields such as architecture, manufacture and aerospace due to its light weight, high strength/stiffness and functionality. General sandwich structure comprises a metal porous core and two face sheets which are always made of CFRP (Carbon Fibre Reinforced Polymer). The thicker, low-density core mainly provides out-plane stiffness for sandwich structure to resist bending deformation, and the thinner, stronger face sheets mainly provide in-plane stiffness fir sandwich structure to resist tension/compression and shear deformation.

In nature, many biological tissues can be found to be similar to sandwich structure [1-3]. For example, periodic vacuoles in grass leaf are clipped between two sheets of epidermal cells as shown in Fig. 1a, and the porous hornbill mouth bone has also similar structure to the foam-core sandwich structure as shown in Fig. 1b. This demonstrates excellent mechanical properties of sandwich structure, and at the same time inspires us to discover more advanced sandwich structure configurations based on the fact that some natural sandwich structure has better properties than others.

More important, present sandwich structures mainly include structures with foam core, honeycomb core, grid core and lattice core all of which are of relative simple forms. However, in modern engineering where the mechanical and multi-physical circumstances structures are in can be very complex, these simple forms of sandwich structure core are always not optimal. Therefore, designing appropriate sandwich structure is a significant problem. In this aspect, topology optimization, which aims finding the material distribution in the design domain to make some property of the structure optimal under designated constraints, can be an effective choice.

Some works relevant to the optimization problem of composite sandwich structure have been done. Taking the weight of fibre-composite structure as the global level objective function, Schmit [4] proposed a multilevel approach to study the optimal sizes of sandwich structure under local/global buckling constraint. In [5], a novel method was proposed to minimize the weight of metal sandwich structures under bending condition, and core/face yielding and buckling constraints are considered. To design functionally graded material in sandwich structures, a layer thickness optimization problem involving two phase materials was studied by Shi and Shimoda [6]. However, the above and most of present works do not consider the change of structural topology and multiple complex constraints, especially the combination of mechanical constraints and functional/physical constraints.

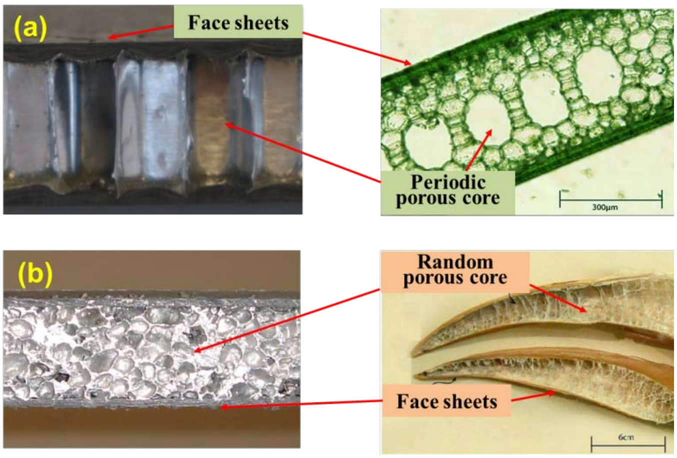

Figure 1: Micro structures of porous-core sandwich structures and biological tissues.
(a) a CFRP/honeycomb sandwich panel and a grass leaf, (b) a CFRP/metal-foam sandwich panel and a pair of hornbill mouth bone.

In the present paper, we develop a topology optimization method considering multiple constraints to optimize the core part of a periodic sandwich structure panel. The unit cell modelled initially by ground structure will be optimized under periodic boundary conditions. The problem takes minimizing solid material of the core part as the optimization objective. Single-constraint and multi-constraint cases including local-buckling, adhesive-area and embedding-volume constraints are considered, respectively.

2 PROBLEM DESCRIPTION

The influence of the CFRP face sheets on the property of sandwich panel is related to their thickness and the laying sequence of carton fiber, so they are not considered in the present topology optimization problem.

During the process of building the computation model of the core part of sandwich panel, three hypotheses should be counted. First, the thickness of the sandwich panel is much small compared with other feature sizes of the panel (e.g., width and length of the panel), thus mechanical variables along thickness of the panel can be regarded as constant and the topology of core part can be represented by a plane model. Second, the sandwich panel is in plane stress state, so the interaction between face sheets and metal core can be neglected. Third, the size of unit cell is relatively small and the number of unit cell is relatively large. In this case, periodic boundary conditions can be imposed.

Since the topology of the core part of sandwich panel is also periodic, only the unit cell needs to be optimized and the topology of the whole core can be obtained by duplicating the topology of the unit cell in the plane. In the present method, ground structure composed of a number of beams and their linkage is adopted to represent the topology of the core.

In this optimization problem, minimization of material weight of ground structure in the unit cell is the objective considering the requirements for lightweight structure in engineering. The objective function can be written as

$$W(\boldsymbol{w}) = \sum_{i=1}^{n_0} \rho w_i l_i t \tag{2.1}$$

where n_0 denotes the number of cell walls, l, t and ρ denote the length, thickness and density of cell wall, respectively. w is the width of cell wall, and is also the design variable. The sensitivity of the objective function $W(\boldsymbol{w})$ with respect to w_i can be expressed as

$$\frac{\partial W(\boldsymbol{w})}{\partial w_i} = \rho_i l_i t. \tag{2.2}$$

In the single-constraint and multi-constraint cases, there are totally three kinds of constraints to be considered: the constraint for local buckling of primary cell walls to ensure the local and global stability of the unit cell structure; the constraint for adhesive areas between face sheets and metal core to ensure enough adhesive strength on the interfaces of different components of sandwich panel; and the constraint for embedding volume to provide space for placing functional materials inside to achieve special functions such as acoustic absorption, wave mediation or heat shielding.

According to buckling equation of compressed bars, the local buckling constraint function can be written as

$$L_1(\boldsymbol{w}) = \sum_{j=1}^{m} \max\left(F_j^c - \frac{\pi^2 E_j w_j^3 t}{12(\lambda l_j)^2},\quad 0\right) \le 0, \tag{2.3}$$

where F_j^c indicates the axial compression of the j-th primary load-bearing cell wall, and the factor λ is chosen as 0.5 here. Then we can get the derivative of Eq. (2.3) with respect to w:

$$\frac{\partial L_1(\boldsymbol{w})}{\partial w_j} = \min\left(-\frac{\pi^2 E_j w_j^2 t}{4(\lambda l_j)^2}, 0\right). \tag{2.4}$$

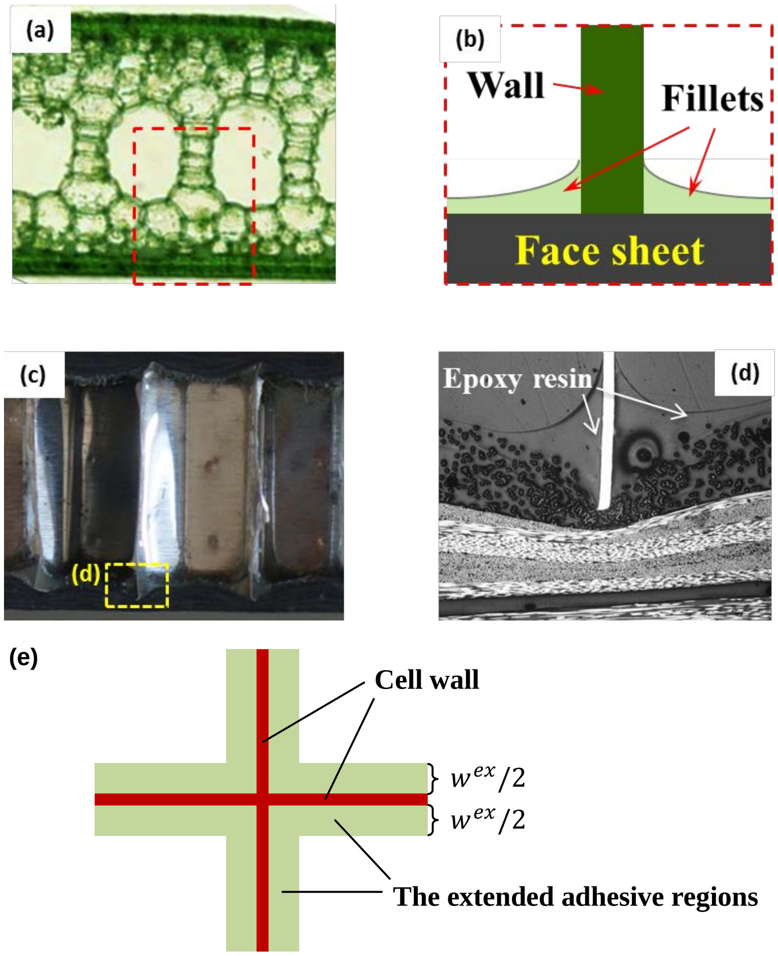

Figure 2: The extended adhesive region caused by the micro "fillet" structure.

The second constraint, namely adhesive area constraint, is critical for sandwich structure from face-core debonding collapse. Adding adhesive materials to interfaces can be effective to help increase the bonding strength between the core and face sheets [7-9]. This treatment also conforms to some natural structures as shown in Fig. 2. The adhesive area includes the contact area of cell wall with face sheet and the extended area caused by the micro "fillet" structure.

$$L_2(\boldsymbol{w}) = \underline{V}^{ad} - \sum_{i=1}^{n_0} l_i(w_i + w^{ex}) \leq 0, \tag{2.5}$$

where $\underline{V}^{ad}$ denotes the lower bound of adhesive area between metal core and one face sheet in the unit cell, and w^{ex} denotes the width of the extended area of cell wall as shown in Fig. 2(e). The derivative of Eq. (2.5) can be obtained in the following form:

$$\frac{\partial L_2(\boldsymbol{w})}{\partial w_i} = -l_i. \tag{2.6}$$

The embedding volume of sandwich structure is defined as the total space of inscribed circles of polygonal rooms enclosed by cell walls, and can be used to fill in functional materials. Therefore, sometimes enough embedding volume is also be regarded as a necessary requirement for material design. The embedding volume constraint can be written as

$$L_3(\boldsymbol{w}) = \underline{V}^{em} - \sum_{k=1}^{p} V_k^{em} \leq 0 \tag{2.7}$$

where $\underline{V}^{em}$ is the lower bound of the embedding volume in the unit cell, and p is the number of closed polygonal rooms in the unit cell. It is worth noting that the volume of those rooms that are open in the unit cell but can be closed in the whole sandwich structure will also be counted. Considering the discontinuity of the embedding volume constraint function, its derivative can be calculated in the following special way:

$$\frac{\partial L_3(\boldsymbol{w})}{\partial w_i} = \left.\frac{L_3(w_i + \Delta w) - L_3(w_i)}{\Delta w}\right|_{\Delta w = -w_i} = \frac{L_3(w_i) - L_3(0)}{w_i}. \tag{2.8}$$

3 NUMERICAL EXAMPLES

This section will provide two examples under the single-constraint condition and multi-constraint condition, respectively. The initial ground structure of the unit cell is shown in Fig. 3. For the sake of simplicity, structural sizes and mechanical data are all dimensionless unless otherwise stated.

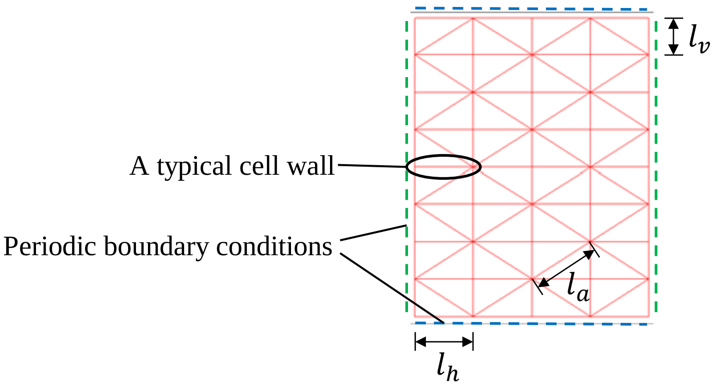

Figure 3: The ground structure of the unit cell.

The lengths of horizontal and vertical cell walls are $l_h = 60$ and $l_v = 20\sqrt{3}$, respectively. The thickness of the core is $t = 50$. The initial width of each cell wall is $w_0 = 1.0$ and the upper bound is $\overline{w} = 5.0$. The elastic modulus and Poisson's ratio are $E = 1.0$ and $\nu = 0.3$, respectively. The density of solid material of the core is $\rho = 0.1$. Periodic boundary conditions are imposed on each side of the unit cell. The horizontal and vertical sides are under uniformly distributed loads with magnitudes $F_h = 70$ and $F_v = 105$, respectively.

In the single-constraint case, only the local buckling constraint is considered. The optimization result is shown in Fig. 4. From the optimized structure, we can see that only part of the horizontal and vertical walls are retained and all of angled walls disappear. This topology of unit cell is just that of grid-core sandwich structure. Since the primary cell walls are the main load-bearing ones, their widths will increase to satisfy the stability constraint.

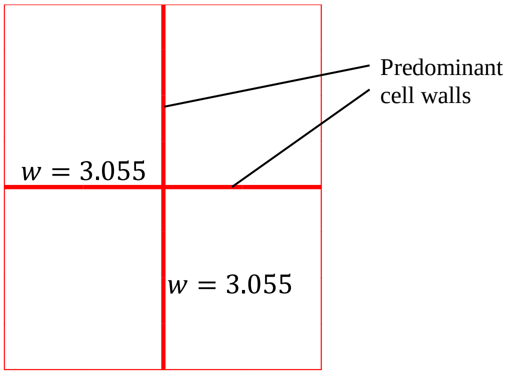

Figure 4: The optimized result in the single-constraint case.

The next example will consider the multiple constraint case and the three constraints introduced in Section 2 (i.e., local buckling, adhesive area and embedding volume constraints) are imposed on the topology optimization problem. Fig. 5 shows the optimized result where hexagonal honeycomb rooms occur except grids in Fig. 4. There are two reasons that account for this phenomenon. On one hand, adhesive area constraint requires more cell walls in the unit cell to enhance the adhesive strength. On the other hand, regular hexagon is the shape whose inscribed circle provides more space for functional material embedding than that of triangle or rectangle. Therefore, the hybrid core (hybrid of grid and honeycomb) is expected to possess both high mechanical and functional properties.

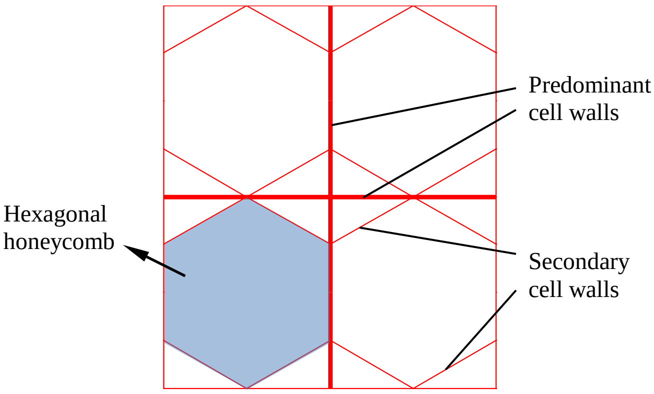

Figure 5: The optimized result in the multi-constraint case.

4 CONCLUDING REMARKS

In the present study, the topology optimization problem of sandwich structure with CFRP face sheets is investigated to improve structural performance under different constraint conditions. By taking the periodic boundary condition into consideration, the optimization can only be carried out on a representative unit cell. By taking structural weight minimization as the optimization objective, the optimized result in the single-constraint case (i.e., only local buckling constraint is considered) is a grid-core sandwich panel. While a grid-honeycomb hybrid core can be obtained when face-core adhesive area and embedding volume constraints are also added. The method developed in the present work can also be used to solve problems where other multiple constraints need to be considered.

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